Dimmings, CWs and other CME-associated activity

Space Weather Live

https://www.spaceweatherlive.com/en.html

Solar Demon **https://www.sidc.be/solardemon/**

Flares, Dimmings and EUV waves event detection

Magnetohydrodynamic (MHD) Waves and Oscillations in the Sun's Corona and MHD Coronal Seismology

Solar Phys. **2021** Topical collection (23 articles)

link.springer.com/journal/11207/topicalCollection/AC_dd43639faf4f387889037783ce77c71b/page/1

Here we use the 195 Å derotated difference images produced by the Novel EIT wave Machine Observing (NEMO) software package (Podladchikova & Berghmans 2005) from **the NEMO EIT Waves and Eruptive Dimmings Catalog.7** https://www.sidc.be/nemo/

From Nitta's Email on 2015.10.06

http://aia.lmsal.com/AIA_Waves/ **AIA (SDO) and EUVI (STEREO-B, STEREO-A)**

http://www.lmsal.com/nitta/movies/AIA_Waves/

http://www.lmsal.com/isolsearch

http://www.lmsal.com/nitta/movies/AIA_Waves/oindex.html

The Nitta's Catalog of AIA Movies and EUVI images for global wave-like disturbances

http://aia.lmsal.com/AIA_Waves/index.html

See Table in ApJ 776 58, ; **2013; File**

http://arxiv.org/pdf/1308.3544v1.pdf

Moreton Waves and EIT Waves Related to the Flare Events of June 3, 2012 and July 6, 2012

A. G. **Admiranto**, R. Priyatikanto, U. Yus'an, E. Puspitaningrum

International Conference on Mathematics and Natural Sciences **2014**

http://arxiv.org/pdf/1502.04039v1.pdf

We present geometrical and kinematical analysis of Moreton waves and EIT waves observed on June 3, 2012 and Moreton waves observed on July 6, 2012. The Moreton waves were recorded in Hα images of Global Oscillation Network Group (GONG) archive and EIT waves obtained from SDO/AIA observations, especially in 193 nm channel. The observed wave of June 3 has angular span of about 70∘ with a broad wave front associated to NOAA active region 11496. It was found that the speed of the wave that started propagating at 17.53 UT is between 950 to 1500 km/s. Related to this wave occurrence, there was solar type II and III radio bursts. The speed of the EIT in this respect about 247 km/sec. On the other hand, the wave of July 6 may be associated to X1.1 class flare that occurred at 23.01 UT around the 11514 active region. From the kinematical analysis, the wave propagated with the initial velocity of about 1180 km/s which is in agreement with coronal shock velocity derived from type II radio burst observation, v∼1200km/s.

Moreton Waves Related to the Flare Event in 3 June 2012 and 6 July 2012

Agustinus Gunawan **Admiranto**, Rhorom Priyatikanto

Journal of the Korean Astronomical Society (http://jkas.kas.org), **2014**

http://arxiv.org/pdf/1408.6677v1.pdf

In this study, we present geometrical and kinematical analysis of Moreton wave observed in 2012 June 3rd and July 6th, recorded in H-α images of Global Oscillation Network Group (GONG) archive. These large-scale waves exhibit different features compared to each other. The observed wave of June 3rd has angular span of about 70 ∘ with a diffuse wave front associated to NOAA active region 11496. It was found that the speed of the wave that started propagating at 17.53 UT is about 931±80 km/s. The broadness nature of this Moreton wave can be interpreted as the vertical extension of the wave over the chromosphere. On the other hand, the wave of July 6th may be associated to X1.1 class flare that occurred at 23.01 UT around the 11515 active region. From the kinematical analysis, the wave propagated with the initial velocity of about 994±70 km/s which is in agreement with coronal shock velocity derived from type II radio burst observation, v∼1100 km/s. These two identified waves add the inventory of the large-scale waves observed in 24th Solar Cycle.

Propagation of a global coronal wave and its interaction with large-scale coronal magnetic structures

A. N. **Afanasyev**, A. N. Zhukov

A&A 614, A139 **2018**

http://sci-hub.tw/10.1051/0004-6361/201731908

Global coronal waves associated with solar eruptions (the so-called EIT waves) often encounter coronal holes and solar active regions and interact with these magnetic structures. This interaction leads to a number of observed effects such as wave reflection and transmission. We consider the propagation of a large-scale coronal shock wave and its interaction with large-scale non-uniformities of the background magnetic field and plasma parameters. Using the Lare2d code, we performed 2.5-dimensional simulations of the interaction of a large-scale single-pulse fast-mode magnetohydrodynamic shock wave of weak-to-moderate intensity with the region of enhanced Alfvén speed as well as with that of reduced Alfvén speed. We analysed simple models of non-uniformity and the surrounding plasma to understand the basic effects in wave propagation. We found the reflected waves of plasma compression and rarefaction, transmitted waves that propagate behind or ahead of the main part of the wave, depending on properties of the plasma non-uniformity, and secondary wave fronts. The obtained results are important to the correct interpretation of the global coronal wave propagation in the solar corona, understanding of theoretical aspects of the interaction of large-scale coronal shock waves with large-scale coronal magnetic structures, and diagnostics of coronal plasma parameters.

Propagation of a fast magnetoacoustic shock wave in the magnetosphere of an active region

A. N. **Afanasyev**, A. M. Uralov, V. V. Grechnev

Astronomy Reports, August **2013**, Volume 57, Issue 8, pp 594-602

Original Russian Text © A.N. Afanasyev, A.M. Uralov, V.V. Grechnev, 2013, published in Astronomicheskii Zhurnal, ***2013****, Vol. 90, No. 8, pp. 648–656.*

The propagation of a fast magnetoacoustic shock wave the magnetosphere of a solar active region is considered the nonlinear geometrical acoustics approximation. The magnetic field is modeled as a subphotospheric magnetic dipole embedded in the radial field of the quiet corona. The initial parameters of the wave are specified at a spherical surface in the depths of the active region. The wave propagates asymmetrically and is reflected from regions of the strong magnetic field, which results in the radiation of the wave energy predominantly upwards. Substantial gradients in the Alfvén speed facilitate appreciable growth in the wave intensity. Non-linear damping of the wave and divergence of the wave front lead to the opposite effect. Analysis of the joint action of these factors shows that a fast magnetoacoustic perturbation outgoing from an active region can correspond to a shock wave of moderate intensity. This supports the scenario in which the primary source of the coronal wave is an eruptive filament that impulsively expands in the magnetosphere of an active region.

Modelling the Propagation of a Weak Fast-Mode MHD Shock Wave near a 2D Magnetic Null Point Using Nonlinear Geometrical Acoustics

A. N. **Afanasyev** and A. M. Uralov

E-print, 28 May, **2012**; Solar Phys. October **2012**, Volume 280, Issue 2, pp 561-574

We present the results of analytical modelling of fast-mode magnetohydrodynamic wave propagation near a 2D magnetic null point. We consider both a linear wave and a weak shock and analyse their behaviour in cold and warm plasmas. We apply the nonlinear geometrical acoustics method based on the Wentzel-Kramers-Brillouin approximation. We calculate the wave amplitude, using the ray approximation and the laws of solitary shock wave damping. We find that a complex caustic is formed around the null point. Plasma heating is distributed in space and occurs at a caustic as well as near the null point due to substantial nonlinear damping of the shock wave. The shock wave passes through the null point even in a cold plasma. The complex shape of the wave front can be explained by the caustic pattern.

Coronal Shock Waves, EUV Waves, and Their Relation to CMEs. II. Modeling MHD Shock Wave Propagation Along the Solar Surface, Using Nonlinear Geometrical Acoustics

A. N. **Afanasyev** and A. M. Uralov

Solar Physics, Volume 273, Number 2, 479-491, **2011**

We model the propagation of a coronal shock wave, using nonlinear geometrical acoustics. The method is based on the Wentzel–Kramers–Brillouin (WKB) approach and takes into account the main properties of nonlinear waves: i) dependence of the wave front velocity on the wave amplitude, ii) nonlinear dissipation of the wave energy, and iii) progressive increase in the duration of solitary shock waves. We address the method in detail and present results of the modeling of the propagation of shock-associated extreme-ultraviolet (EUV) waves as well as Moreton waves along the solar surface in the simplest solar corona model. The calculations reveal deceleration and lengthening of the waves. In contrast, waves considered in the linear approximation keep their length unchanged and slightly accelerate.

AN AUTOMATIC DETECTION METHOD FOR EXTREME-ULTRAVIOLET DIMMINGS ASSOCIATED WITH SMALL-SCALE ERUPTION

N. **Alipour**1, H. Safari1 and D. E. Innes

2012 ApJ 746 12, **File**

Small-scale extreme-ultraviolet (EUV) dimming often surrounds sites of energy release in the quiet Sun. This paper describes a method for the automatic detection of these small-scale EUV dimmings using a feature-based classifier. The method is demonstrated using sequences of 171 Å images taken by the STEREO/Extreme UltraViolet Imager (EUVI) on **2007 June 13** and by Solar Dynamics Observatory/Atmospheric Imaging Assembly on **2010 August 27**. The feature identification relies on recognizing structure in sequences of space-time 171 Å images using the Zernike moments of the images. The Zernike moments space-time slices with events and non-events are distinctive enough to be separated using a support vector machine (SVM) classifier. The SVM is trained using 150 events and 700 non-event space-time slices. We find a total of 1217 events in the EUVI images and 2064 events in the AIA images on the days studied. Most of the events are found between latitudes –35° and +35°. The sizes and expansion speeds of central dimming regions are extracted using a region grow algorithm. The histograms of the sizes in both EUVI and AIA follow a steep power law with slope of about –5. The AIA slope extends to smaller sizes before turning over. The mean velocity of 1325 dimming regions seen by AIA is found to be about 14 km s–1.

ON THE NATURE OF DARK EXTREME ULTRAVIOLET STRUCTURES SEEN BY *SOHO/EIT AND TRACE*

U. **Anzer**, P. Heinzel

The Astrophysical Journal, 622:714–721, **2005**, file

On the nature of transverse coronal waves revealed by wavefront dislocations

A. López **Ariste**, M. Luna, I. Arregui, E. Khomenko, M. Collados

A&A 579, A127 **2015**

http://arxiv.org/pdf/1505.03348v1.pdf

Coronal waves are an important aspect of the dynamics of the plasma in the corona. Wavefront dislocations are topological features of most waves in nature and also of magnetohydrodynamic waves. Are there dislocations in coronal waves? The finding and explanation of dislocations may shed light on the nature and characteristics of the propagating waves, their interaction in the corona and in general on the plasma dynamics. We positively identify dislocations in coronal waves observed by the Coronal Multi-channel Polarimeter (CoMP) as singularities in the Doppler shifts of emission coronal lines. We study the possible singularities that can be expected in coronal waves and try to reproduce the observed dislocations in terms of localization and frequency of appearance. The observed dislocations can only be explained by the interference of a kink and a sausage wave modes propagating with different frequencies along the coronal magnetic field. In the plane transverse to the propagation, the cross-section of the oscillating plasma must be smaller than the spatial resolution, and the two waves result in net longitudinal and transverse velocity components that are mixed through projection onto the line of sight. Alfv\'en waves can be responsible of the kink mode, but a magnetoacoustic sausage mode is necessary in all cases. Higher (flute) modes are excluded. The kink mode has a pressure amplitude that is smaller than the pressure amplitude of the sausage mode, though its observed velocity is larger. This concentrates dislocations on the top of the loop. To explain dislocations, any model of coronal waves must include the simultaneous propagation and interference of kink and sausage wave modes of comparable but different frequencies, with a sausage wave amplitude much smaller than the kink one.

DETERMINATION OF TRANSVERSE DENSITY STRUCTURING FROM PROPAGATING MAGNETOHYDRODYNAMIC WAVES IN THE SOLAR ATMOSPHERE

I. **Arregui**1,2, A. Asensio Ramos1,2, and D. J. Pascoe

2013 ApJ 769 L34

We present a Bayesian seismology inversion technique for propagating magnetohydrodynamic transverse waves observed in coronal waveguides. The technique uses theoretical predictions for the spatial damping of propagating kink waves in transversely inhomogeneous coronal waveguides. It combines wave amplitude damping length scales along the waveguide with theoretical results for resonantly damped propagating kink waves to infer the plasma density variation across the oscillating structures. Provided that the spatial dependence of the velocity amplitude along the propagation direction is measured and the existence of two different damping regimes is identified, the technique would enable us to fully constrain the transverse density structuring, providing estimates for the density contrast and its transverse inhomogeneity length scale.

First Simultaneous Observation of H-alpha Moreton Wave, EUV Wave, and Filament/Prominence Oscillations

Asai, A., Ishii, T.T., Kitai R., Ichimoto, K., UeNo, S., Nagata, S., Morita, S., Nishida, K., Shiota, D., Oi, A., Akioka, M., Shibata, K.

E-print, Dec 2011**;** ApJL **2012** 745 L18; **File**

We report on the first simultaneous observation of an Hα Moreton wave, the corresponding EUV fast coronal waves, and a slow and bright EUV wave (typical EIT wave). Associated with an X6.9 flare that occurred on **2011 August 9** at the active region NOAA 11263, we observed a Moreton wave in the Hα images taken by the Solar Magnetic Activity Research Telescope (SMART) at Hida Observatory of Kyoto University. In the EUV images obtained by the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamic Observatory (SDO) we found not only the corresponding EUV fast ``bright'' coronal wave, but also the EUV fast ``faint'' wave that is not associated with the Hα Moreton wave. We also found a slow EUV wave, which corresponds to a typical EIT wave. Furthermore, we observed, for the first time, the oscillations of a prominence and a filament, simultaneously, both in the Hα and EUV images. To trigger the oscillations by the flare-associated coronal disturbance, we expect a coronal wave as fast as the fast-mode MHD wave with the velocity of about 570 - 800 km/s. These velocities are consistent with those of the observed Moreton wave and the EUV fast coronal wave.

STRONGLY BLUESHIFTED PHENOMENA OBSERVED WITH HINODE EIS IN THE 2006 DECEMBER 13 SOLAR FLARE

Ayumi **Asai**,1, 2,3 Hirohisa Hara,2,3 Tetsuya Watanabe,2,3 Shinsuke Imada,2 Taro Sakao,4 Noriyuki Narukage,4 J. L. Culhane,5 and G. A. Doschek6

Astrophysical Journal, 685:622-628, **2008**

http://www.journals.uchicago.edu/doi/pdf/10.1086/590419

We present a detailed examination of strongly blueshifted emission lines observed with the EUV Imaging Spectrometer on board the Hinode satellite. We found two kinds of blueshifted phenomenon associated with the X3.4 flare that occurred on 2006 December 13. One was related to a plasmoid ejection seen in soft X-rays. It was very bright in all the lines used for the observations. The other was associated with the faint arc-shaped ejection seen in soft X-rays. The soft X-ray ejection is thought to be a magnetohydrodynamic (MHD) fast-mode shock wave. This is therefore the first spectroscopic observation of an MHD fast-mode shock wave associated with a flare.

Global Energetics of Solar Flares: VI. Refined Energetics of Coronal Mass Ejections

Markus J. **Aschwanden**

ApJ **2017**

https://arxiv.org/pdf/1704.01993.pdf

In this study we refine a CME model presented in an earlier study on the global energetics of solar flares and associated CMEs, and apply it to all (860) GOES M- and X-class flare events observed during the first 7 years (2010-2016) of the Solar Dynamics Observatory (SDO) mission, which doubles the statistics of the earlier study. The model refinements include: (1) the CME geometry in terms of a 3D sphere undergoing self-similar adiabatic expansion; (2) the inclusion of solar gravitational deceleration during the acceleration and propagation of the CME, which discriminates eruptive and confined CMEs; (4) a self-consistent relationship between the CME center-of-mass motion detected during EUV dimming and the leading-edge motion observed in white-light coronagraphs; (5) the equi-partition of the CME kinetic and thermal energy; and (6) the Rosner-Tucker-Vaiana (RTV) scaling law. The refined CME model is entirely based on EUV dimming observations (using AIA/SDO data) and complements the traditional white-light scattering model (using LASCO/SOHO data), and both models are independently capable to determine fundamental CME parameters such as the CME mass, speed, and energy. Comparing the two methods we find that: (1) LASCO is less sensitive than AIA in detecting CMEs (in 24% of the cases); (2) CME masses below mcme~1014 g are under-estimated by LASCO; (3) AIA and LASCO masses, speeds, and energy agree closely in the statistical mean after elimination of outliers; (4) the CMEs parameters of the speed v, emission measure-weighted flare peak temperature Te, and length scale L are consistent with the following scaling laws (derived from first principles): v∝T1/2e, v∝(mcme)1/4, and mcme∝L2.

Global Energetics of Solar Flares: IV. Coronal Mass Ejection Energetics

Markus J. **Aschwanden**

ApJ **2016**

http://arxiv.org/pdf/1605.04952v1.pdf **File**

http://www.lmsal.com/~aschwand/eprints/2016_global4.pdf

This study entails the fourth part of a global flare energetics project, in which the mass mcme, kinetic energy Ekin, and the gravitational potential energy Egrav of coronal mass ejections (CMEs) is measured in 399 M and X-class flare events observed during the first 3.5 yrs of the Solar Dynamics Observatory (SDO) mission, using a new method based on the EUV dimming effect. The EUV dimming is modeled in terms of a radial adiabatic expansion process, which is fitted to the observed evolution of the total emission measure of the CME source region. The model derives the evolution of the mean electron density, the emission measure, the bulk plasma expansion velocity, the mass, and the energy in the CME source region. The EUV dimming method is truly complementary to the Thomson scattering method in white light, which probes the CME evolution in the heliosphere at r>2R⊙, while the EUV dimming method tracks the CME launch in the corona. We compare the CME parameters obtained in white light with the LASCO/C2 coronagraph with those obtained from EUV dimming with the Atmospheric Imaging Assembly (AIA) onboard SDO for all identical events in both data sets. We investigate correlations between CME parameters, the relative timing with flare parameters, frequency occurrence distributions, and the energy partition between magnetic, thermal, nonthermal, and CME energies. CME energies are found to be systematically lower than the dissipated magnetic energies, which is consistent with a magnetic origin of CMEs. **2010-10-16, 2010-06-12, 2011-05-29, 2011-08-02, 2011-09-24, 2011-09-28, 2011-11-09, 2012-01-27, 2012-03-10, 2012-03-13, 2012-06-06, 2012-07-05, 2012-07-19, 2012-08-11, 2012-09-09, 2012-11-13, 2013-05-22, 2013-08-17, 2013-10-24, 2013-11-01, 2013-11-03, 2013-11-06, 2013-11-19, 2014-01-07**

Table 3. Temporal and spatial parameters of the first 10 entries (out of the 399 events) listed in the complete machine-readable data file.

Table 4. CME parameters of the first 10 entries (out of the 399 events) listed in the complete machine-readable data file.

3D Reconstruction of Active Regions with STEREO (Invited Review)

Markus J. **Aschwanden** and Jean-Pierre Wuelser

E-print, Feb **2010,** J. Atmos. Solar-Terr. Physics,

We review data analysis and physical modeling related to the 3D reconstruction of active regions in the solar corona, using stereoscopic image pairs from the STEREO/EUVI instrument. This includes the 3D geometry of coronal loops (with measurements of the loop inclination plane, coplanarity, circularity, and hydrostaticity), the 3D electron density and temperature distribution (which enables diagnostics of hydrostatic, hydrodynamic, and heating processes), the 3D magnetic field (independent of any theoretical model based on photospheric extrapolations), as well as the 3D reconstruction of CME phenomena, such as EUV dimming, CME acceleration, CME bubble expansion, and associated Lorentz forces that excite MHD kink-mode oscillations in the surroundings of a CME launch site. The mass of CMEs, usually measured from white-light coronagraphs, can be determined independently from the EUV dimming in the CME source region. The full 3D density and temperature structure of an active region can be reconstructed in unprecedented detail with instant stereoscopic tomography.

2. 3D Geometry of Active Regions
3. 3D Density Reconstruction of Active Regions
4. 3D Temperature Diagnostics of Active Regions
5. 3D Magnetic Field Modeling of Active Regions
6. **3D Reconstruction of EUV Dimming and CME mass**
7. 3D Motion of Loop Oscillations and Waves

Solar Image Processing Techniques with Automated Feature Recognition (Invited Review)

Markus J. **Aschwanden**

E-print, May **2009, File**, Solar Phys.

We present a comprehensive and systematic overview of image processing techniques of solar data that use automated feature detection algorithms. We discuss the aspects of: (1) image pre-processing procedures; (2) automated detection of spatial features; (3) automated detection and tracking of temporal features (events); and (4) post-processing tasks, such as visualization of solar imagery, cataloguing, statistics, theoretical modeling, prediction and forecasting. For each aspect we highlight the most recent developments and science results. We conclude with an outlook on future trends.

4D-Modeling of CME Expansion and EUV Dimming with Fitting to STEREO/EUVI Observations

Markus J. **Aschwanden**

E-print, June **2009**; Annales Geophysicae, 27, 3275-3286, **2009, File**

This is the first attempt to model the kinematics of a CME launch and the resulting EUV dimming quantitatively with a self-consistent model. Our 4D-model assumes self-similar expansion of a spherical CME geometry that consists of a CME front with density compression and a cavity with density rarefaction, satisfying mass conservation of the total CME and swept-up corona. The model contains 12 free parameters and is fitted to the **2008 March 25**, 18:30 UT, CME event observed with STEREO/A and B. Our model is able reproduce the observed CME expansion and related EUV dimming during the initial phase from 18:30 UT to 19:00 UT. The CME kinematics can be characterized by a constant acceleration (i.e., a constant magnetic driving force). While the observations of EUVI/A are consistent with a spherical bubble geometry, we detect significant asymmetries and density inhomogeneities with EUVI/B. This new forward-modeling method demonstrates how the observed EUV dimming can be used to model physical parameters of the CME source region, the CME geometry, and CME kinematics.

First Measurements of the Mass of Coronal Mass Ejections from the EUV Dimming Observed with STEREO EUVI A+B Spacecraft

Markus J. **Aschwanden**, Nariaki V. Nitta, Jean-Pierre Wuelser, James R. Lemen, Anne Sandman, Angelos Vourlidas, Robin C. Colaninno

E-print, April **2009, File**, ApJ

The masses of CoronalMass Ejections (CMEs) have traditionally been determined from whitelight coronagraphs, based on the Thomson scattering of electrons, which depends on the (generally unknown) angle of the CME propagation direction. Here we develop a new method of measuring CME masses from the EUV dimming seen with EUV imaging telescopes in multiple temperature filters. As a test we investigate 8 CME events with previous mass determinations from STEREO/COR2, of which 5 cases are fully detected with EUVI, 2 partially, and 1 not, using an automated multi-wavelength detection code. We find CME masses in the range of mCME = (2 − 7) Ч 1015 g. The agreement between the two EUVI/A and B spacecraft is mA/mB = 1.3 ± 0.6 and the consistency with white-light measurements by COR2 is mEUV I/mCOR2 = 1.1 ± 0.3. The consistency between EUVI and COR2 implies no significant mass backflows (or inflows) at r < 4R⊙ and adequate temperature coverage for the bulk of the CME mass in the range of T ≈ 0.5 − 3.0 MK. The temporal evolution of the EUV dimming allows us also to model the evolution of the CME density ne(t), volume V (t), height-time h(t), and propagation speed v(t) in terms of an adiabatically expanding self-similar geometry. We determine e-folding EUV dimming times of _dim = 1.3±1.4 hr. We test the adiabatic expansion model in terms of the predicted detection delay (_t ≈ 0.7 hr) between EUVI and COR2 for the fastest CME event (2008-Mar-25) and find good agreement with the observed delay (_t ≈ 0.8 hr).

Solar Flare and CME Observations with STEREO/EUVI

M.J. **Aschwanden**, · J.P. Wuelser, N.V. Nitta, · J.R. Lemen1

E-print, Dec **2008**, File; Solar Phys.

STEREO/EUVI observed 185 flare events (detected above the GOES class C1 level or at >25 keV with RHESSI) during the first two years of the mission (Dec 2006 - Nov 2008), while coronal mass ejections (CME) were reported in about a third of these events. We compile a **comprehensive catalog of these EUVI-observed events**, containing the peak fluxes in soft X-rays, hard X-rays, and EUV, as well as a classification and statistics of prominent EUV features: 79% show impulsive EUV emission (coincident with hard X-rays), 73% show delayed EUV emission from postflare loops and arcades, 24% represent occulted flares, 17% exhibit EUV dimming, 5% show loop oscillations or propagating waves, and at least 3% show erupting filaments. We analyze an example of each EUV feature by stereoscopic modeling of their 3D geometry. We find that impulsive EUV emission indicates compression of cold coronal plasma during the flare energy release, in contrast to the delayed postflare EUV emission that results from cooling of the soft X-ray emitting flare loops. Occulted flares allow us to determine CME-related coronal dimming uncontaminated from flare-related EUV emission. From modeling the time evolution of EUV dimming we can accurately quantify the initial expansion of CMEs and determine their masses. Further we find evidence that coronal loop oscillations are excited by the rapid initial expansion of CMEs. These examples demonstrate that stereoscopic

EUV data provide powerful new methods to model the 3D aspects in the hydrodynamics of flares and kinematics of CMEs.

Impulsive Phenomena of the Solar Atmosphere.
I. Some Optical Events Associated with Flares Showing Explosive Phase.

Athay, R.G., Moreton, G.E.,
1961. Astrophys. J. 133, 935–945.

Extreme-ultraviolet Observations of Global Coronal Wave Rotation

G. D. R. **Attrill**1, D. M. Long2, L. M. Green2, L. K. Harra2, and L. van Driel-Gesztelyi
2014 ApJ 796 55

We present evidence of global coronal wave rotation in EUV data from SOHO/EIT, STEREO/EUVI, and SDO/AIA. The sense of rotation is found to be consistent with the helicity of the source region (clockwise for positive helicity, anticlockwise for negative helicity), with the source regions hosting sigmoidal structures. We also study two coronal wave events observed by SDO/AIA where no clear rotation (or sigmoid) is observed. The selected events show supporting evidence that they all originate with flux rope eruptions. We make comparisons across this set of observations (both with and without clear sigmoidal structures). On examining the magnetic configuration of the source regions, we find that the nonrotation events possess a quadrupolar magnetic configuration. The coronal waves that do show a rotation originate from bipolar source regions.

DISPELLING ILLUSIONS OF REFLECTION: A NEW ANALYSIS OF THE 2007 MAY 19 CORONAL “WAVE” EVENT

Gemma D. R. **Attrill**
Astrophysical Journal, 718:494–501, **2010** July, **File**

A new analysis of the **2007 May 19** coronal wave–coronal mass ejection–dimmings event is offered employing base difference extreme-ultraviolet (EUV) images. Previous work analyzing the coronal wave associated with this event concluded strongly in favor of purely an MHD wave interpretation for the expanding bright front. This conclusion was based to a significant extent on the identification of multiple reflections of the coronal wave front. The analysis presented here shows that the previously identified “reflections” are actually optical illusions and result from a misinterpretation of the running difference EUV data. The results of this newmultiwavelength analysis indicate that two coronalwave fronts actually developed during the eruption. This newanalysis has implications for our understanding of diffuse coronal waves and questions the validity of the analysis and conclusions reached in previous studies.

Revealing the Fine Structure of Coronal Dimmings and Associated Flows with *Hinode*/EIS Implications for Understanding the Source Regions of Sustained Outflow Following CMEs

G.D.R. **Attrill** · L.K. Harra · L. van Driel-Gesztelyi · M.J. Wills-Davey
Solar Phys (**2010**) 264: 119–147, **File**

We study two CME events on **13 and 14 December 2006** that were associated with large-scale dimmings. We study the eruptions from pre-event on 11 December through the recovery on 15 December, using a combination of *Hinode*/EIS, SOHO/EIT, SOHO/MDI, and MLSO H〈 data. The GOES X-class flares obscured the core dimmings, but secondary dimmings developed remote from the active region (AR) in both events. The secondary dimmings are found to be formed by a removal of bright coronal material from loops in the plage region to the East of the AR. Using *Hinode*/EIS data, we find that the outflows associated with the coronal-dimming regions are highly structured. The concentrated outflows are located at the footpoints of coronal loops (which exist before, and are re-established after, the eruptions), and these are correlated with regions of positive magnetic elements. Comparative study of the *Hinode*/EIS and SOHO/EIT data shows that the reduction in out-flow velocity is consistent with the recovery in intensity of the studied regions. We find that concentrated downflows develop during the recovery phase of the dimmings and are also correlated with the same positive magnetic elements that were previously related to outflows.
The local behaviour of the flows in and around the dimming regions following the eruptions is found to be dynamic and complex. Despite the global aspects of these events (wide-spread dimmings, CMEs, coronal waves) being largely homologous, there are significant local variations and distinct differences between the flows associated with the two events.

We find that the secondary dimmings recover primarily by re-establishment of the bright coronal loops (the exact configuration changes between the eruptions, which is reflected by the complexity of the flows).

Automatic Detection and Extraction of Coronal Dimmings from SDO/AIA Data

G. D. R. **Attrill** and M. J. Wills-Davey

E-print, Aug, 2009; Solar Phys., 262(2), 461-480, **2010**, **File**

The volume of data anticipated from the Solar Dynamics Observatory/Atmospheric Imaging Assembly (SDO/AIA) highlights the necessity for the development of automatic-detection methods for various types of solar activity. Initially recognised in the 1970s it is now well established that coronal dimmings are closely associated with coronal mass ejections (CMEs), and are particularly noted as a reliable indicator of front-side (halo) CMEs, which can be difficult to detect in white-light coronagraph data. Existing work clearly demonstrates that several properties derived from analysis of coronal dimmings can give useful information about the associated CME. The development and implementation of an automated coronal dimming region detection and extraction algorithm removes visual observer bias, however unintentional, from determination of physical quantities such as spatial location, area, and volume. This allows for reproducible, quantifiable results to be mined from very large datasets. The information derived may facilitate more reliable early space weather detection, as well as offering the potential for conducting large-sample studies focused on determining the geoeffectiveness of CMEs, coupled with analysis of their associated coronal dimming signatures. In this paper we present examples of both simple and complex dimming events extracted using our algorithm, which will be run as a module for the SDO/Computer Vision Centre. Contrasting and well-studied events at both the minimum and maximum of solar cycle 23 are identified in Solar and Heliospheric Observatory/Extreme ultra-violet Imaging Telescope (SOHO/EIT) data. A more recent example extracted from Solar and Terrestrial Relations Observatory/Extreme Ultra-Violet Imager (STEREO/EUVI) data is also presented, demonstrating the potential for the anticipated application to SDO/AIA data. The detection part of our algorithm is based largely on the principle of operation of the NEMO software, namely detection of significant variation in the statistics of the EUV image pixels (Podladchikova & Berghmans, 2005). As well as running on historic datasets, the presented algorithm is capable of detecting and extracting coronal dimmings in near real-time.

*HINODE/*XRT AND *STEREO* OBSERVATIONS OF A DIFFUSE CORONAL "WAVE"–CORONAL MASS EJECTION–DIMMING EVENT

Gemma D. R. **Attrill**, Alexander J. Engell, Meredith J. Wills-Davey, Paolo Grigis, and Paola Testa

Astrophysical Journal, 704:1296–1308, **2009** October; **File**

We report on observations of the first diffuse coronal wave detected by *Hinode/*XRT. The event occurred near the west solar limb on **2007 May 23**, originating from active region (AR) 10956 and was associated with a coronal mass ejection (CME) and coronal dimmings. The bright emission forming the coronal wave expanded predominantly to the east and south of the AR. We use X-Ray Telescope (XRT) and *STEREO Behind* (*B*) data combined with a potential magnetic field extrapolation to derive an understanding of the global magnetic field connectivity. We attribute the brightening to the east of the AR to compression and channeling of the plasma along large-scale loops. The brightening to the south of the AR expands across the quiet Sun, making the southern component a likely candidate for identification as a diffuse coronal wave. We analyze the bright front in *STEREO/*EUVI (*B*) 171, 195, and 284 Å images, as well as in XRT data, finding the strongest components to be largely cospatial in all bandpasses. We also exploit the near-limb location of this event by combining *STEREO/*COR1 and Extreme Ultra-Violet Imaging Telescope (EUVI) data. Using all the data, we derive a full picture of the low-coronal development of the eruption. The COR1 data show that the southernmost outer edge of the CME is progressively displaced southward during the expansion. EUVI data below the COR1 occulting disk show that the CME is significantly distorted in the low corona as a result of the associated filament eruption. The core coronal dimmings map to the core of the CME; the secondary coronal dimmings map to the CME cavity; and the diffuse coronal wave maps to the outermost edge of the expanding CME shell. The analysis of this near-limb event has important implications for understanding earlier eruptions originating from the same AR on 2007 May 16, 19, and 20.

The Recovery of CME-Related Dimmings and the ICME's Enduring Magnetic Connection to the Sun

G.D.R. **Attrill**· L. van Driel-Gesztelyi1·P. D´emoulin· A.N. Zhukov,· K. Steed, L.K. Harra· C.H. Mandrini6· J. Linker7

E-print, July; Solar Phys. 252: 349–372, **2008**, **File**

It is generally accepted that transient coronal holes (TCHs, dimmings) correspond to the magnetic footpoints of CMEs that remain rooted in the Sun as the CME expands out into the interplanetary space. However, the observation that the average intensity of the **12 May 1997** dimmings recover to their pre-eruption intensity in SOHO/EIT data within 48 hours, whilst suprathermal uni-directional electron heat fluxes are observed at 1 AU in the related ICME more than 70 hours after the eruption, leads us to question why and how the dimmings disappear whilst the magnetic connectivity is maintained. We also examine two other CME-related dimming events: **13 May 2005 and 6 July 2006**. We study the morphology of the dimmings and how they recover. We find that, far from exhibiting a uniform intensity, dimmings observed in SOHO/EIT data have a deep central core and a more shallow extended dimming area. The dimmings recover not only by shrinking of their outer boundaries but also by internal brightenings. We quantitatively demonstrate that the model developed by Fisk and Schwadron (Astrophys. J. 560, 425, 2001) of interchange reconnections between "open" magnetic field and small coronal loops, is a strong candidate for the mechanism facilitating the recovery of the dimmings. This process disperses the concentration of "open" magnetic field (forming the dimming) out into the surrounding quiet Sun, thus recovering the intensity of the dimmings whilst still maintaining the magnetic connectivity to the Sun.

1.2. How are Coronal Dimmings Related to Interplanetary Observations?

1.3. Questions Concerning the Relationship Between Dimmings and ICMEs

Low Coronal Signatures of Coronal Mass Ejections:
Coronal "waves" and dimmings

Gemma Diana Ruth **Attrill**

Thesis, **2008, File**

Coronal "Wave": Magnetic Footprint of a Coronal Mass Ejection?

Gemma D. R. **Attrill**, Louise K. Harra, Lidia van Driel-Gesztelyi, and Pascal Demoulin

The Astrophysical Journal Letters, Volume 656, Number 2, Page L101-104, **2007**.

[http://www.journals.uchicago.edu/cgi-bin/resolve?ApJL21209]

We observe deep core dimmings near the flare site and also widespread diffuse dimming, accompanying the expansion of the EIT wave. We also report a new property of these EIT waves, namely, that they display dual brightenings: persistent ones at the outermost edge of the core dimming regions and simultaneously diffuse brightenings constituting the leading edge of the coronal wave, surrounding the expanding diffuse dimmings. We show that such behavior is consistent with a diffuse EIT wave being the magnetic footprint of a CME. We propose a new mechanism where driven magnetic reconnections between the skirt of the expanding CME magnetic field and quiet-Sun magnetic loops generate the observed bright diffuse front.

Coronal "Wave": a signature of the mechanism making CMEs large-scale in the low corona?

G.D.R. **Attrill**, L.K. Harra, L. van Driel-Gesztelyi, P. Demoulin & J.P. Wulser

Astronomische Nachrichten, E- print, April **2007**

We analyse one of the first coronal waves observed by STEREO/EUVI associated with a source region just behind the limb, NOAA 10940. We apply the coronal ?wave? model proposed by Attrill et al. (2007) to explain the evolution of the observed bright fronts, thereby arguing that the bright fronts and dimmings are due to magnetic reconnections between the expanding CME core and surrounding magnetic structures. We offer a discussion showing that this model provides a mechanism via which CMEs, expanding from a small source region can naturally become large-scale in the low corona.

USING THE EVOLUTION OF CORONAL DIMMING REGIONS TO PROBE THE GLOBAL MAGNETIC FIELD TOPOLOGY

"Unidentical Twins": A new interpretation of the **12 May 1997** event

G. **ATTRILL**, M.S. NAKWACKI2, L.K.HARRA1,

L. van DRIEL-GESZTELYI1;3;4, C.H.MANDRINI2, S.DASSO2;5,

J. WANG

Solar Physics, Volume 238 Number 1, p. 117-139, **2006**. E-print file

We demonstrate that study of the evolving magnetic nature of coronal dimming regions can be used to probe the large-scale magnetic structure involved in the eruption of a coronal mass ejection (CME). We analyse the intensity evolution of coronal dimming regions using 195 _A data from the Extreme Ultra-Violet Imaging Telescope (EIT) on board the Solar and Heliospheric Observatory (SOHO). We measure the magnetic flux, using data from the SOHO/Michelson Doppler Imager (MDI), in the regions that seem most likely to be related to plasma removal. Then, we compare these magnetic flux measurements to the flux in the associated magnetic cloud (MC). Here we present our analysis of the well-studied event on 12 May 1997, that took place just after solar minimum in a simple magnetic configuration. We present a synthesis of results already published and propose that driven \interchange reconnection" between the expanding CME structure with \open" _eld lines of the northern coronal hole region led to the asymmetric temporal and spatial evolution of the two main dimming regions, associated with this event. As a result of this reconnection process, we _nd the southern-most dimming region to be the principal foot-point of the MC. The magnetic ux from this dimming region and that of the MC are found to be in close agreement within the same order of magnitude: 10^{21} Mx.

MAGNETIC FIELDS AND INTENSITY CHANGES IN CORONAL DIMMING REGIONS
G.D.R. **Attrill**, N. Narukage(2), K. Shibata(2), L.K. Harra(1)
ESA SP-596, November ***2005****), file*

TRACE observations of driven loop oscillations

I. **Ballai**1, D. B. Jess2 and M. Douglas
A&A 534, A13 (**2011**)
Aims. On **13 June 1998**, the TRACE satellite was fortuitously well placed to observe the effects of a flare-induced **EIT wave** in the corona, and its subsequent interaction with coronal magnetic **loops**. In this study, we use these TRACE observations to corroborate previous theoretical work, which determined the response of a coronal loop to a harmonic driver in the context of ideal magnetohydrodynamics, as well as estimate the magnetic field strength and the degree of longitudinal inhomogeneity.
Methods. Loop edges are tracked, both spatially and temporally, using wavelet modulus maxima algorithms, with corresponding loop displacements from its quiescent state analysed by fitting scaled sinusoidal functions. The physical parameters of the coronal loop are subsequently determined using seismological techniques.
Results. The studied coronal loop is found to oscillate with two distinct periods, 501 ± 5 s and 274 ± 7 s, which could be interpreted as belonging to the fundamental kink mode and first harmonic, or could reflect the stage of an overdriven loop. Additional scenarios for explaining the two periods are listed, each resulting in a different value of the magnetic field and the intrinsic and sub-resolution properties of the coronal loop. When assuming the periods belong to the fundamental kink mode and its first harmonic, we obtain a magnetic field strength inside the oscillating coronal loop of 2.0 ± 0.7 G. In contrast, interpreting the oscillations as a combination of the loop's natural kink frequency and a harmonic EIT wave provides a magnetic field strength of 5.8 ± 1.5 G. Using the ratio of the two periods, we find that the gravitational scale height in the loop is 73 ± 3 Mm.
Conclusions. We show that the observation of two distinct periods in a coronal loop does not necessarily lead to a unique conclusion. Multiple plausible scenarios exist, suggesting that both the derived strength of the magnetic field and the sub-resolution properties of the coronal loop depend entirely on which interpretation is chosen. The interpretation of the observations in terms of a combination of the natural kink mode of the coronal loop, driven by a harmonic EIT wave seems to result in values of the magnetic field consistent with previous findings. Other interpretations, which are realistic, such as kink fundamental mode/first harmonic and the oscillations of two sub-resolution threads result in magnetic field strengths that are below the average values found before.

Forced oscillations of coronal loops driven by EIT waves:

I. **Ballai**, M. Douglas and A. Marcu
A&A 488 (**2008**) 1125-1132
http://www.aanda.org/10.1051/0004-6361:200809833
Aims. We study the generation of transversal oscillations in coronal loops represented as a straight thin flux tube under the effect of an external driver modelling the global coronal EIT wave. We investigate how the generated oscillations depend on the nature of the driver, and the type of interaction between the two systems.
Methods. We consider the oscillations of a magnetic straight cylinder with fixed-ends under the influence of an external driver modelling the force due to the global EIT wave. Given the uncertainties related to the nature of EIT waves, we first approximate the driver by an oscillatory force in time and later by a shock with a finite width.
Results. Results show that for a harmonic driver the dominant period in the generated oscillation belongs to the driver. Depending on the period of driver, compared to the natural periods of the loop, a mixture of standing modes harmonics can be initiated. In the case of a non-harmonic driver (modelling a shock wave), the generated oscillations in the loop are the natural periods only. The amplitude of oscillations is determined by the position of the driver along the tube. The full diagnosis of generated oscillations is achieved using simple numerical methods.

Global Coronal Seismology

I. **Ballai**
Solar Phys (**2007**) 246: 177–185, File
http://www.springerlink.com/content/b014412j82256657/fulltext.pdf
Global large-scale coronal-wave-like disturbances, EIT waves

A global wave generated by sudden energy releases (flares or CMEs) can interact with active region loops or prominences,

ON THE NATURE OF CORONAL EIT WAVES
I. **Ballai**, R. Erde´lyi, and B. Pinte´r
The Astrophysical Journal, 633:L145–L148, **2005, File**
Large-scale eruption events in the solar atmosphere can generate global waves, i.e., waves that propagate over distances comparable to the solar radius. In the low solar corona, global waves observed by *SOHO* EIT, generated by coronal mass ejections or flares, are usually referred to as "EIT waves." The nature of these global waves is the subject of strong debate, and opinions are divided between different interpretations (e.g., fast magnetohydrodynamic waves, shock waves, nonwave feature, etc.). In the present Letter, we studied *TRACE* EUV data to show that these global coronal disturbances are indeed waves with a *well-defined period*.

ON THE ORIGIN OF THE SOLAR MORETON WAVE OF 2006 DECEMBER 6
K. S. **Balasubramaniam**1, E. W. Cliver2, A. Pevtsov3, M. Temmer4, T. W. Henry3, H. S. Hudson5, S. Imada6, A. G. Ling7, R. L. Moore8, N. Muhr4, D. F. Neidig3,12, G. J. D. Petrie9, A. M. Veronig4, B. Vrˇsnak10, and S. M. White11
Astrophysical Journal, 723:587–601, **2010, File**
We analyzed ground- and space-based observations of the eruptive flare (3B/X6.5) and associated Moreton wave (~850 km s^{-1}; ~270° azimuthal span) of **2006 December 6** to determine the wave driver—either flare pressure pulse (blast) or coronal mass ejection (CME). Kinematic analysis favors a CME driver of the wave, despite key gaps in coronal data. The CME scenario has a less constrained/smoother velocity versus time profile than is the case for the flare hypothesis and requires an acceleration rate more in accord with observations. The CME picture is based, in part, on the assumption that a strong and impulsive magnetic field change observed by a GONG magnetograph during the rapid rise phase of the flare corresponds to the main acceleration phase of the CME. The Moreton wave evolution tracks the inferred eruption of an extended coronal arcade, overlying a region of weak magnetic field to thewest of the principal flare inNOAAactive region 10930. Observations ofH*α* foot point brightenings, disturbance contours in off-band H*α* images, and He i 10830 Å flare ribbons trace the eruption from 18:42 to 18:44 UT as it progressed southwest along the arcade. *Hinode* EIS observations show strong blueshifts at foot points of this arcade during the post-eruption phase, indicating mass outflow. At 18:45 UT, the Moreton wave exhibited two separate arcs (one off each flank of the tip of the arcade) that merged and coalesced by 18:47 UT to form a single smooth wave front, having its maximum amplitude in the southwest direction. We suggest that the erupting arcade (i.e., CME) expanded laterally to drive a coronal shock responsible for the Moreton wave. We attribute a darkening in H*α* from a region underlying the arcade to absorption by faint unresolved post-eruption loops.
Animations are available in the online journal.
Хороший обзор в 1. INTRODUCTION и 3. CONCLUSION.

Large scale solar chromospheric eruptive activity - a signature of magnetic reconnection
K. S. **Balasubramaniam**1, A. A. Pevtsov1, D. F. Neidig1 and R. A. Hock2
ILWS WORKSHOP 2006, GOA, FEBRUARY 19-24, **2006, File**
A new class of large-scale solar chromospheric eruptive activity, sequential chromospheric brightenings (SCBs), has been reported by Balasubramaniam et al. (2005). SCBs are chromospheric network points (outside of active regions) that sequentially brighten over a narrow path of chromospheric network points. SCBs appear as single or multiple trains of brightenings, the underlying magnetic poles of each train having the same (negative or positive) polarity. SCBs may be associated with the following phenomena: solar flares, filament eruptions, CMEs, disappearing transequatorial loops, Moreton and EIT waves. We present an understanding of SCBs and their place in respect to these related eruptive phenomena.

SEQUENTIAL CHROMOSPHERIC BRIGHTENINGS BENEATH A TRANSEQUATORIAL HALO CORONAL MASS EJECTION
K. S. **Balasubramaniam** et al., The Astrophysical Journal, 630:1160–1167, **2005, File**
2002 December 19

Are Moreton Waves Coronal Phenomena?
K. S. **Balasubramaniam**, A. A. Pevtsov, and D. F. Neidig
The Astrophysical Journal, 658:1372-1379, 2007
We report on permeability characteristics of the upper solar atmosphere due to the progression of a Moreton wave. 2003 October 29.

Study of Multiple Coronal Mass Ejections at Solar Minimum Conditions
A. **Bemporad**, F. P. Zuccarello, C. Jacobs, M. Mierla, S. Poedts
Solar Physics, November **2012**, Volume 281, Issue 1, pp 223-236, **File**
The aim of this work is to provide a physical explanation for the genesis of multiple coronal mass ejections (CMEs) in an asymmetric coronal field configuration. We analyze STEREO observations of a multiple eruption and compare the results from the data analysis with predictions provided by magnetohydrodynamic (MHD) simulations. To this end, the multiple CMEs (MCMEs) observed on **21 – 22 September 2009** were selected. Both eruptions originated from the same source region and showed approximately the same latitudinal deflection, by more than 15 degrees, toward the heliospheric current sheet (HCS) during their propagation in the COR1 field of view. Numerical MHD simulations of the MCMEs have been performed, starting from an asymmetric coronal field configuration that mimics the potential field source surface extrapolation for 21 September 2009. The results demonstrate that, by shearing the footpoints at the base of the southern arcade, we were able to reproduce the observed dynamics of the MCMEs. Both CMEs are deflected toward the HCS due to an imbalance in the magnetic pressure and tension forces; the global field strength turns out to be a crucial parameter in order to release two subsequent eruptions, and hence to reproduce the observed evolution.

IDENTIFICATION OF SUPER- AND SUBCRITICAL REGIONS IN SHOCKS DRIVEN BY CORONAL MASS EJECTIONS
A. **Bemporad** and S. Mancuso
2011 ApJ 739 L64, **File**
In this work, we focus on the analysis of a coronal mass ejection (CME) driven shock observed by the Solar and Heliospheric Observatory/Large Angle and Spectrometric Coronagraph Experiment. We show that white-light coronagraphic images can be employed to estimate the compression ratio $X = \rho_d / \rho_u$ all along the front of CME-driven shocks. X increases from the shock flanks (where X 1.2) to the shock center (where X 3.0 is maximum). From the estimated X values, we infer the Alfvén Mach number for the general case of an oblique shock. It turns out that only a small region around the shock center is supercritical at earlier times, while higher up in the corona the whole shock becomes subcritical. This suggests that CME-driven shocks could be efficient particle accelerators at the initiation phases of the event, while at later times they progressively loose energy, also losing their capability to accelerate high-energy particles. This result has important implications on the localization of particle acceleration sites and in the context of predictive space weather studies.

Active region EUV transient brightenings - First Results by EIT of SOHO JOP80.
Berghmans, D., Clette, F.,
1999. Solar Phys. 186, 207–229.

The relationship between EUV dimming and coronal mass ejections
I. Statistical study and probability model
D. **Bewsher**, R. A. Harrison[1], and D. S. Brown[2]
A&A 478, 897-906 (2008)
The aim is to confirm whether the dimming-CME association is real or not.
The CDS CME onset campaign data for Mg IX and FE XVI observations on the solar limb are used to compare to LASCO event lists over a period from 1998 to 2005. Dimming events are identified and the physical extent explored, whilst comparing the events to overlying CME activity.
The results confirm the CME-EUV dimming association, using a statistical analysis for the first time. We discuss the repercussions for the study of CME onsets, i.e. analysis of the dimming regions and the periods up to such dimming may be key to understanding the pre-CME onset plasma processes. The results stress that one emission line may not be sufficient for associating dimming regions with CMEs.

Solar phenomena associated with “EIT waves”.
Biesecker, D.A., Myers, D.C., Thompson, B.J., Hammer, D.M., Vourlidas, A.:
2002, *Astrophys. J.* **569**, 1009 – 1015. doi:10.1086/339402., **File**
In an effort to understand what an ‘‘ EIT wave ’’ is and what its causes are, we have looked for correlations between the initiation of EIT waves and the occurrence of other solar phenomena. An EIT wave is a coronal

disturbance, typically appearing as a diffuse brightening propagating across the Sun. A catalog of EIT waves, covering the period from 1997 March through 1998 June, was used in this study. For each EIT wave, the catalog gives the heliographic location and a rating for each wave, where the rating is determined by the reliability of the observations. Since EIT waves are transient, coronal phenomena, we have looked for correlations with other transient, coronal phenomena: X-ray flares, coronal mass ejections (CMEs), and metric type II radio bursts. An unambiguous correlation between EIT waves and CMEs has been found. The correlation of EIT waves with flares is significantly weaker, and EIT waves frequently are not accompanied by radio bursts. To search for trends in the data, proxies for each of these transient phenomena are examined. We also use the accumulated data to show the robustness of the catalog and to reveal biases that must be accounted for in this study.

Photometric and Thermal Cross-calibration of Solar EUV Instruments

P. F. **Boerner**, P. Testa, H. Warren, M. A. Weber, C. J. Schrijver

Solar Physics, June **2014**, Volume 289, Issue 6, pp 2377-2397

We present an assessment of the accuracy of the calibration measurements and atomic physics models that go into calculating the SDO/AIA response as a function of wavelength and temperature. The wavelength response is tested by convolving SDO/EVE and Hinode/EIS spectral data with the AIA effective area functions and by comparing the predictions with AIA observations. For most channels, the AIA intensities summed over the disk agree with the corresponding measurements derived from the current version (V2) of the EVE data to within the estimated 25 % calibration error. This agreement indicates that the AIA effective areas are generally stable in time. The AIA 304 Å channel, however, does show degradation by a factor of almost 3 from May 2010 through September 2011, when the throughput apparently reached a minimum. We also found some inconsistencies in the 335 Å passband, possibly due to higher-order contamination of the EVE data. The intensities in the AIA 193 Å channel agree to within the uncertainties with the corresponding measurements from EIS full CCD observations. Analysis of high-resolution X-ray spectra of the solar-like corona of Procyon and of EVE spectra allowed us to investigate the accuracy and completeness of the CHIANTI database in the AIA shorter wavelength passbands. We found that in the 94 Å channel, the spectral model significantly underestimates the plasma emission owing to a multitude of missing lines. We derived an empirical correction for the AIA temperature responses by performing differential emission measure (DEM) inversion on a broad set of EVE spectra and adjusting the AIA response functions so that the count rates predicted by the full-disk DEMs match the observations.

On the Processing and Analysis of the Data of the CORONAS-F/SPIRIT and Other Solar Experiments

S. A. **Bogachev**, V. V. Grechnev, S. V. Kuzin, V. A. Slemzin, O. I. Bugaenko, and I. M. Chertok

Solar System Research, 2009, Vol. 43, No. 2, pp. 143–150. **2009.**

More than 300000 solar images in the extreme ultraviolet and soft X-ray regions were obtained using two telescopes and four spectroheliometers of the CORONAS-F/SPIRIT device from August 2001 to December 2005. Methods for the processing of such data and extracting physical information are presented, taking into account the experience of processing and analysis of other space experiments on solar research. Some results on applications of the considered methods are presented.

Original Russian Text © S.A. Bogachev, V.V. Grechnev, S.V. Kuzin, V.A. Slemzin, O.I. Bugaenko, I.M. Chertok, 2009, published in Astronomicheskii Vestnik, 2009, Vol. 43, No. 2, pp. 152–159.

Experimental study of Alfvén wave reflection from an Alfvén-speed gradient relevant to the solar coronal holes

Sayak **Bose**, Jason M. TenBarge, Troy Carter, Michael Hahn, Hantao Ji, James Juno, Daniel Wolf Savin, Shreekrishna Tripathi, Stephen Vincena

ApJ **2024**

https://arxiv.org/pdf/2402.06193.pdf

We report the first experimental detection of a reflected Alfvén wave from an Alfvén-speed gradient under conditions similar to those in coronal holes. The experiments were conducted in the Large Plasma Device at the University of California, Los Angeles. We present the experimentally measured dependence of the coefficient of reflection versus the wave inhomogeneity parameter, i.e., the ratio of the wave length of the incident wave to the length scale of the gradient. Two-fluid simulations using the Gkeyll code qualitatively agree with and support the experimental findings. Our experimental results support models of wave heating that rely on wave reflection at low heights from a smooth Alfvén-speed gradient to drive turbulence.

Energy spectra of 3He-rich solar energetic particles associated with coronal waves

R. **Bucik**, D. E. Innes, G. M. Mason, M. E. Wiedenbeck

Presented at 15th Annual International Astrophysics Conference "The Science of Ed Stone". Journal of Physics: Conference Series **2016**
http://arxiv.org/pdf/1609.07266v1.pdf
In addition to their anomalous abundances, 3He-rich solar energetic particles (SEPs) show puzzling energy spectral shapes varying from rounded forms to power laws where the later are characteristics of shock acceleration. Solar sources of these particles have been often associated with jets and narrow CMEs, which are the signatures of magnetic reconnection involving open field. Recent reports on new associations with large-scale EUV waves bring new insights on acceleration and transport of 3He-rich SEPs in the corona. We examined energy spectra for **32 3He-rich SEP events** observed by ACE at L1 near solar minimum in 2007-2010 and compared the spectral shapes with solar flare signatures obtained from STEREO EUV images. We found the events with jets or brightenings tend to be associated with rounded spectra and the events with coronal waves with power laws. This suggests that coronal waves may be related to the unknown second stage mechanism commonly used to interpret spectral forms of 3He-rich SEPs. **2010 February 18**
Table 1. ^{3}He-rich SEP events.

OBSERVATIONS OF EUV WAVES IN 3He-RICH SOLAR ENERGETIC PARTICLE EVENTS
R. **Bučík**1,2,3, D. E. Innes1,2, L. Guo1,2, G. M. Mason4, and M. E. Wiedenbeck
2015 ApJ 812 53
http://arxiv.org/pdf/1512.04664v1.pdf
Small 3He-rich solar energetic particle (SEP) events with their anomalous abundances, markedly different from the solar system, provide evidence for a unique acceleration mechanism that operates routinely near solar active regions. Although the events are sometimes accompanied by coronal mass ejections (CMEs), it is believed that mass and isotopic fractionation is produced directly in the flare sites on the Sun. We report on a large-scale extreme-ultraviolet (EUV) coronal wave observed in association with 3He-rich SEP events. In the two examples discussed, the observed waves were triggered by minor flares and appeared concurrently with EUV jets and type III radio bursts, but without CMEs. The energy spectra from one event are consistent with so-called class-1 (characterized by power laws) 3He-rich SEP events, while the other with class-2 (characterized by rounded 3He and Fe spectra), suggesting different acceleration mechanisms in the two. The observation of EUV waves suggests that large-scale disturbances, in addition to more commonly associated jets, may be responsible for the production of 3He-rich SEP events. **2010 January 26, 2010 February 2**

A statistical correlation of sunquakes based on their seismic, white light, and X-ray emission
J.C. **Buitrago-Casas**, J.C. Martinez Oliveros, C. Lindsey, B. Calvo-Mozo, S. Krucker, L. Glesener,S. Zharkov
Solar Phys. **2015**
http://arxiv.org/pdf/1502.07798v1.pdf
Several mechanisms have been proposed to explain the transient seismic emission, i.e., sunquakes, from some solar flares. Some theories associate high-energy electrons and/or white-light emission with sunquakes. High-energy charged particles and their subsequent heating of the photosphere and/or chromosphere could induce acoustic waves in the solar interior. We carried out a correlative study of solar flares with emission in hard-X rays (HXRs), enhanced continuum emission at 6173{\AA}, and transient seismic emission. We selected those flares observed by RHESSI (Reuven Ramaty High Energy Solar Spectroscopic Imager) with a considerable flux above 50 keV between January 1, 2010 and June 26, 2014. We then used data from the Helioseismic and Magnetic Imager onboard the Solar Dynamic Observatory (SDO/HMI) to search for excess visible continuum emission and new sunquakes not previously reported. We found a total of 18 sunquakes out of 75 investigated. All of the sunquakes were associated with a enhancement of the visible continuum during the flare time. Finally, we calculated a coefficient of correlation for a set of dichotomic variables related to these observations. We found a strong correlation between two of the standard helioseismic detection techniques, and between sunquakes and visible continuum enhancements. We discuss the phenomenological connectivity between these physical quantities and the observational difficulties of detecting seismic signals and excess continuum radiation. **Table 1. Times and locations of the seismically active solar flares**
November 7, 2013

Impulsive Solar Energetic Particle Events: EUV Waves and Jets MINI **REVIEW**
R. **Bucik**
Front. Astron. Space Sci. 8 807961 **2022 File**
https://www.frontiersin.org/articles/10.3389/fspas.2021.807961/full

https://doi.org/10.3389/fspas.2021.807961
https://arxiv.org/abs/2112.14282
Impulsive solar energetic particle (ISEP) events show peculiar elemental composition, with enhanced 3He and heavy-ion abundances, markedly different from our solar system composition. Furthermore, the events are characterized by a wide variety of energy spectral shapes from power laws to rounded spectra toward the low energies. Solar sources of the events have been firmly associated with coronal jets. Surprisingly, new observations have shown that events are often accompanied by so-called extreme-ultraviolet (EUV) coronal waves – a large-scale phenomenon compared to jets. This paper outlines the current understanding of the linkage of EUV waves with jets and energetic ions in ISEP events. **2007 May 23, 2008 Nov 4, 2009 Dec 22, 2010 January 26, 2010 Feb 2, 2010 Jun 12, 2011 Jan 27, 2011 Feb 18, 2014 May 16**

Table 1. The ISEP events with reported EUV wave speed.

Association of 3He-Rich Solar Energetic Particles with Large-Scale Coronal Waves

Radoslav **Bucik**, Davina E. Innes, Glenn M. Mason, Mark E. Wiedenbeck

ApJ **2016**
http://arxiv.org/pdf/1609.05346v1.pdf

Small 3He-rich solar energetic particle (SEP) events have been commonly associated with extreme-ultraviolet (EUV) jets and narrow coronal mass ejections (CMEs) which are believed to be the signatures of magnetic reconnection involving field lines open to interplanetary space. The elemental and isotopic fractionation in these events are thought to be caused by processes confined to the flare sites. In this study we identify 32 3He-rich SEP events observed by the Advanced Composition Explorer near the Earth during the solar minimum period 2007-2010 and examine their solar sources with the high resolution Solar Terrestrial Relations Observatory (STEREO) EUV images. Leading the Earth, STEREO-A provided for the first time a direct view on 3He-rich flares, which are generally located on the Sun's western hemisphere. *Surprisingly, we find that about half of the 3He-rich SEP events in this survey are associated with large-scale EUV coronal waves*. An examination of the wave front propagation, the source-flare distribution and the coronal magnetic field connections suggests that the EUV waves may affect the injection of 3He-rich SEPs into interplanetary space.

Improved methods for determining the kinematics of coronal mass ejections and coronal waves

J. P. **Byrne**, D. M. Long, P. T. Gallagher, D. S. Bloomfield, S. A. Maloney, R. T. J. McAteer, H. Morgan, S. R. Habbal

E-print, July **2013;** A&A

Context: The study of solar eruptive events and associated phenomena is of great importance in the context of solar and heliophysics. Coronal mass ejections (CMEs) and coronal waves are energetic manifestations of the restructuring of the solar magnetic field and mass motion of the plasma. Characterising this motion is vital for deriving the dynamics of these events and thus understanding the physics driving their initiation and propagation. The development and use of appropriate methods for measuring event kinematics is therefore imperative.
Aims: Traditional approaches to the study of CME and coronal wave kinematics do not return wholly accurate nor robust estimates of the true event kinematics and associated uncertainties. We highlight the drawbacks of these approaches, and demonstrate improved methods for accurate and reliable determination of the kinematics.
Methods: The Savitzky-Golay filter is demonstrated as a more appropriate fitting technique for CME and coronal wave studies, and a residual resampling bootstrap technique is demonstrated as a statistically rigorous method for the determination of kinematic error estimates and goodness-of-fit tests.
Results: It is shown that the scatter on distance-time measurements of small sample size can significantly limit the ability to derive accurate and reliable kinematics. This may be overcome by (i) increasing measurement precision and sampling cadence, and (ii) applying robust methods for deriving the kinematics and reliably determining their associated uncertainties. If a priori knowledge exists and a pre-determined model form for the kinematics is available (or indeed any justified fitting-form to be tested against the data), then its precision can be examined using a bootstrapping technique to determine the confidence interval associated with the model/fitting parameters.
Conclusions: Improved methods for determining the kinematics of CMEs and coronal waves are demonstrated to great effect, overcoming many issues highlighted in traditional numerical differencing and error propagation techniques.
2000 January 2, 2007 December 7, 2010 August 14. 2011 January 12

Dynamic Processes of the Moreton Wave on 2014 March 29

Denis P. **Cabezas**, Ayumi Asai, Kiyoshi Ichimoto, Takahito Sakaue, Satoru UeNo, Jose K. Ishitsuka, Kazunari Shibata

ApJ **883** 32 **2019**
https://arxiv.org/pdf/1908.03534.pdf
https://doi.org/10.3847/1538-4357/ab3a35

On **2014 March 29**, an intense solar flare classified as X1.0 occurred in the active region 12017. Several associated phenomena accompanied this event, among them a fast-filament eruption, large-scale propagating disturbances in the corona and the chromosphere including a Moreton wave, and a coronal mass ejection. This flare was successfully detected in multiwavelength imaging in H-alpha line by the Flare Monitoring Telescope (FMT) at Ica University, Peru. We present a detailed study of the Moreton wave associated with the flare in question. Special attention is paid to the Doppler characteristics inferred from the FMT wing (H-alpha±0.8~Å) observations, which are used to examine the downward/upward motion of the plasma in the chromosphere. Our findings reveal that the downward motion of the chromospheric material at the front of the Moreton wave attains a maximum velocity of 4 km/s, whereas the propagation speed ranges between 640 and 859 km/s. Furthermore, utilizing the weak shock approximation in conjunction with the velocity amplitude of the chromospheric motion induced by the Moreton wave, we derive the Mach number of the incident shock in the corona. We also performed the temperature-emission measure analysis of the coronal wave based on the Atmospheric Imaging Assembly (AIA) observations, which allowed us to derive the compression ratio, and to estimate the Alfvén and fast-mode Mach numbers of the order of 1.06-1.28 and 1.05-1.27. Considering these results and the MHD linear theory we discuss the characteristics of the shock front and the interaction with the chromospheric plasma.
RHESSI Science Nugget #357 **2019**
http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/Dynamic_Processes_of_the_Moreton_Wave_on_2014_March_29

"Dandelion" Filament Eruption and Coronal Waves Associated with a Solar Flare on 2011 February 16

Denis P. **Cabezas**, Lurdes M. Martínez, Yovanny J. Buleje, Mutsumi Ishitsuka, José K. Ishitsuka, Satoshi Morita, Ayumi Asai, Satoru UeNo, Takako T. Ishii, Reizaburo Kitai, Shinsuke Takasao, Yusuke Yoshinaga, Kenichi Otsuji, Kazunari Shibata
ApJ **2017**
https://arxiv.org/pdf/1701.00308v1.pdf
Coronal disturbances associated with solar flares, such as Hα Moreton waves, X-ray waves, and extreme ultraviolet (EUV) coronal waves are discussed herein in relation to magnetohydrodynamics fast-mode waves or shocks in the corona. To understand the mechanism of coronal disturbances, full-disk solar observations with high spatial and temporal resolution over multiple wavelengths are of crucial importance. We observed a filament eruption, whose shape is like a "dandelion", associated with the M1.6 flare that occurred on **2011 February 16** in the Hα images taken by the Flare Monitoring Telescope at Ica University, Peru. We derive the three-dimensional velocity field of the erupting filament. We also identify winking filaments that are located far from the flare site in the Hα images, whereas no Moreton wave is observed. By comparing the temporal evolution of the winking filaments with those of the coronal wave seen in the extreme ultraviolet images data taken by the Atmospheric Imaging Assembly on board the {\it Solar Dynamics Observatory} and by the Extreme Ultraviolet Imager on board the {\it Solar Terrestrial Relations Observatory-Ahead}, we confirm that the winking filaments were activated by the EUV coronal wave.

Quasiperiodic acceleration of electrons by a plasmoid-driven shock in the solar atmosphere

Eoin P. **Carley**, David M. Long, Jason P. Byrne, Pietro Zucca, D. Shaun Bloomfield, Joseph McCauley and Peter T. Gallagher
E-print, Oct **2013;** Nature Physics (**2013**) doi:10.1038/nphys2767
Cosmic rays and solar energetic particles may be accelerated to relativistic energies by shock waves in astrophysical plasmas. On the Sun, shocks and particle acceleration are often associated with the eruption of magnetized plasmoids, called coronal mass ejections (CMEs). However, the physical relationship between CMEs and shock particle acceleration is not well understood. Here, we use extreme ultraviolet, radio and white-light imaging of a solar eruptive event on **22 September 2011** to show that a CME-induced shock (Alfvén Mach number 2.4[+0.7,-0.8]) was coincident with a coronal wave and an intense metric radio burst generated by intermittent acceleration of electrons to kinetic energies of 2?46 keV (0.1?0.4 c). Our observations show that plasmoid-driven quasiperpendicular shocks are capable of producing quasiperiodic acceleration of electrons, an effect consistent with a turbulent or rippled plasma shock surface.

Direct evidence of hybrid nature of EUV waves and the reflection of the fast-mode wave

Ramesh **Chandra**, P. F. Chen, Pooja Devi
2024 *ApJ* **971** 53
https://arxiv.org/pdf/2407.03281
https://iopscience.iop.org/article/10.3847/1538-4357/ad613f/pdf
In current study, we perform the analysis of an extreme ultraviolet (EUV) wave on **2022 March 31**. The event originated from the from NOAA active region (AR) 12975 (location: N13W52) in the Atmospheric imaging

Assembly (AIA) onboard Solar Dynamics Observatory (SDO) satellite and exactly the west limb in Solar Terrestrial Relations Observatory-Ahead (STEREO-A) observations. The EUV wave was associated with a GOES medium class i.e. M9.6 eruptive flare. The event was also well observed by MLSO and COR1 coronagraph. For the first time, we found here clear simultaneous observations of two components of EUV wave in AIA as well as in STEREO-A images, which was predicted in EUV wave hybrid model. These components are fast-mode wave and non-wave counterparts. The speed of fast-mode EUV wave in AIA 193 A is ~658±4 km/s, while the non-wave component propagates with a speed of ~157±3 km/s. The computed speed in STEREO-A 195 A for the fast-mode wave and non-wave components are ~590±3 km/s and ~150±2 km/s, respectively. The EUV wave interaction with AR shows the reflection of it above the solar limb. The speed of the reflected and transmitted wave components are 140 and 180 km/s, which is slower than the incident wave. With the precise alignments, we found the fast-mode EUV wave is just ahead of the coronal mass ejection (CME) and the non-wave component is cospatial with the core of the accompanied CME. In addition to these, the event also shows the stationary fronts and the reflection from the AR located towards the south of the EUV wave origin site.

Observational Characteristics of solar EUV waves **Review**

Ramesh **Chandra**, Pooja Devi, P. F. Chen, Brigitte Schmieder, Reetika Joshi, Bhuwan Joshi, Arun Kumar Awasthi

3rd BINA workshop proceeding **2023**

https://arxiv.org/pdf/2310.12844.pdf

Extreme-ultraviolet (EUV) waves are one of the large-scale phenomena on the Sun. They are defined as large propagating fronts in the low corona with speeds ranging from a few tens km/s to a multiple of 1000 km/s. They are often associated with solar filament eruptions, flares, or coronal mass ejections (CMEs). EUV waves show different features, such as, wave and nonwave components, stationary fronts, reflection, refraction, and mode conversion. Apart from these, they can hit the nearby coronal loops and filaments/prominences during their propagation and trigger them to oscillate. These oscillating loops and filaments/prominences enable us to diagnose coronal parameters such as the coronal magnetic field strength. In this article, we present the different observed features of the EUV waves along with existing models. **2011 February 11, 2011 May 11, 2011 August 04, 2016 July 23, 2021 October 28**

Dynamics and Kinematics of the EUV Wave Event on 6 May 2019

Ramesh **Chandra**, P. F. Chen, Pooja Devi, Reetika Joshi, Y. W. Ni

Galaxies Journal **2022**

https://arxiv.org/ftp/arxiv/papers/2204/2204.04936.pdf

We present here the kinematics of the EUV wave associated with a GOES M1.0-class solar flare, which originates in NOAA AR 12740. The event is thoroughly observed with Atmospheric Imaging Assembly (AIA) onboard Solar Dynamics Observatory (SDO) with high spatio-temporal resolutions. This event displays many features of EUV waves, which are very decisive for the understanding of the nature of EUV waves. These features include: a fast-mode wave, a pseudo wave, a slow-mode wave and stationary fronts, probably due to mode conversion. One fast-mode wave also propagates towards the coronal hole situated close to the north pole and the wave speed does not change when it encounters the coronal hole. We intend to provide self-consistent interpretations for all these different features.

Fine Structures of an EUV Wave Event from Multi-Viewpoint Observations

Ramesh **Chandra**, P. F. Chen, Pooja Devi, Reetika Joshi, Brigette Schmieder, Yong-Jae Moon Wahab Uddin

ApJ **919** 9 **2021**

https://arxiv.org/pdf/2106.14024.pdf

https://doi.org/10.3847/1538-4357/ac1077

In this study, we investigate an extreme ultraviolet (EUV) wave event on **2010 February 11**, which occurred as a limb event from the Earth viewpoint and a disk event from the STEREO--B viewpoint. We use the data obtained by the Atmospheric Imaging Assembly (AIA) aboard the Solar Dynamics Observatory (SDO) in various EUV channels. The EUV wave event was launched by a partial prominence eruption. Similar to some EUV wave events in previous works, this EUV wave event contains a faster wave with a speed of ∼445±6 km s−1, which we call coronal Moreton wave, and a slower wave with a speed of ∼298±5 km s−1, which we call "EIT wave". The coronal Moreton wave is identified as a fast-mode wave and the "EIT wave" is identified as an apparent propagation due to successive field-line stretching. We also observe a stationary front associated with the fast mode EUV wave. This stationary front is explained as mode conversion from the coronal Moreton wave to a slow-mode wave near a streamer.

Observations of Two Successive EUV Waves and their Mode Conversion

R. **Chandra**, P. F. Chen, R. Joshi, B. Joshi, B. Schmieder

ApJ **863** 101 **2018**

https://arxiv.org/pdf/1806.11350.pdf

http://sci-hub.tw/10.3847/1538-4357/aad097

In this paper, we present the observations of two successive fast-mode extreme ultraviolet (EUV) wave events observed on **2016 July 23**. Both fast-mode waves were observed by the Atmospheric Imaging Assembly (AIA) instrument on board the Solar Dynamics Observatory (SDO) satellite, with a traveling speed of ~ 675 and 640 km/s, respectively. These two wave events were associated with two filament eruptions and two GOES M-class solar flares from the NOAA active region 12565, which was located near the western limb. The EUV waves mainly move toward the south direction. We observed the interaction of the EUV waves with a helmet streamer further away in the south. When either or one of the EUV waves penetrates into the helmet streamer, a slowly propagating wave with a traveling speed of ~ 150 km/s is observed along the streamer. We suggest that the slowly-moving waves are slow-mode waves, and interpret this phenomenon as the magnetohydrodynamic (MHD) wave mode conversion from the fast mode to the slow mode. Besides, we observed several stationary fronts in the north and south of the source region.

A Study of a long duration B9 flare-CME event and associated piston-driven shock

R. **Chandra**, P. F. Chen, A. Fulara, A. K. Srivastava, W. Uddin

Adv. Space Research **2017**

https://arxiv.org/pdf/1710.08734.pdf

We present and discuss here the observations of a small long duration GOES B- class flare associated with a quiescent filament eruption, a global EUV wave and a CME on **2011 May 11**. The event was well observed by the Solar Dynamics Observatory (SDO), GONG H{\alpha}, STEREO and HiRAS spectrograph. As the fil- ament erupted, ahead of the filament we observed the propagation of EIT wave fronts, as well as two flare ribbons on both sides of the polarity inversion line (PIL) on the solar surface. The observations show the co-existence of two types of EUV waves, i.e., a fast and a slow one. A type II radio burst with up to the third harmonic component was also associated with this event. The evolution of pho- tospheric magnetic field showed flux emergence and cancellation at the filament site before its eruption.

Peculiar Stationary EUV Wave Fronts in the eruption on 2011 May 11

R. **Chandra**, P. F. Chen, A. Fulara, A. K. Srivastava, W. Uddin

ApJ 822 106 **2016 File**

http://arxiv.org/pdf/1602.08693v1.pdf

We present and interpret the observations of extreme ultraviolet (EUV) waves associated with a filament eruption on **2011 May 11**.The filament eruption also produces a small B-class two ribbon flare and a coronal mass ejection (CME). The event is observed by the Solar Dynamic Observatory (SDO) with high spatio-temporal resolution data recorded by Atmospheric Imaging Assembly (AIA). As the filament erupts, we observe two types of EUV waves (slow and fast) propagating outwards. The faster EUV wave has a propagation velocity of ~ 500 km/s and the slower EUV wave has an initial velocity of ~ 120 km/s. We report for the first time that not only the slower EUV wave stops at a magnetic separatrix to form bright stationary fronts, but also the faster EUV wave transits a magnetic separatrix, leaving another stationary EUV front behind.

Can a Fast-mode EUV Wave Generate a Stationary Front?

P. F. **Chen**, C. Fang, R. Chandra, A. K. Srivastava

Solar Physics Volume 291, Issue 11, pp 3195–3206 **2016**

http://arxiv.org/pdf/1604.07982v1.pdf

The discovery of stationary "EIT waves" about 16 years ago posed a big challenge to the then favorite fast-mode wave model for coronal "EIT waves". It encouraged the proposing of various non-wave models, and played an important role in approaching the recent converging viewpoint, {\it i.e.} there are two types of EUV waves. However, it was recently discovered that a stationary wave front can also be generated when a fast-mode wave passes through a magnetic quasi-separatrix layer (QSL). In this paper, we perform a magnetohydrodynamic (MHD) numerical simulation of the interaction between a fast-mode wave and a magnetic QSL, and a stationary wave front is reproduced. The analysis of the numerical results indicates that near the plasma beta ∼1 layer in front of the magnetic QSL, part of the fast-mode wave is converted to a slow-mode MHD wave, which is then trapped inside the magnetic loops, forming a stationary wave front. Our research implies that we have to be cautious in identifying the nature of a wave since there may be mode conversion during the propagation of the waves driven by solar eruptions. 2011 May 11.

Global Coronal Waves **Review**

P. F. **Chen**

Low-Frequency Waves in Space Plasmas, Edited by Andreas Keiling, Dong-Hun Lee, Valery Nakariakov. Geophysical Monograph Series, Vol. 216. ISBN: 978-1-119-05495-5. Wiley, **2016**, p.381-394

http://arxiv.org/pdf/1604.07991v1.pdf **File**

After the {\em Solar and Heliospheric Observatory} ({\em SOHO}) was launched in 1996, the aboard Extreme Ultraviolet Imaging Telescope (EIT) observed a global coronal wave phenomenon, which was initially named "EIT wave" after the telescope. The bright fronts are immediately followed by expanding dimmings. It has been shown that the brightenings and dimmings are mainly due to plasma density increase and depletion, respectively. Such a spectacular phenomenon sparked long-lasting interest and debates. The debates were concentrated on two topics, one is about the driving source, and the other is about the nature of this wavelike phenomenon. The controversies are most probably because there may exist two types of large-scale coronal waves that were not well resolved before the {\em Solar Dynamics Observatory} ({\em SDO}) was launched: one is a piston-driven shock wave straddling over the erupting coronal mass ejection (CME), and the other is an apparently propagating front, which may correspond to the CME frontal loop. Such a two-wave paradigm was proposed more than 13 years ago, and now is being recognized by more and more colleagues. In this paper, we review how various controversies can be resolved in the two-wave framework and how important it is to have two different names for the two types of coronal waves.

1997 May 12, 9 Aug 2011,

A solar type II radio burst from CME-coronal ray interaction: simultaneous radio and EUV imaging

Yao **Chen**, Guohui Du, Li Feng, Shiwei Feng, Xiangliang Kong, Fan Guo, Bing Wang, Gang Li

2014

http://arxiv.org/pdf/1404.3052v1.pdf

Simultaneous radio and extreme ultraviolet (EUV)/white-light imaging data are examined for a solar type II radio burst occurring on **2010 March 18** to deduce its source location. Using a bow-shock model, we reconstruct the 3-dimensional EUV wave front (presumably the type-II emitting shock) based on the imaging data of the two STEREO spacecraft. It is then combined with the Nan\c{c}ay radio imaging data to infer the 3-dimensional position of the type II source. It is found that the type II source coincides with the interface between the CME EUV wave front and a nearby coronal ray structure, providing evidence that the type II emission is physically related to the CME-ray interaction. This result, consistent with those of previous studies, is based on simultaneous radio and EUV imaging data for the first time.

Spectroscopic analysis of interaction between an EIT wave and a coronal upflow region

F. **Chen**, M. D. Ding, P. F. Chen and L. K. Harra

E-print, 28 July 2011**, 2011** ApJ 740 116, **File**

We report a spectroscopic analysis of an EIT wave event that occurred in active region 11081 on **2010 June 12** and was associated with an M2.0 class flare. The wave propagated near circularly. The south-eastern part of the wave front passed over an upflow region nearby a magnetic bipole. Using EIS raster observations for this region, we studied the properties of plasma dynamics in the wave front, as well as the interaction between the wave and the upflow region. We found a weak blueshift for the Fe XII λ195.12 and FE XIII λ202.04 lines in the wave front. The local velocity along the solar surface, which is deduced from the line of sight velocity in the wave front and the projection effect, is much lower than the typical propagation speed of the wave. A more interesting finding is that the upflow and non-thermal velocities in the upflow region are suddenly diminished after the transit of the wave front. This implies a significant change of magnetic field orientation when the wave passed. As the lines in the upflow region are redirected, the velocity along the line of sight is diminished as a result. We suggest that this scenario is more in accordance with what was proposed in the field-line stretching model of EIT waves.

FIRST EVIDENCE OF COEXISTING EIT WAVE AND CORONAL MORETON WAVE FROM SDO/AIA OBSERVATIONS

P. F. **Chen**1,2 and Y. Wu

2011 ApJ 732 L20, **File**

"EIT waves" are a globally propagating wavelike phenomenon. They were often interpreted as fast-mode magnetoacoustic waves in the corona, despite various discrepancies between the fast-mode wave model and observations. To reconcile these discrepancies, we suggested that "EIT waves" are the apparent propagation of the plasma compression due to successive stretching of the magnetic field lines pushed by the erupting flux rope. According to this model, an EIT wave should be preceded by a fast-mode wave, which, however, had rarely been observed. With the unprecedented high cadence and sensitivity of the Solar Dynamics Observatory observations, we discern a fast-moving wave front with a speed of 560 km s–1 ahead of an EIT wave, which had a velocity of ~190 km s–1, in the "EIT wave" event on 2010 July 27. The results, suggesting that "EIT waves" are not fast-mode waves, confirm the prediction of our field-line stretching model for an EIT wave. In particular, it is found that the coronal Moreton wave was ~3 times faster than the EIT wave, as predicted.

First Evidence of Coexisting EIT Wave and Coronal Moreton Wave from SDO/AIA Observations

P. F. **Chen** and Y. Wu

2011, ApJ 732 L20, **File**

“EIT waves” are a globally propagating wavelike phenomenon. They were often interpreted as a fast-mode magnetoacoustic wave in the corona, despite various discrepancies between the fast-mode wave model and observations. To reconcile these discrepancies, we once proposed that “EIT waves” are apparent propagation of the plasma compression due to successive stretching of the magnetic field lines pushed by the erupting flux rope. According to this model, an “EIT wave” should be preceded by a fast-mode wave, which however was rarely observed. With the unprecedented high cadence and sensitivity of the Solar Dynamics Observatory (SDO) observations, we discern a fast-moving wave front with a speed of 560 km s−1, ahead of an “EIT wave”, which had a velocity of _ 190 km s−1, in the “EIT wave” event on **2010 July 27**. The results, suggesting that “EIT waves” are not fast-mode waves, confirm the prediction of our fieldline stretching model for “EIT wave”. In particular, it is found that the coronal Moreton wave was _ 3 times faster than the “EIT wave” as predicted.

Coronal Mass Ejections: Models and Their Observational Basis **Review**

Peng-Fei **Chen**

Living Rev. Solar Phys.， 8，（2011），1，File

http://solarphysics.livingreviews.org/Articles/lrsp-2011-1/ - **best files and two movies**

Coronal mass ejections (CMEs) are the largest-scale eruptive phenomenon in the solar system, expanding from active region-sized nonpotential magnetic structure to a much larger size. The bulk of plasma with a mass of ~ 1011 – 1013 kg is hauled up all the way out to the interplanetary space with a typical velocity of several hundred or even more than 1000 km s–1, with a chance to impact our Earth, resulting in hazardous space weather conditions. They involve many other much smaller-sized solar eruptive phenomena, such as X-ray sigmoids, filament/prominence eruptions, solar flares, plasma heating and radiation, particle acceleration, EIT waves, EUV dimmings, Moreton waves, solar radio bursts, and so on. It is believed that, by shedding the accumulating magnetic energy and helicity, they complete the last link in the chain of the cycling of the solar magnetic field. In this review, I try to explicate our understanding on each stage of the fantastic phenomenon, including their pre-eruption structure, their triggering mechanisms and the precursors indicating the initiation process, their acceleration and propagation. Particular attention is paid to clarify some hot debates, e.g., whether magnetic reconnection is necessary for the eruption, whether there are two types of CMEs, how the CME frontal loop is formed, and whether halo CMEs are special.

SPECTROSCOPIC ANALYSIS OF AN EIT WAVE/DIMMING OBSERVED BY HINODE/EIS

F. **Chen**, M. D. Ding and P. F. Chen

E-print, Aug 2010; ApJ, 720:1254–1261, **2010**, **File**

EUV Imaging Telescope (EIT) waves are a wavelike phenomenon propagating outward from the coronal mass ejection source region, with expanding dimmings following behind. We present a spectroscopic study of an EIT wave/dimming event observed by the Hinode/Extreme-ultraviolet Imaging Spectrometer. Although the identification of the wave front is somewhat affected by the pre-existing loop structures, the expanding dimming is well defined. We investigate the line intensity, width, and Doppler velocity for four EUV lines. In addition to the significant blue shift implying plasma outflows in the dimming region as revealed in previous studies, we find that the widths of all four spectral lines increase at the outer edge of the dimmings. We illustrate that this feature can be well explained by the field line stretching model, which claims that EIT waves are apparently moving brightenings that are generated by the successive stretching of the closed field lines.

19 May 2007; See a **Hinode EIS science nugget** "Spectroscopic analysis of an EUV wave/dimming" by Feng **Chen** http://msslxr.mssl.ucl.ac.uk:8080/SolarB/eisnuggets.jsp

EIT waves and coronal magnetic field diagnostics

P. F. **Chen**

E-print, Feb. **2010,** *Science in China Series G: Physics, Mechanics & Astronomy*, vol. 52, p. 1785 -1789, **File**

Magnetic field in the solar lower atmosphere can be measured by the use of the Zeeman and Hanle effects. In contrast, the coronal magnetic field well above the solar surface, which directly controls various eruptive phenomena, can not be precisely obtained with the traditional techniques. Several attempts are being made to probe the coronal magnetic field, such as force-free extrapolation based on the photospheric magnetograms, gyroresonance radio emissions, and coronal seismology based on MHD waves in the corona. Compared to the waves trapped in the localized coronal loops, EIT waves are the only global-scale wave phenomenon, and thus are the ideal tool for the coronal global seismology. In this paper, we review the observations and modelings of EIT waves, and illustrate how they can be applied to probe the global magnetic field in the corona.

THE RELATION BETWEEN EIT WAVES AND CORONAL MASS EJECTIONS

P. F. **Chen**

Astrophysical Journal, 698:L112–L115, **2009; File**

More and more evidence indicates that “EIT waves” are strongly related to coronal mass ejections (CMEs). However, it is still not clear how the two phenomena are related to each other. We investigate a CME event on **1997 September 9**, which was well observed by both the EUV Imaging Telescope (EIT) and the high-cadence Mark-III K-Coronameter at Mauna Loa Solar Observatory, and compare the spatial relation between the “EIT wave” fronts and the CME leading loops. It is found that “EIT wave” fronts are cospatial with the CME leading loops, and the expanding EUV dimmings are cospatial with the CME cavity. It is also found that the CME stopped near the boundary of a coronal hole, a feature common to observations of “EIT waves.” It is suggested that “EIT waves”/dimmings are the EUV counterparts of the CME leading loop/cavity, based on which we propose that, as in the case of “EIT waves,” CME leading loops are apparently moving density enhancements that are generated by successive stretching (or opening-up) of magnetic loops.

Initiation and propagation of coronal mass ejections **Review**

P. F. **Chen**

E-print, Feb **2008**, **File**; J. Astron. & Astrophys,

This paper **review**s recent progress in the research on the initiation and propagation of CMEs. In the initiation part, several trigger mechanisms are discussed; In the propagation part, the **observations and modelings of EIT waves/dimmings**, as the EUV counterparts of CMEs, are described.

THE RELATION BETWEEN EIT WAVES AND SOLAR FLARES

P. F. **Chen**

The Astrophysical Journal, 641: L153–L156, **2006; File**

In order to determine whether EIT waves are generated by coronal mass ejections (CMEs) or pressure pulses in solar flares, 14 non-CME–associated energetic flares, which should possess strong pressure pulses in their loops, are studied. They are selected near solar minimum, as this favors the detection of EIT waves. It is found that none of these flares are associated with EIT waves. Particular attention is paid to AR 0720, which hosted both CME-associated and non-CME types of flares. The *SOHO*/EIT images convincingly indicate that EIT waves and expanding dimmings appear only when CMEs are present. Therefore, it is unlikely that pressure pulses from flares generate EIT waves.

EIT waves – A signature of global magnetic restructuring in CMEs

P. F. **Chen** and C. Fang

Coronal and Stellar Mass Ejections Proceedings IAU Symposium No. 226, 2005,K. P. Dere, J. Wang & Y. Yan, eds, pp. 55-64, ***2005; File.***

The discovery of “EIT waves” after the launch of SOHO spacecraft sparked wide interest among the coronal mass ejection (CME) community since they may be crucial to the understanding of CMEs. However, the nature of this phenomenon is still being hotly debated between fast-mode wave explanation and non-wave explanation. Accumulating observations have shown various features of the “EIT waves”. For example, they tend to be devoid of magnetic neutral lines and coronal holes; they may stop near the magnetic separatrix between the source region and a nearby active region; they may experience an acceleration from the vicinity of the source active region to the quiet region, and so on. This paper is aimed to review all these features, discuss how these observations may provide constraints for the theoretical models, and point out their implication to the understanding of CMEs.

A FULL VIEW OF EIT WAVES

P. F. **Chen**, C. Fang,1 and K. Shibata2

The Astrophysical Journal, 622:1202–1210, **2005, File**

Here we report on MHD simulations performed to demonstrate how the typical features of EITwaves can all be accounted for within our theoretical model, in which the EIT waves are thought to be formed by successive stretching or opening of closed field lines driven by an erupting flux rope. The relationship between EIT waves, H_ Moreton waves, and type II radio bursts is discussed, with an emphasis on reconciling the discrepancies among different views of the ''EIT wave'' phenomenon.

SYNTHESIS OF CME-ASSOCIATED MORETON AND EIT WAVE FEATURES FROM MHD SIMULATIONS

P. F. **CHEN**∗, M. D. DING and C. FANG

Space Science Reviews (**2005)** 121: 201–211, DOI: 10.1007/s11214-006-3911-0, **File**

Soft X-ray (SXR) waves, EIT waves, and Hα Moreton waves are all associated with coronal mass ejections (CMEs). The knowledge of the characteristics about these waves is crucial for the understanding of CMEs, and hence for the space weather researches. MHD numerical simulation is performed, with the consideration of the quiet Sun atmosphere, to investigate the CME/flare processes. On the basis of the numerical results, SXR,EUV, and Hα images of the eruption are synthesized, where SXR waves, EIT waves, and Hα Moreton waves are identified. It confirms that the EIT waves, which border the expanding dimmming region, are produced by the successive opening (or stretching) of the closed magnetic field lines. Hα Moreton waves are found to propagate outward synchronously with the SXR waves, lagging behind the latter spatially by ~27 Mm in the simulated scenario. However, the EIT wave velocity is only a third of the Moreton wave velocity. The synthesized results also suggest that Hα $\pm$ 0.45 °A would be the best off-band for the detection of Hα Moreton waves.

Waves are ubiquitous phenomena, which exist in various astrophysical systems. Their properties can be used to deduce the physical parameters of the plasma and magnetic field (e.g., Roberts *et al.*, 1983; Nakariakov *et al.*, 1999), in case that the wave mode should be determined. However, quite often the observed wave patterns are apparent features, with no any wave mode to be responsible for their characteristics. The well-known example is the so-called Moreton waves. More than 40 years ago, arc-like Hα disturbances were found in some flare events to propagate through the chromosphere over distances on the order of 5×10^5 km with velocities ranging from 550 to 2500 km s^{-1}, which later came to be called Moreton waves (Moreton, 1960; Moreton and Ramsey, 1960). If they were a kind of waves propagating in the chromosphere, where the fast-mode wave speed is of the order of 100 km s^{-1}, the Mach number would be too large for the wave to travel the observed distance. In this sense, Moreton waves, as a phenomenon in the chromosphere, could not be accounted for by any wave of chromospheric origin. It was 8 years later that Uchida (1968) proposed that the skirt of wave front surface of the coronal fast-mode wave sweeps the chromosphere and produces the Moreton waves. The wave is refracted toward a low Alfv´en velocity region to sharpen into an enhanced fast-mode shock wave that could emit type II radio bursts

EVIDENCE OF EIT AND MORETON WAVES IN NUMERICAL SIMULATIONS

P. F. **Chen**,1,2 S. T. Wu,3 K. Shibata,2 and C. Fang1

Astrophysical Journal, 572:L99–L102, **2002; File**

Solar coronal mass ejections (CMEs) are associated with many dynamical phenomena, among which EIT waves have always been a puzzle. In this Letter MHD processes of CME-induced wave phenomena are numerically simulated. It is shown that as the flux rope rises, a piston-driven shock is formed along the envelope of the expanding CME, which sweeps the solar surface as it propagates. We propose that the legs of the shock produce Moreton waves. Simultaneously, a slower moving wavelike structure, with an enhanced plasma region ahead, is discerned, which we propose corresponds to the observed EIT waves. The mechanism for EIT waves is therefore suggested, and their relation with Moreton waves and radio bursts is discussed.

The Nature of CME-Flare Associated Coronal Dimming

J. X. **Cheng**, J. Qiu
2016 ApJ 825 37
http://arxiv.org/pdf/1604.05443v1.pdf **File**
Coronal mass ejections (CMEs) are often accompanied by coronal dimming evident in extreme ultraviolet (EUV) and soft X-ray observations. The locations of dimming are sometimes considered to map footpoints of the erupting flux rope. As the emitting material expands in the corona, the decreased plasma density leads to reduced emission observed in spectral and irradiance measurements. Therefore, signatures of dimming may reflect properties of CMEs in the early phase of its eruption. In this study, we analyze the event of flare, CME, and coronal dimming on **December 26, 2011**. We use the data from the Atmospheric Imaging Assembly (AIA) on Solar Dynamics Observatories (SDO) for disk observations of the dimming, and analyze images taken by EUVI, COR1, and COR2 onboard the Solar Terrestrial Relations Observatories to obtain the height and velocity of the associated CMEs observed at the limb. We also measure magnetic reconnection rate from flare observations. Dimming occurs in a few locations next to the flare ribbons, and it is observed in multiple EUV passbands. Rapid dimming starts after the onset of fast reconnection and CME acceleration, and its evolution well tracks the CME height and flare reconnection. The spatial distribution of dimming exhibits cores of deep dimming with a rapid growth, and their light curves are approximately linearly scaled with the CME height profile. From the dimming analysis, we infer the process of the CME expansion, and estimate properties of the CME.

Investigation of the Formation and Separation of An EUV Wave from the Expansion of A Coronal Mass Ejection

X. **Cheng**, J. Zhang, O. Olmedo, A. Vourlidas, M. D. Ding, and Y. Liu
E-print, Dec **2011**; ApJL , 745 L5**, 2012, File**
We address the nature of EUV waves through direct observations of the formation of a diffuse wave driven by the expansion of a coronal mass ejection (CME) and its subsequent separation from the CME front. The wave and the CME on **2011 June 7** were well observed by Atmospheric Imaging Assembly onboard Solar Dynamic Observatory. Following the solar eruption onset, marked by the beginning of the rapid increasing of the CME velocity and the X-ray flux of accompanying flare, the CME exhibits a strong lateral expansion. During this impulsive expansion phase, the expansion speed of the CME bubble increases from 100 km s^-1 to 450 km s^-1 in only six minutes. An important finding is that a diffuse wave front starts to separate from the front of the expanding bubble shortly after the lateral expansion slows down. Also a type-II burst is formed near the time of the separation. After the separation, two distinct fronts propagate with different kinematic properties. The diffuse front travels across the entire solar disk; while the sharp front rises up, forming the CME ejecta with the diffuse front ahead of it. These observations suggest that the previously termed EUV wave is a composite phenomenon and driven by the CME expansion. While the CME expansion is accelerating, the wave front is cospatial with the CME front, thus the two fronts are indiscernible. Following the end of the acceleration phase, the wave moves away from the CME front with gradually an increasing distance between them.

Magnetic Flux of EUV Arcade and Dimming Regions as a Relevant Parameter for Early Diagnostics of Solar Eruptions – Sources of Non-recurrent Geomagnetic Storms and Forbush Decreases

I. M. **Chertok**, V. V. Grechnev, A. V. Belov, A. A. Abunin
Solar Physics, January **2013**, Volume 282, Issue 1, pp 175-199
This study aims at the early diagnostics of the geoeffectiveness of coronal mass ejections (CMEs) from quantitative parameters of the accompanying EUV dimming and arcade events. We study events of the 23th solar cycle, in which major non-recurrent geomagnetic storms (GMS) with Dst<−100 nT are sufficiently reliably identified with their solar sources in the central part of the disk. Using the SOHO/EIT 195 Å images and MDI magnetograms, we select significant dimming and arcade areas and calculate summarized unsigned magnetic fluxes in these regions at the photospheric level. The high relevance of this eruption parameter is displayed by its pronounced correlation with the Forbush decrease (FD) magnitude, which, unlike GMSs, does not depend on the sign of the B z component but is determined by global characteristics of ICMEs. Correlations with the same magnetic flux in the solar source region are found for the GMS intensity (at the first step, without taking into account factors determining the B z component near the Earth), as well as for the temporal intervals between the solar eruptions and the GMS onset and peak times. The larger the magnetic flux, the stronger the FD and GMS intensities are and the shorter the ICME transit time is. The revealed correlations indicate that the main quantitative characteristics of major non-recurrent space weather disturbances are largely determined by measurable parameters of solar eruptions, in particular, by the magnetic flux in dimming areas and arcades, and can be tentatively estimated in advance with a lead time from 1 to 4 days. For GMS intensity, the revealed dependencies allow one to estimate a possible value, which can be expected if the B z component is negative.

Large-Scale Activity Initiated BY Halo CMEs

I. **Chertok**1 and V. Grechnev2

*Coronal and Stellar Mass Ejections, Proceedings IAU Symposium No. 226, 2005, K. P. Dere, J. Wang & Y. Yan, eds, **2006**.*

We summarize results of our recent studies of CME-associated EUV dimmings and coronal waves by 'derotated' fixed-difference SOHO/EIT heliograms at 195˚A with 12-min intervals and at 171, 195, 284, 304˚A with 6-h intervals. Correctness of the derotated fixed-difference technique is confirmed by the consideration of the Bastille Day 2000 event. We also demonstrate that long narrow channeled dimmings and anisotropic coronal waves are typical of the complex global solar magnetosphere near the solar cycle maximum. Homology of large-scale dimmings and coronal waves takes place in a series of recurrent eruptive events. Along with dimmings coinciding entirely or partially in all four EIT bands, there exist dimmings that appear different, mainly in the transition-region line of 304 ˚A and high-temperature coronal line of 284 ˚A.

LARGE-SCALE ACTIVITY IN THE BASTILLE DAY 2000 SOLAR EVENT

I. M. **CHERTOK** and V. V. GRECHNEV

Solar Physics (**2005**) 229: 95–114

We have analyzed dimmings, i.e., regions of temporarily reduced brightness, and manifestations of a coronal wave in the famous event of 14 July 2000 using images produced with the EUV telescope SOHO/EIT. Our analysis was inspired by a paper by Andrews (2001, *Solar Phys.* 204, 181 (Paper I)), in which this event was studied using *running*-difference EIT images at 195 °A formed by subtraction of a previous image from each current one. Such images emphasize changes of the brightness, location, and configuration of observed structures occurring during the 12-min interval between two subsequent heliograms. However, they distort the picture of large-scale disturbances caused by a CME, particularly, dimmings. A real picture of dimmings can be obtained from *fixed-base* difference 'de-rotated' images. The latter are formed in two stages: first, the solar rotation is compensated using three-dimensional rotation of all images ('de-rotation') to the time of a pre-event heliogram, here 10:00 UT, and then the base heliogram is subtracted from all others. We show real dimmings to be essentially different from those described by Andrews (Paper I). The restructuring of large-scale magnetic fields in the corona in connection with the CME was accompanied by the appearance and growth of two large dimmings. One of them was located along the central meridian, southward of the eruption center, at the place of the pre-eruption arcade. Another dimming occupied the space between the flare region and a remote western active region. Several smaller dimmings were observed virtually over the whole solar disk, especially, within the northwest quadrant. We have also revealed a propagating disturbance with properties of a coronal wave in the northern polar sector, where no dimmings were observed. This fact is discussed in the context of probable association between dimmings and coronal waves. Having suppressed the 'snowstorm' produced in the EIT images by energetic particles, we have considered dimming manifestations in all four EIT pass bands of 171, 195, 284, and 304 ° A as well as the light curves of the main dimmings including several later images at 195 ° A. Our analysis shows that the major cause of the dimmings was density depletion that reached up to 30% in this event. The picture of dimmings implies that the CME in the Bastille Day event was an octopus-like bundle of some magnetic ropes, with the 'arms' being connected to several active regions disposed over almost the whole visible solar surface.

On the three-dimensional relation between the coronal dimming, erupting filament and CME. Case study of the 28 October 2021 X1.0 event

Galina **Chikunova**, Tatiana Podladchikova, Karin Dissauer, Astrid M. Veronig, Mateja Dumbović, Manuela Temmer, Ewan C.M. Dickson

A&A **2023**

https://arxiv.org/pdf/2308.09815.pdf

We investigate the relation between the spatiotemporal evolution of the dimming region and the dominant direction of the filament eruption and CME propagation for the **28 October 2021** X1.0 flare/CME event observed from multiple viewpoints by Solar Orbiter, STEREO-A, SDO, and SOHO. We propose a method to estimate the dominant dimming direction by tracking its area evolution and emphasize its accurate estimation by calculating the surface area of a sphere for each pixel. To determine the early flux rope propagation direction, we perform 3D reconstruction of the CME via graduated cylindrical shell modeling (GCS) and tie-pointing of the filament. The dimming initially expands radially and later shifts southeast. The orthogonal projections of the reconstructed height evolution of the erupting filament onto the solar surface are located in the sector of the dominant dimming growth, while the orthogonal projections of the inner part of GCS reconstruction align with the total dimming area. The filament reaches a maximum speed of ≈250 km/s at a height of about ≈180 Mm. The direction of its motion is strongly inclined from the radial (64∘ to the East, 32∘ to the South). The 50∘ difference in the 3D direction between the CME and the filament leg closely corresponds to the CME half-width determined from reconstruction, suggesting a potential relation of the reconstructed filament to the associated leg of the CME body. Our findings highlight that the dominant propagation of the dimming growth reflects the direction of the erupting magnetic structure (filament) low in the solar atmosphere, though the filament evolution is not related directly to the direction of the global CME expansion. The overall dimming morphology closely resembles the inner part of the CME reconstruction, validating the use of dimming observations to obtain insight into the CME direction.

Coronal dimmings associated with coronal mass ejections on the solar limb

Galina **Chikunova**, Karin Dissauer, Tatiana Podladchikova, Astrid M. Veronig

ApJ **896** 17 **2020**

https://arxiv.org/pdf/2005.03348.pdf

https://sci-hub.tw/https://iopscience.iop.org/article/10.3847/1538-4357/ab9105 **File**

We present a statistical analysis of 43 coronal dimming events, associated with Earth-directed CMEs that occurred during the period of quasi-quadrature of the SDO and STEREO satellites. We studied coronal dimmings that were observed above the limb by STEREO/EUVI and compared their properties with the mass and speed of the associated CMEs. The unique position of satellites allowed us to compare our findings with the results from Dissauer et al. (2018b, 2019), who studied the same events observed against the solar disk by SDO/AIA. Such statistics is done for the first time and confirms the relation of coronal dimmings and CME parameters for the off-limb viewpoint. The observations of dimming regions from different lines-of-sight reveal a similar decrease in the total EUV intensity (c=0.60±0.14). We find that the (projected) dimming areas are typically larger for off-limb observations (mean value of 1.24±1.23×1011 km2 against 3.51±0.71×1010 km2 for on-disk), with a correlation of c=0.63±0.10. This systematic difference can be explained by the (weaker) contributions to the dimming regions higher up in the corona, that cannot be detected in the on-disk observations. The off-limb dimming areas and brightnesses show very strong correlations with the CME mass (c=0.82±0.06 and c=0.75±0.08), whereas the dimming area and brightness change rate correlate with the CME speed (c∼0.6). Our findings suggest that coronal dimmings have the potential to provide early estimates of mass and speed of Earth-directed CMEs, relevant for space weather forecasts, for satellite locations both at L1 and L5. **2011 October 1, 2012 March 6**

Table 1. For each event we list the STEREO satellite used for the analysis and the derived dimming characteristics: (2010-2012)

Shock wave driven by CME evidenced by metric type II burst and EUV wave

R.D. **Cunha-Silva**, , F.C.R. Fernandes, C.L. Selhorst

Advances in Space Research Volume 56, Issue 12, 15 December **2015**, Pages 2804–2810

http://www.sciencedirect.com/science/article/pii/S0273117715005311

Solar type II radio bursts are produced by plasma oscillations in the solar corona as a result of shock waves. The relationship between type II bursts and coronal shocks is well evidenced by observations since the 1960s. However, the drivers of the shocks associated with type II events at metric wavelengths remain as a controversial issue among solar physicists. The flares and the coronal mass ejections (CMEs) are considered as potential drivers of these shocks. In this article, we present an analysis of a metric type II burst observed on **May 17, 2013**, using data provided by spectrometers from e-CALLISTO (extended-Compound Astronomical Low-cost Low-frequency Instrument for Spectroscopy and Transportable Observatories) and EUV images from the Extreme Ultraviolet Imager (EUVI), aboard the Solar Terrestrial Relations Observatory (STEREO). The event was associated with an M3.2 SXR flare and a halo CME. The EUV wave produced by the expansion of the CME was clear from the EUV images. The heights of the EUV wave fronts proved to be consistent with the heights of the radio source obtained with the 2–4 × Newkirk density model, which provided a clue to an oblique propagation of the type-II-emitting shock segment. The results for the magnetic field in the regions of the shock also revealed to be consistent with the heights of the radio source obtained using the 2–4 × Newkirk density model. Exponential fit on the intensity maxima of the harmonic emission provided a shock speed of ∼580–990 km s−1, consistent with the average speed of the associated EUV wave front of 626 km s−1.

ON THE ORIGINS OF SOLAR EIT WAVES

E. W. **Cliver**, M. Laurenza, M. Storini B. J. Thompson

The Astrophysical Journal, 631:604–611, **2005, File**

Approximately half of the large-scale coronal waves identified in images obtained by the Extreme-Ultraviolet Imaging Telescope (EIT) on the Solar and Heliospheric Observatory from 1997 March to 1998 June were associated with small solar flares with soft X-ray intensities below C class. The probability of a given flare of this intensity having an associated EIT wave is low. For example, of _8,000 B-class flares occurring during this 15 month period, only _1% were linked to EIT waves. These results indicate the need for a special condition that distinguishes flares with EITwaves from the vast majority of flares that lack wave association. Various lines of evidence, including the fact that EIT waves have recently been shown to be highly associated with coronal mass ejections (CMEs), suggest that this special condition is a CME. A CME is not a sufficient condition for a detectable EIT wave, however, because we calculate that _5 times as many front-side CMEs as EIT waves occurred during this period, after taking the various visibility factors for both phenomena into account. In general, EIT wave association increases with CME speed and width.

NUMERICAL SIMULATION OF AN EUV CORONAL WAVE BASED ON THE FEBRUARY 13, 2009 CME EVENT OBSERVED BY STEREO

Ofer **Cohen**1, Gemma D. R. Attrill1, Ward B. Manchester IV2 and Meredith J. Wills-Davey1

ApJ, **2009; File**

On **13 February 2009**, a coronal wave – CME – dimming event was observed in quadrature by the STEREO spacecraft. We analyze this event using a three-dimensional, global magnetohydrodynamic (MHD) model for the solar corona. The numerical simulation is driven and constrained by the observations, and indicates where magnetic reconnection occurs between the expanding CME core and surrounding environment. We focus primarily on the lower corona, extending out to $3R_{\odot}$; this range allows simultaneous comparison with both EUVI and COR1 data. Our simulation produces a diffuse coronal bright front remarkably similar to that observed by STEREO/EUVI at 195 °A. It is made up of two components, and is the result of a combination of both wave and non-wave mechanisms. The CME becomes large-scale quite low (< 200 Mm) in the corona. It is not, however, an inherently large-scale event; rather, the expansion is facilitated by magnetic reconnection between the expanding CME core and the surrounding magnetic environment. In support of this, we also find numerous secondary dimmings, many far from the initial CME source region. Relating such dimmings to reconnecting field lines within the simulation provides further evidence that CME expansion leads to the "opening" of coronal field lines on a global scale. Throughout the CME expansion, the coronal wave maps directly to the CME footprint.

Our results suggest that the ongoing debate over the "true" nature of diffuse coronal waves may be mischaracterized. It appears that both wave and non-wave models are required to explain the observations and understand the complex nature of these events.

Solar type II radio bursts associated with CME expansions as shown by EUV waves

R. D. **Cunha-Silva**, F. C. R. Fernandes, C. L. Selhorst

A&A 578, A38 **2015**

http://arxiv.org/pdf/1504.04323v1.pdf

We investigate the physical conditions of the sources of two metric Type-II bursts associated with CME expansions with the aim of verifying the relationship between the shocks and the CMEs, comparing the heights of the radio sources and the heights of the EUV waves associated with the CMEs. The heights of the EUV waves associated with the events were determined in relation to the wave fronts. The heights of the shocks were estimated by applying two different density models to the frequencies of the Type-II emissions and compared with the heights of the EUV waves. For the 13 June 2010 event, with band-splitting, the shock speed was estimated from the frequency drifts of the upper and lower branches of the harmonic lane, taking into account the H/F frequency ratio fH/fF = 2. Exponential fits on the intensity maxima of the branches revealed to be more consistent with the morphology of the spectrum of this event. For the 6 June 2012 event, with no band-splitting and with a clear fundamental lane on the spectrum, the shock speed was estimated directly from the frequency drift of the fundamental emission, determined by linear fit on the intensity maxima of the lane. For each event, the most appropriate density model was adopted to estimate the physical parameters of the radio source. The **13 June 2010** event presented a shock speed of 664-719 km/s, consistent with the average speed of the EUV wave fronts of 609 km/s. The **6 June 2012** event was related to a shock of speed of 211-461 km/s, also consistent with the average speed of the EUV wave fronts of 418 km/s. For both events, the heights of the EUV wave revealed to be compatible with the heights of the radio source, assuming a radial propagation of the shock.

Simultaneous Horizontal and Vertical Oscillation of a Quiescent Filament observed by CHASE and SDO

Jun **Dai**, Qingmin Zhang, Ye Qiu, Chuan Li, Zhentong Li, Shuting Li, Yingna Su, Haisheng Ji

2023 ApJ 959 71 Focus on Early Results from the Chinese Hα Solar Explorer (CHASE) Mission

https://arxiv.org/pdf/2310.19228.pdf

https://iopscience.iop.org/article/10.3847/1538-4357/ad0839/pdf

In this paper, we present the imaging and spectroscopic observations of the simultaneous horizontal and vertical large-amplitude oscillation of a quiescent filament triggered by an EUV wave on **2022 October 02**. Particularly, the filament oscillation involved winking phenomenon in Ha images and horizontal motions in EUV images. Originally, a filament and its overlying loops across AR 13110 and 13113 erupted with a highly inclined direction, resulting in an X1.0 flare and a non-radial CME. The fast lateral expansion of loops excited an EUV wave and the corresponding Moreton wave propagating northward. Once the EUV wavefront arrived at the quiescent filament, the filament began to oscillate coherently along the horizontal direction and the winking filament appeared concurrently in Ha images. The horizontal oscillation involved an initial amplitude of 10.2 Mm and a velocity amplitude of 46.5 km/s, lasting for 3 cycles with a period of 18.2 minutes and a damping time of 31.1 minutes. The maximum Doppler velocities of the oscillating filament are 18 km/s (redshift) and 24 km/s (blueshift), which was derived from the spectroscopic data provided by CHASE/HIS. The three-dimensional velocity of the oscillation is determined to be 50 km/s at an angle of 50 to the local photosphere plane. Based on the wave-filament interaction, the minimum energy of the EUV wave is estimated to be 2.7 10 20 J. Furthermore, this event provides evidence that Moreton wavesshould be excited by the highly inclined eruptions.

Quadrature Observations of Wave and Non-Wave Components and Their Decoupling in an Extreme-Ultraviolet Wave Event

Y. **Dai**1,2, M. D. Ding1,2, P. F. Chen1,2, and J. Zhang3

E-print, Aug **2012**, **File**; ApJ 759 55, **2012**

We report quadrature observations of an extreme-ultraviolet (EUV) wave event on **2011 January 27** obtained by the Extreme Ultraviolet Imager (EUVI) onboard Solar Terrestrial Relations Observatory (STEREO), and the Atmospheric Imaging Assembly (AIA) onboard the Solar Dynamics Observatory (SDO). Two components are revealed in the EUV wave event. A primary front is launched with an initial speed of _440 km s−1. It appears significant emission enhancement in the hotter channel but deep emission reduction in the cooler channel. When the primary front encounters a large coronal loop system and slows down, a secondary much fainter front emanates from the primary front with a relatively higher starting speed of _550 km s−1. Afterwards the two fronts propagate independently with increasing separation. The primary front finally stops at a magnetic separatrix, while the secondary front travels farther before it fades out. In addition, upon the arrival of the secondary front, transverse oscillations of a prominence are triggered. We suggest that the two components are of different natures. The primary front belongs to a non-wave coronal mass ejection (CME) component, which can be reasonably explained with the field-line stretching model. The multi-temperature behavior may be caused by considerable heating due to the nonlinear adiabatic compression on the CME frontal loop. For the secondary front, most probably it is a linear fast-mode magnetohydrodynamic (MHD) wave that propagates through a medium of the typical coronal temperature. X-ray and radio data provide us with complementary evidence in support of the above scenario.

LARGE-SCALE EXTREME-ULTRAVIOLET DISTURBANCES ASSOCIATED WITH A LIMB CORONAL MASS EJECTION

Dai, Y., Auch`ere, F., Vial, J., Tang, Y.H., Zong, W.G.,

ApJ **708** 913-919, **2010**, **FILE**

We present composite observations of a coronal mass ejection (CME) and the associated large-scale extreme-ultraviolet (EUV) disturbances on **2007 December 31** by the Extreme-ultraviolet Imager (EUVI) and COR1 coronagraph on board the recent Solar Terrestrial Relations Observatory mission. For this limb event, the EUV disturbances exhibit some typical characteristics of EUV Imaging Telescope waves: (1) in the 195 Å bandpass, diffuse brightenings are observed propagating oppositely away from the flare site with a velocity of ~260 km s–1, leaving dimmings behind; (2) when the brightenings encounter the boundary of a polar coronal hole, they stop there to form a stationary front. Multi-temperature analysis of the propagating EUV disturbances favors a heating process over a density enhancement in the disturbance region. Furthermore, the EUVI-COR1 composite display shows unambiguously that the propagation of the diffuse brightenings coincides with a large lateral expansion of the CME, which consequently results in a double-loop-structured CME leading edge. Based on these observational facts, we suggest that the wave-like EUV disturbances are a result of magnetic reconfiguration related to the CME liftoff rather than true waves in the corona. Reconnections between the expanding CME magnetic field lines and surrounding quiet-Sun magnetic loops account for the propagating diffuse brightenings; dimmings appear behind them as a consequence of volume expansion. X-ray and radio data provide us with complementary evidence.

Time Evolution Altitude of an Observed Coronal Wave

Cecile **Delannee**, Guy Artzner, Brigitte Schmieder, Susanna Parenti

Solar Physics, **2014**, Volume 289, Issue 7, pp 2565-2585

http://arxiv.org/pdf/1310.5623v1.pdf **; File**

The nature of coronal wave fronts is deeply debated. They are observed in several wavelength bandpasses in spectra, and are frequently interpreted as magnetosonic waves propagating in the lower solar atmosphere. However, they can be attributed to the line of sight projection of the edges of coronal mass ejections. Therefore, the altitude estimation of these features is crucial to discriminate in favor of one of these two interpretations. We take advantage of a set of

observations obtained from two different points of view by EUVI/SECCHI/STEREO on **December, 7th 2007** to derive the time evolution of the altitude of a coronal wave front. We develop a new technique to compute the altitude.
We find that the observed brightness has an increasing altitude during 5 minutes, then the altitude decreases slightly back to the low corona. We interpret the evolution of the altitude as following: the increase of altitude of the wave front is linked to the rise of a bubble like structure whether it is a magnetosonic wave front or a CME in the first phase. During the second phase, the observed brightness is mixed with the brightening of the underlying magnetic structures as the emission of the plasma of the wave front fades due to the plasma dilution with the altitude.

The role of small versus large scale magnetic topologies in global waves:

C. **Delannee**

A&A 495 (**2009**) 571-575; **File**

Context. Coronal waves are large-scale structures that propagate through the lower corona over distances of hundreds of megameters. They are believed to be related to coronal mass ejections (CMEs). Attrill and collaborators suggested that the propagation of the wave front is due to consecutive reconnections in the quiet Sun of favourably orientated magnetic field lines as a magnetic flux tube expands in an active region.
Aims. I examine the validity of this mechanism describing the computed magnetic field topology underlying a coronal wave studied by Attrill and collaborators.
Methods. I perform an extrapolation of the magnetic field in and around the active region and overlay the magnetic field lines on base difference images of the coronal wave.
Results. The active region is magnetically linked to regions at a distance 300 Mm, including the northern coronal hole and the opposite hemisphere, but not to the quiet Sun surrounding the active region. The outer border of the active region is at the boundary of two different topological magnetic domains. The boundary of magnetic topological domains usually act as a barrier along which magnetic field lines can slip, but through which they cannot pass. Therefore, the quiet Sun around the active region should be barely perturbed by the motion occurring in the active region in such a pre-event magnetic field configuration.
Conclusions. In this magnetic field topology, the quiet Sun should not undergo any reconnection process due to the eruption in the active region, in contrast to the proposal of Attrill and collaborators.

A New Model for Propagating Parts of EIT Waves: a Current Shell in a CME

C. **Delannee**, T. Torok, G. Aulanier, J.-F. Hochedez

E-print, Sept 2007, File, Solar Phys.

Solar Phys (**2008**) 247: 123–150, **File**

EIT waves are observed in EUV as bright fronts. Some of these bright fronts propagate across the solar disk. EIT waves are all associated with a flare and a CME and are commonly interpreted as fast-mode magnetosonic waves. Propagating EIT waves could also be the direct signature of the gradual opening of magnetic field lines during a CME. We quantitatively addressed this alternative interpretation. Using two independent 3D MHD codes, we performed nondimensional numerical simulations of a slowly rotating magnetic bipole, which progressively result in the formation of a twisted magnetic flux tube and its fast expansion, as during a CME. We analyse the origins, the development, and the observability in EUV of the narrow electric currents sheets that appear in the simulations. Both codes give similar results, which we confront with two well-known SOHO/EIT observations of propagating EIT waves (**7 April and 12 May 1997**), by scaling the vertical magnetic field components of the simulated bipole to the line of sight magnetic field observed by SOHO/MDI and the sign of helicity to the orientation of the soft X-ray sigmoids observed by *Yohkoh*/SXT. A large-scale and narrow current shell appears around the twisted flux tube in the dynamic phase of its expansion. This current shell is formed by the return currents of the system, which separate the twisted flux tube from the surrounding fields. It intensifies as the flux tube accelerates and it is co-spatial with weak plasma compression. The current density integrated over the altitude has the shape of an ellipse, which expands and rotates when viewed from above, reproducing the generic properties of propagating EIT waves. The timing, orientation, and location of bright and faint patches observed in the two EIT waves are remarkably well reproduced. We conjecture that propagating EIT waves are the observational signature of Joule heating in electric current shells, which separate expanding flux tubes from their surrounding fields during CMEs or plasma compression inside this current shell. We also conjecture that the bright edges of halo CMEs show the plasma compression in these current shells.

Stationary parts of an EIT and Moreton wave: a topological model.

C. **Delannee**, J.-F. Hochedez, and G. Aulanier.

A&A 465, 603-612 (**2007**); **File**

Context. EIT and Moreton waves came into focus in 1997, when a propagating disturbance on a large area of the solar disc was discovered. The process generating the EIT and Moreton waves has been frequently discussed.
Aims.On May **2, 1998**, a halo CME was observed related to an EIT wave, a Moreton wave, a X1 flare, radio emission sources, and dimmings. We studied this event to find the relation between all these structures.

Methods.We use and co-align multi-wavelength observations and the online potential field source surface (pfss) package.
Results.The observed EIT and Moreton waves present some brightenings that remain at the same location.We relate the connectivity of the coronal potential magnetic field to the stationary brightenings. We find that the areas where the magnetic field lines have drastic jumps of connectivity are cospatial to the stationary brightenings of the waves.
Conclusions.We conclude that the EIT and Moreton waves may be due to Joule heating resulting from the generation of electric currents in the neighboring area of the drastic jumps of magnetic connectivity, while the magnetic field lines are opening during a CME.

Another view of the EIT wave phenomena,
Delann´ee, C.:
Astrophys. J., 545, 512–523, **2000**.

Cme Associated with Transequatorial Loops and a Bald Patch Flare,
Delann´ee, C. and Aulanier, G.:
Solar Phys., 190, 107–129,
doi:10.1023/A:1005249416605, **1999**.

EIT and LASCO Observations of the Initiation of a Coronal Mass Ejection. Solar
Dere, K.P., Brueckner, G.E., Howard, R.A., Koomen, M.J., Korendyke, C.M., Kreplin, R.W., Michels, D.J., Moses, J.D., Moulton, N.E., Socker, D.G., St. Cyr, O.C., Delaboudini`ere, J.P., Artzner, G.E., Brunaud, J., Gabriel, A.H., Hochedez, J.F., Millier, F., Song, X.Y., Chauvineau, J.P., Marioge, J.P., Defise, J.M., Jamar, C., Rochus, P., Catura, R.C., Lemen, J.R., Gurman, J.B., Neupert, W., Clette, F., Cugnon, P., van Dessel, E.L., Lamy, P.L., Llebaria, A., Schwenn, R., Simnett, G.M.,
1997. Phys. 175, 601–612.

The Solar Eruption of 2017 September 10: Wavy with a Chance of Protons
Curt A. **de Koning**1,2, V. J. Pizzo2, and Daniel B. Seaton1,3
2022 ApJ 924 106 **File**
https://iopscience.iop.org/article/10.3847/1538-4357/ac374d/pdf
High-resolution SUVI images reveal an interesting new picture of particle acceleration in powerful solar eruptions. Typically, powerful solar eruptions include a coronal wave component, as well the traditional CME and flare components. At low solar altitudes, coronal waves refract downward, toward the solar surface, because of the slower Alfvén speeds at the base of the corona. The refracted wave plus the shock wave ahead of an intense CME allow for a two-step shock acceleration process that can result in relativistic or GLE particles. This mechanism may be particularly applicable to the first-to-arrive, prompt relativistic particles measured by the Fort Smith neutron monitor during GLE # 72 on **2017 September 10**.
A good Review in Introduction

TRANSIENT CORONAL HOLES AS SEEN IN THE He i 1083 nm MLSO OBSERVATIONS
G. **de Toma**, T. E. Holzer, J. T. Burkepile, and H. R. Gilbert
The Astrophysical Journal, 621:1109–1120, 2005, File

Extreme-Ultraviolet Wave and Accompanying Loop Oscillations
Pooja **Devi**, Ramesh Chandra, Arun Kumar Awasthi, Brigitte Schmieder, Reetika Joshi
Solar Phys. **297**, Article number: 153 **2022**
https://arxiv.org/pdf/2211.07438.pdf
https://doi.org/10.1007/s11207-022-02082-6
We present the observations of an extreme-ultraviolet (EUV) wave, which originated from the active region (AR) NOAA 12887 on **28 October 2021** and its impact on neighbouring loops. The event was observed by the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO) satellite at various wavebands and by the Solar TErrestrial RElations Observatory-Ahead (STEREO-A) with its Extreme-Ultraviolet Imager (EUVI) and COR1 instruments with a different view angle than SDO. We show that the EUV wave event consists of several waves as well as non-wave phenomena. The wave components include: the fast-mode part of the EUV wave event, creation of oscillations in nearby loops, and the appearance of wave trains. The non-wave component consists of stationary fronts. We analyze selected oscillating loops and find that the periods of these oscillations range from 230 - 549 s. Further, we compute the density ratio inside and outside the loops and the

magnetic field strength. The computed density ratio and magnetic field are found in the range of 1.08 - 2.92 and 5.75 - 8.79 G, respectively. Finally, by combining SDO and STEREO-A observations, we find that the observed EUV wave component propagates ahead of the CME leading edge.

Prominence Oscillations activated by an EUV wave

Pooja **Devi**, Ramesh Chandra, Reetika Joshi, P. F. Chen, Brigitte Schmieder, Wahab Uddin, Yong-Jae Moon

Adv. Space Res. **2022**

https://arxiv.org/pdf/2202.13147.pdf

Prominence oscillations are one of interesting phenomena in the solar atmosphere, which can be utilized to infer the embedded magnetic field magnitude. We present here the transverse oscillations of two different prominences located at the East solar limb on **2011 February 11** using the multi-wavebands data of the Atmospheric Imaging Assembly (AIA) on-board the Solar Dynamics Observatory (SDO) satellite. A prominence eruption was observed towards the east direction with an average speed of ~275 km/s. The eruption is fitted with the combination of a linear and an exponential functions of time. An extreme ultraviolet (EUV) wave event was associated with the prominence eruption. This EUV wave triggered the oscillations of both prominences on the East limb. We computed the period of each prominence using the wavelet analysis method. The oscillation period varies from 14 to 22 min. The magnetic field of the prominences was derived, which ranges from 14 to 20 G.

Statistics of coronal dimmings associated with coronal mass ejections. II. Relationship between coronal dimmings and their associated CMEs

Karin **Dissauer**, Astrid M. Veronig, Manuela Temmer, Tatiana Podladchikova

ApJ **874** 123 **2019**

https://arxiv.org/pdf/1810.01589.pdf

https://iopscience.iop.org/article/10.3847/1538-4357/ab0962/pdf

We present a statistical study of 62 coronal dimming events associated with Earth-directed CMEs during the quasi-quadrature period of STEREO and SDO. This unique setting allows us to study both phenomena in great detail and compare characteristic quantities statistically. Coronal dimmings are observed on-disk by SDO/AIA and HMI, while the CME kinematics during the impulsive acceleration phase is studied close to the limb with STEREO/EUVI and COR, minimizing projection effects. The dimming area, its total unsigned magnetic flux and its total brightness, reflecting properties of the total dimming region at its final extent, show the highest correlations with the CME mass (c∼0.6−0.7). Their corresponding time derivatives, describing the dynamics of the dimming evolution, show the strongest correlations with the CME peak velocity (c∼0.6). The highest correlation of c=0.68±0.08 is found with the mean intensity of dimmings, indicating that the lower the CME starts in the corona, the faster it propagates. No significant correlation between dimming parameters and the CME acceleration was found. However, for events where high-cadence STEREO observations were available, the mean unsigned magnetic field density in the dimming regions tends to be positively correlated with the CME peak acceleration (c=0.42±0.20). This suggests that stronger magnetic fields result in higher Lorentz forces providing stronger driving force for the CME acceleration. Specific coronal dimming parameters correlate with both, CME and flare quantities providing further evidence for the flare-CME feedback relationship. For events in which the CME occurs together with a flare, coronal dimmings statistically reflect the properties of both phenomena. **2011 February 13, 2011-06-02, 2011 October 2, 2012-06-14, 2012-09-28**

Table 1. Results of characteristic dimming parameters together with basic flare and CME quantities (2010-2012)

See VarSITI Newsletter・Vol. 20 p.8-9, **2018** http://www.varsiti.org

Statistics of coronal dimmings associated with coronal mass ejections. I. Characteristic dimming properties and flare association

Karin **Dissauer**, Astrid M. Veronig, Manuela Temmer, Tatiana Podladchikova, Kamalam Vanninathan

ApJ **863** 169 **2018**

https://arxiv.org/pdf/1807.05056.pdf

http://iopscience.iop.org/article/10.3847/1538-4357/aad3c6/pdf

Coronal dimmings, localized regions of reduced emission in the EUV and soft X-rays, are interpreted as density depletions due to mass loss during the CME expansion. They contain crucial information on the early evolution of CMEs low in the corona. For 62 dimming events, characteristic parameters are derived, statistically analyzed and compared with basic flare quantities. On average, coronal dimmings have a size of 2.15×1010 km2, contain a total unsigned magnetic flux of 1.75×1021 Mx, and show a total brightness decrease of −1.91×106 DN, which results in a relative decrease of ∼60% compared to the pre-eruption intensity level. Their main evacuation phase lasts for ∼50 minutes. The dimming area, the total dimming brightness, and the total unsigned magnetic flux show the highest correlation with the flare SXR fluence (c≳0.7). Their corresponding time derivatives, describing the dimming dynamics, strongly correlate with the GOES flare class (c≳0.6). For 60% of the events we identified core dimmings,

i.e. signatures of an erupting flux rope. They contain 20% of the magnetic flux covering only 5% of the total dimming area. Secondary dimmings map overlying fields that are stretched during the eruption and closed down by magnetic reconnection, thus adding flux to the erupting flux rope via magnetic reconnection. This interpretation is supported by the strong correlation between the magnetic fluxes of secondary dimmings and flare reconnection fluxes (c=0.63±0.08), the balance between positive and negative magnetic fluxes (c=0.83±0.04) within the total dimmings and the fact that for strong flares (>M1.0) the reconnection and secondary dimming fluxes are roughly equal**. 2011 June 21, 13 Dec 2011, 9 March 2012,10 March 2012,11 May 2012, 2012 June 6**
Table 1. Overview of the events under study 2010-2012

On the detection of coronal dimmings and the extraction of their characteristic properties

Karin **Dissauer**, Astrid M. Veronig, Manuela Temmer, Tatiana Podladchikova, Kamalam Vanninathan
ApJ **855** 137 **2018**
https://arxiv.org/pdf/1802.03185.pdf
https://iopscience.iop.org/article/10.3847/1538-4357/aaadb5/pdf
Coronal dimmings are distinct phenomena associated to coronal mass ejections (CMEs). The study of coronal dimmings and the extraction of their characteristic parameters helps us to obtain additional information of CMEs, especially on the initiation and early evolution of Earth-directed CMEs. We present a new approach to detect coronal dimming regions based on a thresholding technique applied on logarithmic base-ratio images. Characteristic dimming parameters describing the dynamics, morphology, magnetic properties and the brightness of coronal dimming regions are extracted by cumulatively summing newly dimmed pixels over time. It is also demonstrated how core dimming regions are identified as a subset of the overall identified dimming region. We successfully apply our method to two well-observed coronal dimming events. For both events the core dimming regions are identified and the spatial evolution of the dimming area reveals the expansion of the dimming region around these footpoints. We also show that in the early impulsive phase of the dimming expansion the total unsigned magnetic flux involved in the dimming regions is balanced and that up to 30% of this flux results from the localized core dimming regions. Furthermore, the onset in the profile of the area growth rate is co-temporal with the start of the associated flares and in one case also with the fast rise of the CME, indicating a strong relationship of coronal dimmings with both flare and CMEs. **6 September, 2011, October 1, 2011, 26 December 2011**

Projection effects in coronal dimmings and associated EUV wave event

Karin **Dissauer**, Manuela Temmer, Astrid M. Veronig, Kamalam Vanninathan, Jasmina Magdalenić
ApJ **830** 92 **2016**
http://arxiv.org/pdf/1607.05961v1.pdf **File**
We investigate the high-speed (v> 1000 km s−1) extreme-ultraviolet (EUV) wave associated with an X1.2 flare and coronal mass ejection (CME) from NOAA active region 11283 on **2011 September 6** (SOL2011-09-06T22:12). This EUV wave features peculiar on-disk signatures, in particular we observe an intermittent "disappearance" of the front for 120 s in SDO/AIA 171, 193, 211 {\AA} data, whereas the 335 {\AA} filter, sensitive to hotter plasmas (T~2.5 MK), shows a continuous evolution of the wave front. The eruption was also accompanied by localized coronal dimming regions. We exploit the multi-point quadrature position of SDO and STEREO-A, to make a thorough analysis of the EUV wave evolution, with respect to its kinematics and amplitude evolution and reconstruct the SDO line-of-sight (LOS) direction of the identified coronal dimming regions in STEREO-A. We show that the observed intensities of the dimming regions in SDO/AIA depend on the structures that are lying along their LOS and are the combination of their individual intensities, e.g. the expanding CME body, the enhanced EUV wave and CME front. In this context, we conclude that the intermittent disappearance of the EUV wave in the AIA 171, 193, 211 {\AA} filters, which are channels sensitive to plasma with temperatures below ~2 MK is also caused by such LOS integration effects. These observations clearly demonstrate that single-view image data provide us with limited insight to correctly interpret coronal features.
See RHESSI Science Nuggets #281 August **2016**
http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/To_be_or_not_to_be_-_the_role_of_projection_effects_in_EUV_imaging

Stereoscopic observations of the effects of a halo CME on the solar coronal structure⋆

S. **Dolei**, P. Romano, D. Spadaro and R. Ventura
A&A 567, A9 (**2014**)
We investigated the substantial restructuring of the outer solar corona in the aftermath of the halo CME that occurred on **9 March 2012**. To perform our analysis, we used SOHO/LASCO, STEREO/COR1 and SDO/AIA data, which provide observations from different viewpoints. In particular, we applied the polarization ratio technique to

the COR1 calibrated images to derive the three-dimensional structure of the CME and determine its direction and speed of propagation. We also estimated the CME mass from a sequence of four observations of the event and obtained values of up to 2.2 × 1016 g. The COR1 images show a brightness decrease in the coronal sector where the CME propagates. We verified that this intensity reduction is due to a plasma depletion. Moreover, the combined analysis performed by the two STEREO satellites allowed us to deduce that a preexisting streamer is located along the propagation direction of the CME and disappears after the passage of the event. The coronal mass loss associated with the plasma depletion is much lower than the mass expelled from the Sun in the COR1-B data. Conversely, the COR1-A obsevations allowed us to infer that the mass of the streamer carried away from the outer corona corresponds to about half of the CME mass. The results highlight the importance of stereoscopic observations in the study of corona restructuring in the aftermath of a CME event.

ON THE NATURE OF THE SPECTRAL LINE BROADENING IN SOLAR CORONAL DIMMINGS

L. R. **Dolla**1 and A. N. Zhukov1,2

Astrophysical Journal, 730:113 (14pp), **2011** April, **File**

We analyze the profiles of iron emission lines observed in solar coronal dimmings associated with coronal mass ejections, using the EUVImaging Spectrometer on board *Hinode*.We quantify line profile distortions with empirical coefficients (asymmetry and peakedness) that compare the fitted Gaussian to the data. We find that the apparent line broadenings reported in previous studies are likely to be caused by inhomogeneities of flow velocities along the line of sight, or at scales smaller than the resolution scale, or by velocity fluctuations during the exposure time. The increase in the amplitude of Alfv´en waves cannot alone explain the observed features. A double-Gaussian fit of the line profiles shows that, both for dimmings and active region loops, one component is nearly at rest while the second component presents a larger Doppler shift than that derived from a single-Gaussian fit.

Seismic Transients from Flares in Solar Cycle 23

Alina **Donea**

Space Science Reviews, Volume 158, Numbers 2-4, 451-469, **2011**

Some solar flares are known to drive seismic waves into the sub-photospheres of the magnetic regions that host them. Sunquakes, which are identified as a wave-packet of ripples are observed on the solar surface emanating from a focal region, known as seismic source or sometimes as a transient. Not all seismic transients from flares generate sunquakes. How these are produced is still a puzzle. In this paper, I will give an overview of the observed properties of sunquakes and efforts to understanding physics underlying them, including numerical modelling of flare-driven oscillations.

Validation of Global EUV Wave MHD Simulations and Observational Techniques

Cooper **Downs**1, Alexander Warmuth2, David M. Long3, D. Shaun Bloomfield4, Ryun-Young Kwon5, Astrid M. Veronig6,7, Angelos Vourlidas8, and Bojan Vršnak9

2021 ApJ 911 118

https://iopscience.iop.org/article/10.3847/1538-4357/abea78/pdf

https://doi.org/10.3847/1538-4357/abea78

Global EUV waves remain a controversial phenomenon more than 20 yr after their discovery by SOHO/EIT. Although consensus is growing in the community that they are most likely large-amplitude waves or shocks, the wide variety of observations and techniques used to identify and analyze them have led to disagreements regarding their physical properties and interpretation. Here, we use a 3D magnetohydrodynamic (MHD) model of the solar corona to simulate an EUV wave event on **2009 February 13** to enable a detailed validation of the various commonly used detection and analysis techniques of global EUV waves. The simulated event exhibits comparable behavior to that of a real EUV wave event, with similar kinematic behavior and plasma parameter evolution. The kinematics of the wave are estimated via visual identification and profile analysis, with both approaches providing comparable results. We find that projection effects can affect the derived kinematics of the wave, due to the variation in fast-mode wave speed with height in the corona. Coronal seismology techniques typically used for estimates of the coronal magnetic field are also tested and found to estimate fast-mode speeds comparable to those of the model. Plasma density and temperature variations of the wave front are also derived using a regularized inversion approach and found to be consistent with observed wave events. These results indicate that global waves are best interpreted as large-amplitude waves and that they can be used to probe the coronal medium using well-defined analysis techniques.

UNDERSTANDING SDO/AIA OBSERVATIONS OF THE 2010 JUNE 13 EUV WAVE EVENT: DIRECT INSIGHT FROM A GLOBAL THERMODYNAMIC MHD SIMULATION

Cooper **Downs**1, Ilia I. Roussev1, Bart van der Holst2, Noé Lugaz1, and Igor V. Sokolov

2012 ApJ 750 134, **File**

In this work, we present a comprehensive observation and modeling analysis of the **2010 June 13** extreme-ultraviolet (EUV) wave observed by the Atmospheric Imaging Assembly (AIA) aboard the Solar Dynamics Observatory (SDO). Due to extreme advances in cadence, resolution, and bandpass coverage in the EUV regime, the AIA instrument offers an unprecedented ability to observe the dynamics of large-scale coronal wave-like transients known as EUV waves. To provide a physical analysis and further complement observational insight, we conduct a three-dimensional, time-dependent thermodynamic MHD simulation of the eruption and associated EUV wave, and employ forward modeling of EUV observables to compare the results directly observations. We focus on two main aspects: (1) the interpretation of the stark thermodynamic signatures in the multi-filter AIA data within the propagating EUV wave front, and (2) an in-depth analysis of the simulation results and their implication with respect to EUV wave theories. Multiple aspects, including the relative phases of perturbed variables, suggest that the outer, propagating component of the EUV transient exhibits the behavior of a fast-mode wave. We also find that this component becomes decoupled from the evolving structures associated with the coronal mass ejection that are also visible, providing a clear distinction between wave and non-wave mechanisms at play.

STUDYING EXTREME ULTRAVIOLET WAVE TRANSIENTS WITH A DIGITAL LABORATORY: DIRECT COMPARISON OF EXTREME ULTRAVIOLET WAVE OBSERVATIONS TO GLOBAL MAGNETOHYDRODYNAMIC SIMULATIONS

Cooper **Downs**1, Ilia I. Roussev1, Bart van der Holst2, No´e Lugaz1, Igor V. Sokolov2, and Tamas I. Gombosi2

Astrophysical Journal, 728:2 (15pp), **2011** February; **File**

In this work, we describe our effort to explore the signatures of large-scale extreme ultraviolet (EUV) transients in the solar corona (EUV waves) using a three-dimensional thermodynamic magnetohydrodynamic model. We conduct multiple simulations of the **2008 March 25** EUV wave (~18:40 UT), observed both on and off of the solar disk by the *STEREO-A* and *B* spacecraft. By independently varying fundamental parameters thought to govern the physical mechanisms behind EUV waves in each model, such as the ambient magneto-sonic speed, eruption free energy, and eruption handedness, we are able to assess their respective contributions to the transient signature. A key feature of this work is the ability to synthesize the multi-filter response of the *STEREO* Extreme UltraViolet Imagers directly from model data, which gives a means for direct interpretation of EUV observations with full knowledge of the three-dimensional magnetic and thermodynamic structures in the simulations. We discuss the implications of our results with respect to some commonly held interpretations of EUV waves (e.g., fast-mode magnetosonic wave, plasma compression, reconnection front, etc.) and present a unified scenario which includes both a wave-like component moving at the fast magnetosonic speed and a coherent driven compression front related to the eruptive event itself.

Multispectral analysis of solar EUV images: linking temperature to morphology

T. **Dudok de Wit**[1] and F. Auchère[2]

A&A 466, 347-355 (2007)

The source images show more contrast than the original ones, thereby easing the characterisation of morphological structures.

Relation between a Moreton Wave and an EIT Wave Observed on 1997 November 4.

Eto, S., Isobe, H., Narukage, N., Asai, A., Morimoto, T., Thompson, B.,
Yashiro, S.,Wang, T., Kitai, R., Kurokawa, H., Shibata, K.,
2002. Pub. Astron. Soc. Japan 54, 481–491.

Alfv´en Profile in the Lower Corona: Implications for Shock Formation.

Evans, R.M., Opher, M., Manchester, IV, W.B., Gombosi, T.I.,
2008. Astrophys. J. 687, 1355–1362.

Slow Magnetoacoustic Waves in Smoothly Nonuniform Coronal Plasma Structures.

Fedenev, V.V., Nakariakov, V.M. & Anfinogentov, S.A.
Sol Phys 299, 2 (**2024**).
https://doi.org/10.1007/s11207-023-02246-y

Numerical simulations of a propagating slow magnetoacoustic wave guided by a field-aligned low-β plasma nonuniformity are performed in terms of ideal magnetohydrodynamics, aiming at modeling propagating extreme ultraviolet (EUV) emission disturbances observed in the solar corona. The perpendicular profiles of the equilibrium density and temperature are smoothly nonuniform, resulting in smoothly nonuniform profiles of the sound and tube speeds. It is found that an initially plane wavefront perpendicular to the magnetic field experiences a growing deformation with the distance from the driver. The segments of the wavefront located at higher sound speed regions propagate along the field faster. This results in progressively increasing phase mixing. At some distance from the wave driver, at a certain perpendicular cross-section of the nonuniformity, there are opposite phases of the wave. As local perpendicular phase and group speeds are opposite to each other, the slow wave energy tends towards regions of the higher local sound speed. This effect increases with the increase in the plasma-�. Thus, plasma nonuniformities with temperature decreases are slow magnetoacoustic anti-waveguides, while those with temperature increases are waveguides. In the optically thin radiation regime, typical for the EUV emission from the solar corona, phase mixing of slow waves leads to apparent damping of the waves. This damping is not connected with any dissipative process, and is caused by the destructive interference of slow perturbations with different phases, integrated along the line of sight. The apparent damping depends on the combination of magnetic-field strengths, plasma-�, and viewing angles. This effect could be responsible for nonsystematic dependencies of the damping length upon the oscillation periods and the plasma temperature, appearing in observations.

Three-Dimensional Reconstructions of Coronal Wave Surfaces Using a New Mask-Fitting Method

Li **Feng**, Lei Lu, Bernd Inhester, Joseph Plowman, Beili Ying, Marilena Mierla, Matthew J. West, Weiqun Gan

Solar Phys. **295**, Article number: 141 **2020**

https://arxiv.org/pdf/2009.10872.pdf

https://link.springer.com/content/pdf/10.1007/s11207-020-01710-3.pdf

Coronal waves are large-scale disturbances often driven by coronal mass ejections (CMEs). We investigate a spectacular wave event on **7 March 2012**, which is associated with an X5.4 flare (SOL2012-03-07). By using a running center-median (RCM) filtering method for the detection of temporal variations in extreme ultraviolet (EUV) images, we enhance the EUV disturbance observed by the Atmospheric Imaging Assembly (AIA) onboard the Solar Dynamics Observatory (SDO) and the Sun Watcher using Active Pixel System detector and Image Processing (SWAP) onboard the PRoject for Onboard Autonomy 2 (PROBA2). In coronagraph images, a halo front is observed to be the upper counterpart of the EUV disturbance. Based on the EUV and coronagraph images observed from three different perspectives, we have made three-dimensional (3D) reconstructions of the wave surfaces using a new mask-fitting method. The reconstructions are compared with those obtained from forward-fitting methods. We show that the mask fitting method can reflect the inhomogeneous coronal medium by capturing the concave shape of the shock wave front. Subsequently, we trace the developing concave structure and derive the deprojected wave kinematics. The speed of the 3D-wave nose increases from a low value below a few hundred kms−1 to a maximum value of about 3800 kms−1, and then slowly decreases afterwards. The concave structure starts to decelerate earlier and has significantly lower speeds than those of the wave nose. We also find that the 3D-wave in the extended corona has a much higher speed than the speed of EUV disturbances across the solar disk.

Evolution of a Halo Coronal Mass Ejection of March 09, 2012 Associated with EUV Waves

Fernandes, F. C. R.; Sampaio, L. S.; Cunha-Silva, R. D.

Ground-based Solar Observations in the Space Instrumentation Era

ASP Conference Series, Vol. 504, p. 67, **2016**

http://aspbooks.org/publications/504/067.pdf

In this work we analyse the evolution of a halo coronal mass ejection (CME) observed on **March 09, 2012**, exhibiting a velocity of 950 ms-1. The EUV images recorded by the Extreme Ultraviolet Imager (EUVI), aboard STEREO show evidence of a shockwave produced by the expansion of the CME. The event was also associated with an M.6 class X-ray solar flare, starting at 03:22 UT, peaking at 03:53 UT and ending at 04:18 UT. Type II radio emission was also recorded in the metric wavelength (100-250 MHz) by e-Callisto spectrographs. The following spectrum-temporal parameters of type II burst were estimated: starting frequency of (220 ± 5) MHz, ending frequency of (170 ± 5) MHz, frequency bandwidth of 34.3 MHz and starting and ending time of about 03:41:51 UT and 03:46:49 UT, respectively.

Deflection of coronal rays by remote CMEs: shock wave or magnetic pressure?

Boris **Filippov**1 and A.K. Srivastava2

E-print, June **2010**, Solar Phys. (**2010**) 266: 123–134, **, File,** DOI 10.1007/s11207-010-9607-3

We analyze five events of the interaction of coronal mass ejections (CMEs) with the remote coronal rays located up to 90º away from the CME as observed by the SOHO/LASCO C2 coronagraph. Using sequences of SOHO/LASCO C2 images, we estimate the kink propagation in the coronal rays during their interaction with the corresponding CMEs ranging from 180 to 920 km s^{-1} within the interval of radial distances form 3 $R_{\odot}$ to 6 $R_{\odot}$. We conclude that all studied events do not correspond to the expected pattern of shock wave propagation in the corona. Coronal ray deflection can be interpreted as the influence of the magnetic field of a moving flux rope related to a

CME. The motion of a large-scale flux rope away from the Sun creates changes in the structure of surrounding field lines, which are similar to the kink propagation along coronal rays. The retardation of the potential should be taken into account since the flux rope moves at high speed comparable with the Alfvén speed.

Moreton and EUV Waves Associated with an X1.0 Flare and CME Ejection

Carlos **Francile**, Fernando M. López, Hebe Cremades, Cristina H. Mandrini, María Luisa Luoni, David M. Long

Solar Phys. Volume 291, Issue 11, pp 3217–3249 **2016 File**

https://arxiv.org/pdf/1702.03184.pdf

A Moreton wave was detected in active region (AR) 12017 on **29 March 2014** with very high cadence with the H-Alpha Solar Telescope for Argentina (HASTA) in association with an X1.0 flare (SOL2014-03-29T17:48). Several other phenomena took place in connection with this event, such as low-coronal waves and a coronal mass ejection (CME). We analyze the association between the Moreton wave and the EUV signatures observed with the Atmospheric Imaging Assembly onboard the Solar Dynamics Observatory. These include their low-coronal surface-imprint, and the signatures of the full wave and shock dome propagating outward in the corona. We also study their relation to the white-light CME. We perform a kinematic analysis by tracking the wavefronts in several directions. This analysis reveals a high-directional dependence of accelerations and speeds determined from data at various wavelengths. We speculate that a region of open magnetic field lines northward of our defined radiant point sets favorable conditions for the propagation of a coronal magnetohydrodynamic shock in this direction. The hypothesis that the Moreton wavefront is produced by a coronal shock-wave that pushes the chromosphere downward is supported by the high compression ratio in that region. Furthermore, we propose a 3D geometrical model to explain the observed wavefronts as the chromospheric and low-coronal traces of an expanding and outward-traveling bubble intersecting the Sun. The results of the model are in agreement with the coronal shock-wave being generated by a 3D piston that expands at the speed of the associated rising filament. The piston is attributed to the fast ejection of the filament–CME ensemble, which is also consistent with the good match between the speed profiles of the low-coronal and white-light shock waves.

Hα Moreton waves observed on December 06, 2006 -- A 2D case study

C. **Francile**1, A. Costa2,3,4, M. L. Luoni4, 5 and S. Elaska

A&A 552, A3 (**2013**)

Context. We present high temporal resolution observations of a Moreton wave event detected with the Hα Solar Telescope for Argentina (HASTA) in the Hα line 656.3 nm, on **December 6, 2006**.

Aims. The aim is to contribute to the discussion about the nature and triggering mechanisms of Moreton wave events.

Methods. We describe the HASTA telescope capabilities and the observational techniques. We carried out a detailed analysis to determine the flare onset, the radiant point location, the kinematics of the disturbance and the activation time of two distant filaments. We used a 2D reconstruction of the HASTA and corresponding TRACE observations, together with conventional techniques, to analyze the probable origin of the phenomenon.

Results. The kinematic parameters and the probable onset time of the Moreton wave event are determined. A small-scale ejectum and the winking of two remote filaments are analyzed to discuss their relation with the Moreton disturbance.

Conclusions. The analysis of the Moreton wave event favors the hypothesis that the phenomenon can be described as the chromospheric imprint of a single fast coronal shock triggered from a single source in association with a coronal mass ejection. Its onset time is concurrent with a Lorentz force peak measured in the photosphere, as stated by other authors. However, the existence of multiple shock waves that were generated almost simultaneously cannot be discarded.

Global Nature of Solar Coronal Shock Waves shown by Inconsistency between EUV Waves and Type II Radio Bursts

Aarti **Fulara**, Ryun-Young Kwon

ApJLetters **2021**

https://arxiv.org/pdf/2109.01509.pdf

We re-examine the physical relationship between Extreme-UltraViolet (EUV) waves and type II radio bursts. It has been often thought that they are two observational aspects of a single coronal shock wave. However, a lack of their speed correlation hampers the understanding of their respective (or common) natures in a single phenomenon. Knowing the uncertainties in identifying true wave components from observations and measuring their speeds, we re-examine the speeds of EUV waves reported in previous literature and compare these with type II radio bursts and Coronal Mass Ejections (CMEs). This confirms the inconsistency between the speeds of EUV waves and their associated type II radio bursts. Second, CME speeds are found to have a better correlation with type II radio bursts than EUV waves. Finally, there exists a tendency for type II speeds and their range to be much greater than those of

EUV waves. We demonstrate that the speed inconsistency is in fact an intrinsic tendency and elucidate the nature of a coronal shock wave consisting of both driven and non-driven parts. This suggests that the speed inconsistency would remain even if all other uncertainties were removed. **2013 April 11**
Таблица

Kinematics and Energetics of the EUV Waves on 11 April 2013

Aarti **Fulara**, Ramesh Chandra, P. F. Chen, Ivan Zhelyazkov, A. K. Srivastava, Wahab Uddin
Solar Phys. 294:56 **2019**
https://arxiv.org/pdf/1903.12158.pdf
sci-hub.se/10.1007/s11207-019-1445-3
In this study, we present the observations of extreme-ultraviolet (EUV) waves associated with an M6.5 flare on **2013 April 11**. The event was observed by Solar Dynamics Observatory (SDO) in different EUV channels. The flare was also associated with a halo CME and type II radio bursts. We observed both fast and slow components of the EUV wave. The speed of the fast component, which is identified as a fast-mode MHD wave, varies in the range from 600 to 640 km s^-1 , whereas the speed of the slow-component is ~140 km s^-1 . We observed an unusual phenomenon that, as the fast-component EUV wave passes through two successive magnetic quasi-separatrix layers (QSLs), two stationary wave fronts are formed locally. We propose that part of the outward-propagating fast-mode EUV wave is converted into slow-mode magnetohydrodynamic waves, which are trapped in local magnetic field structures, forming successive stationary fronts. Along the other direction, the fast-component EUV wave also creates oscillations in a coronal loop lying ~225 Mm away from the flare site. We have computed the energy of the EUV wave to be of the order of 10^20 J.

Investigating coronal wave energy estimates using synthetic non-thermal line widths

Lianne **Fyfe**, Thomas Howson, Ineke De Moortel, Vaibhav Pant, Tom Van Doorsselaere
A&A **2021**
https://arxiv.org/pdf/2110.00257.pdf
Aims. Estimates of coronal wave energy remain uncertain as a large fraction of the energy is likely hidden in the non-thermal line widths of emission lines. In order to estimate these wave energies, many previous studies have considered the root mean squared wave amplitudes to be a factor of 2–√ greater than the non-thermal line widths. However, other studies have used different factors. To investigate this problem, we consider the relation between wave amplitudes and the non-thermal line widths within a variety of 3D magnetohydrodynamic (MHD) simulations.
Methods. We consider the following 3D numerical models: Alfvén waves in a uniform magnetic field, transverse waves in a complex braided magnetic field, and two simulations of coronal heating in an arcade. We applied the forward modelling code FoMo to generate the synthetic emission data required to analyse the non-thermal line widths.
Results. Determining a single value for the ratio between the non-thermal line widths and the root mean squared wave amplitudes is not possible across multiple simulations. It was found to depend on a variety of factors, including line-of-sight angles, velocity magnitudes, wave interference, and exposure time. Indeed, some of our models achieved the values claimed in recent articles while other more complex models deviated from these ratios.
Conclusions. To estimate wave energies, an appropriate relation between the non-thermal line widths and root mean squared wave amplitudes is required. However, evaluating this ratio to be a singular value, or even providing a lower or upper bound on it, is not realistically possible given its sensitivity to various MHD models and factors. As the ratio between wave amplitudes and non-thermal line widths is not constant across our models, we suggest that this widely used method for estimating wave energy is not robust.

Large-scale Bright Fronts in the Solar Corona: A Review of “EIT waves”

Peter T. **Gallagher** _ David M. Long
ArXiv e-prints 1006.0140 Preprint **2010**, **File**, Space Science Reviews, Volume 158, Numbers 2-4, 365-396, **2011**
‘EIT waves" are large-scale coronal bright fronts (CBFs) that were first observed in 195 A ^\circ images obtained using the Extreme-ultraviolet Imaging Telescope (EIT) onboard the Solar and Heliospheric Observatory (SOHO). Commonly called "EIT waves", CBFs typically appear as diffuse fronts that propagate pseudo-radially across the solar disk at velocities of 100-700 km s-1 with front widths of 50-100 Mm. As their speed is greater than the quiet coronal sound speed (cs \le 200 km s-1) and comparable to the local Alfve 'n speed (vA \le 1000 km s-1), they were initially interpreted as fast-mode magnetoacoustic waves (v f = (c2s + v2A)1/2). Their propagation is now known to be modified by regions where the magnetosonic sound speed varies, such as active regions and coronal holes, but there is also evidence for stationary CBFs at coronal hole boundaries. The latter has led to the suggestion that they may be a manifestation of a processes such as Joule heating or magnetic reconnection, rather than a wave-related phenomena. While the general morphological and kinematic properties of CBFs and their association with coronal mass ejections have now been well described, there are many questions regarding their excitation and propagation.

In particular, the theoretical interpretation of these enigmatic events as magnetohydrodynamic waves or due to changes in magnetic topology remains the topic of much debate.

The Filament-Moreton Wave Interaction of 2006 December 6.

Gilbert, H.R., Daou, A.G., Young, D., Tripathi, D., Alexander, D.,
2008. Astrophys. J. 685, 629–645.

Chromospheric waves observed in the He I spectral line (λ = 10 830 Å): A closer look.

Gilbert, H.R., Holzer, T.E.:
2004, *Astrophys. J.* **610**, 572 – 587. doi:10.1086/421452.

A Comparison of CME-Associated Atmospheric Waves Observed in Coronal (Fe XII 195 °A) and Chromospheric (He I 10830 °A) Lines.

Gilbert, H.R., Holzer, T.E., Thompson, B.J., Burkepile, J.T.,
2004. Astrophys. J. 607, 540–553.

Multiscale optical flow probing of dynamics in solar EUV images - Algorithm, calibration, and first results:

S. F. **Gissot** and J.-F. Hochedez
A&A 464 (**2007**) 1107-1118
http://www.aanda.org/10.1051/0004-6361:20065553

Obscuration of Flare Emission by an Eruptive Prominence

Nat **Gopalswamy** ans seiji Yashiro
E-print, Sept **2013**, PASJ
http://cdaw.gsfc.nasa.gov/publications/gopal/gopal2013PASJ.pdf
We report on the eclipsing of microwave flare emission by an eruptive prominence from a neighboring region as observed by the Nobeyama Radioheliograph at 17 GHz. The obscuration of the flare emission appears as a dimming feature in the microwave flare light curve. We use the dimming feature to derive the temperature of the prominence and the distribution of heating along the length of the filament. We find that the prominence is heated to a temperature above the quiet Sun temperature at 17 GHz. The duration of the dimming is the time taken by the eruptive prominence in passing over the flaring region. We also find evidence for the obscuration in EUV images obtained by the Solar and Heliospheric Observatory (SOHO) mission. **2002/05/21-22**

The Strength and Radial Profile of Coronal Magnetic Field from the Standoff Distance of a CME-driven Shock

Nat **Gopalswamy** and Seiji Yashiro2
E-print, July **2011, File**
We determine the coronal magnetic field strength in the heliocentric distance range 6 to 23 solar radii (Rs) by measuring the shock standoff distance and the radius of curvature of the flux rope during the **2008 March 25** coronal mass ejection (CME) imaged by white-light coronagraphs. Assuming the adiabatic index, we determine the Alfven Mach number, and hence the Alfven speed in the ambient medium using the measured shock speed. By measuring the upstream plasma density using polarization brightness images, we finally get the magnetic field strength upstream of the shock. The estimated magnetic field decreases from ~48 mG around 6 Rs to 8 mG at 23 Rs. The radial profile of the magnetic field can be described by a power law in agreement with other estimates at similar heliocentric distances.

EUV WAVE REFLECTION FROM A CORONAL HOLE

N. **Gopalswamy**, S. Yashiro, M. Temmer, J. Davila, W. T. Thompson, S. Jones, R. T. J. McAteer, J.-P. Wuelser, S. Freeland, and R. A. Howard
ApJ 691 L123-L127 **2009, File**
http://www.iop.org/EJ/abstract/1538-4357/691/2/L123

We report on the detection of EUV wave reflection from a coronal hole, as observed by the Solar Terrestrial Relations Observatory mission. The EUV wave was associated with a coronal mass ejection (CME) erupting near the disk center. It was possible to measure the kinematics of the reflected waves for the first time. The reflected waves were generally slower than the direct wave. One of the important implications of the wave reflection is that the EUV transients are truly a wave phenomenon. The EUV wave reflection has implications for CME propagation, especially during the declining phase of the solar cycle when there are many low-latitude coronal holes

Observations of Ray-Like Structures in Large-Scale Coronal Dimmings Produced by Limb CMEs

F. **Goryaev**, V. Slemzin, D. Rodkin

Solar Phys. **2020**

https://arxiv.org/pdf/2003.11326.pdf

Observations of the off-limb corona with the SWAP wide-field telescope in the 174\,Å passband onboard the PROBA2 mission provide an opportunity to study post-eruptive processes in the dimming regions. We investigate morphology, temporal evolution, and plasma properties for four `deep' off-disk coronal dimmings associated with limb coronal mass ejections (CMEs) in 2010\,--\,2017. Using the SWAP fixed-difference images, we revealed ray-like structures that appeared in the dimming recovery phase stretching quasi-radially to distances from 1.1 to 1.6\,R⨀ and existing from tens of minutes to several hours. Similar rays were detected earlier at distances above 1.7\,R⨀ by the UVCS onboard the SOHO. These structures apparently represent the coronal roots of the flux rope trunks observed by the LASCO-C2 onboard SOHO. The EUVI data onboard the STEREO show the origins of these structures on the disc as fan rays much brighter in the 171\,Å band than in 193\,Å, which suggests their temperature being less than 2\,MK. The differential emission measure (DEM) analysis based on the AIA multi-wavelength images onboard the SDO showed that the emission measure (EM) in these rays compared to the pre-eruption plasma state increased up to 45\,\% at temperatures of 0.6\,--\,0.8\,MK, whereas EM of the ambient coronal plasma with temperatures of 1.3\,--\,3.7\,MK dropped by 19\,--\,43\,\%. For the event on 18 August 2010, the PLASTIC instrument onboard STEREO detected signatures of the cold streams in the CME tail as enriched with the ions Fe8+\,--\,Fe10+, which may be associated with the post-eruptive rays in the solar corona. **18 Aug. 2010, 08 Mar. 2011, 27 Jan. 2012, 10 Sep. 2017**

Brightening and Darkening of the Extended Solar Corona during the Superflares of September 2017

Farid F. **Goryaev**1, Vladimir A. Slemzin1, Denis G. Rodkin1, Elke D'Huys2, O. Podladchikova2, and Matthew J. West2

2018, ApJ, 856, L38,

http://sci-hub.st/10.3847/2041-8213/aab849

On **2017 September 6 and 10**, the strongest X9.3 and X8.2 flares of the decade occurred in the active region NOAA Active Region 12673. During these flares, the Sun Watcher with Active Pixels and Image Processing (SWAP) telescope on board the Project for Onboard Autonomy 2 (PROBA2) satellite registered the unusual alternate brightening and darkening of the western corona at the heliocentric distances ≈1.2–1.7 R ⊙. The X9.3 flare on 2017 September 6 was accompanied by coronal brightening up to 30%–45% at distances ≈1.35–1.7 R ⊙. Numerical simulations showed that this brightening might be produced by resonant scattering of the flare radiation by the Fe ix–Fe xi ions in the coronal plasma at the temperature T ~ 0.8–1 MK, and the densities seriously reduced in comparison with the typical values for the quiet background corona probably moving outward with velocities of 30–40 km s−1. At the maximum of the flare and one hour later, two coronal mass ejections (CMEs) originated, which dimmed the coronal emission in the SWAP 174 Å passband above the western limb by 20%–30%. The X8.2 flare on September 10 was accompanied by a CME, which rose up and progressively dimmed the western part of the corona up to 60%. An hour later the darkening, produced by a global rearrangement of the magnetic field structure and an evacuation of a significant part of the coronal plasma, extended over the complete western limb. A differential emission measure (DEM) analysis showed a decrease in the electron density of the background plasma with T ~ 1–2 MK at distances 1.24–1.33 R ⊙ by 2–3.5 times after the CME. At the same time, an additional DEM peak at T ≈ 0.8 MK appeared, which may be associated with an additional emission in the SWAP passband produced by the flare radiation resonantly scattered by the coronal plasma.

DUAL TRIGGER OF TRANSVERSE OSCILLATIONS IN A PROMINENCE BY EUV FAST AND SLOW CORONAL WAVES: SDO/AIA AND STEREO/EUVI OBSERVATIONS

S. **Gosain**1 and C. Foullon

2012 ApJ 761 103, **File**

We analyze flare-associated transverse oscillations in a quiescent solar prominence on **2010 September 8-9**. Both the flaring active region and the prominence were located near the west limb, with a favorable configuration and viewing angle. The full-disk extreme ultraviolet (EUV) images of the Sun obtained with high spatial and temporal resolution by the Atmospheric Imaging Assembly on board the Solar Dynamics Observatory show flare-associated lateral oscillations of the prominence sheet. The STEREO-A spacecraft, 815 ahead of the Sun-Earth line, provides an on-disk view of the flare-associated coronal disturbances. We derive the temporal profile of the lateral displacement of the prominence sheet by using the image cross-correlation technique. The displacement curve was de-trended and the residual oscillatory pattern was derived. We fit these oscillations with a damped cosine function with a variable period and find that the period is increasing. The initial oscillation period (P 0) is ~28.2 minutes and the damping time (τ D) ~ 44 minutes. We confirm the presence of fast and slow EUV wave components. Using STEREO-A observations, we derive a propagation speed of ~250 km s–1 for the slow EUV wave by applying the time-slice technique to the running difference images. We propose that the prominence oscillations are excited by the fast EUV wave while the increase in oscillation period of the prominence is an apparent effect, related to a phase change due to the slow EUV wave acting as a secondary trigger. We discuss implications of the dual trigger effect for coronal prominence seismology and scaling law studies of damping mechanisms.

Reconciliation of Observational Challenges to the Impulsive-Piston Shock-Excitation Scenario.
II. Shock Waves Produced in CME-less Events with a Null-Point Topology.

Grechnev, V.V., Kiselev, V.I., Uralov, A.M., Myshyakov, I.I.:

Solar Phys., **2022, File See movies of 16 Apr 2014**

Continuing Article I, we revisit challenging events previously identified by different authors, whose analysis led to conclusions about various mechanisms of the shock-wave excitation. Here we reconsider four events that involved fan–spine coronal configurations with a null-point topology (NPT). The presence of Type-II radio bursts in all events as well as extreme-ultraviolet disturbances (EUV waves) observed in three events evidence the presence of shock waves, whereas no coronal mass ejections (CMEs) were detected in most events. One idea proposed to explain observations was the shock-wave excitation by the straightening of a post-reconnection kinked loop. The Type-II burst in another event appeared in association with a compact flare with a high thermal pressure that looked in favor of a flare-generated blast wave. One event was associated with a possible pseudo-CME. All of these challenging events have been reconciled in terms of an impulsively excited piston shock. CME-less filament eruptions in NPT configurations appear to represent a distinct category of events responsible for some of the observed shock waves. **14 November 2005 , 28 February 2011 , 6 March 2014 , 16 April 2014**

Reconciliation of Observational Challenges to the Impulsive-Piston Shock-Excitation Scenario.
I. Kinematic Challenges

V.V. **Grechnev** · V.I. Kiselev · A.M. Uralov

Solar Phys. **2022 File See movies of 8 December 2007**

Until now, there is no consensus on the origin of coronal shock waves. Questions also remain about the patterns that govern the propagation of the presumably related disturbances observed in the extreme ultraviolet (EUV waves). We present arguments in favor of the initial excitation of the waves by the impulsive acceleration of erupting structures. We consider two puzzling events that have been known thanks to the efforts of different research teams. Using recent findings and our methods, we aim to figure out what might actually have happened in these challenging events. In the first event, the expansion of the coronal mass ejection (CME) was determined by gravity starting from the low corona. The previous analysis led the authors to a conclusion about the flare-related origin of the associated shock wave. We also consider another event, in which an EUV wave had a strange kinematics. This was one of the weakest flares accompanied by EUV waves. Both of these challenging events have been reconciled in terms of an impulsively-excited piston shock. **24 December 1996, 8 December 2007**

An Updated View of Solar Eruptive Flares and Development of Shocks and CMEs: History of the 2006 December 13 GLE-Productive Extreme Event

V. **Grechnev**, V. Kiselev, A. Uralov, N. Meshalkina, A. Kochanov

E-print, Aug **2013**; PASJ

An extreme **2006 December 13** event marked the onset of the Hinode era being the last major flare in the solar cycle 23 observed with NoRH and NoRP. The event produced a fast CME, strong shock, and big particle event responsible for GLE70. We endeavor to clarify relations between eruptions, shock wave, and the flare, and to shed light on a debate over the origin of energetic protons. One concept relates it with flare processes. Another one associates acceleration of ions with a bow shock driven by a CME at (2-4)R_sun. The latter scenario is favored by a delayed particle release time after the flare. However, our previous studies have established that a shock wave is typically excited by an impulsively erupting magnetic rope (future CME core) during the flare rise, while the outer CME surface evolves from an arcade whose expansion is driven from inside. Observations of the 2006 December 13 event reveal two shocks following each other, whose excitation scenario contradicts the delayed CME-driven bow-shock hypothesis. Actually, the shocks developed much earlier, and could accelerate protons still before the flare peak. Then, the two shocks merged into a single stronger one and only decelerated and dampened long afterwards.

Coronal Shock Waves, EUV Waves, and Their Relation to CMEs. III. Shock-Associated CME/EUV Wave in an Event with a Two-Component EUV Transient

V. V. **Grechnev**, A. N. Afanasyev, A. M. Uralov, I. M. Chertok, M. V. Eselevich, V. G. Eselevich, G. V. Rudenko and Y. Kubo

Solar Physics, Volume 273, Number 2, 461-477, **2011, File in Chertok's papers**

On **17 January 2010**, STEREO-B observed in extreme ultraviolet (EUV) and white light a large-scale dome-shaped expanding coronal transient with perfectly connected off-limb and on-disk signatures. Veronig et al. (Astrophys. J. Lett. 716, L57, 2010) concluded that the dome was formed by a weak shock wave. We have revealed two EUV components, one of which corresponded to this transient. All of its properties found from EUV, white light, and a metric type II burst match expectations for a freely expanding coronal shock wave, including correspondence with the fast-mode speed distribution, while the transient sweeping over the solar surface had a speed typical of EUV waves. The shock wave was presumably excited by an abrupt filament eruption. Both a weak shock approximation and a power-law fit match kinematics of the transient near the Sun. Moreover, the power-law fit matches the expansion of the CME leading edge up to 24 solar radii. The second, quasi-stationary EUV component near the dimming was presumably associated with a stretched CME structure; no indications of opening magnetic fields have been detected far from the eruption region.

Coronal Shock Waves, EUV Waves, and Their Relation to CMEs. I. Reconciliation of "EIT Waves", Type II Radio Bursts, and Leading Edges of CMEs

V. V. **Grechnev**, A. M. Uralov, I. M. Chertok, I. V. Kuzmenko, A. N. Afanasyev, N. S. Meshalkina, S. S. Kalashnikov and Y. Kubo

Solar Physics, Volume 273, Number 2, 433-460, **2011, File in Chertok's papers**

We show examples of the excitation of coronal waves by flare-related abrupt eruptions of magnetic rope structures. The waves presumably rapidly steepened into shocks and freely propagated afterwards like decelerating blast waves that showed up as Moreton waves and EUV waves. We propose a simple quantitative description for such shock waves to reconcile their observed propagation with drift rates of metric type II bursts and kinematics of leading edges of coronal mass ejections (CMEs). Taking account of different plasma density falloffs for propagation of a wave up and along the solar surface, we demonstrate a close correspondence between drift rates of type II bursts and speeds of EUV waves, Moreton waves, and CMEs observed in a few previously studied events.
24 September 1997, 1 June 2002, 13 July 2004, 19 May 2007

Absorption Phenomena and a Probable BlastWave in the 13 July 2004 Eruptive Event

V.V. **Grechnev** · A.M. Uralov · V.A. Slemzin · I.M. Chertok · I.V. Kuzmenko · K. Shibasaki

Solar Phys (**2008**) 253: 263–290 **File in Chertok's papers**

We present a case study of the **13 July 2004** solar event, in which disturbances caused by eruption of a filament from an active region embraced a quarter of the visible solar surface. Remarkable are the absorption phenomena observed in the SOHO/EIT 304 Å channel, which were also visible in the EIT 195 Å channel, in the H〈 line, and even in total radio flux records. Coronal and Moreton waves were also observed. Multispectral data allowed reconstructing an overall picture of the event. An explosive filament eruption and related impulsive flare produced a CME and blast shock, both of which decelerated and propagated independently. Coronal and Moreton waves were kinematically close and both decelerated in accordance with an expected motion of a coronal blast shock. The CME did not resemble a classical three-component structure, probably because some part of the ejected mass fell back onto the Sun. Quantitative evaluations from different observations provide close estimates of the falling mass,~ 3×1015 g, which is close to the estimated mass of the CME. The falling material was responsible for the observed large-scale absorption phenomena, in particular, shallow widespread moving dimmings observed at 195 Å. By contrast, deep quasi-stationary dimmings observed in this band near the eruption center were due to plasma density decrease in coronal structures.

CORONAS-F/SPIRIT EUV observations of October–November 2003 solar eruptive events in combination with SOHO/EIT data,

Grechnev, V. V., I. M. Chertok, V. A. Slemzin, S. V. Kuzin, A. P. Ignat'ev, A. A. Pertsov, I. A. Zhitnik, J.-P. Delaboudinie`re, and F. Auche`re

(**2005**) J. Geophys. Res., 110, A09S07, **File in Chertok's papers**

The extraordinary solar activity of October–November 2003 manifested itself in many powerful eruptive events, including large coronal mass ejections (CMEs) and extremely powerful flares. A number of major events were accompanied by practically all known phenomena of the solar activity, both local and large-scale, and caused severe space weather disturbances. We study large-scale posteruptive activity manifestations on the Sun associated with CMEs, i.e., dimmings and coronal waves, observed with extremeultraviolet telescopes, the SPIRIT on the CORONAS-F spacecraft and the EIT on the SOHO. During that period, observations with a cadence of 15 to 45 min were carried out by the SPIRIT in the 175 A ° and 304 A ° bands simultaneously. The EIT observed with 12-min cadence in the 195 A ° band as well as with 6-hour cadence in the 171, 284, and 304 A ° bands. These data complement each other both in the temporal and spectral coverage. Our analysis reveals that largest-scale dimmings covered almost the whole southern part of the Sun's visible side and exhibited homology, with one homological structure being changed to another configuration on 28 October. These structures show connections between large superactive and smaller regions that constituted a huge activity complex responsible for the extraordinary solar activity of that period. Coronal waves were observed at 175 A ° as well as at 195 A ° in some events, in areas where there were no active regions, but in the 175 A ° images they look fainter. They were not accompanied by deep, longliving dimmings. By contrast, such dimmings were observed in active regions, in their vicinity, and between them. These facts rule out the direct relation of the phenomena of longterm dimmings and coronal waves. On 18 November, a motion of an ejecta was observed at the solar disk as a propagation of a dark feature only in the 304 A ° band, which can be interpreted as an absorption in a ''cloud'' formed from material of the eruptive filament, which probably failed to become a CME core.

Slow Patchy Extreme-ultraviolet Propagating Fronts Associated With Fast Coronal Magneto-acoustic Waves In Solar Eruptions

Y. **Guo**, M. D. Ding, P. F. Chen

Astrophysical Journal Supplement Series **219** 36 **2015**

Using the high spatiotemporal resolution extreme ultraviolet (EUV) observations of the Atmospheric Imaging Assembly on board the Solar Dynamics Observatory, we conduct a statistical study of the observational properties of the coronal EUV propagating fronts. We find that it might be a universal phenomenon for two types of fronts to coexist in a large solar eruptive event. It is consistent with the hybrid model of EUV propagating fronts, which predicts that coronal EUV propagating fronts consist of both a fast magneto-acoustic wave and a nonwave component. We find that the morphologies, propagation behaviors, and kinematic features of the two EUV propagating fronts are completely different from each other. The fast magneto-acoustic wave fronts are almost isotropic. They travel continuously from the flaring region across multiple magnetic polarities to global distances. On the other hand, the slow nonwave fronts appear as anisotropic and sequential patches of EUV brightening. Each patch propagates locally in the magnetic domains where the magnetic field lines connect to the bottom boundary and stops at the magnetic domain boundaries. Within each magnetic domain, the velocities of the slow patchy nonwave component are an order of magnitude lower than that of the fast-wave component. However, the patches of the slow EUV propagating front can jump from one magnetic domain to a remote one. The velocities of such a transit between different magnetic domains are about one-third to one-half of those of the fast-wave component. The results show that the velocities of the nonwave component, both within one magnetic domain and between different magnetic domains, are highly nonuniform due to the inhomogeneity of the magnetic field in the lower atmosphere.

SPECTROSCOPIC OBSERVATIONS OF A CORONAL MORETON WAVE

Louise K. **Harra**1, Alphonse C. Sterling2,5, Peter Gömöry3 and Astrid Veronig

2011 ApJ 737 L4, **File**

We observed a coronal wave (EIT wave) on 2011 February 16, using EUV imaging data from the Solar Dynamics Observatory/Atmospheric Imaging Assembly (AIA) and EUV spectral data from the Hinode/EUV Imaging Spectrometer (EIS). The wave accompanied an M1.6 flare that produced a surge and a coronal mass ejection (CME). EIS data of the wave show a prominent redshifted signature indicating line-of-sight velocities of ~20 km s–1 or greater. Following the main redshifted wave front, there is a low-velocity period (and perhaps slightly blueshifted), followed by a second redshift somewhat weaker than the first; this progression may be due to oscillations of the EUV atmosphere set in motion by the initial wave front, although alternative explanations may be possible. Along the direction of the EIS slit the wave front's velocity was ~500 km s–1, consistent with its apparent propagation velocity projected against the solar disk as measured in the AIA images, and the second redshifted feature had propagation velocities between ~200 and 500 km s–1. These findings are consistent with the observed wave being generated by the outgoing CME, as in the scenario for the classic Moreton wave. This type of detailed spectral study of coronal waves has hitherto been a challenge, but is now possible due to the availability of concurrent AIA and EIS data.

The Solar Source of a Magnetic Cloud Using a Velocity Difference Technique

L.K. **Harra**, · C.H. Mandrini, · S. Dasso, A.M. Gulisano, · K. Steed, · S. Imada

E-print, Nov **2010**, **File**; Solar Phys.

For large eruptions on the Sun, it is often a problem that the **core dimming region** cannot be observed due to the bright emission from the flare itself. However, spectroscopic data can provide the missing information through the measurement of Doppler velocities. In this paper we analyse the well-studied flare and coronal mass ejection that erupted on the Sun on **13 December 2006** and reached the Earth on 14 December 2006. In this example, although the imaging data were saturated at the flare site itself, we could extract information on the core dimming region through velocity measurements, as well as on the remote dimmings. The purpose of this paper is to determine more accurately the magnetic flux of the solar source region, potentially involved in the ejection, through a new technique. The results of its application are compared to the flux in the magnetic cloud observed at 1AU, as a way to check the reliability of this technique. We analysed data from the {it Hinode} EUV Imaging Spectrometer to estimate the Doppler velocity in the active region and its surroundings before and after the event. This allowed us to determine a Doppler velocity 'difference' image. We used the velocity difference image overlayed on a Michelson Doppler Imager magnetogram to identify the regions in which the blue-shifts were more prominent after the event; the magnetic flux in these regions was used as a proxy for the ejected flux and compared to the magnetic cloud flux. This new method provides a more accurate flux determination in the solar source region.

On-disk signatures of eruptive activity from the Hinode mission

Louise K. **Harra**

Advances in Space Research, Volume 44, Issue 4, 17 August **2009**, Pages 446-450, **File**

On-disk signatures of eruptive activity have been investigated for many years. These include filament eruptions, flares, coronal waves and dimmings. The Hinode mission is providing a new perspective on eruptive activity on the Sun and its linkage to the Earth. Despite being in a period of solar minimum since the launch of Hinode in September 2006, observations have been made of flares and coronal mass ejections (CMEs). A description of flare and CME triggers are presented, followed by a description of the impact of the eruption on the surrounding corona. A review of the more recent results achieved predominantly from the Hinode space mission are given. Some discussion of the future potential is described as a new solar cycle is beginning a slow start.

Coronal dimming observed with Hinode: outflows related to a coronal mass ejection

Harra, Hara, Imada, Young, Williams, Sterling, Korendyke and Attrill

E-print, Sept 2007, File ; *Publ. Astron. Soc. Japan 59, pp.S801-S806 (**2007**)*

PDF(1702kb)

`14 Dec 2006 – 22:15 UT: X1.5 west flare`

Coronal dimming has been a signature used to determine the source of plasma that forms part of a coronal mass ejection (CME) for many years. Generally dimming is detected through imaging instruments such as SOHO EIT by taking difference images. Hinode tracked active region 10930 from which there were a series of flares. We combine dimming observations from EIT with Hinode data to show the impact of flares and coronal mass ejections on the region surrounding the flaring active region, and we discuss evidence that the eruption resulted in **a prolonged steady outflow of material from the corona.** The dimming region shows clear structure with extended loops whose footpoints are the source of the strongest outflow ($approx$ 40 km/s). This confirms that the loops that are disrupted during the event do lose plasma and hence are likely to form part of the CME. This is the first time the velocity of the coronal plasma has been measured in an extended dimming region away from the flare core. In addition there was a weaker steady outflow from extended, faint loops outside the active region before the eruption, which is also long lasting. These were disturbed and the velocity increased following the flare. Such outflows could be the source of the slow solar wind.

Spectroscopic observations of coronal waves and coronal mass ejections
L.K. **Harra**
Advances in Space Research
Volume 41, Issue 1, **2008**, Pages 138-143; **File**
It is common to use imaging instruments such as EUV and X-ray imagers and coronagraphs to study large-scale phenomena such as coronal mass ejections and coronal waves. Although high resolution spectroscopy is generally limited to a small field of view, its importance in understanding global phenomena should not be under-estimated. I will review current spectroscopic observations of large-scale dynamic phenomena such as global coronal waves and coronal mass ejections. The aim is to determine plasma parameters such as flows, temperatures and densities to obtain a physical understanding of these phenomena.

Imaging and Spectroscopic Investigations of a Solar Coronal Wave: Properties of the Wave Front and Associated Erupting Material.
Harra, L.K., Sterling, A.C.,
2003. Astrophys. J. 587, 429–438.

Material Outflows from Coronal Intensity "Dimming Regions" during Coronal Mass Ejection Onset.
Harra, L.K., Sterling, A.C.,
2001. Astrophys. J. 561, L215–L218.

Coronal mass ejection: key issues
Richard **Harrison**
Proceedings of the International Astronomical Union (2008), *N. Gopalswamy & D.F. Webb, eds* , .
4: 191-200, **2009, File**
Coronal Mass Ejections (CMEs) have been addressed by a particularly active research community in recent years. With the advent of the International Heliophysical Year and the new STEREO and Hinode missions, in addition to the on-going SOHO mission, CME research has taken centre stage in a renewed international effort. This **review** aims to touch on some key observational areas, and their interpretation. First, we consider coronal dimming, which has become synonymous with CME onsets, and stress that recent advances have heralded a move from a perceived association between the two phenomena to a firm, well-defined physical link. What this means for our understanding of CME modeling is discussed. Second, with the new STEREO observations, and noting the on-going SMEI observations, it is important to review the opening field of CME studies in the heliosphere. Finally, we discuss some specific points with regard to EIT-waves and the flare-CME relationship. In the opinion of the author, these issues cover key hot topics which need consideration for significant progress in the field.

A benchmark event sequence for mass ejection onset studies - A flare associated CME with coronal dimming, ascending pre-flare loops and a transient cool loop:
R.A. **Harrison** and D. Bewsher
A&A 461 (**2007**) 1155-1162, **file**
Aims.In this study, we report on the spectroscopic observations of a particularly well-observed flare and coronal mass ejection (CME) event sequence which we feel can be used as a benchmark study for CME onsets.
Methods. Specifically, we report on a set of extreme-ultraviolet (EUV) spectroscopic observations using the Solar and Heliospheric Observatory (SOHO) to determine features of the CME onset process revealed through the analysis of plasma at different temperatures.
Results. The flare which occurred on the north-western limb was associated with a large CME. The event in question showed evidence for pre-flare ascending loops containing 1–2 millionK plasma, which disappeared just prior to the flare. This disappearance is interpreted as coronal dimming, and it appears to coincide with the projected mass ejection onset time. In addition, a discrete, shortlived coronal loop containing plasma at transition region temperatures was detected just prior to this eruption. This loop displayed mass motion, along flux tubes, with oppositely directed flows. The nature and timing of this transient loop suggest a close relationship between it and the eruption process. Examinations of the timing and topology, which extend previous studies considerably, are found to be consistent with the mass ejection onset interpretation of Zhang and co-workers.
Conclusions.The clarity of this event sequence suggests that we should regard it as a benchmark in studies of the mass ejection onset process.

Coronal dimming and the coronal mass ejection onset.
Harrison, R.A., Bryans, P., Simnett, G.M., Lyons, M.: **2003**,
Astron. Astrophys. **400**, 1071 – 1083. 2003, doi:10.1051/0004-6361:20030088.

A spectroscopic study of coronal dimming associated with a coronal mass ejection.
Harrison, R.A., Lyons, M.,
2000. Astron. Astrophys. 358, 1097–1108.

Correlation of a Flare-Wave and Type II Burst.
Harvey, K.L., Martin, S.F., Riddle, A.C.,
1974. Solar Phys. 36, 151–155.

Damped large amplitude transverse oscillations in an EUV solar prominence, triggered by large-scale transient coronal waves
J. **Hershaw**1, C. Foullon1, V. M. Nakariakov1,2 and E. Verwichte
A&A 531, A53 (**2011**), **File**

Aims. We investigate two successive trains of large amplitude transverse oscillations in an arched EUV prominence, observed with SoHO/EIT on the north-east solar limb on **30 July 2005**. The oscillatory trains are triggered by two large scale coronal waves, associated with an X-class and a C-class flare occurring in the same remote active region.
Methods. The oscillations are tracked within rectangular slits parallel to the solar limb at different heights, which are taken to move with the apparent height profile of the prominence to account for solar rotation. Time series for the two prominence arch legs are extracted using Gaussian fitting on the 195 Å absorption features, and fitted to a damped cosine curve to determine the oscillatory parameters.
Results. Differing energies of the two triggering flares and associated waves are found to agree with the velocity amplitudes, of 50.6 ± 3.2 and 15.9 ± 8.0 km s-1 at the apex, for the first and second oscillatory trains respectively, as estimated in the transverse direction. The period of oscillation is similar for both trains, with an average of 99 ± 11 min, indicating a characteristic frequency as predicted by magnetohydrodynamics. Increasing velocity amplitude with height during the first oscillatory train, and in-phase starting motions of the two legs regardless of height, for each train, demonstrate that the prominence exhibits a global kink mode to a first approximation. However, discrepancies between the oscillatory characteristics of the two legs and an apparent dependence of period upon height, suggest that the prominence actually oscillates as a collection of separate but interacting threads. Damping times of around two to three cycles are observed. Combining our results with those of previously analysed loop oscillations, we find an approximately linear dependence of damping time upon period for kink oscillations, supporting resonant absorption as the damping mechanism despite limitations in testing this theory.

Interpreting Solar EUV Wave Observations from Different Viewing Angles Using an MHD Model
S. **Hoilijoki**, J. Pomoell, R. Vainio, M. Palmroth, H. E. J. Koskinen
Solar Physics, September **2013**, Volume 286, Issue 2, pp 493-507; **File**

We study the effect of projection and line-of-sight integration on the interpretation of the morphology and kinematics of EUV waves. We have performed a three-dimensional magnetohydrodynamic simulation of a coronal mass ejection (CME) erupting in an environment that mimics the low solar corona and calculated the resulting emission measure of the event from five different viewing angles. Our study provides more quantitative information about the impact of the viewing angle and projection effect on the properties of EUV waves than previous studies on the subject.
Analyzing the emission measure of the lower corona reveals wave-like increases that move away from the eruption site, which we interpret as EUV waves. Behind the EUV wave front we can recognize coronal dimming regions. A comparison of the emission measure and calculated density supports the view that EUV waves are true waves. Our results show that the origin of the observed EUV wave is height-dependent, which means that the measured speed and the morphology depend on the viewing direction. Consequently, care should be taken when EUV observations are used to infer the true propagation speeds of EUV wave fronts.

Three-dimensional Propagation of the Global EUV Wave associated with a solar eruption on 2021 October 28
Zhenyong **Hou**, Hui Tian, Jing-Song Wang, Xiaoxin Zhang, Qiao Song, Ruisheng Zheng, Hechao Chen, Bo Chen, Xianyong Bai, Yajie Chen, Lingping He, Kefei Song, Peng Zhang, Xiuqing Hu, Jinping Dun, Weiguo Zong, Yongliang Song, Yu Xu, Guangyu Tan
ApJ **928** 98 **2022**

https://arxiv.org/pdf/2202.13051.pdf
https://iopscience.iop.org/article/10.3847/1538-4357/ac590d/pdf **File**

We present a case study for the global extreme ultraviolet (EUV) wave and its chromospheric counterpart `Moreton-Ramsey wave' associated with the second X-class flare in Solar Cycle 25 and a halo coronal mass ejection (CME). The EUV wave was observed in the Hα and EUV passbands with different characteristic temperatures. In the 171 Å and 193/195 Å images, the wave propagates circularly with an initial velocity of 600-720 km s−1 and a deceleration of 110-320 m s−2. The local coronal plasma is heated from log(T/K)=5.9 to log(T/K)=6.2 during the passage of the wavefront. The Hα and 304 Å images also reveal signatures of wave propagation with a velocity of 310-540 km s−1. With multi-wavelength and dual-perspective observations, we found that the wavefront likely propagates forwardly inclined to the solar surface with a tilt angle of ~53.2∘. Our results suggest that this EUV wave is a fast-mode magnetohydrodynamic wave or shock driven by the expansion of the associated CME, whose wavefront is likely a dome-shaped structure that could impact the upper chromosphere, transition region and corona.

CHALLENGING SOME CONTEMPORARY VIEWS OF CORONAL MASS EJECTIONS. I. THE CASE FOR BLAST WAVES

T. A. **Howard**1 and V. J. Pizzo

2016 ApJ 824 92 DOI: 10.3847/0004-637X/824/2/92

Since the closure of the "solar flare myth" debate in the mid-1990s, a specific narrative of the nature of coronal mass ejections (CMEs) has been widely accepted by the solar physics community. This narrative describes structured magnetic flux ropes at the CME core that drive the surrounding field plasma away from the Sun. This narrative replaced the "traditional" view that CMEs were blast waves driven by solar flares. While the flux rope CME narrative is supported by a vast quantity of measurements made over five decades, it does not adequately describe every observation of what have been termed CME-related phenomena. In this paper we present evidence that some large-scale coronal eruptions, particularly those associated with EIT waves, exhibit characteristics that are more consistent with a blast wave originating from a localized region (such as a flare site) rather than a large-scale structure driven by an intrinsic flux rope. We present detailed examples of CMEs that are suspected blast waves and flux ropes, and show that of our small sample of 22 EIT-wave-related CMEs, 91% involve a blast wave as at least part of the eruption, and 50% are probably blast waves exclusively. We conclude with a description of possible signatures to look for in determining the difference between the two types of CMEs and with a discussion on modeling efforts to explore this possibility.

Components and anisotropy of 3D QFP waves during the early solar eruption

Jialiang **Hu**, Jing Ye, Yuhao Chen, Zhixing Mei, Shanshan Xu, Jun Lin

ApJ **2024**

https://arxiv.org/pdf/2412.13984

The propagation of disturbances in the solar atmosphere is inherently three dimensional (3D), yet comprehensive studies on the spatial structure and dynamics of 3D wavefronts are scarce. Here we conduct high resolution 3D numerical simulations to investigate filament eruptions, focusing particularly on the 3D structure and genesis of EUV waves. Our results demonstrate that the EUV wavefront forms a dome like configuration subdivided into three distinct zones. The foremost zone, preceding the flux rope, consists of fast-mode shock waves that heat the adjacent plasma. Adjacent to either side of the flux rope, the second zone contains expansion waves that cool the nearby plasma. The third zone, at the juncture of the first two, exhibits minimal disturbances. This anisotropic structure of the wavefront stems from the configuration and dynamics of the flux rope, which acts as a 3D piston during eruptions: compressing the plasma ahead to generate fast mode shocks and evacuating the plasma behind to induce expansion waves. This dynamic results in the observed anisotropic wavefront. Additionally, with synthetic EUV images from simulation data, the EUV waves are observable in Atmospheric Imaging Assembly 193 and 211 ˚A, which are identified as the fast-mode shocksThe detection of EUV waves varies with the observational perspective: the face on view reveals EUV waves from the lower to the higher corona, whereas an edge on view uncovers these waves only in the higher corona.

Limb Observations of Global Solar Coronal EUV Wavefronts: the Inclination, Kinematics, Coupling with the Expanding CMEs, and Connection with the CME-driven Shocks

Huidong **Hu** (1), Bei Zhu (2), Ying D. Liu (1), Chong Chen (3), Rui Wang (1), Xiaowei Zhao (4)

ApJ **976** 9 **2024**

https://arxiv.org/pdf/2409.15017
https://iopscience.iop.org/article/10.3847/1538-4357/ad7ead/pdf

We select and investigate six global solar extreme ultraviolet (EUV) wave events using data from the Solar Dynamics Observatory (SDO) and the Solar and Heliospheric Observatory (SOHO). These eruptions are all on the limb but recorded as halo coronal mass ejections (CMEs) because the CME-driven shocks have expanded laterally to the opposite side. With the limb observations avoiding the projection effect, we have measured the inclination and speed of the EUV wavefront from 1.05 to 1.25 R⊙. We also investigate the coupling and connection of the EUV

wavefront with the CME boundary and the CME-driven shock, respectively. The major findings in the six events are: (1) the forward inclination of the primary and coronal-hole transmitted EUV wavefronts is estimated, respectively, and the origins of these inclinations and their effects on the estimate of actual wavefront speed are investigated; (2) the wavefront speed can be elevated by loop systems near the coronal base, and the average speed in the low corona has no clear correlation with the lateral expansion of the CME-driven shock in the high corona; (3) the fast magnetosonic Mach number of the wavefront is larger than unity from the coronal base; (4) the EUV wavefront is coupled with the CME driver throughout the propagation in two events; (5) after the EUV wavefront vanishes, the CME-driven shock continues traveling on the opposite side and disconnects from the EUV wavefront in four events. These results and their implications are discussed, which provide insight into the properties of global EUV waves. **2011-09-22, 2013-05-13, 2013-11-07, 2015-05-05, 2017-09-10, 2020-11-29**
Table 1. List of six EUV wave events associated with halo CMEs

Excitation of quasi-periodic fast-propagating waves in the early stage of the solar eruption

Jialiang **Hu**, Jing Ye, Yuhao Chen, Zhixing Mei, Zehao Tang, Jun Lin
ApJ **2024**
https://arxiv.org/pdf/2312.17048.pdf
We propose a mechanism for the excitation of large-scale quasi-periodic fast-propagating magnetoacoustic (QFP) waves observed on both sides of the coronal mass ejection (CME). Through a series of numerical experiments, we successfully simulated the quasi-static evolution of the equilibrium locations of the magnetic flux rope in response to the change of the background magnetic field, as well as the consequent loss of the equilibrium that eventually gives rise to the eruption. During the eruption, we identified QFP waves propagating radially outwards the flux rope, and tracing their origin reveals that they result from the disturbance within the flux rope. Acting as an imperfect waveguide, the flux rope allows the internal disturbance to escape to the outside successively via its surface, invoking the observed QFP waves. Furthermore, we synthesized the images of QFP waves on the basis of the data given by our simulations, and found the consistence with observations. This indicates that the leakage of the disturbance outside the flux rope could be a reasonable mechanism of QFP waves.

Effects of Coronal Structures on the Dynamics of the Global Coronal Wave of SOL2017-09-10

Huidong **HU**, Ying D. LIU, and Bei ZHU
RHESSI Nuggets #438 **2022**
https://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/Effects_of_Coronal_Structures_on_the_Dynamics_of_the_Global_Coronal_Wave_of_SOL2017-09-10
Global coronal waves excited by flare/CME events can have very large scales. We have discussed the EUV wave associated with SOL2017-09-10. In this remarkable event the disturbance traversed all longitudes and entered both polar coronal holes; these interactions and others altered the structure of the disturbance.

Effects of Coronal Density and Magnetic Field Distributions on a Global Solar EUV Wave

Huidong **Hu**, Ying D. Liu, Bei Zhu, Hardi Peter, Wen He, Rui Wang, Zhongwei Yang
ApJ **878** 106 **2019**
https://arxiv.org/pdf/1905.01211.pdf
sci-hub.se/10.3847/1538-4357/ab2055
https://iopscience.iop.org/article/10.3847/1538-4357/ab2055/pdf
We investigate a global extreme ultraviolet (EUV) wave associated with a coronal mass ejection (CME)-driven shock on **2017 September 10**. The EUV wave is transmitted by north and south polar coronal holes (CHs), which is observed by SDO and STEREO A from opposite sides of the Sun. We obtain key findings on how the EUV wave interacts with multiple coronal structures, and its connection with the CME-driven shock: (1) the transmitted EUV wave is still connected with the shock that is incurvated to the Sun, after the shock has reached the opposite side of the eruption; (2) the south CH transmitted EUV wave is accelerated inside an on-disk, low-density region with closed magnetic fields, which implies that an EUV wave can be accelerated in both open and closed magnetic field regions; (3) part of the primary EUV wavefront turns around a bright point (BP) with a bipolar magnetic structure when it approaches a dim, low-density filament channel near the BP; (4) the primary EUV wave is diffused and apparently halted near the boundaries of remote active regions (ARs) that are far from the eruption, and no obvious AR related secondary waves are detected; (5) the EUV wave extends to an unprecedented scale of ~360 degrees in latitudes, which is attributed to the polar CH transmission. These results provide insights into the effects of coronal density and magnetic field distributions on the evolution of an EUV wave, and into the connection between the EUV wave and the associated CME-driven shock.

Dimmings and Sustained Gamma-Ray Events

Hugh **Hudson** and Nicola Omodei.
RHESSI Nugget, No. 179, July **2012**

http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/Dimmings_and_Sustained_Gamma-Ray_Events
Coronal disruptions reveal themselves as depletions and gamma-ray emissions
SOL2012-03-07

Coronal loop oscillations and flare shock waves.

Hudson, H.S., Warmuth, A.:
2004, *Astrophys. J.* **614**, L85–L88. doi:10.1086/425314.

Soft X-ray observation of a large-scale coronal wave and its exciter.

Hudson, H.S., Khan, J.I., Lemen, J.R., Nitta, N.V., Uchida, Y.:
2003, *Solar Phys.* **212**, 121 – 149. doi:10.1023/A:1022904125479.

Observing coronal mass ejections without coronagraphs.

Hudson, H.S., Cliver, E.W.,
2001. J. Geophys. Res. 106, 25199–25214.
A coronal mass ejection (CME), strictly speaking, is a phenomenon observed via a white-light coronal imager. In addition to coronagraphs, a wide variety of other instruments provide independent observations of CMEs, in regimes ranging from the chromosphere to interplanetary space. In this paper we list the most important of these noncoronagraphic signatures, many of which had been known even before CMEs were first identified in coronagraph observations about 30 years ago. We summarize the new aspects of CMEs discovered in the past several years, primarily with instruments on the Yohkoh and SOHO satellites. We emphasize the need for detailed statistically based comparisons between SOHO CMEs and their noncoronagraphic manifestations. We discuss how the various aspects of CMEs fit into the current standard model (sigmoids, flux rope, double dimming, arcade). While a class of CMEs follows this pattern, it does not appear to work for all events. In particular, some CMEs involve extended dimming regions and erupting transequatorial X-ray loops, indicating a more complex geometry than a simple bipolar magnetic configuration.

Soft X-ray Signatures of Coronal Ejections,

Hudson, H.S., Webb, D.F.,
1997. in: Coronal Mass Ejections, ed. N. Crooker, J. Joselyn, & J. Feynman,
AGU Geophys. Monograph. Ser., pp. 27–38.

A Long-Duration Solar Flare with Mass Ejection and Global Consequences.

Hudson, H.S., Acton, L.W., Freeland, S.L.,
1996. Astrophys. J. 470, 629–635.
We report observations of a long-duration flare with mass ejection from the corona, using the Yohkoh soft X-ray telescope (SXT). This flare occurred **1994 November 13** near disk center during quiet solar conditions, with excellent temporal coverage of both the core activity in the active region itself and of the global corona. The initial X-ray images reveal two arcades of cusped magnetic loops, connected via a series of thin loops. These loops rise rapidly during the increasing phase of soft X-ray flare brightness. In its final state, the flare has the configuration of postflare loops with a cusp. Large regions of the X-ray corona appear to empty during the evolution of the event. We suggest that this corresponds a coronal mass ejection (CME) seen in soft X-rays. Its detection in the SXT images is consistent with the finding that material participating in a CME exists at elevated coronal temperatures (2.8 x 106 K in this case) before the ejection. We estimate a mass >4 x 1014 g for the ejected material. The X-ray morphology of the event has strong points of similarity with the classical reconnection picture of long-duration event (LDE) formation, but there are significant discrepancies: there is no observed inward flow during the rise phase, the expansions are multiple and appear to be nonradial, and none of the observed motions suggest a reconnection jet. We note the subsequent occurrence of very large scale coronal disturbances, including regions near the boundaries of coronal holes at both poles. We suggest that this global disturbance implies a perturbation reaching as far outward as the heliospheric neutral sheet. The exciter would require a horizontal velocity of approximately 200 km s-1 in such a case, consistent with the projected velocity of the plasma cloud that we identify with a CME in the process of launching.

ONE-DIMENSIONAL MODELING FOR TEMPERATURE-DEPENDENT UPFLOW IN THE DIMMING REGION OBSERVED BY HINODE/EUV IMAGING SPECTROMETER

S. **Imada**1, H. Hara2, T. Watanabe2, I. Murakami3, L. K. Harra4, T. Shimizu1 and E. G. Zweibel

2011 ApJ 743 57, **File**

We previously found a temperature-dependent upflow in the dimming region following a coronal mass ejection observed by the Hinode EUV Imaging Spectrometer (EIS). In this paper, we reanalyzed the observations along with previous work on this event and provided boundary conditions for modeling. We found that the intensity in the dimming region dramatically drops within 30 minutes from the flare onset, and the dimming region reaches the equilibrium stage after ~1 hr. The temperature-dependent upflows were observed during the equilibrium stage by EIS. The cross-sectional area of the flux tube in the dimming region does not appear to expand significantly. From the observational constraints, we reconstructed the temperature-dependent upflow by using a new method that considers the mass and momentum conservation law and demonstrated the height variation of plasma conditions in the dimming region. We found that a super-radial expansion of the cross-sectional area is required to satisfy the mass conservation and momentum equations. There is a steep temperature and velocity gradient of around 7 Mm from the solar surface. This result may suggest that the strong heating occurred above 7 Mm from the solar surface in the dimming region. We also showed that the ionization equilibrium assumption in the dimming region is violated, especially in the higher temperature range.

2006 December 13

Discovery of a Temperature-Dependent Upflow in the Plage Region during a Gradual Phase of the X-Class Flare

Shinsuke **IMADA**, Hirohisa HARA, Tetsuya WATANABE, and Suguru KAMIO, et al.

PASJ: Publ. Astron. Soc. Japan 59, S793–S799, **2007, File**

We present **Hinode/EIS** raster scan observations of the plage region taken during the gradual phase of the GOES X3.2 flare that occurred on **2006 December 13**. The plage region is located 20000 east of the flare arcade. The plage region has a small transient coronal hole. The transient coronal hole is strongly affected by an X-class flare, and upflows are observed at its boundary. Multi-wavelength spectral observations allow us to determine velocities from the Doppler shifts at different temperatures. Strong upflows along with stationary plasma have been observed in the Fe XV line 284.2 °A (logT=K = 6:3) in the plage region. The strong upflows reach almost 150km s_{-1}, which was estimated by a two-component Gaussian fitting. On the other hand, at a lower corona/transition region temperature (He II, 256.3 ° A, logT=K = 4.9), very weak upflows, almost stationary, have been observed. We find that these upflow velocities clearly depend on the temperature with the hottest line, Fe XV, showing the fastest upflow velocity and the second-highest line, Fe XIV, showing the second-highest upflow velocity (130 km s_{-1}). All velocities are below the sound speed. The trend of the upflow dependence on temperature dramatically changes at 1MK. These results suggest that heating may have an important role for strong upflow.

Imada et al. (2007) find that Hinode/EIS data of a dimming shows a dependence of the outflow velocity on temperature, with hotter lines showing a stronger plasma outflow (up to almost 150 km s-1).

STEREO quadrature observations of coronal dimming at the onset of mini-CMEs

D. E. **Innes**1, S. W. McIntosh2, and A. Pietarila1

E-print, May 2010, File, A&A, 517, L7 (**2010**), **File**

Context. Using unique quadrature observations with the two STEREO spacecraft, we investigate coronal dimmings at the onset of small-scale eruptions. In CMEs they are believed to indicate the opening up of the coronal magnetic fields at the start of the eruption.

Aims. It is to determine whether coronal dimming seen in small-scale eruptions starts before or after chromospheric plasma ejection.

Methods.One STEREO spacecraft obtained high cadence, 75 s, images in the He ii 304Å channel, and the other simultaneous images in the Fe ix/Fe x 171Å channel. We concentrate on two well-positioned chromospheric eruptions that occurred at disk center in the 171Å images, and on the limb in 304Å. One was in the quiet Sun and the other was in an equatorial coronal hole. We compare the timing of chromospheric eruption seen in the 304Å limb images with the brightenings and dimmings seen on disk in the 171Å images. Further we use off-limb images of the low frequency 171Å power to infer the coronal structure near the eruptions.

Results. In both the quiet Sun and the coronal hole eruption, on disk 171Å dimming was seen before the chromospheric eruption, and in both cases it extends beyond the site of the chromospheric eruption. The quiet Sun eruption occurred on the outer edge of the enclosing magnetic field of a prominence and may be related to a small disruption of the prominence just before the 171Å dimming.

Conclusions. These small-scale chromospheric eruptions started with a dimming in coronal emission just like their larger counterparts. We therefore suggest that a fundamental step in triggering them was the removal of overlying coronal field.

AWARE: An algorithm for the automated characterization of EUV waves in the solar atmosphere

Jack **Ireland**, Andrew R. Inglis, Albert Y. Shih, Steven Christe, Stuart J. Mumford, Laura A. Hayes, Barbara J. Thompson, V. Keith Hughitt
Solar Phys. 294:158 **2018**
https://arxiv.org/pdf/1804.07325.pdf
https://link.springer.com/content/pdf/10.1007%2Fs11207-019-1505-8.pdf
Extreme ultraviolet (EUV) waves are large-scale propagating disturbances observed in the solar corona, frequently associated with coronal mass ejections and flares. They appear as faint, extended structures propagating from a source region across the structured solar corona. Since their discovery, over two hundred papers discussing their properties, causes and physical nature have been published. However, despite this their fundamental properties and the physics of their interactions with other solar phenomena are still not understood. To further the understanding of EUV waves, we have constructed the Automated Wave Analysis and REduction (AWARE) algorithm for the measurement of EUV waves. AWARE is implemented in two stages. In the first stage, we use a new type of running difference image, the running difference persistence image, which enables the efficient isolation of propagating, brightening wavefronts as they propagate across the corona. In the second stage, AWARE detects the presence of a wavefront, and measures the distance, velocity and acceleration of that wavefront across the Sun. The fit of propagation models to the wave progress isolated in the first stage is achieved using the Random Sample and Consensus (RANSAC) algorithm. AWARE is tested against simulations of EUV wave propagation, and is applied to measure EUV waves in observational data from the Atmospheric Imaging Assembly (AIA). We also comment on unavoidable systematic errors that bias the estimation of wavefront velocity and acceleration. In addition, the full AWARE software suite comes with a package that creates simulations of waves propagating across the disk from arbitrary starting points. **2011/02/13. 2011/02/15 , 2011-02-16, 2011/06/07**

Estimating early coronal mass ejection propagation direction with DIRECD during the severe May 8 and follow-up June 8, 2024 events

Shantanu **Jain**, Tatiana Podladchikova, Astrid M. Veronig, Galina Chikunova, Karin Dissauer, Mateja Dumbovic, Amaia Razquin
A&A 683, A15 **2023**
https://arxiv.org/pdf/2311.13942.pdf
https://www.aanda.org/articles/aa/pdf/2024/03/aa47927-23.pdf
On **May 8, 2024**, solar active region 13664 produced an X-class flare, several M-class flares, and multiple Earth-directed Coronal Mass Ejections (CMEs). The initial CME caused coronal dimmings, characterized by localized reductions in extreme-ultraviolet (EUV) emissions, indicating mass loss and expansion during the eruption. After one solar rotation, on **June 8, 2024**, the same region produced another M-class flare followed by coronal dimmings observed by the SDO and STEREO spacecraft. We analyzed early CME evolution and direction from coronal dimming expansion at the end of the impulsive phase using the DIRECD (Dimming Inferred Estimation of CME Direction) method. To validate the 3D CME cone, we compared CME properties from the low corona with white-light coronagraph data. The May 8 CME expanded radially, with a 7.7 deg inclination, 70 deg angular width, and 0.81 Rsun cone height, while the June 8 CME had a 15.7 deg inclination, 81 deg width, and 0.89 Rsun height. Our study shows that tracking low coronal signatures, like coronal dimming expansion, can estimate CME direction early, providing crucial lead time for space weather forecasts.

Coronal dimmings as indicators of early CME propagation direction

Shantanu **Jain**, Tatiana Podladchikova, Galina Chikunova, Karin Dissauer, Astrid M. Veronig
A&A 683, A15 **2023**
https://arxiv.org/pdf/2311.13942.pdf
https://www.aanda.org/articles/aa/pdf/2024/03/aa47927-23.pdf
Coronal mass ejections (CMEs) are solar eruptions of plasma and magnetic fields that significantly impact Space Weather, causing disruptions in technological systems and potential damage to power grids when directed towards Earth. Traditional coronagraphs along the Sun-Earth line struggle to precisely track the early evolution of Earth-directed CMEs. Coronal dimmings, localized reductions in extreme-ultraviolet (EUV) and soft X-ray emissions, are key indicators of CMEs in the low corona, resulting from mass loss and expansion during the eruption. This study introduces a novel method, DIRECD (Dimming InfeRred Estimate of CME Direction), to estimate the early propagation direction of CMEs based on the expansion of coronal dimmings. The approach involves 3D simulations of CMEs using a geometric cone model, exploring parameters like width, height, source location, and deflection from the radial direction. The dominant direction of dimming evolution is then determined, and an inverse problem is solved to reconstruct an ensemble of CME cones at various heights, widths, and deflections. By comparing the CME orthogonal projections onto the solar sphere with the dimming geometry, the 3D CME direction is derived.Validated through case studies on **October 1, 2011, and September 6, 2011**, the DIRECD method reveals the early propagation directions of CMEs. The CME on October 1, 2011, predominantly expands towards the South-East, while the CME on September 6, 2011, inclines towards the North-West. These findings align with previous studies using multi-viewpoint coronagraphic observations. The study demonstrates the utility of coronal dimming

information for early CME direction estimation, providing valuable data for space weather forecasting and mitigating potential adverse impacts on Earth before observation in coronographs' field-of-view.

HORIZONTAL FLOWS IN ACTIVE REGIONS FROM RING-DIAGRAM AND LOCAL CORRELATION TRACKING METHODS

Kiran **Jain**1, S. C. Tripathy1, B. Ravindra2, R. Komm1, and F. Hil

2016 ApJ 816 5

Continuous high-cadence and high spatial resolution Dopplergrams allow us to study subsurface dynamics that may be further extended to explore precursors of visible solar activity on the surface. Since the p-mode power is absorbed in the regions of high magnetic field, the inferences in these regions are often presumed to have large uncertainties. In this paper, using the Dopplergrams from space-borne Helioseismic Magnetic Imager, we compare horizontal flows in a shear layer below the surface and the photospheric layer in and around active regions. The photospheric flows are calculated using the local correlation tracking (LCT) method, while the ring-diagram technique of helioseismology is used to infer flows in the subphotospheric shear layer. We find a strong positive correlation between flows from both methods near the surface. This implies that despite the absorption of acoustic power in the regions of strong magnetic field, the flows inferred from the helioseismology are comparable to those from the surface measurements. However, the magnitudes are significantly different; the flows from the LCT method are smaller by a factor of 2 than the helioseismic measurements. Also, the median difference between the direction of corresponding vectors is 49°.

THE SOURCE OF 3 MINUTE MAGNETOACOUSTIC OSCILLATIONS IN CORONAL FANS

D. B. **Jess**1, I. De Moortel2, M. Mathioudakis1, D. J. Christian3, K. P. Reardon1,4, P. H. Keys1, and F. P. Keenan

2012 ApJ 757 160

We use images of high spatial, spectral, and temporal resolution, obtained using both ground- and space-based instrumentation, to investigate the coupling between wave phenomena observed at numerous heights in the solar atmosphere. Analysis of 4170 Å continuum images reveals small-scale umbral intensity enhancements, with diameters ~06, lasting in excess of 30 minutes. Intensity oscillations of 3 minutes are observed to encompass these photospheric structures, with power at least three orders of magnitude higher than the surrounding umbra. Simultaneous chromospheric velocity and intensity time series reveal an 87° ± 8° out-of-phase behavior, implying the presence of standing modes created as a result of partial wave reflection at the transition region boundary. We find a maximum waveguide inclination angle of 40° between photospheric and chromospheric heights, combined with a radial expansion factor of <76%. An average blueshifted Doppler velocity of 1.5 km s–1, in addition to a time lag between photospheric and chromospheric oscillatory phenomena, confirms the presence of upwardly propagating slow-mode waves in the lower solar atmosphere. Propagating oscillations in EUV intensity are detected in simultaneous coronal fan structures, with a periodicity of 172 ± 17 s and a propagation velocity of 45 ± 7 km s–1. Numerical simulations reveal that the damping of the magnetoacoustic wave trains is dominated by thermal conduction. The coronal fans are seen to anchor into the photosphere in locations where large-amplitude umbral dot (UD) oscillations manifest. Derived kinetic temperature and emission measure time series display prominent out-of-phase characteristics, and when combined with the previously established sub-sonic wave speeds, we conclude that the observed EUV waves are the coronal counterparts of the upwardly propagating magnetoacoustic slow modes detected in the lower solar atmosphere. Thus, for the first time, we reveal how the propagation of 3 minute magnetoacoustic waves in solar coronal structures is a direct result of amplitude enhancements occurring in photospheric UDs.

SYMPATHETIC FILAMENT ERUPTIONS CONNECTED BY CORONAL DIMMINGS

Yunchun **Jiang**, Jiayan Yang, Junchao Hong, Yi Bi and Ruisheng Zheng

2011 ApJ 738 179, **File?**

We present for the first time detailed observations of three successive, interdependent filament eruptions that occurred one by one within 5 hr from different locations beyond the range of a single active region. The first eruption was observed from an active region and was associated with a coronal mass ejection (CME), during which diffuse and complex coronal dimmings formed, largely extending to the two other filaments located in quiet-Sun regions. Then, both quiescent filaments consecutively underwent the second and third eruptions, while the nearby dimmings were persistent. Comparing the result of a derived coronal magnetic configuration, the magnetic connectivity between the dimmings suggested that they were caused by the joint effect of simple expansion of overlying loop systems forced by the first eruption, as well as by its erupting field interacting or reconnecting with the surrounding magnetic structures. Note that the dimming process in the first eruption indicated a weakening and partial removal of an overlying magnetic field constraint on the two other filaments, and thus one can physically connect these eruptions as sympathetic. It appears that the peculiar magnetic field configuration in our event was largely favorable to the occurrence of sympathetic filament eruptions. Because coronal dimmings are frequent and common phenomena in solar eruptions, especially in CME events, it is very likely that they represent a universal agent that can link consecutive eruptions nearby with sympathetic eruptions.

MAGNETIC INTERACTION: A TRANSEQUATORIAL JET AND INTERCONNECTING LOOPS

Yunchun **Jiang**,1 Yuandeng Shen,1 Bi Yi,1 Jiayan Yang,1 and Jingxiu Wang2

The Astrophysical Journal, 677:699-703, **2008, File**

http://www.journals.uchicago.edu/doi/pdf/10.1086/529417

We present, to our knowledge for the first time, a rare observation of direct magnetic interaction between a transequatorial jet and interconnecting loops (IL) in the southern hemisphere. The jet originated from a flare and appeared to move outward along open field lines, but it passed so close to the IL that its edge met with one of the IL ends. As a result, the IL began to erupt, weak brightenings appeared at the meeting site, and a nearby dark feature was disturbed. After the eruption, in addition to a looplike dimming due to the disappearance of the IL, a dimming region was formed around its another end, which was very probably caused by the expansion or opening of its field lines and represented its evacuated feet. Two coronal mass ejections (CMEs) were observed within 2 hr in association with the event. One was related to the flare and the jet, while the other was due to the IL eruption. These observations suggest that a sole flare can not only trigger a CME but also simultaneously trigger an IL eruption by means of its interaction with a jet, so can lead to two interdependent CMEs, i.e., a sympathetic CME pair physically connected by the jet /IL interaction.

2004 July 23

H-alpha Dimming Associated With the Eruption of a Coronal Sigmoid in the Quiet Sun

Yunchun **Jiang** · Huadong Chen · Yuandeng Shen · Liheng Yang · Kejun Li

Solar Phys (**2007**) 240: 77–87

14 August 2001. During the eruption,
coronal bipolar double dimming took place at the regions with opposite magnetic polarities around the two sigmoid ends, but the underlying chromospheric channel did not show observable changes corresponding to the coronal eruption. Different from the erupting coronal sigmoid itself, however, the coronal dimming had a detectable chromosphere counterpart, i.e., Hα dimming. By regarding the sigmoid as a coronal sign for a flux rope, these observations are explained in the framework of the flux rope model of CMEs. The flux rope is possibly deeply rooted in the chromosphere, and the coronal and Hα dimming regions mark its evacuated feet, through which the material is possibly fed to the halo CME.

Coronal Mass Ejections and Dimmings: A Comparative Study Using MHD Simulations and SDO Observations

Meng **Jin**1,2, Mark C. M. Cheung1, Marc L. DeRosa1, Nariaki V. Nitta1, and Carolus J. Schrijver1

2022 ApJ 928 154

https://iopscience.iop.org/article/10.3847/1538-4357/ac589b/pdf

Solar coronal dimmings have been observed extensively in recent years. Due to their close association with coronal mass ejections (CMEs), there is a critical need to improve our understanding of the physical processes that cause dimmings as well as their relationship with CMEs. In this study, we investigate coronal dimmings by combining simulation and observational efforts. By utilizing a data-constrained global magnetohydrodynamics model (Alfvén-wave solar model), we simulate coronal dimmings resulting from different CME energetics and flux rope configurations. We synthesize the emissions of different EUV spectral bands/lines and compare with SDO/AIA and EVE observations. A detailed analysis of the simulation and observation data suggests that the transient dimming/brightening are related to plasma heating processes, while the long-lasting core and remote dimmings are caused by mass-loss process induced by the CME. Moreover, the interaction between the erupting flux rope with different orientations and the global solar corona could significantly influence the coronal dimming patterns. Using metrics such as dimming depth and dimming slope, we investigate the relationship between dimmings and CME properties (e.g., CME mass, CME speed) in the simulation. Our result suggests that coronal dimmings encode important information about the associated CMEs, which provides a physical basis for detecting stellar CMEs from distant solar-like stars. **2011 February 15**

CORONAL MASS EJECTION INDUCED OUTFLOWS OBSERVED WITH *HINODE/*EIS

M. **Jin**1, M. D. Ding1, P. F. Chen1, C. Fang1, and S. Imada2

Astrophysical Journal, 702:27–38, **2009, File**

We investigate the outflows associated with two halo coronal mass ejections (CMEs) that occurred on **2006 December 13 and 14** in NOAA 10930, using the *Hinode/*EIS observations. Each CME was accompanied by an EIT wave and coronal dimmings. Dopplergrams in the dimming regions are obtained from the spectra of seven EIS lines. The results show that strong outflows are visible in the dimming regions during the CME eruption at different heights from the lower transition region to the corona. It is found that the velocity is positively correlated with the photospheric magnetic field, as well as the magnitude of the dimming. We estimate the mass loss based on height dependent EUV dimmings and find it to be smaller than the CME mass derived from white-light observations. The mass difference is attributed partly to the uncertain atmospheric model, and partly to the transition region outflows, which refill the coronal dimmings.

Chromospheric and Coronal Wave Generation in a Magnetic Flux Sheath

Yoshiaki **Kato**, Osker Steiner, Viggo Hansteen, Boris Gudiksen, Sven Wedemeyer, Mats Carlsson

ApJ **827** 7 **2016**

http://arxiv.org/pdf/1606.08826v1.pdf

Using radiation magnetohydrodynamic simulations of the solar atmospheric layers from the upper convection zone to the lower corona, we investigate the self-consistent excitation of slow magneto-acoustic body waves (slow modes) in a magnetic flux concentration. We find that the convective downdrafts in the close surroundings of a two-dimensional flux slab "pump" the plasma inside it in the downward direction. This action produces a downflow inside the flux slab, which encompasses ever higher layers, causing an upwardly propagating rarefaction wave. The slow mode, excited by the adiabatic compression of the downflow near the optical surface, travels along the magnetic field in the upward direction at the tube speed. It develops into a shock wave at chromospheric heights, where it dissipates, lifts the transition region, and produces an offspring in the form of a compressive wave that propagates further into the corona. In the wake of downflows and propagating shock waves, the atmosphere inside the flux slab in the chromosphere and higher tends to oscillate with a period of $\nu \approx 4$~mHz. We conclude that this process of "magnetic pumping" is a most plausible mechanism for the direct generation of longitudinal chromospheric and coronal compressive waves within magnetic flux concentrations, and it may provide an important heat source in the chromosphere. It may also be responsible for certain types of dynamic fibrils.

Invited Review: Short-term Variability with the Observations from the Helioseismic and Magnetic Imager (HMI) Onboard the Solar Dynamics Observatory (SDO): Insights into Flare Magnetism

Maria D. **Kazachenko**, Marcel F. Albelo-Corchado, Cole A. Tamburri & Brian T. Welsch

Solar Physics volume 297, Article number: 59 (**2022**)

https://link.springer.com/content/pdf/10.1007/s11207-022-01987-6.pdf **File**

Continuous vector magnetic-field measurements by the Helioseismic and Magnetic Imager (HMI) onboard the Solar Dynamics Observatory (SDO) allow us to study magnetic-field properties of many flares. Here, we review new observational aspects of flare magnetism described using SDO data, including statistical properties of magnetic-reconnection fluxes and their rates, magnetic fluxes of flare dimmings, and magnetic-field changes during flares. We summarize how these results, along with statistical studies of coronal mass ejections (CMEs), have improved our understanding of flares and the flare/CME feedback relationship. Finally, we highlight future directions to improve the current state of understanding of solar-flare magnetism using observations. **14 Sep 2011, 7 March 2012, Sep 2014**

2. Flare Ribbons: Footpoints of Reconnected Fields
3. Coronal Dimmings: Footpoints of Expanding Coronal Structures
4. Flare-Associated Magnetic-Field Changes (FAMCs)
5. Relating CMEs and ICMEs to Their Source Regions

THE CORONAL AND HELIOSPHERIC 2007 MAY 19 EVENT: CORONAL MASS EJECTION, EXTREME ULTRAVIOLET IMAGER WAVE, RADIO BURSTS, AND ENERGETIC ELECTRONS

A. **Kerdraon**[1], M. Pick[1], S. Hoang[1], Y.-M.Wang[2], and D. Haggerty[3]

Astrophysical Journal, 715:468–476, **2010** May, **File**

We study the global development of the **2007 May 19** event and investigate the origin and the escape of the energetic electrons responsible for the interplanetary bursts and for the solar energetic particle event. The data analysis combines radio spectral and imaging observations with *STEREO* EUV observations. We also use the direction-finding capabilities on the *Wind/*Waves radio instrument. Electron acceleration and injections into the interplanetary medium occur with some delay after the flare. It is shown that they are related to the expansion of the coronal mass ejection and of the extreme ultraviolet imager wave. There are two accelerations at two different locations in the corona which correspond to two different electron trajectories in the interplanetary medium.

He I 10830Å Dimming During Solar Flares, I: The Crucial Role of Non-Thermal Collisional Ionisations

Graham S. **Kerr**, Yan Xu, Joel C. Allred, Vanessa Polito, Viacheslav M. Sadykov, Nengyi Huang, Haimin Wang

ApJ **912** 153 **2021**

https://arxiv.org/pdf/2103.16686.pdf

https://doi.org/10.3847/1538-4357/abf42d

While solar flares are predominantly characterised by an intense broadband enhancement to the solar radiative output, certain spectral lines and continua will, in theory, exhibit flare-induced dimmings. Observations of transitions of orthohelium He I λλ10830Å and the He I D3 lines have shown evidence of such dimming, usually followed by enhanced emission. It has been suggested that non-thermal collisional ionisation of helium by an electron beam, followed by recombinations to orthohelium, is responsible for overpopulating the those levels, leading to stronger absorption. However it has not been possible observationally to preclude the possibility of overpopulating orthohelium via enhanced photoionisation of He I by EUV irradiance from the flaring corona followed by recombinations. Here we present radiation hydrodynamics simulations of non-thermal electron beam-driven flares where (1) both non-thermal collisional ionisation of Helium and coronal irradiance are included, and (2) only coronal irradiance is included. A grid of simulations covering a range of total energies deposited by the electron beam, and a range of non-thermal electron beam low-energy cutoff values, were simulated. In order to obtain flare-induced dimming of the He I 10830Å line it was necessary for non-thermal collisional ionisations to be present. The effect was more prominent in flares with larger low-energy cutoff values and longer lived in weaker flares and flares with a more gradual energy deposition timescale. These results demonstrate the usefulness of orthohelium line emission as a diagnostic of flare energy transport. **2013 Aug. 17**

RHESSI Nuggets #406 April **2021**

https://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/Negative_He_10830_Flare_Ribbons_and_Non-thermal_Electrons

X-ray observations of a large-scale solar coronal shock wave.

Khan, J.I., Aurass, H.:

2002, *Astron. Astrophys.* **383**, 1018 – 1031. doi:10.1051/0004-6361:20011707.

Reflection of Coronal Global Waves

Ines **Kienreich** and Hugh Hudson

RHESSI Science Nugget, No. 217, **2014**

A homologous series of global coronal waves reflects at a coronal-hole boundary. **27 January 2011**

Solar TErrestrial Relations Observatory-A (STEREO-A) and PRoject for On-Board Autonomy 2 (PROBA2) Quadrature Observations of Reflections of Three EUV Waves from a Coronal Hole

I. W. **Kienreich**, N. Muhr, A. M. Veronig, D. Berghmans, A. De Groof, M. Temmer, B. Vršnak and D. B. Seaton

Solar Physics, August **2013**, Volume 286, Issue 1, pp 201-219, **File**

http://arxiv.org/pdf/1204.6472v1.pdf

We investigate the interaction of three consecutive large-scale coronal waves with a polar coronal hole, simultaneously observed on-disk by the Solar TErrestrial Relations Observatory (STEREO)-A spacecraft and on the limb by the PRoject for On-Board Autonomy 2 (PROBA2) spacecraft on **January 27, 2011**. All three extreme-ultraviolet(EUV) waves originate from the same active region NOAA 11149 positioned at N30E15 in the STEREO-A field-of-view and on the limb in PROBA2. We derive for the three primary EUV waves start velocities in the range of ~310 km/s for the weakest up to ~500 km/s for the strongest event. Each large-scale wave is reflected at the border of the extended coronal hole at the southern polar region. The average velocities of the reflected waves are found to be smaller than the mean velocities of their associated direct waves. However, the kinematical study also reveals that in each case the end velocity of the primary wave matches the initial velocity of the reflected wave. In all three events the primary and reflected waves obey the Huygens-Fresnel principle, as the incident angle with ~10{\deg} to the normal is of the same size as the angle of reflection. The correlation between the speed and the strength of the primary EUV waves, the homologous appearance of both the primary and the reflected waves, and in particular the EUV wave reflections themselves implicate that the observed EUV transients are indeed nonlinear large-amplitude MHD waves.

CASE STUDY OF FOUR HOMOLOGOUS LARGE-SCALE CORONAL WAVES OBSERVED ON 2010 APRIL 28 AND 29

I. W. **Kienreich**[1], A. M. Veronig[1], N. Muhr[1], M. Temmer[1,2], B. Vrˇsnak[3], and N. Nitta[4]
Astrophysical Journal Letters, 727:L43 (6pp), **2011** February, **File**
On **2010 April 28 and 29**, the *Solar TErrestrial Relations Observatory B/*Extreme Ultraviolet Imager observed four homologous large-scale coronal waves, the so-called EIT-waves, within 8 hr. All waves emerged from the same source active region, were accompanied by weak flares and faint coronal mass ejections, and propagated into the same direction at constant velocities in the range of **~**220–340 km s^{-1}. The last of these four coronal wave events was the strongest and fastest, with a velocity of 337 **±** 31 km s^{-1} and a peak perturbation amplitude of **~**1.24, corresponding to a magnetosonic Mach number of M_{ms} **~** 1.09. The magnetosonic Mach numbers and velocities of the four waves are distinctly correlated, suggestive of the nonlinear fast-mode magnetosonic wave nature of the events. We also found a correlation between the magnetic energy buildup times and the velocity and magnetosonic Mach number.

STEREO quadrature observations of the 3D structure and driver of a global coronal wave
I.W. **Kienreich**, M. Temmer, and A.M. Veronig
E-print, Aug **2009**; ApJL, 703:L118–L122, **2009** October**, File**
We present the first observations of a global coronal wave ("EIT wave") from the two Solar Terrestrial Relations Observatory (STEREO) satellites in quadrature. The wave's initiation site was at the disk center in STEREO-B and precisely on the limb in STEREO-A. These unprecedented observations from the STEREO Extreme Ultraviolet Imaging (EUVI) instruments enable us to gain insight into the wave's kinematics, initiation and 3D structure. The wave propagates globally over the whole solar hemisphere visible to STEREO-B with a constant velocity of _ 263±16 kms^{-1}. From the two STEREO observations we derive a height of the wave in the range of _80–100 Mm. Comparison of the wave kinematics with the early phase of the erupting CME structure indicates that the wave is initiated by the CME lateral expansion, and then propagates freely with a velocity close to the fast magnetosonic speed in the quiet solar corona. **13 February 2009**.

Catalogue of the 1997 SOHO-EIT coronal transient waves and associated type II radio burst spectra.
Klassen, A., Aurass, H., Mann, G., Thompson, B.J.,
2000. Astron. Astrophys. Suppl. 141, 357–369.

X-ray and radio evidence on the origin of a coronal shock wave.
Klein, K., Khan, J.I., Vilmer, N., Delouis, J., Aurass, H.,
1999. Astron. Astrophys. 346, L53–L56.

Sunquakes and starquakes **Review**
A. G. **Kosovichev**
E-print, Feb **2014**; "Precision Asteroseismology", Proceedings of IAU Symposium No. 301, 2014, J.A. Guzik, W.J. Chaplin, G. Handler & A. Pigulski, eds
http://arxiv.org/pdf/1401.8036v1.pdf
In addition to well-known mechanisms of excitation of solar and stellar oscillations by turbulent convection and instabilities, the oscillations can be excited by an impulsive localized force caused by the energy release in solar and stellar flares. Such oscillations have been observed on the Sun (`sunquakes'), and created a lot of interesting discussions about physical mechanisms of the impulsive excitation and their relationship to the flare physics. The observation and theory have shown that most of a sunquake's energy is released in high-degree, high-frequency p modes. In addition, there have been reports on helioseismic observations of low-degree modes excited by strong solar flares. Much more powerful flares observed on other stars can cause `starquakes' of substantially higher amplitude. Observations of such oscillations can provide new asteroseismic information and also constraints on mechanisms of stellar flares. The basic properties of sunquakes and initial attempts to detect flare-excited oscillations in Kepler short-cadence data are discussed.

Sunquakes: helioseismic response to solar flares **Review**
A. G. **Kosovichev**
E-print, Feb **2014**; "Extraterrestrial Seismology", Cambridge Univ. Press

Sunquakes observed in the form of expanding wave ripples on the surface of the Sun during solar flares represent packets of acoustic waves excited by flare impacts and traveling through the solar interior. The excitation impacts strongly correlate with the impulsive flare phase, and are caused by the energy and momentum transported from the energy release sites. The flare energy is released in the form of energetic particles, waves, mass motions, and radiation. However, the exact mechanism of the localized hydrodynamic impacts which generate sunquakes is unknown. Solving the problem of the sunquake mechanism will substantially improve our understanding of the flare physics. In addition, sunquakes offer a unique opportunity for studying the interaction of acoustic waves with magnetic fields and flows in flaring active regions, and for developing new approaches to helioseismic acoustic tomography

HELIOSEISMIC RESPONSE TO THE X2.2 SOLAR FLARE OF 2011 FEBRUARY 15
A. G. **Kosovichev**
2011 ApJ 734 L15, **File**
The X2.2-class solar flare of **2011 February 15** produced a powerful "sunquake" event, representing a helioseismic response to the flare impact in the solar photosphere, which was observed with the Helioseismic and Magnetic Imager (HMI) instrument on board the Solar Dynamics Observatory (SDO). The impulsively excited acoustic waves formed a compact wave packet traveling through the solar interior and appearing on the surface as expanding wave ripples. The initial flare impacts were observed in the form of compact and rapid variations of the Doppler velocity, line-of-sight magnetic field, and continuum intensity. These variations formed a typical two-ribbon flare structure, and are believed to be associated with thermal and hydrodynamic effects of high-energy particles heating the lower atmosphere. The analysis of the SDO/HMI and X-ray data from RHESSI shows that the helioseismic waves were initiated by the photospheric impact in the early impulsive phase, observed prior to the hard X-ray (50-100 keV) impulse, and were probably associated with atmospheric heating by relatively low-energy electrons (~6-50 keV) and heat flux transport. The impact caused a short motion in the sunspot penumbra prior to the appearance of the helioseismic wave. It is found that the helioseismic wave front traveling through a sunspot had a lower amplitude and was significantly delayed relative to the front traveling outside the spot. These observations open new perspectives for studying the flare photospheric impacts and for using the flare-excited waves for sunspot seismology.

First Sunquake of Solar Cycle 24 Observed by Solar Dynamics Observatory
Kosovichev A.
E-print, Feb **2011;** prepared for RHESSI Science Nuggets
http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/First_Sunquake_of_Solar_Cycle_24_Observed_by_Solar_Dynamics_Observatory
The X2.2-class solar flare of **February 15, 2011**, produced a powerful `sunquake' event, representing a seismic response to the flare impact. The impulsively excited seismic waves formed a compact wavepacket traveling through the solar interior and appeared on the surface as expanding wave ripples. The Helioseismic and Magnetic Imager (HMI), instrument on SDO, observes variations of intensity, magnetic field and plasma velocity (Dopplergrams) on the surface of Sun almost uninterruptedly with high resolution (0.5 arcsec/pixel) and high cadence (45 sec). The flare impact on the solar surface was observed in the form of compact and rapid variations of the HMI observables (Doppler velocity, line-of-sight magnetic field and continuum intensity). These variations, caused by the impact of high-energy particles in the photosphere, formed a typical two-ribbon flare structure. The sunquake can be easily seen in the raw Dopplergram differences without any special data processing. The source of this quake was located near the outer boundary of a very complicated complicated sunspot region, NOAA 1158, in a sunspot penumbra and at the penumbra boundary. This caused an interesting plasma dynamics in the impact region. I present some preliminary results of analysis of the near-real-time data from HMI, and discuss properties of the sunquake and the flare impact sources.

Properties of Flares-Generated Seismic Waves on the Sun
Kosovichev A.
Solar Physics, Volume 238, Issue 1, pp.1-11б **2006**
http://arxiv.org/pdf/astro-ph/0601006v1.pdf
The helioseismic waves excited by solar flares ("sunquakes") are observed as circular, expanding waves on the Sun's surface. The first sunquake was observed for a flare on **July 9, 1996**, by the Solar and Heliospheric Observatory (SOHO) space mission. This paper presents results of new observations and a detailed qualitative analysis of the basic properties of the helioseismic waves generated by four solar flares in 2003 2005. For two of these flares, the X17 flare of **October 28, 2003**, and the X1.2 flare of **January 15, 2005**, the helioseismology observations are compared with simultaneous observations of flare X-ray fluxes measured from the RHESSI satellite. These observations show a close association between the flare seismic waves and the hard X-ray source, indicating that high-energy electrons accelerated during the flare impulsive phase produced strong compression

waves in the photosphere, causing the sunquake. The results also reveal new physical properties such as strong anisotropy of the seismic waves, the amplitude of which varies significantly with the direction of propagation. The waves travel through surrounding sunspot regions to large distances, up to 120 Mm, without significant distortion. These observations open new perspectives for helioseismic diagnostics of flaring active regions on the Sun and for understanding the mechanisms of the energy release and transport in solar flares.

Analyzing the propagation of EUV waves and their connection with type II radio bursts by combining numerical simulations and multi-instrument observations★

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A&A 644, A90 (**2020**)
https://doi.org/10.1051/0004-6361/202038699
https://www.aanda.org/articles/aa/pdf/2020/12/aa38699-20.pdf

Context. EUV (EIT) waves are wavelike disturbances of enhanced extreme ultraviolet (EUV) emission that propagate away from an eruptive active region across the solar disk. Recent years have seen much debate over their nature, with three main interpretations: the fast-mode magneto-hydrodynamic (MHD) wave, the apparent wave (reconfiguration of the magnetic field), and the hybrid wave (combination of the previous two).
Aims. By studying the kinematics of EUV waves and their connection with type II radio bursts, we aim to examine the capability of the fast-mode interpretation to explain the observations, and to constrain the source locations of the type II radio burst emission.
Methods. We propagate a fast-mode MHD wave numerically using a ray-tracing method and the WKB (Wentzel-Kramers-Brillouin) approximation. The wave is propagated in a static corona output by a global 3D MHD Coronal Model, which provides density, temperature, and Alfvén speed in the undisturbed coronal medium (before the eruption). We then compare the propagation of the computed wave front with the observed wave in EUV images (PROBA2/SWAP, SDO/AIA). Lastly, we use the frequency drift of the type II radio bursts to track the propagating shock wave, compare it with the simulated wave front at the same instant, and identify the wave vectors that best match the plasma density deduced from the radio emission. We apply this methodology for two EUV waves observed during SOL**2017-04-03**T14:20:00 and SOL**2017-09-12**T07:25:00.
Results. The simulated wave front displays a good qualitative match with the observations for both events. Type II radio burst emission sources are tracked on the wave front all along its propagation. The wave vectors at the ray-path points that are characterized as sources of the type II radio burst emission are quasi-perpendicular to the magnetic field.
Conclusions. We show that a simple ray-tracing model of the EUV wave is able to reproduce the observations and to provide insight into the physics of such waves. We provide supporting evidence that they are likely fast-mode MHD waves. We also narrow down the source region of the radio burst emission and show that different parts of the wave front are responsible for the type II radio burst emission at different times of the eruptive event.
CESRA nugget # 2817 March **2021** http://www.astro.gla.ac.uk/users/eduard/cesra/?p=2817

CME Expansion as the Driver of Metric Type II Shock Emission as Revealed by Self-Consistent Analysis of High Cadence EUV Images and Radio Spectrograms

Kouloumvakos, A.; Patsourakos, S.; Hillaris, A.; Vourlidas, A.; Preka-Papadema, P.; Moussas, X.; Caroubalos, C.; Tsitsipis, P.; Kontogeorgos, A.

E-print, Dec 2013, File; Solar Phys. June **2014**, Volume 289, Issue 6, pp 2123-2139

On 13 June 2010, an eruptive event occurred near the solar limb. It included a small filament eruption and the onset of a relatively narrow coronal mass ejection (CME) surrounded by an extreme ultraviolet wave front recorded by the Solar Dynamics Observatory's (SDO) Atmospheric Imaging Assembly (AIA) at high cadence. The ejection was accompanied by a GOES M1.0 soft X-ray flare and a Type-II radio burst; high-resolution dynamic spectra of the latter were obtained by the ARTEMIS IV radio spectrograph. The combined observations enabled a study of the evolution of the ejecta and the **EUV wavefront** and its relationship with the coronal shock manifesting itself as metric Type-II burst. By introducing a novel technique, which deduces a proxy of the EUV compression ratio from AIA imaging data and compares it with the compression ratio deduced from the band-split of the Type-II metric radio burst, we are able to infer the potential source locations of the radio emission of the shock on that AIA images. Our results indicate that the expansion of the CME ejecta is the source for both EUV and radio shock emissions. Early in the CME expansion phase, the Type-II burst seems to originate in the sheath region between the EUV bubble and the EUV shock front in both radial and lateral directions. This suggests that both the nose and the flanks of the expanding bubble could have driven the shock.

The Coronal Analysis of SHocks and Waves (CASHeW) Framework

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Journal of Space Weather and Space Climate (SWSC) 7, A32 **2017**

https://arxiv.org/pdf/1710.05302.pdf
https://www.swsc-journal.org/articles/swsc/pdf/2017/01/swsc170030.pdf
Coronal Bright Fronts (CBF) are large-scale wavelike disturbances in the solar corona, related to solar eruptions. They are observed in extreme ultraviolet (EUV) light as transient bright fronts of finite width, propagating away from the eruption source. Recent studies of individual solar eruptive events have used EUV observations of CBFs and metric radio type II burst observations to show the intimate connection between low coronal waves and coronal mass ejection (CME)-driven shocks. EUV imaging with the Atmospheric Imaging Assembly(AIA) instrument on the Solar Dynamics Observatory (SDO) has proven particularly useful for detecting CBFs, which, combined with radio and in situ observations, holds great promise for early CME-driven shock characterization capability. This characterization can further be automated, and related to models of particle acceleration to produce estimates of particle fluxes in the corona and in the near Earth environment early in events. We present a framework for the Coronal Analysis of SHocks and Waves (CASHeW). It combines analysis of NASA Heliophysics System Observatory data products and relevant data-driven models, into an automated system for the characterization of off-limb coronal waves and shocks and the evaluation of their capability to accelerate solar energetic particles (SEPs). The system utilizes EUV observations and models written in the Interactive Data Language (IDL). In addition, it leverages analysis tools from the SolarSoft package of libraries, as well as third party libraries. We have tested the CASHeW framework on a representative list of coronal bright front events. Here we present its features, as well as initial results. With this framework, we hope to contribute to the overall understanding of coronal shock waves, their importance for energetic particle acceleration, as well as to the better ability to forecast SEP events fluxes.
2011-05-11, June 7, 2011, December 12, 2013

Properties of a Coronal Shock Wave as a Driver of Early SEP Acceleration

K. A. **Kozarev**1, J. C. Raymond2, V. V. Lobzin3,5, and M. Hamme
2015 ApJ 799 167
http://arxiv.org/pdf/1406.2363v1.pdf
Coronal mass ejectmons (CMEs) are thought to drive collisionless shocks in the solar corona, which in turn have been shown to be capable of accelerating solar energetic particles (SEPs) in minutes. It has been notoriously difficult to extract information about energetic particle spectra in the corona, owing to a lack of in situ measurements. It is possible, however, to combine remote observations with data-driven models in order to deduce coronal shock properties relevant to the local acceleration of SEPs and their heliospheric connectivity to near-Earth space. We present such novel analysis applied to the **2011 May 11** CME event on the western solar limb, focusing on the evolution of the eruption-driven, dome-like shock wave observed by the Atmospheric Imaging Assembly (AIA) EUV telescopes on board the Solar Dynamics Observatory spacecraft. We analyze the shock evolution and estimate its strength using emission measure modeling. We apply a new method combining a geometric model of the shock front with a potential field source surface model to estimate time-dependent field-to-shock angles and heliospheric connectivity during shock passage in the low corona. We find that the shock was weak, with an initial speed of ~450 km s–1. It was initially mostly quasi-parallel, but a significant portion of it turned quasi-perpendicular later in the event. There was good magnetic connectivity to near-Earth space toward the end of the event as observed by the AIA instrument. The methods used in this analysis hold a significant potential for early characterization of coronal shock waves and forecasting of SEP spectra based on remote observations.

OFF-LIMB SOLAR CORONAL WAVEFRONTS FROM SDO/AIA EXTREME-ULTRAVIOLET OBSERVATIONS—IMPLICATIONS FOR PARTICLE PRODUCTION

K. A. **Kozarev**1,5, K. E. Korreck2, V. V. Lobzin3, M. A. Weber2 and N. A. Schwadron
2011 ApJ 733 L25, **File**
http://arxiv.org/pdf/1406.2372v1.pdf
We derive kinematic properties for two recent solar coronal transient waves observed off the western solar limb with the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO) mission. The two waves occurred over ~10 minute intervals on consecutive days—**2010 June 12 and 13**. For the first time, off-limb waves are imaged with a high 12 s cadence, making possible detailed analysis of these transients in the low corona between ~1.1 and 2.0 solar radii (RS). We use observations in the 193 and 211 Å AIA channels to constrain the kinematics of both waves. We obtain initial velocities for the two fronts of ~1287 and ~736 km s–1, and accelerations of –1170 and –800 m s–2, respectively. Additionally, differential emission measure analysis shows the June 13 wave is consistent with a weak shock. Extreme-ultraviolet (EUV) wave positions are correlated with positions from simultaneous type II radio burst observations. We find good temporal and height association between the two, suggesting that the waves may be the EUV signatures of coronal shocks. Furthermore, the events are associated with significant increases in proton fluxes at 1 AU, possibly related to how waves propagate through the coronal magnetic field. Characterizing these coronal transients will be key to connecting their properties with energetic particle production close to the Sun.

Solar Demon – an approach to detecting flares, dimmings, and EUV waves on SDO/AIA images

Emil **Kraaikamp*** and Cis Verbeeck

J. Space Weather Space Clim., 5, A18 (**2015**) **File**

http://www.swsc-journal.org/articles/swsc/pdf/2015/01/swsc140062.pdf

Flares, dimmings, and extreme ultraviolet (EUV) waves are three types of eruptive phenomena on the Sun, which are main drivers of space weather. Fast and reliable detection of these phenomena helps augment space weather predictions. In the current paper, we introduce Solar Demon, the first software that detects all three phenomena, using a modular design to exploit synergies. While Solar Demon runs in near real-time on SDO/AIA synoptic quick-look images to provide fast detections of flares, dimmings, and EUV waves for space weather purposes, it also processes new Atmospheric Imaging Assembly (AIA) synoptic science images on a regular basis to build dedicated science quality catalogs. An overview of Solar Demon is given, with a focus on the algorithms for EUV wave detection and characterization. Several first results, such as flare and dimming butterfly diagrams for the rising part of Solar Cycle 24, are presented. The main advantages, challenges, and future prospects for Solar Demon are outlined in the Section 5.

February 15, 2011, October 23, 2012, July 8, 2014, Oct 27, 2014, 2014-11-03, December 12, 2014,

Are EIT waves slow mode blast waves?

Krasnoselskikh, V., Podladchikova, O.,

2007. AGU Fall Meeting Abstracts , A1047.

Are CMEs capable of producing Moreton waves? A case study: the 2006 December 6 event

G. **Krause**; M. Cécere; E. Zurbriggen; A. Costa; C. Francile ...

Monthly Notices of the Royal Astronomical Society, Volume 474, Issue 1, 11 February **2018**, Pages 770–778, https://doi.org/10.1093/mnras/stx2817

https://academic.oup.com/mnras/article/474/1/770/4688933

Considering the chromosphere and a stratified corona, we examine, by performing 2D compressible magnetohydrodynamics simulations, the capability of a coronal mass ejection (CME) scenario to drive a Moreton wave. We find that given a typical flux rope (FR) magnetic configuration, in initial pseudo-equilibrium, the larger the magnetic field and the lighter (and hotter) the FR, the larger the amplitude and the speed of the chromospheric disturbance, which eventually becomes a Moreton wave. We present arguments to explain why Moreton waves are much rarer than CME occurrences. In the frame of the present model, we explicitly exclude the action of flares that could be associated with the CME. Analysing the Mach number, we find that only fast magnetosonic shock waves will be able to produce Moreton events. In these cases an overexpansion of the FR is always present and it is the main factor responsible for the Moreton generation. Finally, we show that this scenario can account for the Moreton wave of the **2006 December 6** event (Francile et al. 2013).

A Study of Dimmings, CMEs, and Flares during the STEREO-SOHO Quadrature

Larisza D. **Krista**1,2,3, Drew Manning4, and Matthew J. West5

2022 ApJ 930 165

https://iopscience.iop.org/article/10.3847/1538-4357/ac67d7/pdf

During the quadrature period (2010 December–2011 August) the STEREO-A and B satellites were approximately at right angles to the SOHO satellite. This alignment was particularly advantageous for determining the coronal mass ejection (CME) properties, since the closer a CME propagates to the plane of sky, the smaller the measurement inaccuracies are. Our primary goal was to study dimmings and their relationship to CMEs and flares during this time. We identified 53 coronal dimmings using STEREO/EUVI 195 Å observations, and linked 42 of the dimmings to CMEs (observed with SOHO/LASCO/C2) and 23 to flares. Each dimming in the catalog was processed with the Coronal Dimming Tracker which detects transient dark regions in extreme ultraviolet images directly, without the use of difference images. This approach allowed us to observe footpoint dimmings: the regions of mass depletion at the footpoints of erupting magnetic flux rope structures. Our results show that the CME mass has a linear, moderate correlation with dimming total EUV intensity change, and a monotonic, moderate correlation with dimming area. These results suggest that the more the dimming intensity drops and the larger the erupting region is, the more plasma is evacuated. We also found a strong correlation between the flare duration and the total change in EUV intensity. The correlation between dimming properties showed that larger dimmings tend to be brighter; they go through more intensity loss and generally live longer—supporting the hypothesis that larger transient open regions release more plasma and take longer to close down and refill with plasma. **9-10 May 2011**

Statistical Study of Solar Dimmings Using CoDiT

Larisza D. **Krista**1,2 and Alysha A. Reinard1,3

2017 ApJ 839 50

http://iopscience.iop.org.sci-hub.cc/0004-637X/839/1/50/
https://arxiv.org/pdf/1705.08555.pdf
https://iopscience.iop.org/article/10.3847/1538-4357/aa6626/pdf
We present the results from analyzing the physical and morphological properties of 154 dimmings (transient coronal holes) and the associated flares and coronal mass ejections (CMEs). Each dimming in our 2013 catalog was processed with the semi-automated Coronal Dimming Tracker using Solar Dynamics Observatory AIA 193 Å observations and HMI magnetograms. Instead of the typically used difference images, we used our coronal hole detection algorithm to detect transient dark regions "directly" in extreme ultraviolet (EUV) images. This allowed us to study dimmings as the footpoints of CMEs—in contrast with the larger, diffuse dimmings seen in difference images that represent the projected view of the rising, expanding plasma. Studying the footpoint-dimming morphology allowed us to better understand the CME structure in the low corona. While comparing the physical properties of dimmings, flares, and CMEs we were also able to identify relationships between the different parts of this complex eruptive phenomenon. We found that larger dimmings are longer-lived, suggesting that it takes longer to "close down" large open magnetic regions. Also, during their growth phase, smaller dimmings acquire a higher magnetic flux imbalance (i. e., become more unipolar) than larger dimmings. Furthermore, we found that the EUV intensity of dimmings (indicative of local electron density) correlates with how much plasma was removed and how energetic the eruption was. Studying the morphology of dimmings (single, double, fragmented) also helped us identify different configurations of the quasi-open magnetic field. **1-2 Feb 2013**

STUDY OF THE RECURRING DIMMING REGION DETECTED AT AR 11305 USING THE CORONAL DIMMING TRACKER (CoDiT)

Larisza D. **Krista**1,2 and Alysha Reinard

2013 ApJ 762 91, **File**

https://iopscience.iop.org/article/10.1088/0004-637X/762/2/91/pdf

We present a new approach to coronal dimming detection using the COronal DImming Tracker tool (CODIT), which was found to be successful in locating and tracking multiple dimming regions. This tool, an extension of a previously developed coronal hole tracking software, allows us to study the properties and the spatial evolution of dimming regions at high temporal and spatial cadence from the time of their appearance to their disappearance. We use Solar Dynamics Observatory/Atmospheric Imaging Assembly 193 Å wavelength observations and Helioseismic and Magnetic Imager magnetograms to study dimmings. As a demonstration of the detection technique we analyzed six recurrences of a dimming observed near AR 11305 between **2011 September 29 and October 2**. The dimming repeatedly appeared and formed in a similar way, first expanding then shrinking and occasionally stabilizing in the same location until the next eruption. The dimming areas were studied in conjunction with the corresponding flare magnitudes and coronal mass ejection (CME) masses. These properties were found to follow a similar trend during the observation period, which is consistent with the idea that the magnitude of the eruption and the CME mass affect the relative sizes of the consecutive dimmings. We also present a hypothesis to explain the evolution of the recurrent single dimming through interchange reconnection. This process would accommodate the relocation of quasi-open magnetic field lines and hence allow the CME flux rope footpoint (the dimming) to expand into quiet-Sun regions. By relating the properties of dimmings, flares, and CMEs we improve our understanding of the magnetic field reconfiguration caused by reconnection.

On the signatures of flare-induced global waves in the Sun: GOLF and VIRGO observations

Brajesh **Kumar**, Savita Mathur, Rafael A. Garcia, Antonio Jimenez

MNRAS, Vol. 471, Issue 4, November **2017**

https://arxiv.org/pdf/1710.06245.pdf

Recently, several efforts have been made to identify the seismic signatures of flares and magnetic activity in the Sun and Sun-like stars. In this work, we have analyzed the disk-integrated velocity and intensity observations of the Sun obtained from the GOLF and VIRGO/SPM instruments, respectively, on board the SOHO space mission covering several successive flare events, for the period from **11 February 2011 to 17 February 2011**, of which 11 February 2011 remained a relatively quiet day and served as a "null test" for the investigation. Application of the spectral analysis to these disk-integrated Sun-as-a-star velocity and intensity signals indicates that there is enhanced power of the global modes of oscillations in the Sun during the flares, as compared to the quiet day. The GOLF instrument obtains velocity observations using the Na I D lines which are formed in the upper solar photosphere, while the intensity data used in our analysis are obtained by VIRGO/SPM instrument at 862~nm, which is formed within the solar photosphere. Despite the fact that the two instruments sample different layers of the solar atmosphere using two different parameters (velocity v/s intensity), we have found that both these observations show the signatures of flare-induced global waves in the Sun. These results could suffice in identifying the asteroseismic signatures of stellar flares and magnetic activity in the Sun-like stars.

Initiation of a type II radio burst without a CME

Pankaj **Kumar**, Davina Innes, and Kyung-Suk Cho

RHESSI Science Nuggets #278 July **2016**

http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/Initiation_of_a_type_II_radio_burst_without_a_CME

We present a well-observed type II burst associated with a flare-generated shock wave on **24 April 2016** (SOL2014-04-16 (M1.0)) [1]. This event did not show any evidence of an associated CME. However, a mini-filament was seen to erupt in the opposite direction of the fast **EUV wave**. Such events are of great interest, because they challenge a common assumption that CMEs are always required to generate coronal shocks.

We have reported direct observation of a fast EUV (shock) wave propagating through solar coronal arcade loops, which was associated with CME-less type II radio burst. The wave was observed in the AIA 335, 193, and 171 channels, with a speed of 800-1490 km/s. The wave was most likely triggered by a magnetic reconnection process. A small filament eruption (~340 km/s) was observed shortly after the formation of a quasi-circular ribbon, which moved in the opposite direction of the shock wave and failed to erupt. We did not see any EUV wavefront ahead of filament and speed of the filament was 3-4 times less than the EUV wave speed. The EUV wave was highly directional [3] and excited kink oscillations of the arcade loops during its passage through them.

Flare Generated Shock Wave Propagation Through Solar Coronal Arcade Loops and Associated Type II Radio Burst

Pankaj **Kumar**, D.E. Innes, K.S. Cho

ApJ **2016**

http://arxiv.org/pdf/1606.05056v1.pdf

This paper presents multiwavelength observations of a flare-generated type II radio burst. The kinematics of the shock derived from the type II closely match a fast EUV wave seen propagating through coronal arcade loops. The EUV wave was closely associated with an impulsive M1.0 flare without a related coronal mass ejection, and was triggered at one of the footpoints of the arcade loops in active region NOAA 12035. It was initially observed in the AIA 335 \AA\ images with a speed of ~800 km/s and accelerated to ~1490 km/s after passing through the arcade loops. A fan-spine magnetic topology was revealed at the flare site. A small, confined filament eruption (~340 km/s) was also observed moving in the opposite direction to the EUV wave. We suggest that breakout reconnection in the fan-spine topology triggered the flare and associated EUV wave that propagated as a fast shock through the arcade loops. **16 April 2014**.

Partial Reflection and Trapping of a Fast-mode Wave in Solar Coronal Arcade Loops

Pankaj **Kumar**, D.E. Innes

ApJL **2015**

http://arxiv.org/pdf/1503.08165v1.pdf

We report on the first direct observation of a fast-mode wave propagating along and perpendicular to cool (171 {\AA}) arcade loops observed by the SDO/AIA. The wave was associated with an impulsive/compact flare, near the edge of a sunspot. The EUV wavefront expanded radially outward from the flare center and decelerated in the corona from 1060-760 km/s within ~3-4 minute. Part of the EUV wave propagated along a large-scale arcade of cool loops and was partially reflected back to the flare site. The phase speed of the wave was about 1450 km/s, which is interpreted as a fast-mode wave. A second overlying loop arcade, orientated perpendicular to the cool arcade, is heated and becomes visible in the AIA hot channels. These hot loops sway in time with the EUV wave, as it propagated to and fro along the lower loop arcade. We suggest that an impulsive energy release at one of the footpoints of the arcade loops causes the onset of an EUV shock wave that propagates along and perpendicular to the magnetic field. **6 March 2014**.

Multiwavelength Observations of an Eruptive Flare: Evidence for Blast Waves and Break-Out

Pankaj **Kumar**, D. E. Innes

E-print, April **2013; File,** Solar Physics, November 2013, Volume 288, Issue 1, pp 255-268

Images of an east-limb flare on **3 November 2010** taken in the 131 Å channel of the Atmospheric Imaging Assembly onboard the Solar Dynamics Observatory provide a convincing example of a long current sheet below an erupting plasmoid, as predicted by the standard magnetic reconnection model of eruptive flares. However, the 171 Å and 193 Å channel images hint at an alternative scenario. These images reveal that large-scale waves with velocity greater than 1000 km s^{-1} propagated alongside and ahead of the erupting plasmoid. Just south of the plasmoid, the waves coincided with type-II radio emission, and to the north, where the waves propagated along plume-like structures, there was increased decimetric emission. Initially, the cavity around the hot plasmoid expanded. Later, when the erupting plasmoid reached the height of an overlying arcade system, the plasmoid structure changed, and the lower parts of the cavity collapsed inwards. Hot loops appeared alongside and below the erupting plasmoid. We consider a scenario in which the fast waves and the type-II emission were a consequence of a flare blast wave, and the cavity collapse and the hot loops resulted from the break-out of the flux rope through an overlying coronal arcade.

Eruption of a plasma blob, associated M-class flare, and large-scale extreme-ultraviolet wave observed by SDO⋆

P. **Kumar**1 and P. K. Manoharan

A&A 553, A109 (**2013**); **File**

We present a multiwavelength study of the formation and ejection of a plasma blob and associated extreme ultraviolet (EUV) waves in active region (AR) NOAA 11176, observed by SDO/AIA and STEREO on **25 March 2011**. The EUV images observed with the AIA instrument clearly show the formation and ejection of a plasma blob from the lower atmosphere of the Sun at ~9 min prior to the onset of the M1.0 flare. This onset of the M-class flare happened at the site of the blob formation, while the blob was rising in a parabolic path with an average speed of ~300 km s. The blob also showed twisting and de-twisting motion in the lower corona, and the blob speed varied from ~10−540 km s. The faster and slower EUV wavefronts were observed in front of the plasma blob during its impulsive acceleration phase. The faster EUV wave propagated with a speed of ~785 to 1020 km s, whereas the slower wavefront speed varied in between ~245 and 465 km s. The timing and speed of the faster wave match the shock speed estimated from the drift rate of the associated type II radio burst. The faster wave experiences a reflection by the nearby AR NOAA 11177. In addition, secondary waves were observed (only in the 171 Å channel), when the primary fast wave and plasma blob impacted the funnel-shaped coronal loops. The Helioseismic Magnetic Imager (HMI) magnetograms revealed the continuous emergence of new magnetic flux along with shear flows at the site of the blob formation. It is inferred that the emergence of twisted magnetic fields in the form of arch-filaments/“anemone-type” loops is the likely cause for the plasma blob formation and associated eruption along with the triggering of M-class flare. Furthermore, the faster EUV wave formed ahead of the blob shows the signature of fast-mode MHD wave, whereas the slower wave seems to be generated by the field line compression by the plasma blob. The secondary wave trains originated from the funnel-shaped loops are probably the fast magnetoacoustic waves.

Multiwavelength Study of a Solar Eruption from AR NOAA 11112: II. Large-Scale Coronal Wave and Loop Oscillation

Pankaj **Kumar**1 , K.-S. Cho1, 2, 3, P. F. Chen4, S.-C. Bong1 and Sung-Hong Park

Solar Physics, February **2013**, Volume 282, Issue 2, pp 523-541, **File**

We analyze multiwavelength observations of an M2.9/1N flare that occurred in AR NOAA 11112 on **16 October 2010**. AIA 211 Å EUV images reveal the presence of a faster coronal wave (decelerating from ≈ 1390 to ≈ 830 km s−1) propagating ahead of a slower wave (decelerating from ≈ 416 to ≈ 166 km s−1) towards the western limb. The dynamic radio spectrum from Sagamore Hill radio telescope shows the presence of a metric type II radio burst, which reveals the presence of a coronal shock wave (speed ≈ 800 km s−1). The speed of the faster coronal wave, derived from AIA 211 Å images, is found to be comparable to the coronal shock speed. AIA 171 Å high-cadence observations showed that a coronal loop, which was located at a distance of ≈ 0.32R ⊙ to the west of the flaring region, started to oscillate by the end of the impulsive phase of the flare. The results indicate that the faster coronal wave may be the first driver of the transversal oscillations of coronal loop. As the slower wave passed through the coronal loop, the oscillations became even stronger. There was a plasmoid eruption observed in EUV and a white-light CME was recorded, having velocity of ≈ 340 – 350 km s−1. STEREO 195 Å images show an EIT wave, propagating in the same direction as the lower-speed coronal wave observed in AIA, but decelerating from ≈ 320 to ≈ 254 km s−1. These observations reveal the co-existence of both waves (i.e. coronal Moreton and EIT waves), and the type II radio burst seems to be associated with the coronal Moreton wave.

TESIS experiment on EUV imaging spectroscopy of the Sun

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Advances in Space Research , Volume 43, Issue 6, 16 March **2009**, Pages 1001-1006

TESIS is a set of solar imaging instruments in development by the Lebedev Physical Institute of the Russian Academy of Science, to be launched aboard the Russian spacecraft CORONAS-PHOTON in December 2008. The main goal of TESIS is to provide complex observations of solar active phenomena from the transition region to the inner and outer solar corona with high spatial, spectral and temporal resolution in the EUV and Soft X-ray spectral bands. TESIS includes five unique space instruments: the MgXII Imaging Spectroheliometer (MISH) with spherical bent crystal mirror, for observations of the Sun in the monochromatic MgXII 8.42 Å line; the EUV Spectoheliometer (EUSH) with grazing incidence difraction grating, for the registration of the full solar disc in monochromatic lines of the spectral band 280–330 Å; two Full-disk EUV Telescopes (FET) with multilayer mirrors covering the band 130–136 and 290–320 Å; and the Solar EUV Coronagraph (SEC), based on the Ritchey–Chretien scheme, to observe the inner and outer solar corona from 0.2 to 4 solar radii in spectral band 290–320 Å. TESIS experiment will start at the rising phase of the 24th cycle of solar activity. With the advanced capabilities of its instruments, TESIS will help better understand the physics of solar flares and high-energy phenomena and provide new data on parameters of solar plasma in the temperature range $10^5 - 10^7$ K. This paper gives a brief description of the experiment, its equipment, and its scientific objectives.

Investigating the Wave Nature of the Outer Envelope of Halo Coronal Mass Ejections

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2017 ApJ 836 246

http://sci-hub.cc/doi/10.3847/1538-4357/aa5b92

We investigate the nature of the outer envelope of halo coronal mass ejections (H-CMEs) using multi-viewpoint observations from the Solar Terrestrial Relations Observatory-A, -B, and SOlar and Heliospheric Observatory coronagraphs. The 3D structure and kinematics of the halo envelopes and the driving CMEs are derived separately using a forward modeling method. We analyze three H-CMEs with peak speeds from 1355 to 2157 km s−1; sufficiently fast to drive shocks in the corona. We find that the angular widths of the halos range from 192° to 252°, while those of the flux ropes range between only 58° and 91°, indicating that the halos are waves propagating away from the CMEs. The halo widths are in agreement with widths of Extreme Ultraviolet (EUV) waves in the low corona further demonstrating the common origin of these structures. To further investigate the wave nature of the halos, we model their 3D kinematic properties with a linear fast magnetosonic wave model. The model is able to reproduce the position of the halo flanks with realistic coronal medium assumptions but fails closer to the CME nose. The CME halo envelope seems to arise from a driven wave (or shock) close to the CME nose, but it is gradually becoming a freely propagating fast magnetosonic wave at the flanks. This interpretation provides a simple unifying picture for CME halos, EUV waves, and the large longitudinal spread of solar energetic particles. **2011 March 7, 2013 April 11, and 2014 February 25**

NEW INSIGHTS INTO THE PHYSICAL NATURE OF CORONAL MASS EJECTIONS AND ASSOCIATED WAVES/SHOCKS WITHIN THE FRAMEWORK OF THREE-DIMENSIONAL STRUCTURE

Ryun-Young **Kwon**, Jie Zhang, and Oscar Olmedo

ApJ, **2014**

http://spaceweather.gmu.edu/public/rkwon/ **File**

We present new insights into the physical nature of coronal mass ejections (CMEs) and associated shock waves within the framework of the threedimensional (3D) structure. We have developed a compound model in order to determine the 3D structure of multiple fronts composing a CME, using data sets taken from STEREO, SDO, and SOHO. We applied the method to time series observations of a CME on **2012 March 7**. From the analyses, we revealed that a CME could consist of two different fronts: one is represented well with the ellipsoid model, implying that CMEs are bubble-shaped structures and the other is reproduced well with the graduated cylindrical shell model, indicating that CMEs are flux rope-shaped structures. The bubble-shaped structure is seen as the outermost front of the CME, and the flux rope-shaped structure is seen as the bright frontal loop or three-part morphology. From our results, we conclude that (1) a CME could consist of two distinct structures, a bubble shaped structure and a flux rope-shaped structure, (2) the bubble-shaped structure is a fast magnetosonic shock wave while the flux rope-shaped structure is the mass carried outward by the underlying magnetic structure, (3) the driven shock front could be either a piston-shock type or a bow-shock type, (4) the observed EUV wave in the low corona is the footprint of the bubble-shaped wave, and (5) the halo CME is primarily the projection of the bubble-shaped shock wave but not the underlying flux rope.

Global Coronal Seismology in the Extended Solar Corona through Fast Magnetosonic Waves Observed by STEREO SECCHI COR1

Ryun-Young **Kwon**1,2,3, Maxim Kramar1,2, Tongjiang Wang1,2, Leon Ofman1,2,4, Joseph M. Davila2, Jongchul Chae5, and Jie Zhang

2013 ApJ 776 55

We present global coronal seismology for the first time, which allows us to determine inhomogeneous magnetic field strength in the extended corona. From the measurements of the propagation speed of a fast magnetosonic wave associated with a coronal mass ejection (CME) and the coronal background density distribution derived from the polarized radiances observed by the STEREO SECCHI COR1, we determined the magnetic field strengths along the trajectories of the wave at different heliocentric distances. We found that the results have an uncertainty less than 40%, and are consistent with values determined with a potential field model and reported in previous works. The characteristics of the coronal medium we found are that (1) the density, magnetic field strength, and plasma β are lower in the coronal hole region than in streamers; (2) the magnetic field strength decreases slowly with height but the electron density decreases rapidly so that the local fast magnetosonic speed increases while plasma β falls off with height; and (3) the variations of the local fast magnetosonic speed and plasma β are dominated by variations in the electron density rather than the magnetic field strength. These results imply that Moreton and EIT waves are downward-reflected fast magnetosonic waves from the upper solar corona, rather than freely propagating fast magnetosonic waves in a certain atmospheric layer. In addition, the azimuthal components of CMEs and the driven waves may play an important role in various manifestations of shocks, such as type II radio bursts and solar energetic particle events.

STEREO OBSERVATIONS OF FAST MAGNETOSONIC WAVES IN THE EXTENDED SOLAR CORONA ASSOCIATED WITH EIT/EUV WAVES

Ryun-Young **Kwon**1,2, Leon Ofman1,2,3, Oscar Olmedo4, Maxim Kramar1,2, Joseph M. Davila2, Barbara J. Thompson2, and Kyung-Suk Cho

2013 ApJ 766 55, **File**

We report white-light observations of a fast magnetosonic wave associated with a coronal mass ejection observed by STEREO/SECCHI/COR1 inner coronagraphs on **2011 August 4**. The wave front is observed in the form of density compression passing through various coronal regions such as quiet/active corona, coronal holes, and streamers. Together with measured electron densities determined with STEREO COR1 and Extreme UltraViolet Imager (EUVI) data, we use our kinematic measurements of the wave front to calculate coronal magnetic fields and find that the measured speeds are consistent with characteristic fast magnetosonic speeds in the corona. In addition, the wave front turns out to be the upper coronal counterpart of the EIT wave observed by STEREO EUVI traveling against the solar coronal disk; moreover, stationary fronts of the EIT wave are found to be located at the footpoints of deflected streamers and boundaries of coronal holes, after the wave front in the upper solar corona passes through open magnetic field lines in the streamers. Our findings suggest that the observed EIT wave should be in fact a fast magnetosonic shock/wave traveling in the inhomogeneous solar corona, as part of the fast magnetosonic wave propagating in the extended solar corona.

Plasma diagnostic in eruptive prominences from SDO/AIA observations at 304 Å

N. **Labrosse** and K. McGlinchey

A&A 537, A100 (**2012**)

Context. Theoretical calculations have shown that when solar prominences move away from the surface of the Sun, their radiative output is affected via the Doppler dimming or brightening effects.
Aims. In this paper we ask whether observational signatures of the changes in the radiative output of eruptive prominences can be found in EUV (extreme ultraviolet) observations of the first resonance line of ionised helium at 304 Å. We also investigate whether these observations can be used to perform a diagnostic of the plasma of the eruptive prominence.
Methods. We first look for suitable events in the SDO/AIA database. The variation of intensity of arbitrarily selected features in the 304 channel is studied as a function of velocity in the plane of the sky. These results are then compared with new non-LTE radiative transfer calculations of the intensity of the He ii 304 resonance line.
Results. We find that observations of intensities in various parts of the four eruptive prominences studied here are sometimes consistent with the Doppler dimming effect on the He ii 304 Å line. However, in some cases, one observes an increase in intensity in the 304 channel with velocity, in contradiction to what is expected from the Doppler dimming effect alone. The use of the non-LTE models allows us to explain the different behaviour of the intensity by changes in the plasma parameters inside the prominence, in particular the column mass of the plasma and its temperature.
Conclusions. The non-LTE models used here are more realistic than what was used in previous calculations. They are able to reproduce qualitatively the range of observations from SDO/AIA analysed in this study. With the help of non-LTE modelling, we can infer the plasma parameters in eruptive prominences from SDO/AIA observations at 304 Å.

The Solar Energetic Particle Event on 2013 April 11: An Investigation of its Solar Origin and Longitudinal Spread

D. **Lario**, N.E. Raouafi, R.-Y. Kwon, J. Zhang, R. Gomez-Herrero, N. Dresing, P. Riley
2014
http://arxiv.org/pdf/1410.5490v1.pdf

We investigate the solar phenomena associated with the origin of the solar energetic particle (SEP) event observed on **2013 April 11** by a number of spacecraft distributed in the inner heliosphere over a broad range of heliolongitudes. We use Extreme UltraViolet (EUV) and white-light coronagraph observations from the Solar Dynamics Observatory (SDO), the SOlar and Heliospheric Observatory (SOHO) and the twin Solar TErrestrial RElations Observatory spacecraft (STEREO-A and STEREO-B) to determine the angular extent of the EUV wave and coronal mass ejection (CME) associated with the origin of the SEP event. We compare the estimated release time of SEPs observed at each spacecraft with the arrival time of the structures associated with the CME at the footpoints of the field lines connecting each spacecraft with the Sun. Whereas the arrival of the EUV wave and CME-driven shock at the footpoint of STEREO-B is consistent, within uncertainties, with the release time of the particles observed by this spacecraft, the EUV wave never reached the footpoint of the field lines connecting near-Earth observers with the Sun, even though an intense SEP event was observed there. We show that the west flank of the CME-driven shock propagating at high altitudes above the solar surface was most likely the source of the particles observed near Earth, but it did not leave any EUV trace on the solar disk. **We conclude that the angular extent of the EUV wave on the solar surface did not agree with the longitudinal extent of the SEP event in the heliosphere. Hence EUV waves cannot be used reliably as a proxy for the solar phenomena that accelerates and injects energetic particles over broad ranges of longitudes.**

Are the Faint Structures Ahead of Solar Coronal Mass Ejections Real Signatures of Driven Shocks?

Jae-Ok **Lee**1, Y.-J. Moon1,2, Jin-Yi Lee2, Kyoung-Sun Lee3, Sujin Kim4, and Kangjin Lee
2014 ApJ 796 L16

Recently, several studies have assumed that the faint structures ahead of coronal mass ejections (CMEs) are caused by CME-driven shocks. In this study, we have conducted a statistical investigation to determine whether or not the appearance of such faint structures depends on CME speeds. For this purpose, we use 127 Solar and Heliospheric Observatory/Large Angle Spectroscopic COronagraph (LASCO) front-side halo (partial and full) CMEs near the limb from 1997 to 2011. We classify these CMEs into two groups by visual inspection of CMEs in the LASCO-C2 field of view: Group 1 has the faint structure ahead of a CME and Group 2 does not have such a structure. We find the following results. (1) Eighty-seven CMEs belong to Group 1 and 40 CMEs belong to Group 2. (2) Group 1 events have much higher speeds (average = 1230 km s–1 and median = 1199 km s–1) than Group 2 events (average = 598 km s–1 and median = 518 km s–1). (3) The fraction of CMEs with faint structures strongly depends on CME speeds (V): 0.93 (50/54) for fast CMEs with V ≥ 1000 km s–1, 0.65 (34/52) for intermediate CMEs with 500 km s–1 ≤ V < 1000 km s–1, and 0.14 (3/21) for slow CMEs with V < 500 km s–1. We also find that the fraction of CMEs with deca-hecto metric type II radio bursts is consistent with the above tendency. Our results indicate that the observed faint structures ahead of fast CMEs are most likely an enhanced density manifestation of CME-driven shocks.

FAST EXTREME-ULTRAVIOLET DIMMING ASSOCIATED WITH A CORONAL JET SEEN IN MULTI-WAVELENGTH AND STEREOSCOPIC OBSERVATIONS

K.-S. **Lee**1, D. E. Innes2, Y.-J. Moon1,3, K. Shibata4, Jin-Yi Lee1, and Y.-D. Park
2013 ApJ 766 1

We have investigated a coronal jet observed near the limb on **2010 June 27** by the Hinode/X-Ray Telescope (XRT), EUV Imaging Spectrograph (EIS), and Solar Optical Telescope (SOT), and by the Solar Dynamics Observatory (SDO)/Atmospheric Imaging Assembly (AIA), and on the disk by STEREO-A/EUVI. From EUV (AIA and EIS) and soft X-ray (XRT) images we have identified both cool and hot jets. There was a small loop eruption seen in Ca II images of the SOT before the jet eruption. We found that the hot jet preceded its associated cool jet by about 2 minutes. The cool jet showed helical-like structures during the rising period which was supported by the spectroscopic analysis of the jet's emission. The STEREO observation, which enabled us to observe the jet projected against the disk, showed dimming at 195 Å along a large loop connected to the jet. We measured a propagation speed of ~800 km s–1 for the dimming front. This is comparable to the Alfvén speed in the loop computed from a magnetic field extrapolation of the photospheric field measured five days earlier by the SDO/Helioseismic and Magnetic Imager, and the loop densities obtained from EIS Fe XIV λ264.79/274.20 line ratios. We interpret the dimming as indicating the presence of Alfvénic waves initiated by reconnection in the upper chromosphere.

Sources of SEP Acceleration during a Flare–CME Event

N.J. **Lehtinen** · S. Pohjolainen, K. Huttunen-Heikinmaa · R. Vainio, E. Valtonen · A.E. Hillaris

E-print, Nov 2007, Solar Phys.; File

A high-speed halo-type coronal mass ejection (CME), associated with a GOES M4.6 soft X-ray flare in NOAA AR 0180 at S12W29 and an **EIT wave and dimming**, occurred on **9 November 2002**.

Simultaneous detection of flare-associated kink oscillations and extreme-ultraviolet waves

Dong **Li**, Zhenyong Hou, Xianyong Bai, Chuan Li, Matthew Fang, Haisheng Zhao, Jincheng Wang, Zongjun Ning

Science China Technological Sciences **2023**

https://arxiv.org/pdf/2311.08767.pdf

Kink oscillations, which are frequently observed in coronal loops and prominences, are often accompanied by extreme-ultraviolet (EUV) waves. However, much more needs to be explored regarding the causal relationships between kink oscillations and EUV waves. In this article, we report the simultaneous detection of kink oscillations and EUV waves that are both associated with an X2.1 flare on 2023 March 03 (SOL**2023-03-03T17**:39). The kink oscillations, which are almost perpendicular to the axes of loop-like structures, are observed in three coronal loops and one prominence. One short loop shows in-phase oscillation within the same period of 5.2 minutes at three positions. This oscillation could be triggered by the pushing of an expanding loop and interpreted as the standing kink wave. Time lags are found between the kink oscillations of the short loop and two long loops, suggesting that the kink wave travels in different loops. The kink oscillations of one long loop and the prominence are possibly driven by the disturbance of the CME, and that of another long loop might be attributed to the interaction of the EUV wave. The onset time of the kink oscillation of the short loop is nearly same as the beginning of an EUV wave. This fact demonstrates that they are almost simultaneous. The EUV wave is most likely excited by the expanding loop structure and shows two components. The leading component is a fast coronal wave, and the trailing one could be due to the stretching magnetic field lines.

SDO/AIA Observations of Secondary Waves Generated by Interaction of the 2011 June 7 Global EUV Wave With Solar Coronal Structures

Ting **Li**, Jun Zhang, Shuhong Yang, Wei Liu

E-print, 8 Nov **2011**, **File**; ApJ, 746 13, **2012, File**

We present SDO/AIA observations of the interaction of a global EUV wave on **2011 June 7** with active regions (ARs), coronal holes (CHs) and coronal bright structures. The primary global wave has a three-dimensional dome shape, with propagation speeds ranging from 430-780 km/s in different directions. The primary coronal wave runs in front of the expanding loops involved in the CME and its propagation speeds are approximately constant within 10-20 minutes. Upon arrival at an AR on its path, the primary EUV wave apparently disappears and a secondary wave rapidly reemerges 75 Mm within the AR boundary at a similar speed. When the EUV wave encounters a coronal bright structure, an additional wave front appears there and propagates in front of it at a velocity nearly a factor of 2 faster. Reflected waves from a polar CH and a coronal bright structure are observed and propagate fractionally slower than the primary waves. Some of these phenomena can be equally explained by either a wave or non-wave model alone. However, taken together, these observations provide new evidence for the multitudes of global EUV waves, in which a true MHD fast-mode wave or shock propagates in front of an expanding CME bubble.

The Solar Magnetic Field and Coronal Dynamics of the Eruption on 2007 May 19

Y. **Li**, B. J. Lynch, G. Stenborg, J. G. Luhmann, K. E. J. Huttunen, B. T. Welsch, P. C. Liewer, and A. Vourlidas

The Astrophysical Journal Letters, Vol. 681, No. 1: L37-L40, **2008**.

http://www.journals.uchicago.edu/doi/pdf/10.1086/590340

The solar eruption on 2007 May 19, from AR 10956 near solar disk center, consisted of a B9.5 flare (12:48 UT), a filament eruption, an EUV dimming, a coronal wave, and a multifront CME. The eruption was observed by the twin *STEREO* spacecraft at a separation angle of 8.5 . We report analysis of the source region photospheric _ magnetic field and its preeruption evolution using MDI magnetograms, the coronal magnetic field topology estimated via PFSS modeling, and the coronal dynamics of the eruption through *STEREO* EUVI wavelet-enhanced anaglyph movies. Despite its moderate magnitude and size, AR 10956 was a complex and highly nonpotential active region with a multipolar configuration, and hosted frequent flares, multiple filament eruptions, and CMEs.

In the 2 days prior to the May 19 eruption, the total unsigned magnetic flux of the region decreased by ~17%.

We interpret the photospheric magnetic field evolution, the coronal field topology, and the observed coronal dynamics in the context of current models of CME initiation and discuss the prospects for future MHD modeling inspired by these analyses.

Multi-spacecraft Observations of the 2022 March 25 CME and EUV Wave: An Analysis of Their Propagation and Interrelation

Alessandro **Liberatore**, Paulett C. Liewer, Angelos Vourlidas, Carlos R. Braga, Marco Velli, Olga Panasenco, Daniele Telloni, and Salvatore Mancuso

2023 ApJ 957 110

https://iopscience.iop.org/article/10.3847/1538-4357/acf8bf/pdf

This paper reports on a well-defined EUV wave associated with a coronal mass ejection (CME) observed on **2022 March 25**. The CME was observed by Solar Orbiter (SolO) during its first close perihelion (0.32 au) and by several other spacecraft from different viewpoints. The EUV wave was visible by the Extreme Ultraviolet Imager on board the Solar Terrestrial Relations Observatory (STEREO-A/STA) in near quadrature to SolO. We perform a detailed analysis of the early phase of this CME in relation to the evolution of the associated EUV wave. The kinematics of the EUV wave and CME are derived via visual identification of the fronts using both the STA and SolO data. The analysis of an associated metric type II radio burst provides information on the early phase of the CME and wave propagation. Finally, we compare the EUV speed to the local magnetic field and Alfvén speed using standard models of the corona. The analysis of the decoupling between the EUV wave and the CME driver via imaging, consistent with a wave initially driven by the lateral expansion of the CME, which evolves into a fast-mode magnetosonic wave after decoupling from the CME.

SO Nuggets #23 **2023** https://www.cosmos.esa.int/web/solar-orbiter/-/science-nugget-multi-spacecraft-observations-of-the-2022-march-25-cme-and-euv-wave-an-analysis-of-their-propagation-and-interrelation

Transient Dimming of the Bright Fe xiv Emission Region in the Solar Corona of the 21 August 2017 Total Solar Eclipse

D. H. **Liebenberg**

Solar Physics March **2019**, 294:25

https://doi.org/10.1007/s11207-019-1414-x

sci-hub.tw/10.1007/s11207-019-1414-x

During the **21 August 2017** total solar eclipse the corona was observed through a narrowband filter centered at the Fe xiv green emission line at a cadence of 30 frames/s. A bright region on the east limb was observed to dim during the 2 m 35 s totality. Details of the temporal behavior of this region are reported. The likely association of the dimming with a coronal mass ejection (CME) in progress during the eclipse or the small sunspot group with coronal loops near the east limb is discussed.

Stereoscopic Analysis of the 19 May 2007 Erupting Filament

P.C. **Liewer** · E.M. De Jong · J.R. Hall · R.A. Howard · W.T. Thompson · J.L. Culhane · L. Bone · L. van Driel-Gesztelyi

Solar Phys (**2009**) 256: 57–72, DOI 10.1007/s11207-009-9363-4, **File**

STEREO SCIENCE RESULTS AT SOLAR MINIMUM

A filament eruption, accompanied by a B9.5 flare, coronal dimming, and an EUV wave, was observed by the *Solar TERrestrial Relations Observatory* (STEREO) on 19 May 2007, beginning at about 13:00 UT. Here, we use observations from the SECCHI/EUVI telescopes and other solar observations to analyze the behavior and geometry of the filament before and during the eruption. At this time, STEREO A and B were separated by about 8.5°, sufficient to determine the three-dimensional structure of the filament using stereoscopy. The filament could be followed in SECCHI/EUVI 304 Å stereoscopic data from about 12 hours before to about 2 hours after the eruption, allowing us to determine the 3D trajectory of the erupting filament. From the 3D reconstructions of the filament and the chromospheric ribbons in the early stage of the eruption, simultaneous heating of both the rising filamentary material and the chromosphere directly below is observed, consistent with an eruption resulting from magnetic reconnection below the filament. Comparisons of the filament during eruption in 304 Å and H〈 show that when it becomes emissive in He II, it tends to disappear in H〈, indicating that the disappearance probably results from heating or motion, not loss, of filamentary material.

The Role of Magnetic Fields in Transient Seismic Emission Driven by Atmospheric Heating in Flares

C. **Lindsey**, A.-C. Donea, J. C. Martínez Oliveros, H. S. Hudson

Solar Physics, May **2014**, Volume 289, Issue 5, pp 1457-1469

http://arxiv.org/pdf/1303.3299v1.pdf

Transient seismic emission in flares remains largely mysterious. Its discoverers proposed that seismic transients are driven by impulsive heating of the flaring chromosphere. Simulations of such heating show strong shocks, but these are damped by heavy radiative losses as they proceed downward. Because compression of the gas the shock enters both heats it and increases its density, the radiative losses increase radically with the strength of the shock, leaving doubt that sufficient energy can penetrate into the solar interior to explain helioseismic signatures. We note that simulations to date have no account for strong, inclined magnetic fields characteristic of transient-seismic-source

environments. A strong horizontal magnetic field, for example, greatly increases the compressional modulus of the chromospheric medium, greatly reducing compression of the gas, hence radiative losses. Inclined magnetic fields, then, must be fundamental to the role of impulsive heating in transient seismic emission.
This could explain the strong affinity of seismic sources to regions of strong, highly inclined penumbral magnetic fields, including the neutral lines separating opposing polarities in δ-configuration sunspots. The basic point, then, is that the role of inclined magnetic fields is fundamental to our understanding of the role of impulsive heating in transient seismic emission. Obliquely inclined magnetic fields will complicate simulations of impulsive heating considerably. However, horizontal magnetic fields, as a preliminary control simulation, can be incorporated into standard 1-D thick-target-heating simulations with a relatively simple adaptation of existing HD codes. 2005 January 15. **2011-02-15**

An extreme ultraviolet wave associated with the possible expansion of sheared arcades

Yihan **Liu**, Ruisheng Zheng, Liang Zhang, Hengyuan Wei, Ze Zhong, Shuhong Yang, Yao Chen

A&A 674, A167 **2023**

https://arxiv.org/pdf/2304.14862.pdf

https://www.aanda.org/articles/aa/pdf/2023/06/aa45836-23.pdf

Context. Solar extreme ultraviolet (EUV) waves are propagating disturbances in the corona, and they usually accompany with various solar eruptions, from large-scale coronal mass ejections to small-scale coronal jets. Aims. Generally, it is believed that EUV waves are driven by the rapid expansion of coronal loops overlying the erupting cores. In this Letter, we present an exception of EUV wave that was not triggered by the expansion of coronal loops overlying the erupting core. Methods. Combining the multiwavelength observations from multiple instruments, we studied the event in detail. Results. The eruption was restricted in the active region (AR) and disturbed the nearby sheared arcades (SAs) connecting the source AR to a remote AR. Interestingly, following the disturbance, an EUV wave formed close to the SAs, but far away from the eruption source. Conclusions. All the results showed that the EUV wave had a closer temporal and spatial relationship with the disappearing part of SAs than the confined eruption. Hence, we suggest that the EUV wave was likely triggered by the expansion of some strands of SAs, rather than the expansion of erupting loops. It can be a possible complement for the driving mechanisms of EUV waves.
2015 December 11

Impacts of EUV Wavefronts on Coronal Structures in Homologous Coronal Mass Ejections

Rui **Liu**, Yuming Wang, Jeongwoo Lee, Chenglong Shen

ApJ **870** 15 **2018**

https://arxiv.org/pdf/1811.01326.pdf

Large-scale propagating fronts are frequently observed during solar eruptions, yet it is open whether they are waves or not, partly because the propagation is modulated by coronal structures, whose magnetic field we still cannot measure. However, when a front impacts coronal structures, an opportunity arises for us to look into the magnetic properties of both interacting parties in the low-β corona. Here we studied large-scale EUV fronts accompanying three coronal mass ejections (CMEs), each originating from a kinking rope-like structure in the NOAA active region (AR) 12371. These eruptions were homologous and the surrounding coronal structures remained stationary. Hence we treated the events as one observed from three different viewing angles, and found that the primary front directly associated with the CME consistently transmits through 1) a polar coronal hole, 2) the ends of a crescent-shaped equatorial coronal hole, leaving a stationary front outlining its AR-facing boundary, and 3) two quiescent filaments, producing slow and diffuse secondary fronts. The primary front also propagates along an arcade of coronal loops and slows down due to foreshortening at the far side, where local plasma heating is indicated by an enhancement in 211 Å (Fe XIV) but a dimming in 193 Å (Fe XII) and 171 Å (Fe IX). The strength of coronal magnetic field is therefore estimated to be ∼2 G in the polar coronal hole and ∼4 G in the coronal arcade neighboring the active region. These observations substantiate the wave nature of the primary front and shed new light on slow fronts. **2015 June 21, 22 and 25**

A Truly Global EUV Wave From the SOL2017-09-10 X8.2 Solar Flare-CME Eruption

Wei **Liu**, Meng Jin, Cooper Downs, Leon Ofman, Mark Cheung, Nariaki V. Nitta

ApJL **864** L24 **2018**

https://arxiv.org/pdf/1807.09847.pdf

http://iopscience.iop.org/article/10.3847/2041-8213/aad77b/pdf

We report SDO/AIA observations of an extraordinary global extreme ultraviolet (EUV) wave triggered by the X8.2 flare-CME eruption on **2017 September 10**. This was one of the best EUV waves ever observed with modern instruments, yet likely the last one of such magnitudes of Solar Cycle 24 as the Sun heads toward the minimum. Its remarkable characteristics include: (1) The wave was observed, for the first time, to traverse the full-Sun corona over the entire visible solar disk and off-limb circumference, manifesting a truly global nature, owing to its exceptionally large amplitude, e.g., with EUV enhancements by up to 300% at 1.1 Rsun from the eruption. (2) This leads to strong transmissions (besides commonly observed reflections) in and out of both polar coronal holes, which are usually devoid of EUV waves. It has elevated wave speeds >2000 km/s within them, consistent with the expected higher fast-mode magnetosonic speeds. The coronal holes essentially serve as new "radiation centers" for the waves being refracted out of them, which then travel toward the equator and collide head-on, causing additional EUV enhancements. (3) The wave produces significant compressional heating to local plasma upon its impact, indicated by long-lasting EUV intensity changes and differential emission measure increases at higher temperatures (e.g., log T=6.2) accompanied by decreases at lower temperatures (log T=6.0). These characteristics signify the potential of such EUV waves for novel magnetic and thermal diagnostics of the solar corona {\it on global scales}.

Quasi-periodic Fast-mode Magnetosonic Wave Trains Within Coronal Waveguides Associated with Flares and CMEs

Wei **Liu**, Leon Ofman, Brittany Broder, Marian Karlicky, and Cooper Downs
Proceedings of the 14th International Solar Wind Conference, **201**5
http://sun.stanford.edu/~weiliu/research/publications/2016/2016AIP_WeiLiu_QFPs_SolWind14.pdf
http://arxiv.org/pdf/1512.07930v1.pdf

Quasi-periodic, fast-mode, propagating wave trains (QFPs) are a new observational phenomenon recently discovered in the solar corona by the Solar Dynamics Observatory with extreme ultraviolet (EUV) imaging observations. They originate from flares and propagate at speeds up to ~2000 km s-1 within funnel-shaped waveguides in the wakes of coronal mass ejections (CMEs). QFPs can carry sufficient energy fluxes required for coronal heating during their occurrences. They can provide new diagnostics for the solar corona and their associated flares. We present recent observations of QFPs focusing on their spatio-temporal properties, temperature dependence, and statistical correlation with flares and CMEs. Of particular interest is the **2010-Aug-01** C3.2 flare with correlated QFPs and drifting zebra and fiber radio bursts, which might be different manifestations of the same fast-mode wave trains. We also discuss the potential roles of QFPs in accelerating and/or modulating the solar wind.

Early Evolution of an Energetic Coronal Mass Ejection and Its Relation to EUV Waves

Rui **Liu**, Yuming Wang, and Chenglong Shen
ApJ, 797 37 **2014; File**
http://arxiv.org/pdf/1410.1960v1.pdf

We study a coronal mass ejection (CME) associated with an X-class flare, whose initiation is clearly observed in low corona with high-cadence, high-resolution EUV images, providing us a rare opportunity to witness the early evolution of an energetic CME in detail. The eruption starts with a slow expansion of cool overlying loops (~1 MK) following a jet-like event in the periphery of the active region. Underneath the expanding loop system a reverse S-shaped dimming is seen immediately above the brightening active region in hot EUV passbands. The dimming is associated with a rising diffuse arch (~6 MK), which we interpret as a preexistent, high-lying flux rope. This is followed by the arising of a double hot channel (~10 MK) from the core of the active region. The higher structures rise earlier and faster than lower ones, with the leading front undergoing extremely rapid acceleration up to 35 km s^2. This suggests that the torus instability is the major eruption mechanism and that it is the high-lying flux rope rather than the hot channels that drives the eruption. The compression of coronal plasmas skirting and overlying the expanding loop system, whose aspect ratio h/r increases with time as a result of the rapid upward acceleration, plays a significant role in driving an outward-propagating global EUV wave and a sunward-propagating local EUV wave, respectively. **2013 May 15**

Advances in Observing Various Coronal EUV Waves in the SDO Era and Their Seismological Applications (Invited Review)

Wei **Liu**, Leon Ofman
E-print, April **2014**; Solar Physics (Topical Issue, "Exploring the Network of SDO Science"), Volume 289, Issue 9, pp 3233-3277, **2014**
http://arxiv.org/pdf/1404.0670v1.pdf
http://sun.stanford.edu/~weiliu/research/publications/2014/2014SolPhy_Liu_Ofman_SDO-EUV-wave-review.pdf

Global extreme ultraviolet (EUV) waves are spectacular traveling disturbances in the solar corona associated with energetic eruptions such as coronal mass ejections (CMEs) and flares. Over the past 15 years, observations from three generations of space-borne EUV telescopes have shaped our understanding of this phenomenon and at the same time led to controversy about its physical nature. Since its launch in 2010, the Atmospheric Imaging Assembly (AIA) onboard the Solar Dynamics Observatory (SDO) has observed more than 210 global EUV waves in exquisite detail, thanks to its high spatio-temporal resolution and full-disk, wide-temperature coverage. A combination of statistical analysis of this large sample, 30 some detailed case studies, and data-driven MHD modeling, has been leading their physical interpretations to a convergence, favoring a bimodal composition of an outer, fast-mode magnetosonic wave component and an inner, non-wave CME component. Adding to this multifaceted picture, AIA has also discovered new EUV wave and wave-like phenomena associated with various eruptions, including quasi-periodic fast propagating (QFP) wave trains, magnetic Kelvin-Helmholtz instabilities (KHI) in the corona and associated nonlinear waves, and a variety of mini EUV waves. Seismological applications using such waves are now being actively pursued, especially for the global corona. We review such advances in EUV wave research focusing on recent SDO/AIA observations, their seismological applications, related data analysis techniques, and numerical and analytical models.

Observation of A Moreton Wave and Wave-Filament Interactions Associated with the Renowned X9 Flare on 1990 May 24

Rui **Liu**, Chang Liu, Yan Xu, Wei Liu, Bernhard Kliem, Haimin Wang

E-print, June **2013**, **File, 2013** ApJ 773 166;

Using BBSO film data recently digitized at NJIT, we investigate a Moreton wave associated with an X9 flare on 1990 May 24, as well as its interactions with four filaments F1--F4 located close to the flaring region. The interaction yields interesting insight into physical properties of both the wave and the filaments. The first clear Moreton wavefront appears at the flaring-region periphery at approximately the same time as the peak of a microwave burst and the first of two gamma-ray peaks. The wavefront propagates at different speeds ranging from 1500 -2600 km/s in different directions, reaching as far as 600 Mm away from the flaring site. Sequential chromospheric brightenings are observed ahead of the Moreton wavefront. A slower diffuse front at 300-600 km/s is observed to trail the fast Moreton wavefront about 1 min after the onset. The Moreton wave decelerates to ~550 km/s as it sweeps through F1. The wave passage results in F1's oscillation which is featured by ~1 mHz signals with coherent Fourier phases over the filament, the activation of F3 and F4 followed by gradual recovery, but no disturbance in F2. Different height and magnetic environment together may account for the distinct responses of the filaments to the wave passage. The wavefront bulges at F4 whose spine is oriented perpendicular to the upcoming wavefront. The deformation of the wavefront is suggested to be due to both the forward inclination of the wavefront and the enhancement of the local Alfvén speed within the filament channel.

Table 3. AIA observed EIT waves and their characteristics.

Table 6. AIA observed small-scale EUV waves.

Quasi-periodic Fast-mode Wave Trains Within a Global EUV Wave and Sequential Transverse Oscillations Detected by SDO/AIA

Wei **Liu**, Leon Ofman, Nariaki V. Nitta, Markus J. Aschwanden, Carolus J. Schrijver, Alan M. Title, Theodore D. Tarbell

E-print, Apr. **2012**; Ap. J. 753 52, **2012, File**

We present the first unambiguous detection of quasi-periodic wave trains within the broad pulse of a global EUV wave (so-called "EIT wave") occurring on the limb. These wave trains, running ahead of the lateral CME front of 2-4 times slower, coherently travel to distances $>R_{sun}/2$ along the solar surface, with initial velocities up to 1400 km/s decelerating to ~650 km/s. The rapid expansion of the CME initiated at an elevated height of 110 Mm produces a strong downward and lateral compression, which may play an important role in driving the primary EUV wave and shaping its front forwardly inclined toward the solar surface. The waves have a dominant 2 min periodicity that matches the X-ray flare pulsations, suggesting a causal connection. The arrival of the leading EUV wave front at increasing distances produces an uninterrupted chain sequence of deflections and/or transverse (likely fast kink mode) oscillations of local structures, including a flux-rope coronal cavity and its embedded filament with delayed onsets consistent with the wave travel time at an elevated (by ~50%) velocity within it. This suggests that the EUV wave penetrates through a topological separatrix surface into the cavity, unexpected from CME caused magnetic reconfiguration. These observations, when taken together, provide compelling evidence of the fast-mode MHD wave nature of the {\it primary (outer) fast component} of a global EUV wave, running ahead of the {\it secondary (inner) slow} component of CME-caused restructuring.

2010 September 8–9

FIRST *SDO* AIA OBSERVATIONS OF A GLOBAL CORONAL EUV "WAVE": MULTIPLE COMPONENTS AND "RIPPLES"

Wei **Liu**[1,2], Nariaki V. Nitta[1], Carolus J. Schrijver[1], Alan M. Title[1], and Theodore D. Tarbell[1]

Astrophysical Journal Letters, 723:L53–L59, **2010, File**

We present the first *Solar Dynamics Observatory* Atmospheric Imaging Assembly (AIA) observations of a global coronal EUV disturbance (so-called "EIT wave") revealed in unprecedented detail. The disturbance observed on **2010 April 8** exhibits two components: one *diffuse pulse* superimposed, on which are multiple *sharp fronts* that have slow and fast components. The disturbance originates in front of erupting coronal loops and some sharp fronts undergo accelerations, both effects implying that the disturbance is driven by a coronal mass ejection. The diffuse pulse, propagating at a uniform velocity of 204–238 km s^{-1} with very little angular dependence within its extent in the south, maintains its coherence and stable profile for **~**30 minutes. Its arrival at increasing distances coincides with the onsets of loop expansions and the slow sharp front. The fast sharp front overtakes the slow front, producing multiple "ripples" and steepening the local pulse, and both fronts propagate independently afterward. This behavior resembles the nature of real waves. Unexpectedly, the amplitude and FWHM of the diffuse pulse decrease linearly

with distance. A hybrid model, combining both wave and non-wave components, can explain many, but not all, of the observations. Discoveries of the two-component fronts and multiple ripples were made possible for the first time thanks to AIA's high cadences (_20 s) and high signal-to-noise ratio.
Animations are available in the online journal.

Halo Coronal Mass Ejections and Configuration of the Ambient Magnetic Fields -- Y. **Liu**, ApJL, 2006, E-print, Dec. **2006, File**

The 2003 October-November Fast Halo Coronal Mass Ejections and the Large-Scale Magnetic Field Structures
Liu, Y.; Hayashi, K. The Astrophysical Journal, 640:1135–1141, **2006, File**

Localised acceleration of energetic particles by a weak shock in the solar corona
David M. **Long**, Hamish A. S. Reid, Gherardo Valori, Jennifer O'Kane
ApJ **921** 61 **2021**
https://arxiv.org/pdf/2108.05068.pdf
https://doi.org/10.3847/1538-4357/ac1cdf
Globally-propagating shocks in the solar corona have long been studied to quantify their involvement in the acceleration of energetic particles. However, this work has tended to focus on large events associated with strong solar flares and fast coronal mass ejections (CMEs), where the waves are sufficiently fast to easily accelerate particles to high energies. Here we present observations of particle acceleration associated with a global wave event which occurred on **1 October 2011**. Using differential emission measure analysis, the global shock wave was found to be incredibly weak, with an Alfvén Mach number of ~1.008-1.013. Despite this, spatially-resolved type III radio emission was observed by the Nançay RadioHeliograph at distinct locations near the shock front, suggesting localised acceleration of energetic electrons. Further investigation using a magnetic field extrapolation identified a fan structure beneath a magnetic null located above the source active region, with the erupting CME contained within this topological feature. We propose that a reconfiguration of the coronal magnetic field driven by the erupting CME enabled the weak shock to accelerate particles along field lines initially contained within the fan and subsequently opened into the heliosphere, producing the observed type III emission. These results suggest that even weak global shocks in the solar corona can accelerate energetic particles via reconfiguration of the surrounding magnetic field.

Quantifying the relationship between Moreton-Ramsey waves and "EIT waves" using observations of 4 homologous wave events
David M. **Long**, Jack Jenkins, Gherardo Valori
ApJ **882** 90 **2019**
https://arxiv.org/pdf/1907.07963.pdf
https://doi.org/10.3847/1538-4357/ab338d
Freely-propagating global waves in the solar atmosphere are commonly observed using Extreme UltraViolet passbands (EUV or "EIT waves"), and less regularly in H-alpha (Moreton-Ramsey waves). Despite decades of research, joint observations of EUV and Moreton-Ramsey waves remain rare, complicating efforts to quantify the connection between these phenomena. We present observations of four homologous global waves originating from the same active region between **28-30 March 2014** and observed using both EUV and H-alpha data. Each global EUV wave was observed by the Solar Dynamics Observatory, with the associated Moreton-Ramsey waves identified using the Global Oscillations Network Group (GONG) network. All of the global waves exhibit high initial velocity (e.g., 842-1388 km s^{-1} in the 193A passband) and strong deceleration (e.g., -1437 - -782 m s^{-2} in the 193A passband) in each of the EUV passbands studied, with the EUV wave kinematics exceeding those of the Moreton-Ramsey wave. The density compression ratio of each global wave was estimated using both differential emission measure and intensity variation techniques, with both indicating that the observed waves were weakly shocked with a fast magnetosonic Mach number slightly greater than one. This suggests that, according to current models, the global coronal waves were not strong enough to produce Moreton-Ramsey waves, indicating an alternative explanation for these observations. Instead, we conclude that the evolution of the global waves was restricted by the surrounding coronal magnetic field, in each case producing a downward-angled wavefront propagating towards the north solar pole which perturbed the chromosphere and was observed as a Moreton-Ramsey wave.

A Statistical Analysis of the Solar Phenomena Associated with Global EUV Waves (Review)

David M. **Long**, Pearse Murphy, Georgina Graham, Eoin P. Carley, David Pérez-Suárez
Solar Phys. 292:185 **2017**
https://arxiv.org/pdf/1711.02530.pdf
Solar eruptions are the most spectacular events in our solar system and are associated with many different signatures of energy release including solar flares, coronal mass ejections, global waves, radio emission and accelerated particles. Here, we apply the Coronal Pulse Identification and Tracking Algorithm (CorPITA) to the high cadence synoptic data provided by the Solar Dynamic Observatory (SDO) to identify and track global waves observed by SDO. 164 of the 362 solar flare events studied (45%) are found to have associated global waves with no waves found for the remaining 198 (55%). A clear linear relationship was found between the median initial velocity and the acceleration of the waves, with faster waves exhibiting a stronger deceleration (consistent with previous results). No clear relationship was found between global waves and type II radio bursts, electrons or protons detected in-situ near Earth. While no relationship was found between the wave properties and the associated flare size (with waves produced by flares from B to X-class), more than a quarter of the active regions studied were found to produce more than one wave event. These results suggest that the presence of a global wave in a solar eruption is most likely determined by the structure and connectivity of the erupting active region and the surrounding quiet solar corona rather than by the amount of free energy available within the active region. **2010 August 14, 2011 January 27, 2011 June 7**
Table CorPITA analysis. **2010-2016**
CESRA Highlight #1763 Jan 2018 http://cesra.net/?p=1763

Measuring the magnetic field of a trans-equatorial loop system using coronal seismology
David M. **Long**, Gherardo Valori, David Pérez-Suárez, Richard J. Morton, Alberto Marcos Vásquez
A&A 603, A101 **2017**
https://arxiv.org/pdf/1703.10020.pdf **File**
"EIT waves" are freely-propagating global pulses in the low corona which are strongly associated with the initial evolution of coronal mass ejections (CMEs). They are thought to be large-amplitude, fast-mode magnetohydrodynamic waves initially driven by the rapid expansion of a CME in the low corona. An "EIT wave" was observed on **6 July 2012** to impact an adjacent trans-equatorial loop system which then exhibited a decaying oscillation as it returned to rest. Observations of the loop oscillations were used to estimate the magnetic field strength of the loop system by studying the decaying oscillation of the loop, measuring the propagation of ubiquitous transverse waves in the loop and extrapolating the magnetic field from observed magnetograms. Observations from the Atmospheric Imaging Assembly onboard the Solar Dynamics Observatory (SDO/AIA) and the Coronal Multi-channel Polarimeter (CoMP) were used to study the event. An Empirical Mode Decomposition analysis was used to characterise the oscillation of the loop system in CoMP Doppler velocity and line width and in AIA intensity. The loop system was shown to oscillate in the 2nd harmonic mode rather than at the fundamental frequency, with the seismological analysis returning an estimated magnetic field strength of ~5.5±1.5 G. This compares to the magnetic field strength estimates of ~1-9 G and ~3-9 G found using the measurements of transverse wave propagation and magnetic field extrapolation respectively. ***Erratum*** A&A 607, C3 (**2017**)

Understanding the Physical Nature of Coronal "EIT Waves" **Review**
David M. **Long**, D. Shaun Bloomfield, Peng-Fei Chen, Cooper Downs, Peter T. Gallagher, Ryun Young Kwon, Kamalam Vanninathan, Astrid M. Veronig, Angelos Vourlidas, Bojan Vrsnak, Alexander Warmuth, Tomislav Zic
Solar Phys. **2017,** 292:7
https://arxiv.org/pdf/1611.05505v1.pdf **File**
https://link.springer.com/content/pdf/10.1007%2Fs11207-016-1030-y.pdf
For almost 20 years the physical nature of globally propagating waves in the solar corona (commonly called "EIT waves") has been controversial and subject to debate. Additional theories have been proposed over the years to explain observations that did not fit with the originally proposed fast-mode wave interpretation. However, the incompatibility of observations made using the Extreme-ultraviolet Imaging Telescope (EIT) onboard the Solar and Heliospheric Observatory with the fast-mode wave interpretation was challenged by differing viewpoints from the twin Solar Terrestrial Relations Observatory spacecraft and higher spatial/temporal resolution data from the Solar Dynamics Observatory. In this article, we reexamine the theories proposed to explain "EIT waves" to identify measurable properties and behaviours that can be compared to current and future observations. Most of us conclude that "EIT waves" are best described as fast-mode large-amplitude waves/shocks that are initially driven by the impulsive expansion of an erupting coronal mass ejection in the low corona.

The energetics of a global shock wave in the low solar corona
David M. **Long**, Deborah Baker, David R. Williams, Eoin P. Carley, Peter T. Gallagher, Pietro Zucca
ApJ **799** 224 **2015**

http://arxiv.org/pdf/1412.2964v1.pdf **File**

As the most energetic eruptions in the solar system, coronal mass ejections (CMEs) can produce shock waves at both their front and flanks as they erupt from the Sun into the heliosphere. However, the amount of energy produced in these eruptions, and the proportion of their energy required to produce the waves, is not well characterised. Here we use observations of a solar eruption from **2014 February 25** to estimate the energy budget of an erupting CME and the globally-propagating "EIT wave" produced by the rapid expansion of the CME flanks in the low solar corona. The "EIT wave" is shown using a combination of radio spectra and extreme ultraviolet images to be a shock front with a Mach number greater than one. Its initial energy is then calculated using the Sedov-Taylor blast-wave approximation, which provides an approximation for a shock front propagating through a region of variable density. This approach provides an initial energy estimate of ≈2.8×1031 ergs to produce the "EIT wave", which is approximately 10% the kinetic energy of the associated CME (shown to be ≈2.5×1032 ergs). These results indicate that the energy of the "EIT wave" may be significant and must be considered when estimating the total energy budget of solar eruptions.

See EIS Nugget - Esitmating the energy of a global 'EIT wave'

http://solarb.mssl.ucl.ac.uk/SolarB/nuggets/nugget_2015jan.jsp

CorPITA: An Automated Algorithm for the Identification and Analysis of Coronal "EIT Waves"

David M. **Long**, D. Shaun Bloomfield, Peter T. Gallagher, David Pérez-Suárez

Solar Phys., Volume 289, Issue 9, pp 3279-3295, **2014**

http://arxiv.org/pdf/1403.6722v1.pdf

The continuous stream of data available from the Atmospheric Imaging Assembly (AIA) telescopes onboard the Solar Dynamics Observatory (SDO) spacecraft has allowed a deeper understanding of the Sun. However, the sheer volume of data has necessitated the development of automated techniques to identify and analyse various phenomena. In this article, we describe the Coronal Pulse Identification and Tracking Algorithm (CorPITA) for the identification and analysis of coronal "EIT waves". CorPITA uses an intensity-profile technique to identify the propagating pulse, tracking it throughout its evolution before returning estimates of its kinematics. The algorithm is applied here to a data-set from February 2011, allowing its capabilities to be examined and critiqued. This algorithm forms part of the SDO Feature Finding Team initiative and will be implemented as part of the Heliophysics Event Knowledgebase (HEK). This is the first fully automated algorithm to identify and track the propagating "EIT wave" rather than any associated phenomena and will allow a deeper understanding of this controversial phenomenon.

Measuring the Magnetic Field Strength of the Quiet Solar Corona Using “EIT Waves”

D.M. **Long**, D.R. Williams, S.Regnier, L.K. Harra

E-print, May **2013**; Solar Phys (**2013**) 288:567–583

Variations in the propagation of globally-propagating disturbances (commonly called "EIT waves") through the low solar corona offer a unique opportunity to probe the plasma parameters of the solar atmosphere. Here, high-cadence observations of two "EIT wave" events taken using the Atmospheric Imaging Assembly (AIA) instrument onboard the Solar Dynamics Observatory (SDO) are combined with spectroscopic measurements from the Extreme ultraviolet Imaging Spectrometer (EIS) onboard the Hinode spacecraft and used to examine the variability of the quiet coronal magnetic-field strength. The combination of pulse kinematics from SDO/AIA and plasma density from Hinode/EIS is used to show that the magnetic-field strength is in the range ~2-6 G in the quiet corona. The magnetic-field estimates are then used to determine the height of the pulse, allowing a direct comparison with theoretical values obtained from magnetic-field measurements from the Helioseismic and Magnetic Imager (HMI) onboard SDO using PFSS and local-domain extrapolations. While local-scale extrapolations predict heights inconsistent with prior measurements, the agreement between observations and the PFSS model indicates that "EIT waves" are a global phenomenon influenced by global-scale magnetic field.

Using EIS to measure the coronal magnetic field

David **Long**, David Williams, Stéphane Régnier, Louise Harra

EIS Nugget, May **2013**

http://solarb.mssl.ucl.ac.uk/SolarB/nuggets/nugget_2013may.jsp

Although the Sun's magnetic field is responsible for much of the activity that makes the Sun such an interesting star, it continues to be difficult to accurately estimate its strength in the low corona. This can be done using Zeeman splitting (cf. Lin et al., 2004) or the Hanle effect (cf. Raouafi et al., 2002), but this is generally only possible near active regions where the magnetic field strength is high. In quieter regions, the lower magnetic field strength can be inferred by examining variations in how global coronal waves (commonly called "EIT Waves") propagate through the corona, a technique called coronal seismology (e.g., Uchida, 1970, Roberts et al., 1984, West et al., 2011).

"EIT Waves" are large-scale global perturbations travelling at velocities of up to 1000 km/s that can traverse the Sun in less than an hour. Originally discovered using SOHO/EIT (Thompson et al., 1998), they have been variously interpreted as fast-mode magnetohydrodynamic waves or the signature of magnetic reconnection as a CME erupts into the heliosphere. Recent results by Warmuth & Mann, (2011) have suggested that the pulse velocity may indicate its physical nature, with faster pulses consistent with a MHD wave interpretation while pulses exhibiting irregular kinematics are more consistent with the "pseudo-wave" interpretation.

In Long et al. (2013) we estimate the magnetic field strength of the quiet solar corona by combining high cadence images from SDO/AIA with high-resolution spectra from Hinode/EIS. These results are then compared to magnetic field extrapolations to determine the height-range of the feature. **12-June-2010, 16-February-2011**

The Wave Properties of Coronal Bright Fronts Observed Using SDO/AIA

Long, David M., DeLuca, Edward E., Gallagher, Peter T.

E-print, Sept 2011, ApJL, 741 L21, **2011**, **File**

Coronal bright fronts (CBFs) are large scale wavefronts that propagate though the solar corona at hundreds of kilometers per second. While their kinematics have been studied in detail, many questions remain regarding the temporal evolution of their amplitude and pulse width. Here, contemporaneous high cadence, multi-thermal observations of the solar corona from the Solar Dynamic Observatory (SDO) and Solar TErrestrial RElations Observatory (STEREO) spacecraft are used to determine the kinematics and expansion rate of a CBF wavefront observed on **2010 August 14**. The CBF was found to have a lower initial velocity with weaker deceleration in STEREO observations compared to SDO (~340 km s−1 and −72 m s−2 as opposed to ~410 km s−1 and −279 m s−2). The CBF kinematics from SDO were found to be highly passband-dependent, with an initial velocity ranging from 379±12 km s−1 to 460±28 km s−1 and acceleration ranging from −128±28 m s−2 to −431±86 m s−2 in the 335 °A and 304 °A passbands respectively. These kinematics were used to estimate a quiet coronal magnetic field strength range of ~1–2 G. Significant pulse broadening was also observed, with expansion rates of ~130 km s−1 (STEREO) and ~220 km s−1 (SDO). By treating the CBF as a linear superposition of sinusoidal waves within a Gaussian envelope, the resulting dispersion rate of the pulse was found to be ~8–13 Mm2 s−1. These results are indicative of a fast-mode magnetoacoustic wave pulse propagating through an inhomogeneous medium.

Deceleration and dispersion of large-scale coronal bright fronts

Long, D. M., Gallagher, P. T., McAteer, R. T. J., & Bloomfield, D. S.

E-print, April, 2011;Astronomy & Astrophysics, Volume 531, id.A42, **2011**

Context. One of the most dramatic manifestations of solar activity are large-scale coronal bright fronts (CBFs) observed in extreme ultraviolet (EUV) images of the solar atmosphere. To date, the energetics and kinematics of CBFs remain poorly understood, due to the low image cadence and sensitivity of previous EUV imagers and the limited methods used to extract the features.

Aims: In this paper, the trajectory and morphology of CBFs was determined in order to investigate the varying properties of a sample of CBFs, including their kinematics and pulse shape, dispersion, and dissipation.

Methods: We have developed a semi-automatic intensity profiling technique to extract the morphology and accurate positions of CBFs in 2.5-10 min cadence images from STEREO/EUVI. The technique was applied to sequences of 171 Å and 195 Å images from STEREO/EUVI in order to measure the wave properties of four separate CBF events.

Results: Following launch at velocities of ~240-450 km s-1 each of the four events studied showed significant negative acceleration ranging from ~-290 to -60 m s-2. The CBF spatial and temporal widths were found to increase from ~50 Mm to ~200 Mm and ~100 s to ~1500 s respectively, suggesting that they are dispersive in nature. The variation in position-angle averaged pulse-integrated intensity with propagation shows no clear trend across the four events studied. These results are most consistent with CBFs being dispersive magnetoacoustic waves.

Figures 3-8, 10, 11, 13-15, 17, 18 and the movie are available in electronic form at http://www.aanda.org

The kinematics of a globally propagating disturbance in the low corona

David M. **Long**, Peter T. Gallagher, R. T. James McAteer and D. Shaun Bloomfield

E-print, April **2008, File;** ApJ 680: L81–L84, **2008**

http://www.journals.uchicago.edu/doi/pdf/10.1086/589742

http://www.maths.tcd.ie/~dlong/Papers/letters/ApJ_2008.pdf

http://arxiv.org/pdf/0805.2023v1.pdf

The kinematics of a globally propagating disturbance (also known as an 'EIT wave') is discussed using Extreme UltraViolet Imager (EUVI) data from Solar Terrestrial Relations Observatory (STEREO). We show for the first time that an impulsively generated propagating disturbance has similar kinematics in all four EUVI passbands (304,

171, 195, and 284 A). In the 304 A passband the disturbance shows a velocity peak of 238+/-20 km s−1 within □28 minutes of its launch, varying in acceleration from 76 m s−2 to -102 m s−2. This passband contains a strong contribution from a Si XI line (303.32 A) with a peak formation temperature of □1.6 MK. therefore be coronal rather than chromospheric in origin. Comparable velocities and accelerations are found in the coronal 195 A passband, while lower values are found in the lower cadence 284 A passband. In the higher cadence 171 A passband the velocity varies significantly, peaking at 475+/-47 km s −1 within ~ variation in acceleration from 816 m s−2 to -413 m s−2. The high image cadence of the 171 A passband (2.5 minutes compared to 10 minutes for the similar temperature response 195 A passband) is found to have a major effect on the measured velocity and acceleration of the pulse, which increase by factors of □2 and □10, respectively. This implies that previously measured values (e.g., using EIT) may have been underestimated. We also note that the disturbance shows strong reflection from a coronal hole in both the 171 and 195 A passbands. The observations are consistent with an impulsively generated fast-mode magnetoacoustic wave.
19 May 2007 ~12:30 UT, B9 flare; outstanding EIT wave (tsunami); STEREO data; no EIT data

Imaging evidence for solar wind outflows originating from a CME footpoint

Juraj **Lörinčík**, Jaroslav Dudík, Guillaume Aulanier, Brigitte Schmieder, Leon Golub

2021 *ApJ* **906** 62

https://arxiv.org/pdf/2010.04250.pdf

https://doi.org/10.3847/1538-4357/abc8f6

We report on the Atmospheric Imaging Assembly (AIA) observations of plasma outflows originating in a coronal dimming during the **2015 April 28th** filament eruption. After the filament started to erupt, two flare ribbons formed, one of which had a well-visible hook enclosing a core (twin) dimming region. Along multiple funnels located in this dimming, a motion of plasma directed outwards started to be visible in the 171\,Å~and 193\,Å~filter channels of the instrument. In time-distance diagrams, this motion generated a strip-like pattern, which lasted for more than five hours and which characteristics did not change along the funnel. We therefore suggest the motion to be a signature of outflows corresponding to velocities ranging between ≈70 and 140 km\,s−1. Interestingly, the pattern of the outflows as well as their velocities were found to be similar to those we observed in a neighboring ordinary coronal hole. Therefore, the outflows were most likely a signature of a CME-induced slow solar wind flowing along the open-field structures rooted in the dimming region. Further, the evolution of the hook encircling the dimming region was examined in the context of the latest predictions imposed for the three-dimensional magnetic reconnection. The observations indicate that the filament's footpoints were, during their transformation to the dimming region, reconnecting with surrounding canopies. To our knowledge, our observations present the first imaging evidence for outflows of plasma from a dimming region.

Estimating the mass of CMEs from the analysis of EUV dimmings

F. M. **López**1,2, H. Cremades3, L. A. Balmaceda4, F. A. Nuevo5 and A. M. Vásquez5,6

A&A 627, A8 (**2019**)

https://doi.org/10.1051/0004-6361/201834163

Context. Reliable estimates of the mass of coronal mass ejections (CMEs) are required to quantify their energy and predict how they affect space weather. When a CME propagates near the observer's line of sight, these tasks involve considerable errors, which motivated us to develop alternative means for estimating the CME mass.
Aims. We aim at further developing and testing a method that allows estimating the mass of CMEs that propagate approximately along the observer's line of sight.
Methods. We analyzed the temporal evolution of the mass of 32 white-light CMEs propagating across heliocentric heights of 2.5–15 R⊙, in combination with that of the mass evacuated from the associated low coronal dimming regions. The mass of the white-light CMEs was determined through existing methods, while the mass evacuated by each CME in the low corona was estimated using a recently developed technique that analyzes the dimming in extreme-UV (EUV) images. The combined white-light and EUV analyses allow the quantification of an empirical function that describes the evolution of CME mass with height.

Mass Loss Evolution in the EUV Low Corona from SDO/AIA Data

Fernando M. **López**, Hebe Cremades, Federico A. Nuevo, Laura A. Balmaceda, Alberto A. Vásquez

Solar Phys. January **2017**, 292:6

https://arxiv.org/pdf/1611.00849v1.pdf

We carry out an analysis of the evacuated mass from three coronal dimming regions observed by the {\it Atmospheric Imaging Assembly} (AIA) on board the {\it Solar Dynamics Observatory}. The three events are unambiguously identified with white-light coronal mass ejections (CMEs) associated in turn with surface activity of diverse nature: an impulsive (M-class) flare, a weak (B-class) flare and a filament eruption without a flare. The use of three AIA coronal passbands allows applying a differential emission measure technique to define the dimming regions and identify their evacuated mass through the analysis of the electronic density depletion associated to the eruptions. The temporal evolution of the mass loss from the three dimmings can be approximated by an exponential equation followed by a linear fit. We determine the mass of the associated CMEs from COR2 data. The results show that the evacuated masses from the low corona represent a considerable amount of the mass of the CMEs. We also find that plasma is still being evacuated from the low corona at the time when the CMEs reach the COR2 field of view. The temporal evolution of the angular width of the CMEs, of the dimming regions in the low corona, and of the flux registered by GOES in soft X-rays are all in close relation with the behavior of mass evacuation from the low corona. We discuss the implications of our findings toward a better understanding of the temporal evolution of several parameters associated to the analyzed dimmings and CMEs. **23 May 2010, 7 August 2010, 30 November 2010**

Constraining the Physical Properties of Stellar Coronal Mass Ejections with Coronal Dimming: Application to Far-ultraviolet Data of Eridani

R. O. Parke **Loyd**1,2, James Paul Mason3, Meng Jin4,5, Evgenya L. Shkolnik2, Kevin France6, Allison Youngblood7, Jackie Villadsen8, Christian Schneider9, Adam C. Schneider10,11, Joe Llama12Show full author list

2022 ApJ 936 170

https://iopscience.iop.org/article/10.3847/1538-4357/ac80c1/pdf

Coronal mass ejections (CMEs) are a prominent contributor to solar system space weather and might have impacted the Sun's early angular momentum evolution. A signal diagnostic of CMEs on the Sun is coronal dimming: a drop in coronal emission, tied to the mass of the CME, that is the direct result of removing emitting plasma from the corona. We present the results of a coronal dimming analysis of Fe xii 1349 Å and Fe xxi 1354 Å emission from ϵ Eridani (ϵ Eri), a young K2 dwarf, with archival far-ultraviolet observations by the Hubble Space Telescope's Cosmic Origins Spectrograph. Following a flare in 2015 February, ϵ Eri's Fe xxi emission declined by 81 ± 5%. Although enticing, a scant 3.8 minutes of preflare observations allows for the possibility that the Fe xxi decline was the decay of an earlier, unseen flare. Dimming nondetections following each of three prominent flares constrain the possible mass of ejected Fe xii-emitting (1 MK) plasma to less than a few × 1015 g. This implies that CMEs ejecting this much or more 1 MK plasma occur less than a few times per day on ϵ Eri. On the Sun, 1015 g CMEs occur once every few days. For ϵ Eri, the mass-loss rate due to CME-ejected 1 MK plasma could be < 0.6 $\dot{M}_\odot$, well below the star's estimated 30 $\dot{M}_\odot$ mass-loss rate (wind + CMEs). The order-of-magnitude formalism we developed for these mass estimates can be broadly applied to coronal dimming observations of any star.

Spatially Resolved Moving Radio Burst in Association with an EUV Wave

Lei **Lu**, Li Feng, Weiqun Gan

ApJL **2022**

https://arxiv.org/pdf/2205.03047.pdf

Coronal mass ejections (CMEs) are large clouds of magnetized plasma ejected from the Sun, and are often associated with acceleration of electrons that can result in radio emission via various mechanisms. However, the underlying mechanism relating the CMEs and particle acceleration still remains a subject of heated debate. Here, we report multi-instrument radio and extreme ultraviolet (EUV) imaging of a solar eruption event on **24 September 2011**. We determine the emission mechanism of a moving radio burst, identify its three-dimensional (3D) location with respect to a rapidly expanding EUV wave, and find evidence for CME shocks that produce quasiperiodic acceleration of electron beams.

Formation of Coronal Shock Waves

S. **Lulić**, B. Vršnak, T. Žic, I. W. Kienreich, N. Muhr, M. Temmer, A. M. Veronig

Solar Physics, September **2013**, Volume 286, Issue 2, pp 509-528

Magnetosonic wave formation driven by an expanding cylindrical piston is numerically simulated to obtain better physical insight into the initiation and evolution **of large-scale coronal waves** caused by coronal eruptions. Several very basic initial configurations are employed to analyze intrinsic characteristics of MHD wave formation that do not depend on specific properties of the environment. It turns out that these simple initial configurations result in piston/wave morphologies and kinematics that reproduce common characteristics of coronal waves. In the initial stage, the wave and the expanding source region cannot be clearly resolved; i.e. a certain time is needed before the wave detaches from the piston. Thereafter, it continues to travel as what is called a "simple wave." During the acceleration stage of the source region inflation, the wave is driven by the piston expansion, so its amplitude and phase-speed increase, whereas the wavefront profile steepens. At a given point, a discontinuity forms in the wavefront profile; i.e. the leading edge of the wave becomes shocked. The time/distance required for the shock formation is shorter for a more impulsive source-region expansion. After the piston stops, the wave amplitude and phase speed start to decrease. During the expansion, most of the source region becomes strongly rarefied, which reproduces the coronal dimming left behind the eruption. However, the density increases at the source-region boundary, and stays enhanced even after the expansion stops, which might explain stationary brightenings that are sometimes observed at the edges of the erupted coronal structure. Also, in the rear of the wave a weak density depletion develops, trailing the wave, which is sometimes observed as weak transient coronal dimming. Finally, we find a well-defined relationship between the impulsiveness of the source-region expansion and the wave amplitude and phase speed. The results for the cylindrical piston are also compared with the outcome for a planar wave that is formed by a one-dimensional piston, to find out how different geometries affect the evolution of the wave.

Imaging Preflare Broadband Pulsations in the Decimetric-metric Wavelengths

Maoshui **Lv**, Baolin Tan, Ruisheng Zheng, Zhao Wu, Bing Wang, Xiangliang Kong, Yao Chen
ApJ **2023**
https://arxiv.org/pdf/2304.11785.pdf

Preflare activities contain critical information about the pre-cursors and causes of solar eruptions. Here we investigate the characteristics and origin of a group of broadband pulsations (BBPs) in the decimetric-metric wavelengths, taking place during the preflare stage of the M7.1 flare dated on **2011 September 24**. The event was recorded by multiple solar instruments including the Nançay Radioheliograh that measure the properties of the radio source. The BBPs start ∼24 min before the flare onset, extending from < 360 to above 800 MHz with no discernible spectral drift. The BBPs consist of two stages, during the first stage the main source remains stationary, during the second stage it moves outward along with a steepening extreme-ultraviolet (EUV) wave driven by the eruption of a high-temperature structure. In both stages, we observe frequent EUV brightenings and jets originating from the flare region. During the second stage, the BBPs become denser in number and stronger in general, with the level of the polarization increasing gradually from < 20% to > 60% in the right-handed sense. These observations indicate the steepening EUV wave is important to the BBPs during the second stage, while the preflare reconnections causing the jets and EUV brightenings are important in both stages. This is the first time such a strong association of an EUV wave with BBPs is reported. We suggest a reconnection plus shock-sweeping-across-loop scenario for the cause of the BBPs.

Sources of the Multi-Lane Type II Solar Radio Burst on 5 November 2014

M. S. **Lv**, Y. Chen, C. Y. Li, I. Zimovets, G. H. Du, B. Wang, S. W. Feng, S. L. Ma
Solar Physics December **2017**, 292:194
https://link.springer.com/content/pdf/10.1007%2Fs11207-017-1218-9.pdf

We report the well-observed event of a multi-lane type II solar radio burst with a combined analysis of radio dynamic spectra and radio and extreme-ultraviolet (EUV) imaging data. The burst is associated with an EUV wave driven by a coronal mass ejection (CME) that is accompanied by a GOES X-ray M7.9 flare on 5 November 2014. This type of event is rarely observed with such a complete data set. The type II burst presents three episodes (referred to as A, B, and C), characterized by a sudden change in spectral drift, and contains more than ten branches, including both harmonic-fundamental (H–F) pairs and split bands. The sources of the three episodes present a general outward propagating trend. There exists a significant morphology change from single source (Episode A) to double source (Episode B). Episode C maintains the double-source morphology at 150 MHz (no imaging data are available at a lower frequency). The double-source centroids are separated by ∼300″ to 500″. The southeastern (SE) source is likely the continuation of the source of Episode A since both are at the same section of the shock (i.e. the EUV wave) and close to each other. The northwestern (NW) source is coincident with (thus, possibly originates from) the interaction of the shock with a nearby mini-streamer-like structure. Comparing the simultaneously observed sources of the F and H branches of Episode A, we find that their centroids are separated by less than 200″. The centroids of the split bands of Episode B are cospatial within the observational uncertainties. This study shows the source evolution of a multi-lane type II burst and the source locations of different lanes relative to each other and to the EUV wave generated by a CME. The study indicates the intrinsic complexity underlying a type II dynamic spectrum.

OBSERVATIONS AND INTERPRETATION OF A LOW CORONAL SHOCK WAVE OBSERVED IN THE EUV BY THE SDO/AIA

Suli **Ma**1,2, John C. Raymond1, Leon Golub1, Jun Lin3, Huadong Chen2, Paolo Grigis1, Paola Testa1 and David Long
2011 ApJ 738 160, **File?**

Taking advantage of both the high temporal and spatial resolutions of the Atmospheric Imaging Assembly on board the Solar Dynamics Observatory, we studied a limb coronal shock wave and its associated extreme ultraviolet (EUV) wave that occurred on **2010 June 13**. Our main findings are: (1) the shock wave appeared clearly only in the channels centered at 193 Å and 211 Å as a dome-like enhancement propagating ahead of its associated semi-spherical coronal mass ejection (CME) bubble; (2) the density compression of the shock is 1.56 according to radio data and the temperature of the shock is around 2.8 MK; (3) the shock wave first appeared at 05:38 UT, 2 minutes after the associated flare has started and 1 minute after its associated CME bubble appeared; (4) the top of the dome-like shock wave set out from about 1.23 R and the thickness of the shocked layer is ~2 × 104 km; (5) the speed of the shock wave is consistent with a slight decrease from about 600 km s–1 to 550 km s–1; and (6) the lateral expansion of the shock wave suggests a constant speed around 400 km s–1, which varies at different heights and directions. Our findings support the view that the coronal shock wave is driven by the CME bubble, and the on-limb EUV wave is consistent with a fast wave or at least includes the fast wave component.

A NEW VIEW OF CORONAL WAVES FROM *STEREO*

S. **Ma**, M. J. Wills-Davey2, J. Lin1,2, P. F. Chen4, G. D. R. Attrill2, H. Chen5, S. Zhao1, Q. Li1, and L. Golub2

Astrophysical Journal, 707:503–509, **2009** December; **File**

On **2007 December 7**, there was an eruption from AR 10977, which also hosted a sigmoid. An EUV Imaging Telescope (EIT) wave associated with this eruption was observed by EUVI on board the *Solar Terrestrial Relations Observatory* (*STEREO*). Using EUVI images in the 171 Å and the 195 Å passbands from both *STEREO A* and *B*, we study the morphology and kinematics of this EIT wave. In the early stages, images of the EIT wave from the two *STEREO* spacecrafts differ markedly. We determine that the EUV fronts observed at the very beginning of the eruption likely include some intensity contribution from the associated coronal mass ejection (CME). Additionally, our velocity measurements suggest that the EIT wave front may propagate at nearly constant velocity. Both results offer constraints on current models and understanding of EIT waves.

A coronal wave and an asymmetric eruptive filament in SUMER, CDS, EIT, and TRACE co-observations

M.S. **Madjarska**, J.G. Doyle, J. Shetye

A&A, 575, A39 **2015**

http://arxiv.org/pdf/1412.1984v1.pdf

The objectives of the present study is to provide a better physical understanding of the complex inter-relation and evolution of several solar coronal features comprising a double-peak flare, a coronal dimming caused by a CME, a CME-driven compression, and a fast-mode wave. For the first time, the evolution of an asymmetric eruptive filament is analysed in simultaneous SUMER spectroscopic and TRACE and EIT imaging data. We use imaging observations from EIT and TRACE in the 195A channel and spectroscopic observations from the CDS in a rastering and SUMER in a sit-and-stare observing mode. The SUMER spectra cover spectral lines with formation temperatures from logT(K) ~ 4.0 to 6.1. Although the event was already analysed in two previous studies, our analysis brings a wealth of new information on the dynamics and physical properties of the observed phenomena. We found that the dynamic event is related to a complex flare with two distinct impulsive peaks, one according to the GOES classification as C1.1 and the second - C1.9. The first energy release triggers a fast-mode wave and a CME with a clear CME driven compression ahead of it. This activity is related to, or possibly caused, by an asymmetric filament eruption. The filament is observed to rise with its leading edge moving at a speed of ~300 km/s detected both in the SUMER and CDS data. The rest of the filament body moves at only ~150 km/s while untwisting. No signature is found of the fast-mode wave in the SUMER data, suggesting that the plasma disturbed by the wave had temperatures above 600 000 K. The erupting filament material is found to emit only in spectral lines at transition region temperatures. Earlier identification of a coronal response detected in the Mg X 609.79 A line is found to be caused by a blend from the O IV 609.83 A line. **1998 June 13**

A movie associated to Fig. A.1 is available in electronic form at http://www.aanda.org

ORIGIN OF CORONAL SHOCK WAVES ASSOCIATED WITH SLOW CORONAL MASS EJECTIONS

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Astrophysical Journal, 718:266–278, **2010** July; **File**

We present a multiwavelength study of five coronal mass ejection/flare events (CME/flare) and associated coronal shock waves manifested as type II radio bursts. The study is focused on the events in which the flare energy release, and not the associated CME, is themost probable source of the shock wave. Therefore, we selected events associated with rather slow CMEs (reported mean velocity below 500 km s-1). To ensure minimal projection effects, only events related to flares situated close to the solar limb were included in the study. We used radio dynamic spectra, positions of radio sources observed by the Nan¸cay Radioheliograph, *GOES* soft X-ray flux measurements, Large Angle Spectroscopic Coronagraph, and Extreme-ultraviolet Imaging Telescope observations. The kinematics of the shock wave signatures, type II radio bursts, were analyzed and compared with the flare evolution and the CME kinematics.We found that the velocities of the shock waves were significantly higher, up to one order of magnitude, than the contemporaneous CME velocities. On the other hand, shock waves were closely temporally associated with the flare energy release thatwas very impulsive in all events. This suggests that the impulsive increase of the pressure in the flare was the source of the shock wave. In four events the shock wave was most probably flare-generated, and in one event results were inconclusive due to a very close temporal synchronization of the CME, flare, and shock.

A Flare-Generated Shock during a Coronal Mass Ejection on 24 December 1996

J. **Magdaleni´c** · B. Vršnak · S. Pohjolainen · M. Temmer · H. Aurass · N.J. Lehtinen

Solar Phys, 253: 305–317, **2008**, DOI 10.1007/s11207-008-9220-x; **File**

We present a multiwavelength study of the large-scale coronal disturbances associated with the CME– flare event recorded on 24 December 1996. The kinematics of the shock wave signature, the type II radio burst, is analyzed and compared with the flare evolution and the CME kinematics. We employ radio dynamic spectra, position of the Nançay Radioheliograph sources, and LASCO-C1 observations, providing detailed study of this limb event. The obtained velocity of the shock wave is significantly higher than the contemporaneous CME velocity (1000 and 235 km s^{-1}, respectively). Moreover, since the main acceleration phase of the CME took place 10 – 20min after the shock wave was launched, we conclude that the shock wave on 24 December 1996 was probably not driven by the CME. However, the shock wave was closely associated with the flare impulsive phase, indicating that it was ignited by the energy release in the flare.

Radio evidence for a shock wave reflected by a coronal hole

S. **Mancuso**, A. Bemporad, F. Frassati, D. Barghini, S. Giordano, D. Telloni, C. Taricco

A&A 651, L14 **2021**

https://arxiv.org/pdf/2107.05931.pdf

https://www.aanda.org/articles/aa/pdf/2021/07/aa41387-21.pdf

https://doi.org/10.1051/0004-6361/202141387

We report the first unambiguous observational evidence in the radio range of the reflection of a coronal shock wave at the boundary of a coronal hole. The event occurred above an active region located at the northwest limb of the Sun and was characterized by an eruptive prominence and an extreme-ultraviolet (EUV) wave steepening into a shock. The EUV observations acquired by the Atmospheric Imaging Assembly (AIA) instrument on board the Solar Dynamics Observatory(SDO) and the Extreme Ultraviolet Imager (EUVI) instrument on board the Solar TErrestrial RElations Observatory(STEREO-A) were used to track the development of the EUV front in the inner corona. Metric type II radio emission, a distinguishing feature of shock waves propagating in the inner corona, was simultaneously recorded by ground-based radio spectrometers. The radio dynamic spectra displayed an unusual reversal of the type II emission lanes, together with type III-like herringbone emission, indicating shock-accelerated electron beams. Combined analysis of imaging data from the two space-based EUV instruments and the Nancay Radioheliograph (NRH) evidences that the reverse-drifting typeiiemission was produced at the intersection of the shock front, reflected at a coronal hole boundary, with an intervening low-Alfvén-speed region characterized by an open field configuration. We also provide an outstanding data-driven reconstruction of the spatiotemporal evolution in the inner corona of the shock-accelerated electron beams produced by the reflected shock. **2011 August 11**

The link between CME-associated dimmings and interplanetary magnetic clouds

Cristina H. **Mandrini**1, Marrıa S. Nakwacki1, Gemma Attrill2,6, Lidia van Driel-Gesztelyi2,3,4, Sergio Dasso1,5 and Pascal Dremoulin3

Universal Heliophysical Processes,Proceedings IAU Symposium No. 257, 2008, N. Gopalswamy & D.F. Webb, eds., p. 265-270, ***2009, File***

Coronal dimmings often develop in the vicinity of erupting magnetic configurations. It has been suggested that they mark the location of the footpoints of ejected flux ropes and, thus, their magnetic flux can be used as a proxy for the ejected flux. If so, this quantity can be compared to the flux in the associated interplanetary magnetic cloud (MC) to find clues about the origin of the ejected flux rope. In the context of this interpretation, we present several events for which we have done a comparative solar-interplanetary analysis. We combine SOHO/Extreme Ultraviolet Imaging Telescope (EIT) data and Michelson Doppler Imager (MDI) magnetic maps to identify and measure the flux in the dimmed regions. We model the associated MCs and compute their magnetic flux using in situ observations. We find that the magnetic fluxes in the dimmings and MCs are compatible in some events; though this is not the case for large-scale and intense eruptions that occur in regions that are not isolated from others. We conclude that, in these particular cases, a fraction of the dimmed regions can be formed by reconnection between the erupting field and the surrounding magnetic structures, via a stepping process that can also explain other CME associated events.

Are CME-Related Dimmings Always a Simple Signature of Interplanetary Magnetic Cloud Footpoints?

C.H. **Mandrini** · M.S. Nakwacki · G. Attrill · L. van Driel-Gesztelyi · P. Démoulin · S. Dasso · H. Elliott

Solar Phys (**2007**) 244: 25–43. **File**

It has been suggested that dimmings mark the location of the footpoints of ejected flux ropes and, thus, their magnetic flux can be used as a proxy for the flux involved in the ejection.

28 October 2003

We find that the magnetic fluxes of the dimmings and magnetic cloud are incompatible, in contrast to what has been found in previous studies. We conclude that, in certain cases, especially in large-scale events and eruptions that occur in regions that are not isolated from other flux concentrations, the interpretation of dimmings requires a deeper analysis of the global magnetic configuration, since at least a fraction of the dimmed regions is formed by reconnection between the erupting field and the surrounding magnetic structures.

Propagation of a dome-shaped, large-scale extreme-ultraviolet wave in the solar corona

Gottfried **Mann**1 and Astrid M. Veronig2,3

A&A 676, A144 (**2023**)

https://www.aanda.org/articles/aa/pdf/2023/08/aa45688-22.pdf

Context. The first observation of a dome-shaped extreme-ultraviolet (EUV) wave was recorded by the EUVI instrument on board the STEREO-B spacecraft on **January 17, 2010**. This observation has allowed us to study the three-dimensional propagation of a large-scale EUV wave in the solar corona, which is considered to be a manifestation of a large-amplitude magnetohydrodynamic (MHD) wave.
Aims. These unique observations by EUVI offer the opportunity to compare the theory of large-amplitude MHD waves with observations.
Methods. Nonlinear MHD equations were employed for describing large-amplitude fast magnetosonic waves in terms of so-called simple waves.
Results. Measuring the velocity of the EUV wave across the solar surface allows us to determine the quiet Sun's magnetic field to be ≈3.2 G. This magnetic field can be extrapolated to the corona by means of magnetic flux conservation. Then, the height dependence of the Alfvén velocity can be calculated, adopting an isothermal, gravitationally stratified density model with a temperature of 1.4 MK for the quiet corona. The Alfvén velocity has a local maximum of ≈680 km s^{-1} at a height of ≈1030 Mm above the photosphere. The observations show that the EUV wave initially steepens and subsequently decays during its further evolution along the solar surface. This behavior can be aptly explained in terms of simple MHD waves. Initially, the wave front steepens due to nonlinear effects. Since the EUV waves are circularly or spherically propagating waves in the corona, their amplitudes are decreasing during the evolution. Hence, the wave steepening vanishes at the final state of the evolution of the EUV wave, which is consistent with the observations. In reality, the nature of the considered EUV wave is a combination of that of a circular and a spherical wave in the corona.
Conclusions. The propagation of this dome-shaped EUV wave can be well described by the theory of large amplitude (simple) MHD waves.

Kinematical evolution of large-scale EUV waves in the solar corona

G. **Mann**, A. Warmuth and H. Önel

A&A 675, A129 (**2023**)

https://www.aanda.org/articles/aa/pdf/2023/07/aa46378-23.pdf

Context. Large-scale coronal waves, also referred to as extreme-ultraviolet (EUV) waves, are a common phenomenon of solar activity in the Sun's corona. They are observed in EUV light as global waves travelling over one hemisphere of the Sun. Previous studies of EUV waves defined three classes based on their kinematical properties. In particular, class 1 waves show a decrease in velocity during their evolution over the solar surface. These special EUV waves are considered as the manifestation of large-amplitude magnetohydrodynamic (MHD) waves in the corona.
Aims. We use a sample of seven class 1 EUV waves observed by the EUVI instruments onboard the two STEREO spacecraft to derive the relationship between the initial velocity and deceleration. This relationship can be explained in terms of the theory of large-amplitude MHD waves.
Methods. We employ non-linear MHD equations to describe large-amplitude, fast magnetosonic waves in terms of so-called 'simple MHD waves'.
Results. The theory of simple MHD waves provides a relationship between the initial velocity and deceleration of the wave. The observations agree well with the non-linear evolution of a spherical large-amplitude, fast magnetosonic wave.
Conclusions. The kinematical properties of large-scale EUV waves can be well described by the theory of large-amplitude (simple) MHD waves**. 05/19/2007, 12/31/2007, 12/22/2009, 12/06/2010, 08/07/2010, 08/14/2010, 08/09/2010**

Table 1. Parameters of the class 1 EUV waves studied in this paper.

Recent Research: Large-scale Disturbances, their Origin and Consequences

G. **Mann** and B. Vrˇsnak:,

Lect. Notes Phys. **725**, 203–218 (**2007**), **File**

DOI 10.1007/978-3-540-71570-2 10

This article gives a flavour of recent research dedicated to the large-scale coronal disturbances and the related interplanetary phenomena. The discussions include the take-off and propagation of coronal mass ejections (CMEs); the CME-flare relationship;

the origin and propagation of shocks; the role of flares, CMEs, and shocks in particle acceleration; radio signatures of CMEs and shocks; coronal and IP plasma diagnostics offered by the radio emission excited by these phenomena.

Coronal Transient Waves and Coronal Shock Waves

Mann, G.; Klassen, A.; Estel, C.; Thompson, B. J.
Proc. of 8th SOHO Workshop, ESA Special Publications 446, Edited by J.-C. Vial and B. Kaldeich-Schmann., p.477, **1999, File**

Coronal transient (or EIT) waves have been discovered by the EIT instrument aboard the SOHO spacecraft as a global wave phenomenon in the low corona. Most of them are associated with solar type II radio bursts appearing predominantly in the radio frequency range 40-100 MHz. Such type II radio bursts are signatures of shock waves travelling outwards in the upper corona. The mean EIT wave velocity of 290 km/s is well above the sound speed in the corona. Therefore, these waves are considered as fast magnetosonic waves propagating nearly perpendicular to the ambient magnetic field in the low corona. On the other hand, the type II burst related shock waves have mean velocities of 970 km/s, which must be well above the local Alfven speed. Considering both phenomena, i.e., coronal transient waves and type II burst related shock waves, to be caused by the same initial energy release (flare), these waves can be used as diagnostic tools for the magnetic field in the solar corona. Thus, a magnetic field strength of about 5 G is deduced from the EIT wave speeds at 0.08 solar radii above the photosphere. Such values are well expected above nonactive regions in the low corona. In the upper corona, i.e., at 0.5 solar radii above the photosphere, typical magnetic field strengths of about 2.5 G are deduced from the measurements. This value corresponds to a typical Alfven speed of 600-1000 km/s, which is well below the type II related shock speeds as expected.

FORWARD MODELING OF EMISSION IN SOLAR DYNAMICS OBSERVATORY/ATMOSPHERIC IMAGING ASSEMBLY PASSBANDS FROM DYNAMIC THREE-DIMENSIONAL SIMULATIONS

Juan **Martínez-Sykora**1,2, Bart De Pontieu1, Paola Testa3 and Viggo Hansteen
2011 ApJ 743 23

It is typically assumed that emission in the passbands of the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO) is dominated by single or several strong lines from ions that under equilibrium conditions are formed in a narrow range of temperatures. However, most SDO/AIA channels also contain contributions from lines of ions that have formation temperatures that are significantly different from the "dominant" ion(s). We investigate the importance of these lines by forward modeling the emission in the SDO/AIA channels with three-dimensional radiative MHD simulations of a model that spans the upper layer of the convection zone to the low corona. The model is highly dynamic. In addition, we pump a steadily increasing magnetic flux into the corona, in order to increase the coronal temperature through the dissipation of magnetic stresses. As a consequence, the model covers different ranges of coronal temperatures as time progresses. The model covers coronal temperatures that are representative of plasma conditions in coronal holes and quiet Sun. The 131, 171, and 304 Å AIA passbands are found to be the least influenced by the so-called non-dominant ions, and the emission observed in these channels comes mostly from plasma at temperatures near the formation temperature of the dominant ion(s). On the other hand, the other channels are strongly influenced by the non-dominant ions, and therefore significant emission in these channels comes from plasma at temperatures that are different from the "canonical" values. We have also studied the influence of non-dominant ions on the AIA passbands when different element abundances are assumed (photospheric and coronal), and when the effects of the electron density on the contribution function are taken into account.

The SDO/EVE Solar Irradiance Coronal Dimming Index Catalog. I. Methods and Algorithms

James Paul **Mason**1,2, Raphael Attie1, Charles N. Arge1, Barbara Thompson1, and Thomas N. Woods2
2019 ApJS 244 13
https://iopscience.iop.org/article/10.3847/1538-4365/ab380e/pdf

When a coronal mass ejection departs, it leaves behind a temporary void. That void is known as coronal dimming, and it contains information about the mass ejection that caused it. Other physical processes can cause parts of the corona to have transient dimmings, but mass ejections are particularly interesting because of their influence in space weather. Prior work has established that dimmings are detectable even in disk-integrated irradiance observations, i.e., Sun-as-a-star measurements. The present work evaluates four years of continuous Solar Dynamics Observatory Extreme Ultraviolet Experiment (EVE) observations to greatly expand the number of dimmings we may detect and characterize, and collects that information into James's EVE Dimming Index catalog. This paper details the algorithms used to produce the catalog, provides statistics on it, and compares it with prior work. The catalog contains 5051 potential events (rows), which correspond to all robustly detected solar eruptive events in this time period as defined by >C1 flares. Each row has a corresponding 27,349 elements of metadata and parameterizations (columns). In total, this catalog is the result of analyzing 7.6 million solar ultraviolet light curves. **2010-05-07, 2010-05-08, 2010-08-07, 2012-08-03, 2013-04-10, 2013-11-03**

Relationship of EUV Irradiance Coronal Dimming Slope and Depth to Coronal Mass Ejection Speed and Mass

James Paul **Mason**, Thomas N. Woods, David F. Webb, Barbara J. Thompson, Robin C. Colaninno,Angelos Vourlidas

ApJ 830 20 **2016**

http://arxiv.org/pdf/1607.05284v1.pdf **File**

Extreme ultraviolet (EUV) coronal dimmings are often observed in response to solar eruptive events. These phenomena can be generated via several different physical processes. For space weather, the most important of these is the temporary void left behind by a coronal mass ejection (CME). Massive, fast CMEs tend to leave behind a darker void that also usually corresponds to minimum irradiance for the cooler coronal emissions. If the dimming is associated with a solar flare, as is often the case, the flare component of the irradiance light curve in the cooler coronal emission can be isolated and removed using simultaneous measurements of warmer coronal lines. We apply this technique to 37 dimming events identified during two separate two-week periods in 2011, plus an event on 2010 August 7 analyzed in a previous paper, to parameterize dimming in terms of depth and slope. We provide statistics on which combination of wavelengths worked best for the flare-removal method, describe the fitting methods applied to the dimming light curves, and compare the dimming parameters with corresponding CME parameters of mass and speed. The best linear relationships found are vCME[kms]mCME[g]≈………These relationships could be used for space weather operations of estimating CME mass and speed using near-realtime irradiance dimming measurements. **2010 Aug 7, February 10-24 and August 1-14 2011**

Table 1. Event list. Times and locations are approximate. Only 29 of the events have dimming and CME derived parameters to allow the study of the relationships between dimmings and CMEs.

Mechanisms and Observations of Coronal Dimming for the 2010 August 7 Event

J. P. **Mason**, T. N. Woods, A. Caspi, B. J. Thompson, R. A. Hock

2014, ApJ 789 61

http://arxiv.org/pdf/1404.1364v1.pdf

Coronal dimming has the potential to be a useful forecaster of coronal mass ejections (CMEs). As emitting material leaves the corona, a temporary void is left behind which can be observed in spectral images and irradiance measurements. The velocity and mass of the CMEs should impact the character of those observations. However, other physical processes can confuse the observations. We describe these processes and the expected observational signature, with special emphasis placed on the differences. We then apply this understanding to a coronal dimming event with an associated CME that occurred on **2010 August 7**. Data from the Solar Dynamics Observatorys (SDO) Atmospheric Imaging Assembly (AIA) and Extreme ultraviolet Variability Experiment (EVE) are used for observations of the dimming, while the Solar and Heliospheric Observatorys (SOHO) Large Angle and Spectrometric Coronagraph (LASCO) and the Solar Terrestrial Relations Observatorys (STEREO) COR1 and COR2 are used to obtain velocity and mass estimates for the associated CME. We develop a technique for mitigating temperature effects in coronal dimming from full-disk irradiance measurements taken by EVE. We find that for this event, nearly 100% of the dimming is due to mass loss in the corona.

The Impact of New EUV Diagnostics on CME-Related Kinematics

Scott W. **McIntosh** · Bart De Pontieu · Robert J. Leamon

Solar Phys (**2010**) 265: 5–17; **File**

We present the application of novel diagnostics to the spectroscopic observation of a Coronal Mass Ejection (CME) on disk by the Extreme Ultraviolet Imaging Spectrometer (EIS) on the *Hinode* spacecraft. We apply a recently developed line profile asymmetry analysis to the spectroscopic observation of NOAA AR 10930 on **14 – 15 December 2006** to three raster observations before and during the eruption of a 1000 km s^{-1} halo CME. We see the impact that the observer's line-of-sight and magnetic field geometry have on the diagnostics used. Further, and more importantly, we identify the on-disk signature of a high-speed outflow behind the CME in the dimming region arising as a result of the eruption. Supported by recent coronal observations of the STEREO spacecraft, we speculate about the momentum flux resulting from this outflow as a secondary momentum source to the CME. The results presented highlight the importance of spectroscopic measurements in

relation to CME kinematics, and the need for full-disk synoptic spectroscopic observations of the coronal and chromospheric plasmas to capture the signature of such explosive energy release as a way of providing better constraints of CME propagation times to L1, or any other point of interest in the heliosphere.
Electronic Supplementary Material:
http://springerlink.com/content/08576315n003w53u/11207_2010_Article_9538_ESM.html

THE INCONVENIENT TRUTH ABOUT CORONAL DIMMINGS

Scott W. **McIntosh**

Astrophysical Journal, 693:1306–1309, **2009; File**

http://www.iop.org/EJ/toc/-alert=43190/0004-637X/693/2

We investigate the occurrence of a coronal mass ejection (CME)-driven coronal dimming using unique high resolution spectral images of the corona from the **Hinode** spacecraft. Over the course of the dimming event, we observe the dynamic increase of nonthermal line broadening in the 195.12 Å emission line of Fe XII as the corona opens. As the corona begins to close, refill and brighten, we see a reduction of the nonthermal broadening toward the pre-eruption level. We propose that the dynamic evolution of the nonthermal broadening is the result of the growth of Alfv´en wave amplitudes in the magnetically open rarefied dimming region, compared to the dense closed corona prior to the CME. We suggest, based on this proposition, that, as open magnetic regions, coronal dimmings must act just as coronal holes and be sources of the fast solar wind, but only temporarily. Further, we propose that such a rapid transition in the thermodynamics of the corona to a solar wind state may have an impulsive effect on the CME that initiates the observed dimming. This last point, if correct, poses a significant physical challenge to the sophistication of CME modeling and capturing the essence of the source region thermodynamics necessary to correctly ascertain CME propagation speeds, etc.

THE POSTERUPTIVE EVOLUTION OF A CORONAL DIMMING

Scott W. **McIntosh**,1, 2 Robert J. Leamon,3 Alisdair R. Davey,1 and Meredith J. Wills-Davey

The Astrophysical Journal, 660:1653-1659, **2007**, **File**

We discuss the posteruptive evolution of a ‘‘coronal dimming’’ based on observations of the EUV corona from the Solar and Heliospheric Observatory and the Transition Region and Coronal Explorer (TRACE). This discussion highlights the roles played by magnetoconvection-driven magnetic reconnection and the global magnetic environment of the plasma in the ‘‘filling’’ and apparent motion of the region following the eruption of a coronal mass ejection (CME). A crucial element in our understanding of the dimming region’s evolution is developed by monitoring the disappearance and reappearance of bright TRACE ‘‘moss’’ around the active region that gives rise to the CME. We interpret the change in the TRACE moss as a proxy of the changing coronal magnetic field topology behind the CME front. We infer that the change in the global magnetic topology also results in a shift of the energy balance in the process responsible for the production of the moss emission while the coronal magnetic topology evolves from closed to open and back to closed again because, following the eruption, the moss reforms around the active region in almost exactly its pre-event configuration. As a result of the moss’s evolution, combining our discussion with recent spectroscopic results of an equatorial coronal hole, we suggest that the interchangeable use of the term ‘‘transient coronal hole’’ to describe a coronal dimming is more than just a simple coincidence.

(See: The Recovery of CME-Related Dimmings and the ICME’s Enduring Magnetic Connection to the Sun. G.D.R. Attrill· L. van Driel-Gesztelyi1·P. D´emoulin· A.N. Zhukov,· K. Steed, L.K. Harra· C.H. Mandrini6· J. Linker7, E-print, July 2008, File; Solar Phys.)

Discovery in 1960 of the Flare Nimbus Phenomenon and Changes with Time in Its Interpretation

Susan M. P. **McKenna-Lawlor**

Solar Physics, Volume 272, Number 2, 257-299, **2011**

During the International Geophysical Year (IGY, 1957/1958) Dunsink Observatory near Dublin in Ireland was a World Data Centre for Solar Activity. In this circumstance, Hα Lyot Heliograph records secured on a daily basis between 07:00 – 14:00 UT at the Cape of Good Hope (then an integral link in a network of similar instruments contributing during the IGY to global monitoring of solar chromospheric activity) were routinely sent to Dunsink for analysis and dissemination. The investigations carried out at Dunsink on these data resulted, inter alia, in the discovery of the Flare Nimbus phenomenon. The nimbus comprises a dark expanding halo seen in the plage regions around major flares at, or within a few minutes of, the time of flare maximum intensity in Hα light. It reaches its greatest extent about 30 minutes after flare maximum. Its maximum dimensions (estimated visually) lie in the range 2 – 4×105 km and its duration ranges from ~ 1 – 2 hours. Within the nimbus the striation pattern is either completely destroyed or loses its pre-flare configuration. An account of this phenomenon and its interpretation appeared primarily, although not exclusively, in the locally produced Dunsink Observatory Publications which are not now easily accessible to the world community of solar researchers. Also, at around the time when the nimbus was first identified and recorded in Lyot Heliograph data at several observatories, techniques in solar physics shifted towards high resolution narrow field observations. Under these conditions no further examples of the nimbus were recorded and the subject has remained dormant over several decades. The present paper again places the scientific results obtained with regard to the nimbus in the public domain, together with an account of the evolution within the scientific community of an explanation of this phenomenon. It is suggested here for the first time, in the light of present day data concerning coronal mass ejections (CMEs) and coronal **dimming**, that the nimbus provides a signature of CME-related reorganization of the magnetic field in the chromosphere (such that the transverse magnetic field component decreases and transforms into the line of sight component as the vector field stretches out). Coronal dimming provides a complementary signature of CME-related mass depletion in the corona.

Velocity Distribution Associated With EUV Disturbances Caused by Eruptive MFR

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Front. Astron. Space Sci. 8:771882. **2021**
https://www.frontiersin.org/articles/10.3389/fspas.2021.771882/full
https://doi.org/10.3389/fspas.2021.771882

Extreme ultraviolet (EUV) disturbances are ubiquitous during eruptive phenomena like solar flare and Coronal Mass Ejection (CME). In this work, we have performed a three-dimensional (3D) magnetohydrodynamic numerical simulation of CME with an analytic magnetic fluxrope (MFR) to study the complex velocity distribution associated with EUV disturbances. When the MFR erupts upward, a fast shock (FS) appears as a 3D dome, followed by outward moving plasma. In the center of the eruptive source region, an expanding CME bubble and a current sheet continuously grow, both of which are filled by inward moving plasma. At the flanks of the CME bubble, a complex velocity distribution forms because of the dynamical interaction between inward and outward plasma, leading to the formation of slow shock (SS) and velocity separatrix (VS). We note two types of vortices near the VS, not mentioned in the preceding EUV disturbance simulations. In first type of vortex, the plasma converges toward the vortex center, and in the second type, the plasma spreads out from the center. The forward modeling method has been used to create the synthetic SDO/AIA images, in which the eruptive MFR and the FS appear as bright structures. Furthermore, we also deduce the plasma velocity field by utilizing the Fourier local correlation tracking method on the synthetic images. However, we do not observe the VS, the SS, and the two types of vortices in this deduced velocity field.

3D numerical experiment for EUV waves caused by flux rope eruption

Z X **Mei**, R Keppens, Q W Cai, J Ye, X Y Xie ...

Mon Not R Astron Soc, Volume 493, Issue 4, April **2020**, Pages 4816–4829,
sci-hub.ru/10.1093/mnras/staa555

We present a 3D magnetohydrodynamic numerical experiment of an eruptive magnetic flux rope (MFR) and the various types of disturbances it creates, and employ forward modelling of extreme ultraviolet (EUV) observables to directly compare numerical results and observations. In the beginning, the MFR erupts and a fast shock appears as an expanding 3D dome. Under the MFR, a current sheet grows, in which magnetic field lines reconnect to form closed field lines, which become the outermost part of an expanding coronal mass ejection (CME) bubble. In our synthetic SDO/AIA images, we can observe the bright fast shock dome and the hot MFR in the early stages. Between the MFR and the fast shock, a dimming region appears. Later, the MFR expands so its brightness decays and it becomes difficult to identify the boundary of the CME bubble and distinguish it from the bright MFR in synthetic images. Our synthetic images for EUV disturbances observed at the limb support the bimodality interpretation for coronal disturbances. However, images for disturbances propagating on-disc do not support this interpretation because the morphology of the bright MFR does not lead to circular features in the EUV disturbances. At the flanks of the CME bubble, slow shocks, velocity vortices and shock echoes can also be recognized in the velocity distribution. The slow shocks at the flanks of the bubble are associated with a 3D velocity separatrix. These features are found in our high-resolution simulation, but may be hard to observe as shown in the synthetic images.

Flare-Produced Coronal Waves,

Meyer, F.,

1968. in: K. O. Kiepenheuer (Ed.), Structure and Development of Solar Active Regions, pp. 485–489.

Two Quasi-periodic Fast-propagating Magnetosonic Wave Events Observed In Active Region NOAA 11167

Yuhu **Miao**, Yu Liu, A. Elmhamdi, A. S. Kordi, Y. D. Shen, Rehab Al-Shammari, Khaled Al-Mosabeh, Chaowei Jiang, Ding Yuan

ApJ **889** 139 **2020**

https://arxiv.org/pdf/1912.11792.pdf
https://doi.org/10.3847/1538-4357/ab655f
We report a detailed observational study of two quasi-periodic fast-propagating (QFP) magnetosonic wave events occurred on **2011 March 09 and 10**, respectively. Interestingly, both the two events have two wave trains (WTs): one main and strong (WT-1) whereas the second appears small and weak (WT-2). Peculiar and common characteristics of the two events are observed, namely: 1) the two QFP waves are accompanied with brightenings during the whole stage of the eruptions; 2) both the two main wave trains are nearly propagating along the same direction; 3) EUV waves are found to be associated with the two events. Investigating various aspects of the target events, we argue that: 1) the second event is accompanied with a flux rope eruption during the whole stage; 2) the second event eruption produces a new filament-like (FL) dark feature; 3) the ripples of the two WT-2 QFP waves seem to result from different triggering mechanisms. Based on the obtained observational results, we propose that the funnel-like coronal loop system is indeed playing an important role in the two WT-1 QFP waves. The development of the second WT-2 QFP wave can be explained as due to the dispersion of the main EUV front. The co-existence of the two events offer thereby a significant opportunity to reveal what driving mechanisms and structures are tightly related to the waves.

A Quasi-periodic propagating wave and EUV waves excited simultaneously in a solar eruption event

Y. H. **Miao**, Y. Liu, Y. D. Shen, H. B. Li, Z. Z. Abidin, A. Elmhamdi, A. S. Kordi
ApJL 871 L2 **2019**
https://iopscience.iop.org/article/10.3847/2041-8213/aafaf9/pdf
https://arxiv.org/pdf/1812.09858.pdf
sci-hub.ru/10.3847/2041-8213/aafaf9
Quasi-periodic fast-propagating (QFP) magnetosonic waves and extreme ultraviolet (EUV) waves were proposed to be driven by solar flares and coronal mass ejections (CMEs), respectively. In this Letter, we present a detailed analysis of an interesting event in which we find that both QFP magnetosonic waves and EUV waves are excited simultaneously in one solar eruption event. The co-existence of the two wave phenomena offers an excellent opportunity to explore their driving mechanisms. The QFP waves propagate in a funnel-like loop system with a speed of 682--837 \speed{} and a lifetime of 2 minutes. On the contrary, the EUV waves, which present a faster component and a slower component, propagate in a wide angular extent, experiencing reflection and refraction across a magnetic quasi-separatrix layer. The faster component of the EUV waves travels with a speed of 412--1287 \speed{}, whereas the slower component travels with a speed of 246--390 \speed{}. The lifetime of the EUV waves is ~15 minutes. It is revealed that the faster component of the EUV waves is cospatial with the first wavefront of the QFP wave train. Besides, The QFP waves have a period of about 45±5 seconds, which is absent in the associated flares. All these results imply that QFP waves can also be excited by mass ejections, including CMEs or jets. **2011 March 10**

Coronal Dimmings and the Early Phase of a CME Observed with STEREO and Hinode/EIS

C. **Miklenic**, A. M. Veronig, M. Temmer, C. Möstl and H. K. Biernat
Solar Physics, Volume 273, Number 1, 125-142, **2011, File**
We investigate the early phase of the **13 February 2009** coronal mass ejection (CME). Observations with the twin STEREO spacecraft in quadrature allow us to compare for the first time in one and the same event the temporal evolution of coronal EUV dimmings, observed simultaneously on-disk and above-the-limb. We find that these dimmings are synchronized and appear during the impulsive acceleration phase of the CME, with the highest EUV intensity drop occurring a few minutes after the maximum CME acceleration. During the propagation phase two confined, bipolar dimming regions, appearing near the footpoints of a pre-flare sigmoid structure, show an apparent migration away from the site of the CME-associated flare. Additionally, they rotate around the 'center' of the flare site, i.e., the configuration of the dimmings exhibits the same 'sheared-to-potential' evolution as the postflare loops. We conclude that the motion pattern of the twin dimmings reflects not only the eruption of the flux rope, but also the ensuing stretching of the overlying arcade. Finally, we find that: i) the global-scale dimmings, expanding from the source region of the eruption, propagate with a speed similar to that of the leaving CME front; ii) the mass loss occurs mainly during the period of strongest CME acceleration. Two hours after the eruption Hinode/EIS observations show no substantial plasma outflow, originating from the 'open' field twin dimming regions.

Solar Energetic Particles and Associated EIT Disturbances in Solar Cycle 23

R. **Miteva**, K.-L. Klein, I. Kienreich, M. Temmer, A. Veronig, O. E. Malandraki
E-print, Feb **2014**, File; Solar Phys. Volume 289, Issue 7, pp 2601-2631, **2014**
http://arxiv.org/pdf/1402.1676v1.pdf

We explore the link between solar energetic particles (SEPs) observed at 1 AU and large-scale disturbances propagating in the solar corona, named after the Extreme ultraviolet Imaging Telescope (EIT) as EIT waves, which trace the lateral expansion of a coronal mass ejection (CME). A comprehensive search for SOHO/EIT waves was carried out for 179 SEP events during Solar Cycle 23 (1997-2006). 87% of the SEP events were found to be accompanied by EIT waves. In order to test if the EIT waves play a role in the SEP acceleration, we compared their extrapolated arrival time at the footpoint of the Parker spiral with the particle onset in the 26 eastern SEP events that had no direct magnetic connection to the Earth. We find that the onset of proton events was generally consistent with this scenario. However, in a number of cases the first near-relativistic electrons were detected too early. Furthermore, the electrons had in general only weakly anisotropic pitch-angle distributions. This poses a problem for the idea that the SEPs were accelerated by the EIT wave or in any other spatially confined region in the low corona. The presence of weak electron anisotropies in SEP events from the eastern hemisphere suggests that transport processes in interplanetary space, including cross-field diffusion, play a role in giving the SEPs access to a broad range of helio-longitudes. 1997-04-01, **1997-09-24, 1998-04-29, 2000-01-18, 2000-02-17, 2000-06-06, 2000-07-10, 2000-10-29, 2000-11-25, 2001-01-20, 2001-06-15, 2001-09-17, 2001-09-24, 2001-10-09, 2001-11-28, 2002-05-20, 2002-08-16, 2003-04-25, 2003-06-15, 2003-07-17, 2003-10-26, 2003-11-18, 2004-11-04, 2005-01-15, 2005-05-13, 2006-11-06,**

Table 1. Solar energetic particle events with origin at western [W] helio-longitudes and associated EIT disturbances, flares and CMEs.

Table 2. Solar energetic particle events with origin at eastern [E] helio-longitudes and associated EIT disturbances, flares and CMEs.

Table 3. Properties of all 29 eastern particle events associated with EIT waves.

Table 4. Properties of 26 eastern EIT waves for which at least two wave fronts could be identified.

THE CORONAL-DIMMING FOOTPRINT OF A STREAMER-PUFF CORONAL MASS EJECTION: CONFIRMATION OF THE MAGNETIC-ARCH-BLOWOUT SCENARIO

Ronald L. **Moore** and Alphonse C. Sterling

The Astrophysical Journal, 661:543*Y*550, 2007, file

Streamer-puff CMEs are a subclass (one variety) of a broader class of ‘‘over-and-out’’ CMEs that are often much larger than streamer puffs but are similar to them in that they are produced by the blowout of a large quasi-potential magnetic arch by a magnetic explosion that erupts from one foot of the large arch, where it is marked by a filament eruption and/or an ejective flare.

Hα Shock Wave and Winking Filaments with the Flare of 20 September 1963.

Moreton, G.F.,

1964. Astronom. J. 69, 145.

Hα Observations of Flare-Initiated Disturbances with Velocities ˜1000 km/sec.

Moreton, G.E.,

1960. Astronom. J. 65, 494–495.

Recent Observations of Dynamical Phenomena Associated with Solar Flares.

Moreton, G.E., Ramsey, H.E.,

1960. Pub. Astron. Soc. Pac. 72, 357–358.

Multi-scale Gaussian normalization for solar image processing

Huw **Morgan**, Miloslav Druckmuller

Solar Phys., 2014

http://arxiv.org/pdf/1403.6613v1.pdf

Extreme UltraViolet images of the corona contain information over a large range of spatial scales, and different structures such as active regions, quiet Sun and filament channels contain information at very different brightness regimes. Processing of these images is important to reveal information, often hidden within the data, without introducing artifacts or bias. It is also important that any process be computationally efficient, particularly given the fine spatial and temporal resolution of Atmospheric Imaging Assembly on the Solar Dynamics Observatory (AIA/SDO) , and consideration of future higher-resolution observations. A very efficient process is described here which is based on localized normalizing of the data at many different spatial scales. The method reveals information at the finest scales, whilst maintaining enough of the larger-scale information to provide context. It also intrinsically flattens noisy regions and can reveal structure in off-limb regions out to the edge of the field of view. The method is also successfully applied to a white light coronagraph observation.

EIT observations of the extreme ultraviolet sun.

Moses, D., Clette, F., Delaboudinière, J.P., Artzner, G.E., *et al.*:
1997, *Solar Phys.* **175**, 571 – 599. doi:10.1023/A:1004902913117.

JHelioviewer - Visualizing large sets of solar images using JPEG 2000

Daniel **Mueller**, George Dimitoglou, Benjamin Caplins, Juan Pablo Garcia Ortiz, Benjamin Wamsler, Keith Hughitt, Alen Alexanderian, Jack Ireland, Desmond Amadigwe, Bernhard Fleck
E-print, June **2009**; Computing in Science & Engineering
Across all disciplines that work with image data - from astrophysics to medical research and historic preservation - there is a growing need for efficient ways to browse and inspect large sets of high-resolution images. We present the development of a visualization software for solar physics data based on the JPEG 2000 image compression standard. Our implementation consists of the JHelioviewer client application that enables users to browse petabyte-scale image archives and the JHelioviewer server, which integrates a JPIP server, metadata catalog and an event server. JPEG 2000 offers many useful new features and has the potential to revolutionize the way high-resolution image data are disseminated and analyzed. This is especially relevant for solar physics, a research field in which upcoming space missions will provide more than a terabyte of image data per day. Providing efficient access to such large data volumes at both high spatial and high time resolution is of paramount importance to support scientific discovery.
http://www.helioviewer.org

Statistical Analysis of Large-scale EUV Waves Observed by STEREO/EUVI

Nicole **Muhr**, Astrid Maria Veronig, Ines Waltraud Kienreich, Bojan Vrsnak, Manuela Temmer, Bianca Maria Bein
Solar Phys., **2014**
http://arxiv.org/pdf/1408.2513v1.pdf; **File**
We present a statistical analysis of **60 strong large-scale EUV wave events** that occurred during January 2007 to February 2011 with the STEREO twin spacecraft regarding their kinematical evolution and wave pulse characteristics. For the start velocity, we obtain for the arithmetic mean 312±115 km s−1 (within a range of 100−630 km s−1). For the mean (linear) velocity, the arithmetic mean is 254±76 km s−1 (within a range of 130−470 km s −1). 52 % of all waves under study show a distinct deceleration during their propagation (a≤−50 m s−2), the other 48 % are consistent with a constant speed within the uncertainties (−50≤a≤50 m s−2). The start velocity and the acceleration show a strong anticorrelation with c≈−0.8, \textit i.e initially faster events undergo stronger deceleration than slower events. The (smooth) transition between constant propagation for slow events and deceleration in faster events occurs at an EUV wave start velocity of v≈230 km s−1, which corresponds well to the fast-mode speed in the quiet corona. These findings provide strong evidence that the EUV waves under study are indeed large-amplitude fast-mode MHD waves. This interpretation is further supported by the correlations obtained between the peak velocity and the peak amplitude, impulsiveness, and build-up time of the disturbance. We obtained the following association rates of EUV wave events to other solar phenomena: 95 % are associated with a coronal mass ejection (CME), 74 % to a solar flare, 15 % to interplanetary type II bursts, and 22 % to coronal type II bursts. These findings are consistent with the interpretation that the associated CMEs are the EUV waves' driving agent.
Table 1.: EUV wave events under study.

Analysis of characteristic parameters of large-scale coronal waves observed by STEREO/EUVI

N. **Muhr**, A.M. Veronig, I.W. Kienreich, M. Temmer, B. Vrsnak
E-print, 4 Aug **2011, File**; **2011** ApJ 739 89
https://iopscience.iop.org/article/10.1088/0004-637X/739/2/89/pdf
The kinematical evolution of four EUV waves, well observed by the Extreme UltraViolet Imager (EUVI) onboard the Solar-Terrestrial Relations Observatory (STEREO), is studied by visually tracking the wave fronts as well as by a semiautomatized perturbation profile method leading to results matching each other within the error limits. The derived mean velocities of the events under study lie in the range of 220-350 km/s. The fastest of the events (May 19, 2007) reveals a significant deceleration of \approx -190 m s-2 while the others are consistent with a constant velocity during the wave propagation. The evolution of the maximum intensity values reveals initial intensification by 20 up to 70%, and decays to original levels within 40-60 min, while the width at half maximum and full

maximum of the perturbation profiles are broadening by a factor of 2 - 4. The integral below the perturbation profile remains basically constant in two cases, while it shows a decrease by a factor of 3 - 4 in the other two cases. From the peak perturbation amplitudes we estimate the corresponding magnetosonic Mach numbers Mms which are in the range of 1.08-1.21. The perturbation profiles reveal three distinct features behind the propagating wave fronts: coronal dimmings, stationary brightenings and rarefaction regions. All of them appear after the wave passage and are only slowly fading away. Our findings indicate that the events under study are weak shock fast-mode MHD waves initiated by the CME lateral expansion.
2007 May 19, 2009 Feb 13, 2010 Jan 17, 2010 Apr 29

Analysis of a global Moreton wave observed on October 28, 2003

N. **Muhr**, B. Vrsnak, M. Temmer, A. M. Veronig, J. Magdalenic

ApJ, **708** 1639-1649, **2010**, **FILE**

We study the well pronounced Moreton wave that occurred in association with the X17.2 flare/CME event of **October 28, 2003**. This Moreton wave is striking for its global propagation and two separate wave centers, which implies that two waves were launched simultaneously. The mean velocity of the Moreton wave, tracked within different sectors of propagation direction, lies in the range of v ~ 900 − 1100 km/s with two sectors showing wave deceleration. The perturbation profile analysis of the wave indicates amplitude growth followed by amplitude weakening and broadening of the perturbation profile, which is consistent with a disturbance first driven and then evolving into a freely propagating wave. The EIT wave front is found to lie on the same kinematical curve as the Moreton wavefronts indicating that both are different signatures of the same physical process. Bipolar coronal dimmings are observed on the same opposite East-West edges of the active region as the Moreton wave ignition centers. The radio type II source, which is co-spatially located with the first wave front, indicates that the wave was launched from an extended source region (~ 60 Mm). These findings suggest that the Moreton wave is initiated by the CME expanding flanks.

Hale cycle in solar hemispheric radio flux and sunspots: Evidence for a northward-shifted relic field

K. **Mursula**

A&A 674, A182 (**2023**)

https://www.aanda.org/articles/aa/pdf/2023/06/aa45999-23.pdf

Context. Solar and heliospheric parameters occasionally depict notable differences between the northern and southern solar hemisphere. Although the hemispheric asymmetries of some heliospheric parameters vary systematically with the Hale cycle, this has not been found to be commonly valid for solar parameters. Also, no verified physical mechanism exists that can explain possible systematic hemispheric asymmetries.
Aims. We use a novel method of high heliolatitudinal vantage points to increase the fraction of one hemisphere in solar 10.7 cm radio fluxes and sunspot numbers. We aim to explore the possibility that solar radio fluxes and sunspot numbers, the two most fundamental solar parameters, depict systematic, possibly mutually similar patterns in their hemispheric activities during the last 75 yr.
Methods. We used three different sets of time intervals with increasing mean heliographic latitude and calculated corresponding hemispheric high-latitude radio fluxes and sunspot numbers. We also normalized these fluxes by yearly means in order to study the variation of fluxes in the two hemispheres over the whole 75 yr time interval.
Results. We find that cycle-maximum radio fluxes and sunspot numbers in each odd solar cycle (19, 21, 23) are larger at northern high latitudes than at southern high latitudes, while maximum fluxes and numbers in all even cycles (18, 20, 22 24) are larger at southern high latitudes than at northern high latitudes. This alternation indicates a new form of systematic, Hale-cycle-related variation in solar activity. Hemispheric differences at cycle maxima are 15% for radio flux and 23% for sunspot numbers, on average. The difference is largest during cycle 19 and smallest in cycle 24. Normalized radio fluxes depict a dominant Hale-cycle variation in both hemispheres, with an opposite phase and overall amplitude of about 5% in the north and 4% in the south. Thus, there is systematic Hale-cycle alternation in magnetic flux emergence in both hemispheres.
Conclusions. The hemispheric Hale cycle in flux emergence can be explained if there is a northward-directed relic magnetic field, which is slightly shifted northward. In that case, in odd cycles, the northern hemisphere is enhanced more than the southern hemisphere, and in even cycles, the northern hemisphere is reduced more than the southern hemisphere, establishing the observed hemispheric alternation. The temporal change of asymmetry during the seven cycles can be explained if the relic shift oscillates at the 210 yr Suess/deVries period, which also provides a physical cause to this periodicity. Gleissberg cycles are explained as off-equator excursions of the relic, each Gleissberg cycle forming one half of the full relic shift oscillation cycle. Having a relic field in the Sun also offers interesting possibilities for century-scale forecasting of solar activity.

Three Successive and Interacting Shock Waves Generated by a Solar Flare

Noriyuki **Narukage**, Takako T. Ishii, Shin'ichi Nagata, Satoru UeNo, Reizaburo Kitai, Hiroki Kurokawa,

Maki Akioka, and Kazunari Shibata
The Astrophysical Journal Letters, Vol. 684, No. 1: L45-L49, 2008
http://www.journals.uchicago.edu/doi/pdf/10.1086/592108
We discovered three successive Moreton waves generated by a single solar flare on **2005 August 3**. Although this flare was not special in magnitude or configuration, Moreton waves (shock waves) successively occurred three times. Multiple shock waves generated during a single flare have not been reported before. Furthermore, the faster second-generated Moreton wave caught up and merged with the slower first-generated one. This is the first report of shock-shock interaction associated with a solar flare. The shock-plasma interaction was also detected. When the third-generated Moreton wave passed through an erupting filament, the filament was accelerated by the Moreton wave. In this event, filaments also erupted three times. On the basis of this observation, we consider that filament eruption is indispensable to the generation of Moreton waves.

Simultaneous observation of a Moreton wave on 3 November 1997 in Hα and soft X-rays.
Narukage, N., Hudson, H.S., Morimoto, T., Akiyama, S., *et al.*:
2002, *Astrophys. J.* **572**, L109 – L112. doi:10.1086/341599.

Neidig,D. F., ˇSvestka, Z.,Cliver, E.W.,Airapetian,V.,&Henry, T.W.
1997, Sol. Phys., 170, 321
Neidig et al. (1997) have previously reported such dimming in 'magnetically neutral' regions lying outside but adjacent to bright flare emission. *Hα Dimmings.*

Transient coronal extreme ultraviolet emission before and during the impulsive phase of a solar flare.
Neupert, W.M.:
1989, *Astrophys. J.* **344**, 504 – 512. doi:10.1086/167819.
An EUV counterpart of the Moreton wave was reported by Neupert (1989), and a decade later these coronal disturbances were directly imaged by the Extremeultraviolet Imaging Telescope (EIT; Delaboudinière *et al.*, 1995) on the Solar and Heliospheric Observatory (SoHO). The discovery of "EIT-waves" (Moses *et al.*, 1997; Thompson *et al.*, 1998) prompted a search for wave signatures in other spectral domains.

The Merging of a Coronal Dimming and the Southern Polar Coronal Hole
Nawin **Ngampoopun**, David M. Long, Deborah Baker, Lucie M. Green, Stephanie L. Yardley, Alexander W. James, Andy S.H. To
ApJ **2023**
https://arxiv.org/pdf/2305.06106.pdf
We report on the merging between the southern polar coronal hole and an adjacent coronal dimming induced by a coronal mass ejection on **2022 March 18**, resulting in the merged region persisting for at least 72 hrs. We use remote sensing data from multiple co-observing spacecraft to understand the physical processes during this merging event. The evolution of the merger is examined using Extreme-UltraViolet (EUV) images obtained from the Atmospheric Imaging Assembly onboard the Solar Dynamic Observatory and Extreme Ultraviolet Imager onboard the Solar Orbiter spacecraft. The plasma dynamics are quantified using spectroscopic data obtained from the EUV Imaging Spectrometer onboard Hinode. The photospheric magnetograms from the Helioseismic and Magnetic Imager are used to derive magnetic field properties. To our knowledge, this work is the first spectroscopical analysis of the merging of two open-field structures. We find that the coronal hole and the coronal dimming become indistinguishable after the merging. The upflow speeds inside the coronal dimming become more similar to that of a coronal hole, with a mixture of plasma upflows and downflows observable after the merging. The brightening of bright points and the appearance of coronal jets inside the merged region further imply ongoing reconnection processes. We propose that component reconnection between the coronal hole and coronal dimming fields plays an important role during this merging event, as the footpoint switching resulting from the reconnection allows the coronal dimming to intrude onto the boundary of the southern polar coronal hole.

Observations of a high-quality quasi-periodic rapidly-propagating wave train using SDO/AIA
G. **Nistico**, D. J. Pascoe, V. M. Nakariakov
E-print, June **2014**; A&A 569, A12 (**2014**)
http://www2.warwick.ac.uk/fac/sci/physics/research/cfsa/people/nistico/publications/paper_wave_train.pdf

Context. We present a new event of quasi-periodic wave trains observed in EUV wavebands, rapidly-propagating away from an active region after a flare.
Aims. We measure parameters of a wave train observed on **7 December 2013** after an M2.1 flare, i.e. phase speeds, periods and wavelengths, in relationship to the local coronal environment and the energy sources.
Methods. We compare our observations with a numerical simulation of fast magnetoacoustic waves undergoing dispersive evolution and leakage in a coronal loop embedded in a potential magnetic field.
Results. The wave train is observed to propagate as several arc-shaped intensity disturbances, for almost half an hour, with a speed greater than 1000 km/s and a period of about 1 min. The wave train followed two different patterns of propagation, in accordance with the magnetic structure of the active region. The oscillatory signal is found to be of high quality, i.e. there is a large number (10 or more) of subsequent wave fronts observed. The observations are found to be consistent with the numerical simulation of a fast wave train generated by a localised impulsive energy release.
Conclusions. Transverse structuring in the corona can efficiently create and guide high quality quasi-periodic propagating fast wave trains.

Email on 2015.10.06 about coronal wave data

Nitta Nariaki V.

I enjoy looking at solar images that show spectacular eruptions. This is the main reason I have made a list of EUV or EIT waves (or large-scale coronal propagating fronts (LCPFs), coronal bright fronts (CBFs), or whatever the nomenclature may be) as observed by SDO/AIA and STEREO/EUVI. The list and the associated movies are online at http://aia.lmsal.com/AIA_Waves, which is the link to http://www.lmsal.com/nitta/movies/AIA_Waves. The events are also searchable in the Heliophysics Events Knowledgebase (HEK, http://www.lmsal.com/isolsearch, under “Coronal Wave” and use “Filters” to specify FRM_Name = Nariaki Nitta). The time resolution of the AIA movies is 144 seconds.
I am writing this to remind you that movies of all the AEC-off frames, at the 24 second cadence (12 second before October 2010), are kept on http://aia.lmsal.com/AIA_Waves/oindex.html (http://www.lmsal.com/nitta/movies/AIA_Waves/oindex.html). During Cooper D’s visit here last week, I realized these higher time resolution movies may not be widely known, even locally in the building where I work. In general these movies may be too bulky to run on machines with a small RAM, but this cadence may allow you to find rapidly changing features associated with coronal waves.
Since my ApJ paper in 2013, which included the URL for the 144 second movies, the number of events have more than doubled. I will try to update the list and movies even sacrificing my free time, largely because I hope you will find them useful for conducting your great scientific work. Of course I myself may sometimes try to produce some meaning results to avoid criticisms (by, for example, Barbara T and Angelos V) that I never publish... I keep space-time profiles along great circles in 24 15-deg sectors or around the limb at various heights for most of the events, from which it is relatively easy to retrieve kinematic parameters. Some time down the road, I look forward to comparing them systematically with those derived in an automatic fashion using more sophisticated software (e.g. CorPITA, Solar Demon, etc.) Of course one can question the meaning of such measurements in light of the 3D nature of solar eruptions and unavoidable projection effect, etc. Therefore I am presently reluctant to put them online for general use.

The Relation Between Large-Scale Coronal Propagating Fronts and Type II Radio Bursts

Nariaki V. **Nitta**, Wei Liu, Nat Gopalswamy, Seiji Yashiro
Solar Phys., **2014**
http://www.lmsal.com/nitta/publ/SP_typeII_20140904.pdf
http://arxiv.org/pdf/1409.4754v1.pdf **File**

Large-scale, wave-like disturbances in extreme-ultraviolet (EUV) and type II radio bursts are often associated with coronal mass ejections (CMEs). Both phenomena may signify shock waves driven by CMEs. Taking EUV full-disk images at an unprecedented cadence, the Atmospheric Imaging Assembly (AIA) onboard the Solar Dynamics Observatory has observed the so-called EIT waves or large-scale coronal propagating fronts (LCPFs) from their early evolution, which coincides with the period when most metric type II bursts occur. This article discusses the relation of LCPFs as captured by AIA with metric type II bursts. We show examples of type II bursts without a clear LCPF and fast LCPFs without a type II burst. Part of the disconnect between the two phenomena may be due to the difficulty in identifying them objectively. Furthermore, it is possible that the individual LCPFs and type II bursts may reflect different physical processes and external factors. In particular, the type II bursts that start at low frequencies and high altitudes tend to accompany an extended arc- shaped feature, which probably represents the 3D structure of the CME and the shock wave around it, rather than its near-surface track, which has usually been identified with EIT waves. This feature expands and propagates toward and beyond the limb. These events may be characterized by stretching of field lines in the radial direction, and be distinct from other LCPFs, which may be explained in terms of sudden lateral expansion of the coronal volume. Neither LCPFs nor type II bursts by themselves serve as necessary conditions for coronal shock waves, but these phenomena may provide useful information on the early evolution of the shock waves in 3D when both are clearly identified in eruptive events.

2010-11-12, 2011-03-07, 2 Aug 2011, 10 Oct 2011, 2011-11-23, 26 Dec 2011. 5 Apr 2012, 4 Mar 2012, 2 july 2012, 12 Jul 2012, 27 Sep 2012, 2012-10-23

Large-scale Coronal Propagating Fronts in Solar Eruptions as Observed by the Atmospheric Imaging Assembly on Board the Solar Dynamics Observatory - An Ensemble Study

Nitta, N. V., Schrijver, C. J., Title, A. M., Liu, W.
E-print, Aug **2013, File**; **2013** ApJ 776 58
http://arxiv.org/pdf/1308.3544v1.pdf

This paper presents a study of a large sample of global disturbances in the solar corona with characteristic propagating fronts as intensity enhancement, similar to the phenomena that have often been referred to as EIT waves or EUV waves. Now Extreme Ultraviolet (EUV) images obtained by the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO) provide a significantly improved view of these large-scale coronal propagating fronts (LCPFs). Between April 2010 and January 2013, a total of 171 LCPFs have been identified through visual inspection of AIA images in the 193 A channel. Here we focus on the 138 LCPFs that are seen to propagate across the solar disk, first studying how they are associated with flares, coronal mass ejections (CMEs) and type II radio bursts. We measure the speed of the LCPF in various directions until it is clearly altered by active regions or coronal holes. The highest speed is extracted for each LCPF. It is often considerably higher than EIT waves. We do not find a pattern where faster LCPFs decelerate and slow LCPFs accelerate. Furthermore, the speeds are not strongly correlated with the flare intensity or CME magnitude, nor do they show an association with type II bursts. We do not find a good correlation either between the speeds of LCPFs and CMEs in a subset of 86 LCPFs observed by one or both of the Solar and Terrestrial Relations Observatory (STEREO) spacecraft as limb events.
2011 February 15;
Table 1. The 171 LCPFs; The catalog of LCPFs with all these movies are online at
http://aia.lmsal.com/AIA_Waves/index.html

The Association of Solar Flares with Coronal Mass Ejections During the Extended Solar Minimum

Nitta, N. V., Aschwanden, A. M., Freeland, S. L., Lemen, J. R., Wuelser, J.-P., Zarro, D. M.
E-print, Aug **2013, File**; Solar Phys.

We study the association of solar flares with coronal mass ejections (CMEs) during the deep, extended solar minimum of 2007-2009, using extreme-ultraviolet (EUV) and white-light (coronagraph) images from the Solar Terrestrial Relations Observatory (STEREO). Although all of the fast (v > 900 km s-1) and wide (theta > 100 deg) CMEs are associated with a flare that is at least identified in GOES soft X-ray light curves, a majority of flares with relatively high X-ray intensity for the deep solar minimum (e.g. >=1 10-6 W m-2 or C1) are not associated with CMEs. Intense flares tend to occur in active regions with strong and complex photospheric magnetic field, but the active regions that produce CME-associated flares tend to be small, including those that have no sunspots and therefore no NOAA active-region numbers. Other factors on scales comparable to and larger than active regions seem to exist that contribute to the association of flares with CMEs. We find the possible low coronal signatures of CMEs, namely eruptions, dimmings, EUV waves, and Type III bursts, in 91%, 74%, 57%, and 74%, respectively, of the 35 flares that we associate with CMEs. None of these observables can fully replace direct observations of CMEs by coronagraphs.
14 May 2007. 3 June 2007, **2007-12-31, 2009-02-13,**
Table 2. Coronal waves observed by EUVI during March 2007 -December 2009

Investigation of a Color-Color Method to Determine Temperatures along Coronal Structures Using TRACE Data

J. B. **Noglik** and R. W. Walsh
The Astrophysical Journal, 655:1127-1133, 2007
http://www.journals.uchicago.edu/cgi-bin/resolve?ApJ64935

This paper readdresses the double filter ratio temperature analysis method employed on *TRACE* 171, 195, and 284 Å coronal images.

Quasi-periodic Counter-propagating Fast Magnetosonic Wave Trains from Neighboring Flares: SDO/AIA Observations and 3D MHD Modeling

Leon **Ofman**, Wei Liu

ApJ 860 54 **2018**

https://arxiv.org/pdf/1805.00365.pdf

Since their discovery by SDO/AIA in EUV, rapid (phase speeds of 1000 km/s), quasi-periodic, fast-mode propagating wave trains (QFPs) have been observed accompanying many solar flares. They typically propagate in funnel-like structures associated with the expanding magnetic field topology of the active regions (ARs). The waves provide information on the associated flare pulsations and the magnetic structure through coronal seismology. The reported waves usually originate from a single localized source associated with the flare. Here, we report the first detection of counter-propagating QFPs associated with two neighboring flares on **2013 May 22**, apparently connected by large-scale, trans-equatorial coronal loops. We present the first results of 3D MHD model of counter-propagating QFPs an idealized bi-polar AR. We investigate the excitation, propagation, nonlinearity, and interaction of the counter-propagating waves for a range of key model parameters, such as the properties of the sources and the background magnetic structure. In addition to QFPs, we also find evidence of trapped fast (kink) and slow mode waves associated with the event. We apply coronal seismology to determine the magnetic field strength in an oscillating loop during the event. Our model results are in qualitative agreement with the AIA-observed counter propagating waves and are used to identify the various MHD wave modes associated with the observed event providing insights into their linear and nonlinear interactions. Our observations provide the first direct evidence of counter-propagating fast magnetosonic waves that can potentially lead to turbulent cascade and carry significant energy flux for coronal heating in low-corona magnetic structures.

MODELING SUPER-FAST MAGNETOSONIC WAVES OBSERVED BY SDO IN ACTIVE REGION FUNNELS

L. **Ofman**1,2,5, W. Liu3,4, A. Title3 and M. Aschwanden

2011 ApJ 740 L33

Recently, quasi-periodic, rapidly propagating waves have been observed in extreme ultraviolet by the Solar Dynamics Observatory/Atmospheric Imaging Assembly (AIA) instrument in about 10 flare/coronal mass ejection (CME) events thus far. A typical example is the **2010 August 1** C3.2 flare/CME event that exhibited arc-shaped wave trains propagating in an active region (AR) magnetic funnel with ~5% intensity variations at speeds in the range of 1000-2000 km s–1. The fast temporal cadence and high sensitivity of AIA enabled the detection of these waves. We identify them as fast magnetosonic waves driven quasi-periodically at the base of the flaring region and develop a three-dimensional MHD model of the event. For the initial state we utilize the dipole magnetic field to model the AR and include gravitationally stratified density at coronal temperature. At the coronal base of the AR, we excite the fast magnetosonic wave by periodic velocity pulsations in the photospheric plane confined to a funnel of magnetic field lines. The excited fast magnetosonic waves have similar amplitude, wavelength, and propagation speeds as the observed wave trains. Based on the simulation results, we discuss the possible excitation mechanism of the waves, their dynamical properties, and the use of the observations for coronal MHD seismology.

SDO/AIA OBSERVATION OF KELVIN–HELMHOLTZ INSTABILITY IN THE SOLAR CORONA

L. **Ofman**1,2,3 and B. J. Thompson

2011 ApJ 734 L11,

We present observations of the formation, propagation, and decay of vortex-shaped features in coronal images from the Solar Dynamics Observatory associated with an eruption starting at about 2:30 UT on **2010 April 8**. The series of vortices were formed along the interface between an erupting (dimming) region and the surrounding corona. They ranged in size from several to 10 arcsec and traveled along the interface at 6-14 km s–1. The features were clearly visible in six out of the seven different EUV wave bands of the Atmospheric Imaging Assembly. Based on the structure, formation, propagation, and decay of these features, we identified the event as the first observation of the Kelvin-Helmholtz instability (KHI) in the corona in EUV. The interpretation is supported by linear analysis and by a nonlinear 2.5-dimensional magnetohydrodynamic model of KHI. We conclude that the instability is driven by the velocity shear between the erupting and closed magnetic field of the coronal mass ejection. The shear-flow-driven instability can play an important role in energy transfer processes in coronal plasma.

Three-dimensional MHD Model of Wave Activity in a Coronal Active Region.

Ofman, L.,

2007. Astrophys. J. 655, 1134–1141.

Interaction of EIT Waves with Coronal Active Regions.
Ofman, L., Thompson, B.J.,
2002. Astrophys. J. 574, 440–452.

FILAMENT OSCILLATIONS AND MORETON WAVES ASSOCIATED WITH EIT WAVES
Takenori J. **Okamoto** et al. The Astrophysical Journal, 608:1124–1132, **2004, File**

Secondary Waves, and/or the "Reflection" From and "Transmission" Through a Coronal Hole of an EUV Wave Associated With the 2011 February 15 X2.2 Flare Observed With SDO/AIA and STEREO/EUVI

O. **Olmedo**, A. Vourlidas, J. Zhang, X. Cheng
E-print, July **2012**, ApJ, 756 143, **2012**
For the first time, the kinematic evolution of a coronal wave over the entire solar surface is studied. Full Sun maps can be made by combining images from the Solar Terrestrial Relations Observatory satellites, Ahead and Behind, and the Solar Dynamics Observatory, thanks to the wide angular separation between them. We study the propagation of a coronal wave, also known as "EIT" wave, and its interaction with a coronal hole resulting in secondary waves and/or reflection and transmission. We explore the possibility of the wave obeying the law of reflection of waves. In a detailed example we find that a loop arcade at the coronal hole boundary cascades and oscillates as a result of the EUV wave passage and triggers a wave directed eastwards that appears to have reflected. We find that the speed of this wave decelerates to an asymptotic value, which is less than half of the primary EUV wave speed. Thanks to the full Sun coverage we are able to determine that part of the primary wave is transmitted through the coronal hole. This is the first observation of its kind. The kinematic measurements of the reflected and transmitted wave tracks are consistent with a fast-mode MHD wave interpretation. Eventually, all wave tracks decelerate and disappear at a distance. A possible scenario of the whole process is that the wave is initially driven by the expanding coronal mass ejection and subsequently decouples from the driver and then propagates at the local fast-mode speed.

QUANTITATIVE MEASUREMENTS OF CORONAL MASS EJECTION-DRIVEN SHOCKS FROM LASCO OBSERVATIONS
Veronica **Ontiveros**[1,3] and Angelos Vourlidas
Astrophysical Journal, 693:267–275, **2009** March 1; **File**
In this paper, we demonstrate that coronal mass ejection (CME)-driven shocks can be detected in white light coronagraph images and in which properties such as the density compression ratio and shock direction can be measured. Also, their propagation direction can be deduced via simple modeling. We focused on CMEs during the ascending phase of solar cycle 23 when the large-scale morphology of the corona was simple. We selected events which were good candidates to drive a shock due to their high speeds ($V > 1500$ km s^{-1}). The final list includes 15 CMEs. For each event, we calibrated the LASCO data, constructed excess mass images, and searched for indications of faint and relatively sharp fronts ahead of the bright CME front. We found such signatures in 86% (13/15) of the events and measured the upstream/downstream densities to estimate the shock strength. Our values are in agreement with theoretical expectations and show good correlations with the CME kinetic energy and momentum. Finally, we used a simple forward modeling technique to estimate the threedimensional shape and orientation of the white light shock features.We found excellent agreement with the observed density profiles and the locations of the CME source regions. Our results strongly suggest that the observed brightness enhancements result from density enhancements due to a bow-shock structure driven by the CME.

A solar tornado triggered by flares?

N. K. **Panesar**, D. E. Innes, S. K. Tiwari, B. C. Low
E-print, Nov **2012; File**; A&A, 549, A105 (**2013**)
Solar tornados are dynamical, conspicuously helical magnetic structures mainly observed as a prominence activity. We investigate and propose a triggering mechanism for the solar tornado observed in a prominence cavity by SDO/AIA on **September 25, 2011**. High-cadence EUV images from the SDO/AIA and the Ahead spacecraft of STEREO/EUVI are used to correlate three flares in the neighbouring active-region (NOAA 11303), and their EUV waves, with the dynamical developments of the tornado. The timings of the flares and EUV waves observed on-disk in 195AA are analyzed in relation to the tornado activities observed at the limb in 171AA. Each of the three flares and its related EUV wave occurred within 10 hours of the onset of the tornado. They have an observed causal relationship with the commencement of activity in the prominence where the tornado develops. Tornado-like rotations along the side of the prominence start after the second flare. The prominence cavity expands with acceleration of tornado motion after the third flare. Flares in the neighbouring active region may have affected the cavity prominence system and triggered the solar tornado. A plausible mechanism is that the active-region coronal

field contracted by the `Hudson effect' due to the loss of magnetic energy as flares. Subsequently the cavity expanded by its magnetic pressure to fill the surrounding low corona. We suggest that the tornado is the dynamical response of the helical prominence field to the cavity expansion.

Study of Solar Energetic Particle Associations with Coronal Extreme-ultraviolet Waves

Jinhye **Park**1, D. E. Innes2, R. Bucik2,3, Y.-J. Moon1,4, and S. W. Kahler

2015 ApJ 808 3 **File**

https://www.academia.edu/35052617/STUDY_OF_SOLAR_ENERGETIC_PARTICLE_ASSOCIATIONS_WITH_CORONAL_EXTREME-ULTRAVIOLET_WAVES?email_work_card=view-paper

We study the relationship between large gradual solar energetic particle (SEP) events and associated extreme-ultraviolet (EUV) wave properties in 16 events that occurred between 2010 August and 2013 May and were observed by SDO, the Solar and Heliospheric Observatory (SOHO), and/or STEREO. We determine onset times, peak times, and peak fluxes of the SEP events in the SOHO/ERNE and STEREO/LET proton channels (6–10 MeV). The EUV wave arrival times and their speeds from the source sites to the spacecraft footpoints in the photosphere, which are magnetically connected to the spacecraft by Parker spiral and potential fields, are determined by spacetime plots from the full-Sun heliographic images created by combining STEREO-A andSTEREO-B 195 Å and SDO 193 Å images. The SEP peak fluxes increase with the EUV wave speeds, and the SEP spectral indices become harder with the speeds. This shows that higher energetic particle fluxes are associated with faster EUV waves, which are considered as the lateral expansions of coronal-mass-ejection-driven shocks in the low corona.

2010 August 14, 2012 May 26, 2012 July 18, 2012 August 31, 2013 March 15, 2013 April 11, 2013 May 13

Table 1 The Solar Sources of the SEP Events (2010-2013)

Table 2 Properties of the SEP Events and Associated EUV Wave

The Source Regions of Solar Energetic Particles Detected by Widely Separated Spacecraft

Jinhye **Park**1, D. E. Innes2, R. Bucik2, and Y.-J. Moon

2013 ApJ 779 184

We studied the source regions of 12 solar energetic particle (SEP) events seen between 2010 August and 2012 January at STEREO-A, B, and/or Earth (Advanced Composition Explorer/Solar and Heliospheric Observatory/GOES), when the two STEREO spacecraft were separated by about 180°. All events were associated with flares (C1 to X6) and fast coronal mass ejections and, except for one, accompanied by type II radio bursts. We have determined the arrival times of the SEPs at the three positions. **Extreme ultraviolet (EUV) waves**, observed in the 195 Å and 193 Å channels of STEREO and the Solar Dynamics Observatory, are tracked across the Sun to determine their arrival time at the photospheric source of open field lines connecting to the spacecraft. There is a good correlation between the EUV wave arrival times at the connecting footpoints and the SEP onset times. The delay time between electron onset and the EUV wave reaching the connecting footpoint is independent of distance from the flare site. The proton delay time increases with distance from the flare site. In three of the events, secondary flare sites may have also contributed to the wide longitudinal spread of SEPs.

On the Nature and Genesis of EUV Waves: A Synthesis of Observations from SOHO, STEREO, SDO, and Hinode Review

Spiros **Patsourakos** 1 _ Angelos Vourlidas

arXiv-print, **2012**; Solar Physics, Special Issue "The Sun in 360", November **2012**, Volume 281, Issue 1, pp 187-222**, File**

A major, albeit serendipitous, discovery of the SOlar and Heliospheric Observatory mission was the observation by the Extreme Ultraviolet Telescope (EIT) of large-scale Extreme Ultraviolet (EUV) intensity fronts propagating over a signi_cant fraction of the Sun's surface. These so-called EIT or EUV waves are associated with eruptive phenomena and have been studied intensely. However, their wave nature has been challenged by non-wave (or pseudo-wave) interpretations and the subject remains under debate. A string of recent solar missions has provided a wealth of detailed EUV observations of these waves bringing us closer to resolving their nature. With this review, we gather the current state-of-art knowledge in the field and synthesize it into a picture of an EUV wave driven by the lateral expansion of the CME. This picture can account for both wave and pseudo-wave interpretations of the observations, thus resolving the controversy over the nature of EUV waves to a large degree but not completely. We close with a discussion of several remaining open questions in the field of EUV waves research.

25 January 2007, 19 May 2007, 25 March 2008, 13 February 2009, 17 Janurary 2010, 3 April 2010, 10 April 2010, 13 June 2010, 27 July 2010, 14 August 2010, 15 February 2011, 16 February 2011 .

'EUV Waves' are Waves: First Quadrature Observations of an EUV Wave from STEREO

Spiros **Patsourakos**, Angelos Vourlidas

ApJL, 700, Number 2, L182-L186, **2009, File**

The nature of CME-associated low corona propagating disturbances, 'EUV waves', has been controversial since their discovery by EIT on SOHO. The low cadence, single viewpoint EUV images and the lack of simultaneous inner corona white light observations has hindered the resolution of the debate on whether they are true waves or just projections of the expanding CME. The operation of the twin EUV imagers and inner corona coronagraphs aboard STEREO has improved the situation dramatically. During early **2009**, the STEREO Ahead (STA) and Behind (STB) spacecraft observed the Sun in quadrature having an _ 90_ angular separation. An EUV wave and CME erupted from active region 11012, on **February 13**, when the region was exactly at the limb for STA and hence at disk center for STB. The STEREO observations capture the development of a CME and its accompanying EUV wave not only with high cadence but also in quadrature. The resulting unprecentented dataset allowed us to separate the CME structures from the EUV wave signatures and to determine without doubt the true nature of the wave. It is a fast-mode MHD wave after all!

What is the Nature of EUV Waves? First STEREO 3D Observations and Comparison with Theoretical Models

Patsourakos, S.; Vourlidas, A.; Wang, Y. -M.; Stenborg, G.; Thernisien, A.

E-print, May 2009**;** Solar Phys. (**2009**) 259: 49–71, **File**

One of the major discoveries of the Extreme ultraviolet Imaging Telescope (EIT) on SOHO were intensity enhancements propagating over a large fraction of the solar surface. The physical origin(s) of the so-called `EIT' waves is still strongly debated. They are considered to be either wave (primarily fast-mode MHD waves) or non-wave (pseudo-wave) interpretations. The difficulty in understanding the nature of EUV waves lies with the limitations of the EIT observations which have been used almost exclusively for their study. They suffer from low cadence, and single temperature and viewpoint coverage. These limitations are largely overcome by the SECCHI/EUVI observations on-board the STEREO mission. The EUVI telescopes provide high cadence, simultaneous multi-temperature coverage, and two well-separated viewpoints. We present here the first detailed analysis of an EUV wave observed by the EUVI disk imagers on **December 07, 2007** when the STEREO spacecraft separation was $approx 45^circ$. Both a small flare and a CME were associated with the wave. We also offer the first comprehensive comparison of the various wave interpretations against the observations. Our major findings are: (1) high-cadence (2.5 min) 171AA, images showed a strong association between expanding loops and the wave onset and significant differences in the wave appearance between the two STEREO viewpoints during its early stages; these differences largely disappeared later, (2) the wave appears at the active region periphery when an abrupt disappearance of the expanding loops occurs within an interval of 2.5 minutes, (3) almost simultaneous images at different temperatures showed that the wave was most visible in the 1-2 MK range and almost invisible in chromospheric/transition region temperatures, (4) triangulations of the wave indicate it was rather low-lying ($approx$90 Mm above the surface), (5) forward-fitting of the corresponding CME as seen by the COR1 coronagraphs showed that the projection of the best-fit model on the solar surface was not consistent with the location and size of the co-temporal EUV wave and (6) simulations of a fast-mode wave were found in a good agreement with the overall shape and location of the observed wave. Our findings give significant support for a fast-mode interpretation of EUV waves and indicate that they are probably triggered by the rapid expansion of the loops associated with the CME.

Emerging Dimming as Coronal Heating Episodes

Anna V. **Payne**, Xudong Sun

ApJ **912** 1 **2021**

https://arxiv.org/pdf/2103.09087.pdf

https://doi.org/10.3847/1538-4357/abee8d

Emerging dimming occurs in isolated solar active regions (ARs) during the early stages of magnetic flux emergence. Observed by the Atmospheric Imaging Assembly, it features a rapid decrease in extreme-ultraviolet (EUV) emission in the 171 Å channel images, and a simultaneous increase in the 211 Å images. Here, we analyze the coronal thermodynamic and magnetic properties to probe its physical origin. We calculate the time-dependent differential emission measures for a sample of 18 events between 2010 and 2012. The emission measure (EM) decrease in the temperature range 5.7≤log10T≤5.9 is well correlated with the EM increase in 6.2≤log10T≤6.4 over eight orders of magnitude. This suggests that the coronal plasma is being heated from the quiet-Sun, sub-MK temperature to 1-2 MK, more typical for ARs. Potential field extrapolation indicates significant change in the local magnetic connectivity: the dimming region is now linked to the newly emerged flux via longer loops. We conclude that

emerging dimming is likely caused by coronal heating episodes, powered by reconnection between the emerging and the ambient magnetic fields. **11-12 Sep 2012**
Table 1. Thermodynamic properties of all 18 emerging dimming events analyzed in this work.

The Coupling of an EUV Coronal Wave and Ion Acceleration in a Fermi-LAT Behind-the-Limb Solar Flare

Melissa **Pesce-Rollins**1, Nicola Omodei2, Säm Krucker3, Niccolò Di Lalla4, Wen Wang5,6, Andrea F. Battaglia5, Alexander Warmuth7, Astrid M. Veronig8, and Luca Baldini9
2022 ApJ 929 172
https://iopscience.iop.org/article/10.3847/1538-4357/ac5f0c/pdf
We present the Fermi-LAT observations of the behind-the-limb (BTL) flare of **2021 July 17** and the joint detection of this flare by STIX on board the Solar Orbiter. The separation between Earth and the Solar Orbiter was 99°.2 at 05:00 UT, allowing STIX to have a front view of the flare. The location of the flare was S20E140 in Stonyhurst heliographic coordinates, making this the most distant behind-the-limb flare ever detected in >100 MeV gamma-rays. The LAT detection lasted for ∼16 minutes, the peak flux was 3.6 ± 0.8 (10^{-5}) ph cm^{-2} s^{-1} with a significance >15σ. A coronal wave was observed from both STEREO-A and SDO in extreme ultraviolet (EUV), with an onset on the visible disk in coincidence with the LAT onset. A complex type II radio burst was observed by GLOSS also in coincidence with the onset of the LAT emission, indicating the presence of a shock wave. We discuss the relation between the time derivative of the EUV wave intensity profile at 193 Å as observed by STEREO-A and the LAT flux to show that the appearance of the coronal wave at the visible disk and the acceleration of protons as traced by the observed >100 MeV gamma-ray emission are coupled. We also report how this coupling is present in the data from three other BTL flares detected by Fermi-LAT, suggesting that the protons driving the gamma-ray emission of BTL solar flares and the coronal wave share a common origin.

Effects of different coronal hole geometries on simulations of the interaction between coronal waves and coronal holes

I. **Piantschitsch**1,2,3, J. Terradas1,2, E. Soubrie2,4, S. G. Heinemann5, S. J. Hofmeister6, R. Soler1,2 and M. Temmer3
A&A, 687, A200 (**2024**)
https://www.aanda.org/articles/aa/pdf/2024/07/aa48003-23.pdf
The geometry of a coronal hole (CH) affects the density profile of the reflected part of an incoming global coronal wave (CW). In this study, we perform for the first time magnetohydrodynamic (MHD) simulations of fast-mode MHD waves that interact with CHs of different geometries, such as circular, elliptic, convex, and concave shapes. We analysed the effect of these geometries on the density profiles of the reflected waves, and we generated the corresponding simulation-based time-distance plots. Within these time-distance plots, we determined regions that exhibit specific density features, such as large reflected density amplitudes. In a further step, these interaction features can be compared to actual observed CW–CH interaction events, which will enable us to explain interaction parameters of the observed interaction events, such as the density structure of the reflected wave. These parameters are usually difficult to understand comprehensively based on an analysis of the measurements alone. Moreover, we show that the interaction between a concave CH and CWs, whose density profile includes an enhanced as well as a depleted wave part, can lead to reflected density amplitudes that are more than twice larger than the incoming density amplitudes. Another effect of the interplay between the constructive and destructive interference of the reflected wave parts is a strongly depleted region in the middle of the CW–CH interaction process. In addition, we show that the choice of the path that is used to generate the time-distance plots is important and that this choice affects the interpretation of the CW–CH interaction results.

Role of initial density profiles in simulations of coronal wave-coronal hole interactions★

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A&A 679, A136 (**2023**)
https://arxiv.org/pdf/2308.08928.pdf
https://www.aanda.org/articles/aa/pdf/2023/11/aa46871-23.pdf
Interactions between global coronal waves (CWs) and coronal holes (CHs) reveal many interesting features of reflected waves and coronal hole boundaries (CHB). However, such interactions have scarcely been studied thus far. Magnetohydrodynamic (MHD) simulations can help us to better understand what is happening during these interaction events and thus to achieve a broader understanding of the parameters involved. In this study, we performed the first 2D MHD simulations of a CW–CH interaction that include a realistic initial wave density profile consisting of an enhanced wave component as well as a depleted one. We varied several initial parameters, such as the initial density amplitudes of the incoming wave, the CH density, and the CHB width, which are all based on

actual measurements. We analysed the effects of different incident angles on the interaction features and we used the corresponding time-distance plots to detect specific features of the incoming and the reflected waves. We found that the specific combination of a small CH density, a realistic initial density profile, and a sufficiently small incident angle can lead to remarkable interaction features, such as a large density amplitude for the reflected wave and greater phase speed for the reflected wave with respect to the incoming one. The parameter studies in this paper provide a tool for comparing time-distance plots based on observational measurements to those created from simulations. This has enabled us to derive interaction parameters from observed CW–CH interaction events that usually cannot be obtained directly. The simulation results in this study are augmented by analytical expressions for the reflection coefficient of the CW–CH interaction, which allows us to verify the simulations results in an complementary way. This work, with its focus on parameter studies that examine the initial density profile of CWs, is the first of a series of studies aiming to ultimately reconstruct actual observed CW–CH interaction events by means of MHD simulations. These results improve our understanding of the involved interaction parameters in a comprehensive way.

Geometrical properties of the interaction between oblique incoming coronal waves and coronal holes

I. **Piantschitsch**, J. Terradas

A&A 651, A67 **2021**

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https://www.aanda.org/articles/aa/pdf/2021/07/aa40182-20.pdf

Observations of coronal waves (CWs) interacting with coronal holes (CHs) show the formation of typical wave-like features, such as reflected, refracted and transmitted waves (collectively, secondary waves). In accordance with these observations, numerical evidence for the wave characteristics of CWs is given by simulations which demonstrate effects of deflection and reflection when a CW interacts with regions exhibiting a sudden density drop, such as CHs. However, secondary waves are usually weak in their signal and simulations are limited in the way the according idealisations have to be chosen. Hence, several properties of the secondary waves during a CW-CH interaction are unclear or ambiguous and might lead to misinterpretations. In this study we follow a theoretical approach and focus in particular on the geometrical properties of secondary waves caused by the interaction between oblique incoming CWs and CHs. Based on a linear theory, we derive analytical expressions for reflection and transmission coefficients, which tell us how strongly the amplitudes of the secondary waves increase and decrease with respect to the incoming wave, respectively. Additionally, we provide analytical terms for crucial incidence angles that are capable of giving information about the energy flux, the phase and the reflection properties of the secondary waves. These novel expressions provide a supplementary tool for estimating CW properties in a fast and straightforward way and, therefore, might have relevant consequences for a possible new interpretation of already studied CW-CH interaction events and the clarification of ambiguous observational data.

A new method for estimating global coronal wave properties from their interaction with solar coronal holes

I. **Piantschitsch**, J. Terradas, M. Temmer

A&A 641, A21 **2020**

https://arxiv.org/pdf/2006.07293.pdf

https://doi.org/10.1051/0004-6361/202038182

Global coronal waves (CWs) and their interaction with coronal holes (CHs) result, among other effects, in the formation of reflected and transmitted waves. Observations of such events provide us with measurements of different CW parameters, such as phase speed and intensity amplitudes. However, several of these parameters are provided with only intermediate observational quality, other parameters, such as the phase speed of transmitted waves, can hardly be observed in general. We present a new method to estimate crucial CW parameters, such as density and phase speed of reflected as well as transmitted waves, Mach numbers and density values of the CH's interior, by using analytical expressions in combination with basic and most accessible observational measurements. The transmission and reflection coefficients are derived from linear theory and subsequently used to calculate estimations for phase speeds of incoming, reflected and transmitted waves. The obtained analytical expressions are validated by performing numerical simulations of CWs interacting with CHs. This new method enables to determine in a fast and straightforward way reliable CW and CH parameters from basic observational measurements which provides a powerful tool to better understand the observed interaction effects between CWs and CHs. **January 27, 2011, 2011 February 15**

Numerical Simulation of Coronal Waves Interacting with Coronal Holes. III. Dependence on Initial Amplitude of the Incoming Wave

Isabell **Piantschitsch**1, Bojan Vršnak2, Arnold Hanslmeier1, Birgit Lemmerer1, Astrid Veronig1, Aaron Hernandez-Perez1, and Jaša Čalogović2
2018 ApJ 860 24
http://sci-hub.tw/10.3847/1538-4357/aabe7f
https://arxiv.org/pdf/1811.12735.pdf
We performed 2.5D magnetohydrodynamic (MHD) simulations showing the propagation of fast-mode MHD waves of different initial amplitudes and their interaction with a coronal hole (CH), using our newly developed numerical code. We find that this interaction results in, first, the formation of reflected, traversing, and transmitted waves (collectively, secondary waves) and, second, in the appearance of stationary features at the CH boundary. Moreover, we observe a density depletion that is moving in the opposite direction of the incoming wave. We find a correlation between the initial amplitude of the incoming wave and the amplitudes of the secondary waves as well as the peak values of the stationary features. Additionally, we compare the phase speed of the secondary waves and the lifetime of the stationary features to observations. Both effects obtained in the simulation, the evolution of secondary waves, as well as the formation of stationary fronts at the CH boundary, strongly support the theory that coronal waves are fast-mode MHD waves.

Numerical Simulation of Coronal Waves Interacting with Coronal Holes. II. Dependence on Alfvén Speed Inside the Coronal Hole

Isabell **Piantschitsch**, Bojan Vršnak, Arnold Hanslmeier, Birgit Lemmerer, Astrid Veronig, Aaron Hernandez-Perez, and Jaša Čalogović
2018 ApJ 857 130
http://sci-hub.tw/10.3847/1538-4357/aab709
https://arxiv.org/pdf/1811.12726.pdf
We used our newly developed magnetohydrodynamic (MHD) code to perform 2.5D simulations of a fast-mode MHD wave interacting with coronal holes (CHs) of varying Alfvén speed that result from assuming different CH densities. We find that this interaction leads to effects like reflection, transmission, stationary fronts at the CH boundary, and the formation of a density depletion that moves in the opposite direction to the incoming wave. We compare these effects with regard to the different CH densities and present a comprehensive analysis of morphology and kinematics of the associated secondary waves. We find that the density value inside the CH influences the phase speed and the amplitude values of density and magnetic field for all different secondary waves. Moreover, we observe a correlation between the CH density and the peak values of the stationary fronts at the CH boundary. The findings of reflection and transmission on the one hand and the formation of stationary fronts caused by the interaction of MHD waves with CHs on the other hand strongly support the theory that large-scale disturbances in the corona are fast-mode MHD waves.

A Numerical Simulation of Coronal Waves Interacting with Coronal Holes. I. Basic Features

Isabell **Piantschitsch**1, Bojan Vršnak2, Arnold Hanslmeier1, Birgit Lemmerer1, Astrid Veronig1, Aaron Hernandez-Perez1, Jaša Čalogović2, and Tomislav Žic3
2017 ApJ 850 88
http://sci-hub.cc/http://iopscience.iop.org/0004-637X/850/1/88/
https://arxiv.org/pdf/1811.12073.pdf
We have developed a new numerical code that is able to perform 2.5D simulations of a magnetohydrodynamic (MHD) wave propagation in the corona, and its interaction with a low-density region, such as a coronal hole (CH). We show that the impact of the wave on the CH leads to different effects, such as reflection and transmission of the incoming wave, stationary features at the CH boundary, or formation of a density depletion. We present a comprehensive analysis of the morphology and kinematics of primary and secondary waves, i.e., we describe in detail the temporal evolution of density, magnetic field, plasma flow velocity, phase speed, and position of the wave amplitude. Effects like reflection, refraction, and transmission of the wave strongly support the theory that large-scale disturbances in the corona are fast MHD waves and distinguish that theory from the competing pseudo-wave theory. The formation of stationary bright fronts was one of the main reasons for the development of pseudo-waves. Here, we show that stationary bright fronts can be produced by interactions of an MHD wave with a CH. We find secondary waves that are traversing through the CH and we show that one part of these traversing waves leaves the CH again, while another part is being reflected at the CH boundary inside the CH. We observe a density depletion that is moving in the opposite direction of the primary wave propagation. We show that the primary wave pushes the CH boundary to the right, caused by the wave front exerting dynamic pressure on the CH.

On the Disk Hα and Radio Observations of the 2003 October 28 Flare and Coronal Mass

Ejection Event.
Pick, M., Malherbe, J., Kerdraon, A., Maia, D.J.F.,
2005. Astrophys. J. 631, L97–L100.

A center-median filtering method for detection of temporal variation in coronal images
Joseph **Plowman***
J. Space Weather Space Clim., 6, A8 (**2016**)
http://www.swsc-journal.org/articles/swsc/pdf/2016/01/swsc150009.pdf
http://arxiv.org/pdf/1511.04481v1.pdf
Events in the solar corona are often widely separated in their timescales, which can allow them to be identified when they would otherwise be confused with emission from other sources in the corona. Methods for cleanly separating such events based on their timescales are thus desirable for research in the field. This paper develops a technique for identifying time-varying signals in solar coronal image sequences which is based on a per-pixel running median filter and an understanding of photon-counting statistics. Example applications to "EIT waves" (named after EIT, the EUV Imaging Telescope on the Solar and Heliospheric Observatory) and small-scale dynamics are shown, both using 193 Å data from the Atmospheric Imaging Assembly (AIA) on the Solar Dynamics Observatory. The technique is found to discriminate EIT waves more cleanly than the running and base difference techniques most commonly used. It is also demonstrated that there is more signal in the data than is commonly appreciated, finding that the waves can be traced to the edge of the AIA field of view when the data are rebinned to increase the signal-to-noise ratio. **2013-04-11**

Three-part structure of solar coronal mass ejection observed in low coronal signatures of Solar Orbiter
Tatiana **Podladchikova**, Shantanu Jain, Astrid M. Veronig, Stefan Purkhart, Galina Chikunova, Karin Dissauer, Mateja Dumbovic
Publication in Astronomy and Astrophysics **2024**
?A&A 2024
https://arxiv.org/pdf/2410.20603
This study examines the relationship between early solar coronal mass ejection (CME) propagation, the associated filament eruption, and coronal dimming in the rare event observed on **March 28, 2022**, which featured a three-part CME in the low corona of active region AR 12975, including a bright core/filament, dark cavity, and bright front edge. We employ 3D filament and CME shock reconstructions using data from SolO, STEREO-A, and SDO to track the filament's path, height, and kinematics. Our analysis across three viewpoints shows the outer front in SolO/EUI 304 Å aligns with shock structures in STEREO-A/EUVI 195 Å, showing a full 3D EUV wave dome, later matching the outer CME front in STEREO-A COR2. We introduce the method ATLAS-3D (Advanced Technique for single Line-of-sight Acquisition of Structures in 3D) and validate it against traditional approaches to reconstruct CME shock using SOLO data exclusively. Additionally, we estimate early CME propagation characteristics based on coronal dimming evolution with the DIRECD method. Results indicate that the filament height increased from 28 to 616 Mm (0.04 to 0.89 Rs) within 30 minutes (11:05 to 11:35 UT), reaching peak velocity of around 648 km/s and acceleration of around 1624 m/s2. At 11:45 UT, the filament deflected by 12° to a height of 841 Mm (1.21 Rs), while the CME shock expanded from 383 to 837 Mm (0.55 to 1.2 Rs) over 10 minutes. Key parameters include a CME direction inclined by 6°, a 21° half-width, and a 1.12 Rs cone height at the dimming's impulsive phase end. This event demonstrates that expanding dimming correlates with early CME development, with the DIRECD method linking 2D dimming to 3D CME evolution. These insights underscore the value of multi-viewpoint observations and advanced reconstructions for improving space weather forecasting.

3D reconstructions of EUV wave front heights and their influence on wave kinematics
Tatiana **Podladchikova**, Astrid M. Veronig, Karin Dissauer, Manuela Temmer, Olena Podladchikova
ApJ **877** 68 **2019**
https://arxiv.org/pdf/1904.09427.pdf
sci-hub.se/10.3847/1538-4357/ab1b3a
EUV waves are large-scale disturbances in the solar corona initiated by coronal mass ejections. However, solar EUV images show only the wave fronts projections along the line-of-sight of the spacecraft. We perform 3D reconstructions of EUV wave front heights using multi-point observations from STEREO-A and STEREO-B, and study their evolution to properly estimate the EUV wave kinematics. We develop two different methods to solve the matching problem of the EUV wave crest on pairs of STEREO-A/-B images by combining epipolar geometry with the investigation of perturbation profiles. The proposed approaches are applicable at the early and maximum stage of the event when STEREO-A/-B see different facets of the EUV wave, but also at the later stage when the wave front becomes diffusive and faint. The techniques developed are demonstrated on two events observed at different separation of the STEREO spacecraft (42∘ and 91∘). For the **7 December 2007** event, we find that the emission of the EUV wave front mainly comes from a height range up to 90-104 Mm, decreasing later to 7-35 Mm. Including

the varying height of the EUV wave front allows us to correct the wave kinematics for the projection effects, resulting in velocities in the range 217-266 km/s. For the **13 February 2009** event, the wave front height doubled from 54 to 93 Mm over 10 min, and the velocity derived is 205-208 km/s. In the two events under study, the corrected speeds differ by up to 25% from the uncorrected ones, depending on the wave front height evolution.

Recent Developments of NEMO: Detection of EUV Wave Characteristics

O. **Podladchikova**, A. Vuets, P. Leontiev and R. A. M. Van der Linden

Solar Physics, Volume 276, Numbers 1-2, 479-490, **2012, File**

Recent developments in space instrumentation for solar observations and increased telemetry have necessitated the creation of advanced pattern recognition tools for different classes of solar events. The Extreme Ultraviolet Imaging Telescope (EIT) onboard the SOHO spacecraft has uncovered a new class of eruptive events on the solar disk, which are often identified as signatures of the initiation of coronal mass ejections (CMEs). The development of an automatic detection tool of these signatures is an important task. The **Novel EIT Wave Machine Observing (NEMO)** code (**http://sidc.be/nemo**) is an operational tool that automatically detects EUV waves using a sequence of EUV images. NEMO applies techniques based on the general statistical properties of the underlying physical mechanisms of eruptive events. Originally, the technique was applied to images taken with the EIT telescope. In this work, the most recent updates of the NEMO code are presented. These updates include calculations of the area of the dimming region, a novel clustering technique for the extraction of dimming regions, and new criteria to identify eruptive dimmings based on their complex characteristics. The efficiency of NEMO has been significantly increased and now permits the extraction of dimming regions observed near the solar limb and also the detection of small-scale events. Furthermore, the catalogs of solar eruptive events based on the updated NEMO may include a larger number of physical parameters associated with the dimming regions.

EXTREME ULTRAVIOLET OBSERVATIONS AND ANALYSIS OF MICRO-ERUPTIONS AND THEIR ASSOCIATED CORONAL WAVES

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Astrophysical Journal, 709:369–376, **2010** January, **File**

The Solar Terrestrial Relations Observatory EUV telescopes have uncovered small-scale eruptive events, tentatively referred to as “mini-CMEs” because they exhibit morphologies similar to large-scale coronal mass ejections (CMEs). Coronal waves and widespread diffuse dimmings followed by the expansion of the coronal waves are the most brightly manifestations of large-scale CMEs. The high temporal and spatial resolution of the EUV data allows us to detect and analyze these eruptive events, to resolve their fine structure, and to show that the observed “mini-waves” have a strong similarity to the large-scale “EIT’ waves. Here, we analyze a micro-event observed on **2007 October 17** by the Sun Earth Connection Coronal and Heliospheric Investigation EUV Imager (EUVI) in 171 Å (Fe ix) with a 2.5 minute cadence. The mini-CME differs from its large-scale counterparts by having smaller geometrical size, a shorter lifetime, and reduced intensity of coronal wave and dimmings. The small-scale coronal wave develops from micro-flaring sites and propagate up to a distance of 40,000 km in a wide angular sector of the quiet Sun over 20 minutes. The area of the small-scale dimming is two orders of magnitude smaller than for large-scale events. The average speed of the small-scale coronal wave studied is 14 km s^{-1}. Our observations give strong indications that small-scale EUV coronal waves associated with the micro-eruptions propagate in the form of slow mode waves almost perpendicular to the background magnetic field.

Automated Detection Of Eit Waves And Dimmings.

Podladchikova, O., Berghmans, D.,

2005. Solar Phys. 228, 265–284.

Radio Bursts and Pulsations in Association with Flare, Ejecta, and Propagating Shock Waves

S. **Pohjolainen** · K. Hori · T. Sakurai

Solar Phys, 253: 291–303, **2008**, DOI 10.1007/s11207-008-9260-2; **File**

We investigate coronal transients associated with a GOES M6.7 class flare and a coronal mass ejection (CME) on **13 July 2004.** During the rising phase of the flare, a filament eruption, loop expansion, a Moreton wave, and an ejecta were observed. An EIT wave was detected later on. The main features in the radio dynamic spectrum were a frequency-drifting continuum and two type II bursts. Our analysis shows that if the first type II burst was formed in the low corona, the burst heights and speed are close to the projected distances, and speed of the Moreton wave (a chromospheric shock wave signature). The frequency drifting radio continuum, starting above 1 GHz, was formed almost two minutes prior to any shock features becoming visible, and a fast-expanding piston (visible as the continuum) could have launched another shock wave. A possible scenario is that a flare blast overtook the earlier transient and ignited the first type II burst. The second type II burst may have been formed by the same shock, but only if the shock was propagating at a constant speed.

This interpretation also requires that the shock-producing regions were located at different parts of the propagating structure or that the shock was passing through regions with highly different atmospheric densities. This complex event, with a multitude of radio features and transients at other wavelengths, presents evidence for both blast-wave-related and CME related radio emissions.

Early signatures of large-scale field line opening. Multi-wavelength analysis of features connected with a "halo" CME event,
Pohjolainen, S., Vilmer, N., Khan, J. I., and Hillaris, A. E.:
Astron. Astrophys., 434, 329–341, doi:10.1051/0004-6361:20041378, **2005**.

On-the-Disk Development of the Halo Coronal Mass Ejection on 1998 May 2,
Pohjolainen, S., Maia, D., Pick, M., Vilmer, N., Khan, J. I., Otruba, W., Warmuth, A., Benz, A., Alissandrakis, C., and Thompson, B. J.:
Astrophys. J., 556, 421–431, doi: 10.1086/321577, **2001**.

MHD modeling of coronal large-amplitude waves related to CME lift-off,
Pomoell, J., Vainio, R., and Kissmann, R.:
E-print, March **2008**, **File**; Solar Phys., 253: 249–261, **2008**.
We have employed a two-dimensional magnetohydrodynamic simulation code to study mass motions and large-amplitude coronal waves related to the lift-off of a coronal mass ejection (CME). The eruption of the filament is achieved by an artificial force acting on the plasma inside the flux rope. By varying the magnitude of this force, the reaction of the ambient corona to CMEs with different acceleration profiles can be studied. Our model of the ambient corona is gravitationally stratified with a quadrupolar magnetic field, resulting in an ambient Alfvén speed that increases as a function of height, as typically deduced for the low corona. The results of the simulations show that the erupting flux rope is surrounded by a shock front, which is strongest near the leading edge of the erupting mass, but also shows compression near the solar surface. For rapidly accelerating filaments, the shock front forms already in the low corona. Although the speed of the driver is less than the Alfvén speed near the top of the atmosphere, the shock survives in this region as well, but as a freely propagating wave. The leading edge of the shock becomes strong early enough to drive a metric type II burst in the corona. The speed of the weaker part of the shock front near the surface is lower corresponding to the magnetosonic speed there. We analyze the (line-of-sight) emission measure of the corona during the simulation and recognize a wave receding from the eruption site, which strongly resembles EIT waves in the low corona. Behind the EIT wave, we clearly recognize a coronal dimming, also observed during CME lift-off. We point out that the morphology of the hot downstream region of the shock would be that of a hot erupting loop, so care has to be taken not to misinterpret soft X-ray imaging observations in this respect. Finally, the geometry of the magnetic field around the erupting mass is analyzed in terms of precipitation of particles accelerated in the eruption complex. Field lines connected to the shock are further away from the photospheric neutral line below the filament than the field lines connected to the current sheet below the flux rope. Thus, if the DC fields in the current sheet accelerate predominantly electrons and the shock accelerates ions, the geometry is consistent with recent observations of gamma rays being emitted further out from the neutral line than hard X-rays.

Magnetohydrodynamic Simulation of Magnetic Null-point Reconnections and Coronal dimmings during the X2.1 flare in NOAA AR 11283
Avijeet **Prasad**, Karin Dissauer, Qiang Hu, R. Bhattacharyya, Astrid M. Veronig, Sanjay Kumar, Bhuwan Joshi
ApJ **903** 129 **2020**
https://arxiv.org/pdf/2009.11109.pdf
https://doi.org/10.3847/1538-4357/abb8d2
The magnetohydrodynamics of active region NOAA 11283 is simulated using an initial non-force-free magnetic field extrapolated from its photospheric vector magnetogram. We focus on the magnetic reconnections at a magnetic null point that participated in the X2.1 flare on **2011 September 6** around 22:21 UT (SOL2011-09-06T22:21X2.1) followed by the appearance of circular flare ribbons and coronal dimmings. The initial magnetic field from extrapolation displays a three-dimensional (3D) null topology overlying a sheared arcade. Prior to the flare, magnetic loops rise due to the initial Lorentz force, and reconnect at the 3D null, leading to expansion and loss of confined plasma that produce the observed pre-flare coronal dimmings. Further, the simulated dynamics documents the transfer of twist from the arcade to the overlying loops through reconnections, developing a flux rope. The non-parallel field lines comprising the rope and lower-lying arcades form an X-type geometry. Importantly, the simultaneous reconnections at the 3D null and the X-type geometry can explain the observed circular and parallel flare ribbons. Reconnections at the 3D null transform closed inner spine field lines into open field lines of the outer

spine. The footpoints of these open field lines correspond to a ring-shaped coronal dimming region, tracing the dome. Further, the flux rope bifurcates because of these reconnections which also results in the generation of open magnetic field lines. The plasma loss along the open field lines can potentially explain the observed coronal dimming.

An Investigation of the CME of 3 November 2011 and Its Associated Widespread Solar Energetic Particle Event

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Solar Physics, May **2014**, Volume 289, Issue 5, pp 1731-1744

http://arxiv.org/pdf/1312.2965v1.pdf

Multi-spacecraft observations are used to study the in-situ effects of a large coronal mass ejection (CME) erupting from the farside of the Sun on 3 November 2011, with particular emphasis on the associated solar energetic particle (SEP) event. At that time both Solar Terrestrial Relations Observatory (STEREO) spacecraft were located more than 90 degrees from Earth and could observe the CME eruption directly, with the CME visible on-disk from STEREO-B and off the limb from STEREO-A. Signatures of pressure variations in the corona such as deflected streamers were seen, indicating the presence of a coronal shock associated with this CME eruption. The evolution of the CME and an associated extreme-ultraviolet (EUV) wave were studied using EUV and coronagraph images. It was found that the lateral expansion of the CME low in the corona closely tracked the propagation of the **EUV wave**, with measured velocities of 240±19 km s−1 and 221±15 km s−1 for the CME and wave, respectively. Solar energetic particles were observed to arrive first at STEREO-A, followed by electrons at the Wind spacecraft at L1, then STEREO-B, and finally protons arrived simultaneously at Wind and STEREO-B. By carrying out a velocity-dispersion analysis on the particles arriving at each location, it was found that energetic particles arriving at STEREO-A were released first and that the release of particles arriving at STEREO-B was delayed by about 50 minutes. Analysis of the expansion of the CME to a wider longitude range indicates that this delay is a result of the time taken for the CME edge to reach the footpoints of the magnetic-field lines connected to STEREO-B. The CME expansion is not seen to reach the magnetic footpoint of Wind at the time of solar-particle release for the particles detected here, suggesting that these particles may not be associated with this CME.

Gradual Solar Coronal Dimming and Evolution of Coronal Mass Ejectionin the Early Phase

Jiong **Qiu**1 and Jianxia Cheng

2017 ApJL 838 L6   DOI 10.3847/2041-8213/aa6798

http://sci-hub.cc/10.3847/2041-8213/aa6798

Weak gradual dimming persists for more than half an hour before the onset of the two-ribbon flare and the fast rise of the CME. It is followed by abrupt rapid dimming. The two-stage dimming occurs in a pair of conjugate dimming regions adjacent to the two flare ribbons, and the flare onset marks the transition between the two stages of dimming. At the onset of the two-ribbon flare, transient brightenings are also observed inside the dimming regions, before rapid dimming occurs at the same places. These observations suggest that the CME structure, most probably anchored at the twin dimming regions, undergoes a slow rise before the flare onset, and its kinematic evolution has significantly changed at the onset of flare reconnection. We explore diagnostics of the CME evolution in the early phase with analysis of the gradual dimming signatures prior to the CME eruption. **2011 December 26**

ON THE MAGNETIC FLUX BUDGET IN LOW-CORONA MAGNETIC RECONNECTION AND INTERPLANETARY CORONAL MASS EJECTIONS

Jiong **Qiu**,1 Qiang Hu,2 Timothy A. Howard,1 and Vasyl B. Yurchyshyn3

The Astrophysical Journal, 659:758Y772, **2007**

We present the first quantitative comparison between the total magnetic reconnection flux in the low corona in the wake of coronal mass ejections (CMEs) and the magnetic flux in magnetic clouds (MCs) that reach 1 AU 2Y3 days after CME onset. The total reconnection flux is measured from flare ribbons, and theMC flux is computed using in situ observations at 1 AU, all ranging from 10^{20} to 10^{22} Mx. It is found that for the nine studied events in which the association between flares, CMEs, and MCs is identified, the MC flux is correlated with the total reconnection flux $\_{r}$. Further, the poloidal (azimuthal) MC flux $\_{p}$ is comparable with the reconnection flux $\_{r}$, and the toroidal (axial) MC flux $\_{t}$ is a fraction of $\_{r}$. Events associated with filament eruption do not exhibit a different $\_{t,\,p}$-$\_{r}$ relation from events not accompanied by erupting filaments. The relations revealed between these independently measured physical quantities suggest that for the studied samples, the magnetic flux and twist of interplanetary magnetic flux ropes, reflected by MCs, are highly relevant to low-corona magnetic reconnection during the eruption.We discuss the implications of this result for the formation mechanism of twisted magnetic flux ropes, namely, whether the helical structure of the magnetic flux rope is largely pre-existing or formed in situ by low-corona magnetic reconnection. **We also measure magnetic flux encompassed in coronal dimming regions ($\_{d}$) and discuss its relation to the reconnection flux inferred from flare ribbons and MC flux.**

THE RELATIONSHIP BETWEEN CORONAL DIMMING AND CORONAL MASS EJECTION PROPERTIES

A. A. **Reinard**[1,3] and D. A. Biesecker[2]

Astrophysical Journal, 705:914–919, **2009, File**

Coronal dimmings are closely related to the footpoints of coronal mass ejections (CMEs) and, as such, offer information about CME origins and evolution. In this paper, we investigate the relationship between CME and dimming properties. In particular, we compare CME quantities for events with and without associated dimmings. We find that dimming-associated CMEs, on average, have much higher speeds than non-dimming-associated events. In fact, CMEs without an associated dimming do not appear to travel faster than 800 km s^{-1}, i.e., the fast solar wind speed. Dimming-associated events are also more likely to be associated with flares, and those flares tend to have the highest magnitudes. We propose that each of these phenomena is affected by the energy available in the source region. Highly energetic source regions produce fast CMEs that are accompanied by larger flares and visible dimmings, while less energetic source regions produce slow CMEs that are accompanied by smaller flares and may or may not have dimmings. The production of dimmings in the latter case may depend on a number of factors including initiation height of the CME, source region magnetic configuration, and observational effects. These results have important implications for understanding and predicting CME initiations.

CORONAL MASS EJECTION-ASSOCIATED CORONAL DIMMINGS

A. A. **Reinard**, D. A. Biesecker,

The Astrophysical Journal, 674:576-585, **2008, File**

We report on a statistical analysis of 96 CME-associated EUV coronal dimmings between 1998 and 2000. We investigate the size and location of the events and characterize how these events evolve with time. The durations typically range from 3 to 12 hr. The dimmings appear most frequently within the belt of active regions (20_-50_ latitude). Dimming events are generally symmetric in latitude and longitude with some tendency to be broader in latitude. The temporal profiles of most events are characterized by a sharp rise and a gradual recovery. Although the majority of cases are well fit by a single recovery slope, a large minority of events have a two-part decay with an initial decaying slope that is similar in magnitude to the rising slope and a secondary, flatter, decay lasting several hours.

Tracking the motion of a shock along a channel in the low solar corona

J. **Rigney** (1 and 2 and 3), P. T. Gallagher (1), G. Ramsay (2), J. G. Doyle (2), D. M. Long (4 and3), O. Stepanyuk (5), K. Kozarev (5)

A&A **2024**

https://arxiv.org/pdf/2403.17659.pdf

Context. Shock waves are excited by coronal mass ejections (CMEs) and large-scale extreme-ultraviolet (EUV) wave fronts and can result in low-frequency radio emission under certain coronal conditions. Aims. In this work, we investigate a moving source of low-frequency radio emission as a CME and an associated EUV wave front move along a channel of a lower density, magnetic field, and Alfvén speed in the solar corona. Methods. Observations from the Atmospheric Imaging Assembly on board the Solar Dynamics Observatory, the Nançay Radio Heliograph (NRH), and the Irish Low Frequency Array (I-LOFAR) were analysed. Differential emission measure maps were generated to determine densities and Alfvén maps, and the kinematics of the EUV wave front was tracked using CorPITA. The radio sources' positions and velocity were calculated from NRH images and I-LOFAR dynamic spectra. Results. The EUV wave expanded radially with a uniform velocity of ∼ 500 km s^{-1} . However, the radio source was observed to be deflected and appeared to move along a channel of a lower Alfvén speed, abruptly slowing from 1700 km s^{-1} to 250 km s^{-1} as it entered a quiet-Sun region. A shock wave with an apparent radial velocity of > 420 km s^{-1} was determined from the drift rate of the associated Type II radio burst. Conclusions. The apparent motion of the radio source may have resulted from a wave front moving along a coronal wave guide or by different points along the wave front emitting at locations with favourable conditions for shock formation. **10 May 2022**

The Temperature-Dependent Nature of Coronal Dimmings

Eva **Robbrecht** and Yi-Ming Wang

E-print 2 Aug **2010**, **File**; ApJL

The opening-up of the magnetic field during solar eruptive events is often accompanied by a dimming of the local coronal emission. From observations of filament eruptions recorded with the Extreme-Ultraviolet Imager on STEREO during 2008–2009, it is evident that these dimmings are much more pronounced in 19.5 nm than in the lower-temperature line 17.1 nm, as viewed either on the disk or above the limb. We conclude that most of the cooler coronal plasma is not ejected but remains gravitationally bound when the loops open up. This result is consistent with Doppler measurements by Imada and coworkers, who found that the upflow speeds in a transient coronal hole increased dramatically above a temperature of 1 MK; it is also consistent with the quasistatic behavior of polar plumes, as compared with the hotter interplume regions that are the main source of the fast solar wind. When the open flux reconnects and closes down again, the trapped plasma is initially heated to such high temperatures that it is no longer visible at Fe IX 17.1 nm. Correspondingly, 17.1 nm images show a dark ribbon or "heat wave" propagating away from the polarity inversion line and coinciding with the brightened Fe XV 28.4 nm and Fe XII 19.5 nm post-eruptive loops and their footpoint areas. Such dark ribbons provide a clear example of dimmings that are not caused by a density depletion. The propagation of the "heat wave" is driven by the closing-down, not the opening-up, of flux and can be observed both off-limb and on-disk.

Prediction of Geomagnetic Storms Associated with Interplanetary Coronal Mass Ejections

Rodkin, D.G., Slemzin, V.A.

Astronomy Reports. Volume: 68. Issue: 2. 192–199, **2024**
https://doi.org/10.1134/S1063772924700185

Geomagnetic storms have a significant impact on the performance of technical systems both in space and on Earth. The sources of strong geomagnetic storms are most often interplanetary coronal mass ejections (ICMEs), generated by coronal mass ejections (CMEs) in the solar corona. The ICME forecast is based on regular optical observations of the Sun, which make it possible to detect CMEs at the formation stage. It is known that the intensity of geomagnetic storms correlates with the magnitude of the southern component of the magnetic field (Bz) of the ICME. However, it is not possible yet to predict the sign and magnitude of Bz from solar observations for the operational forecast of an arbitrary CME. Under these conditions, a preliminary forecast of the magnetic storm probability can be obtained under the assumption that the strength of the storm is related to the magnitude of the magnetic flux from the eruption region, observed as dimming. In this paper, we examine the relationship between the integral magnetic flux from the dimming region and the probability that CMEs associated with them will cause geomagnetic storms, using a series of 37 eruptive events in 2010–2012. It is shown that there is a general trend toward an increase in the ICMEs geoefficiency with an increase in the magnitude of the magnetic flux from the dimming region. It has been demonstrated that the frequency of moderate and severe storms observation increases in cases of complex events associated with the interaction of CMEs with other solar wind streams in the heliosphere.

Recovery of coronal dimmings

Giulia M. **Ronca**, Galina Chikunova, Karin Dissauer, Tatiana Podladchikova, Astrid M. Veronig

A&A 691, A195 **2024**
https://arxiv.org/pdf/2410.02585
https://www.aanda.org/articles/aa/pdf/2024/11/aa47934-23.pdf
https://doi.org/10.1051/0004-6361/202347934

Coronal dimmings are regions of reduced emission in the lower corona, observed after coronal mass ejections (CMEs) and representing their footprints. In order to investigate the long-term evolution of coronal dimming and its recovery, we propose two approaches that focus on both the global and the local evolution of dimming regions: the fixed mask approach and the pixel boxes approach. We present four case studies (**September 6, 2011; March 7, 2012; June 14, 2012; and March 8, 2019**) in which a coronal dimming is associated with a flare/CME eruption. We identified the dimming region by image segmentation, then restricted the analysis to a specific portion of the dimming and tracked the time evolution of the dimming brightness and area. In addition, we studied the behavior of small subregions inside the dimming area, of about 3x3 pixels, to compare the recovery in different regions of the dimming. Three out of the four cases show a complete recovery 24 hours after the flare/CME eruption. The recovery of the brightness follows a two-step trend, with a steeper and quicker segment followed by a slower one. In addition, some parts of the dimming, which may be core dimmings, are still present at the end of the analysis time and do not recover within 3 days, whereas the peripheral regions (secondary dimmings) show a full recovery. We demonstrate that the primary mechanism for recovery identified in the observations is the expansion of coronal loops into the dimming region, which gradually increase their intensity. Our developed approaches enable the analysis of dimmings alongside these bright structures, revealing different timescales of recovery for core and secondary/twin dimming regions. Combined with magnetic field modeling, these methods lay the foundation for further systematic analysis of dimming recovery and enhance the knowledge gained from already-analyzed events.

THE LONGITUDINAL PROPERTIES OF A SOLAR ENERGETIC PARTICLE EVENT INVESTIGATED USING MODERN SOLAR IMAGING

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2012 ApJ 752 44, **File**
We use combined high-cadence, high-resolution, and multi-point imaging by the Solar-Terrestrial Relations Observatory (STEREO) and the Solar and Heliospheric Observatory to investigate the hour-long eruption of a fast and wide coronal mass ejection (CME) on **2011 March 21** when the twin STEREO spacecraft were located beyond the solar limbs. We analyze the relation between the eruption of the CME, the evolution of an Extreme Ultraviolet (EUV) wave, and the onset of a solar energetic particle (SEP) event measured in situ by the STEREO and near-Earth orbiting spacecraft. Combined ultraviolet and white-light images of the lower corona reveal that in an initial CME lateral "expansion phase," the EUV disturbance tracks the laterally expanding flanks of the CME, both moving parallel to the solar surface with speeds of ~450 km s–1. When the lateral expansion of the ejecta ceases, the EUV disturbance carries on propagating parallel to the solar surface but devolves rapidly into a less coherent structure. Multi-point tracking of the CME leading edge and the effects of the launched compression waves (e.g., pushed streamers) give anti-sunward speeds that initially exceed 900 km s–1 at all measured position angles. We combine our analysis of ultraviolet and white-light images with a comprehensive study of the velocity dispersion of energetic particles measured in situ by particle detectors located at STEREO-A (STA) and first Lagrange point (L1), to demonstrate that the delayed solar particle release times at STA and L1 are consistent with the time required (30-40 minutes) for the CME to perturb the corona over a wide range of longitudes. This study finds an association between the longitudinal extent of the perturbed corona (in EUV and white light) and the longitudinal extent of the SEP event in the heliosphere.

Slowly moving disturbances in the X-ray corona.
Rust, D.M., Svestka, Z.,
1979. Solar Phys. 63, 279–295.

Coronal mass ejection-related particle acceleration regions during a simple eruptive event
Carolina **Salas-Matamoros**1,5, Karl-Ludwig Klein1,2 and Alexis P. Rouillard3
A&A 590, A135 (**2016**) **File**
http://www.aanda.org/articles/aa/pdf/2016/06/aa28015-15.pdf
An intriguing feature of many solar energetic particle (SEP) events is the detection of particles over a very extended range of longitudes in the heliosphere. This may be due to peculiarities of the magnetic field in the corona, to a broad accelerator, to cross-field transport of the particles, or to a combination of these processes. The eruptive flare on **26 April 2008** provided an opportunity to study relevant processes under particularly favourable conditions since it occurred in a very quiet solar and interplanetary environment. This enabled us to investigate the physical link between a single well-identified coronal mass ejection (CME), electron acceleration as traced by radio emission, and the production of SEPs. We conduct a detailed analysis, which combines radio observations (Nançay Radio Heliograph and Nançay Decametre Array, Wind/Waves spectrograph) with remote-sensing observations of the corona in extreme ultraviolet (EUV) and white light, as well as in situ measurements of energetic particles near 1AU (SoHO and STEREO spacecraft). By combining images taken from multiple vantage points, we were able to derive the time-dependent evolution of the 3D pressure front that was developing around the erupting CME. Magnetic reconnection in the post-CME current sheet accelerated electrons, which remained confined in closed magnetic fields in the corona, while the acceleration of escaping particles can be attributed to the pressure front ahead of the expanding CME. The CME accelerated electrons remotely from the parent active region, owing to the interaction of its laterally expanding flank, which was traced by an EUV wave, with the ambient corona. SEPs detected at one STEREO spacecraft and SoHO were accelerated later, when the frontal shock of the CME intercepted the spacecraft-connected interplanetary magnetic field line. The injection regions into the heliosphere inferred from the radio and SEP observations are separated in longitude by about 140°. The observations for this event show that it is misleading to interpret multi-spacecraft SEP measurements in terms of one acceleration region in the corona. The different acceleration regions are linked to different vantage points in the interplanetary space.

Global simulation of an EIT wave
J. M. **Schmidt** and L. Ofman
E-print, Oct 2009; *ApJ* **713** 1008, **2010**; **File;**
We use the observation of an EIT wave in the lower solar corona, seen with the two STEREO spacecraft in extreme ultraviolet light on **19 May 2007**, to model the same event with a three-dimensional (3D) time-depending magneto hydrodynamic (MHD) code that includes solar coronal magnetic fields derived with Wilcox Solar Observatory magnetogram data, and a solar wind outflow accelerated with empirical heating functions. The model includes a coronal mass ejection (CME) of Gibson and Low flux rope type above the reconstructed active region with

parameters adapted from observations to excite the EIT wave. We trace the EIT wave running as circular velocity enhancement around the launching site of the CME in the direction tangential to the sphere produced by the wave front, and compute the phase velocities of the wave front. We find that the phase velocities are in good agreement with theoretical values for a fast magnetosonic wave, derived with the physical parameters of the model, and with observed phase speeds of an incident EIT wave reflected by a coronal hole and running at about the same location. We also produce in our 3D MHD model the observed reflection of the EIT wave at the coronal hole boundary, triggered by the magnetic pressure difference between the wave front hitting the hole and the boundary magnetic fields of the coronal hole, and the response of the coronal hole, which leads to the generation of secondary reflected EIT waves radiating away in different direction than the incident EIT wave. This is the first 3D MHD model of an EIT wave triggered by CME that includes realistic solar magnetic field, with results comparing favorably to STEREO EUVI observations.

THE 2011 FEBRUARY 15 X2 FLARE, RIBBONS, CORONAL FRONT, AND MASS EJECTION: INTERPRETING THE THREE-DIMENSIONAL VIEWS FROM THE SOLAR DYNAMICS OBSERVATORY AND STEREO GUIDED BY MAGNETOHYDRODYNAMIC FLUX-ROPE MODELING

Carolus J. **Schrijver**1, Guillaume Aulanier2, Alan M. Title1, Etienne Pariat2 and Cecile Delannée
E-print, June **2011**, **File**; **2011** ApJ 738 167, **File?**

The **2011 February 15** X2.2 flare and associated Earth-directed halo coronal mass ejection were observed in unprecedented detail with high resolution in spatial, temporal, and thermal dimensions by the Atmospheric Imaging Assembly (AIA) on the Solar Dynamics Observatory, as well as by instruments on the two STEREO spacecraft, then at near-quadrature relative to the Sun-Earth line. These observations enable us to see expanding loops from a flux-rope-like structure over the shearing polarity-inversion line between the central δ-spot groups of AR 11158, developing a propagating coronal front ("EIT wave"), and eventually forming the coronal mass ejection moving into the inner heliosphere. The observations support the interpretation that all of these features, including the "EIT wave," are signatures of an expanding volume traced by loops (much larger than the flux rope only), surrounded by a moving front rather than predominantly wave-like perturbations; this interpretation is supported by previously published MHD models for active-region and global scales. The lateral expansion of the eruption is limited to the local helmet-streamer structure and halts at the edges of a large-scale domain of connectivity (in the process exciting loop oscillations at the edge of the southern polar coronal hole). The AIA observations reveal that plasma warming occurs within the expansion front as it propagates over quiet Sun areas. This warming causes dimming in the 171 Å (Fe IX and Fe X) channel and brightening in the 193 and 211 Å (Fe XII-XIV) channels along the entire front, while there is weak 131 Å (Fe VIII and Fe XXI) emission in some directions. An analysis of the AIA response functions shows that sections of the front running over the quiet Sun are consistent with adiabatic warming; other sections may require additional heating which MHD modeling suggests could be caused by Joule dissipation. Although for the events studied here the effects of volumetric expansion are much more obvious than true wave phenomena, we discuss how different magnetic environments within and around the erupting region can lead to the signatures of either or both of these aspects.

Numerical Simulations of Dome-Shaped EUV Waves from Different Active-Region Configurations

M. **Selwa**, S. Poedts, C. R. DeVore
Solar Physics, June **2013**, Volume 284, Issue 2, pp 515-539

Recently, 3D STEREO observations explained the 3D structure of EUV waves. Patsourakos and Vourlidas (Astrophys. J. 700, L182, 2009), Veronig et al. (Astrophys. J. 716, L57, 2010) and Selwa, Poedts, and DeVore (Astrophys. J. 747, L21, 2012) reported on the dome-shaped EUV waves resulting from different events. Here, we model, by means of 3D MHD simulations, the formation of dome-shaped EUV waves in rotating active regions (ARs). The numerical simulations are initialized with idealized (multi-)dipolar coronal (low β) configurations. Next, we apply a sheared rotational motion to the central parts of all the positive and negative flux regions at the photospheric boundary. As a result, the flux tubes connecting the flux sources become twisted. We find that in all the studied configurations of idealized ARs, the rotating motion results in a dome-shaped structure originating from the AR. However, the shape of the dome depends on the initial configuration (topology of the AR). The initial stage of the wave evolution consists of multiple fronts that later merge together forming a single wave. The observed EUV wave propagates nearly isotropically on the disk and also in the upward direction. We remark that the initial stage of the evolution is determined by the driver and not caused by a magnetic reconnection event. At a later stage, however, the wave propagates freely. We study the different wave properties resulting from different driver speeds and find that independent of the initial AR topology the 3D dome-shaped wave is excited in the system. The symmetry of the 3D dome depends on the topology of the AR and on the duration of the driver. The EUV wave triggered is independent of the temporal profile of the driver. However, the properties of the wave (speed, sharpness of the cross-section, etc.) depend on the type of the trigger.

DOME-SHAPED EUV WAVES FROM ROTATING ACTIVE REGIONS

M. **Selwa**1, S. Poedts1 and C. R. DeVore

2012 ApJ 747 L21, **File**

Recent STEREO observations enabled the study of the properties of EUV waves in more detail. They were found to have a three-dimensional (3D) dome-shaped structure. We investigate, by means of 3D MHD simulations, the formation of EUV waves as the result of the interaction of twisted coronal magnetic loops. The numerical simulation is initialized with an idealized dipolar active region and is performed under coronal (low β) conditions. A sheared rotational motion is applied to the central parts of both the positive and negative flux regions at the photosphere so that the flux tubes in between them become twisted. We find that the twisting motion results in a dome-shaped structure followed in space by a dimming and in time by an energy release (flare). The rotation of the sunspots is the trigger of the wave which initially consists of two fronts that later merge together. The resulting EUV wave propagates nearly isotropically on the disk and ~2 times faster in the upward direction. The initial stage of the evolution is determined by the driver, while later the wave propagates freely with a nearly Alfvénic speed.

Direct observations of different sunspot waves influenced by umbral flashes

Aishawnnya **Sharma**, G. R. Gupta, Durgesh Tripathi, V. Kashyap, Amit Pathak

ApJ **2017**

https://arxiv.org/pdf/1710.08438.pdf

We report the simultaneous presence of chromospheric umbral flashes and associated umbral waves, and propagating coronal disturbances, in a sunspot and related active region. We have analyzed time-distance maps obtained using the observations from Atmospheric Imaging Assembly (AIA) on-board Solar Dynamics Observatory (SDO). These maps show the simultaneous occurrence of different sunspot oscillation and waves such as umbral flashes, umbral waves, and coronal waves. Analysis of the original light curves, i.e., without implementing any Fourier filtering on them, show that the amplitudes of different sunspot waves observed at different atmospheric layers change in synchronization with the light curves obtained from the umbral flash region, thus demonstrating that these oscillations are modulated by umbral flashes. This study provides the first observational evidence of the influence of sunspot oscillations within the umbra on other sunspot waves extending up to the corona. The properties of these waves and oscillations can be utilized to study the inherent magnetic coupling among different layers of the solar atmosphere above sunspots. **December 11, 2010**

Sunquakes of Solar Cycle 24

I.N. **Sharykin**, A.G. Kosovichev

ApJ **2019**

https://arxiv.org/pdf/1911.04197.pdf

The paper presents results of a search for helioseismic events (sunquakes) produced by M-X class solar flares during Solar Cycle 24. The search is performed by analyzing photospheric Dopplergrams from Helioseismic Magnetic Imager (HMI). Among the total number of 500 M-X class flares, 82 helioseismic events were detected. This result is quite unexpected, since it was previously thought that sunquakes were very rare and observed mainly in strong flares. However, our analysis has shown that there many strong sunquakes were produced by solar flares of low M class, while in some powerful X-class flares helioseismic waves were not observed or were weak. Our analysis also revealed several active regions characterized by the most efficient generation of helioseismic waves during flares. We found that the sunquake power correlates with the maximum value of soft X-ray flux time derivative better than with the X-ray class, indicating that the sunquake mechanism is associated with high-energy particles. We also show that the seismically active flares are more impulsive than the flares without photospheric and helioseismic perturbations. We present a new catalog of helioseismic solar flares, which opens opportunities for performing statistical studies to better understand physics of sunquakes as well as flare energy release and transport. **October 23, 2012, November 5, 2013**

Table 2011-2017

Dynamics of Electric Currents, Magnetic Field Topology and Helioseismic Response of a Solar Flare

I. N. **Sharykin**, A. G. Kosovichev

2015

http://arxiv.org/pdf/1502.05190v1.pdf

The solar flare on **July 30, 2011** was of a modest X-ray class (M9.3), but it made a strong photospheric impact and produced a "sunquake," observed with the Helioseismic and Magnetic Imager (HMI) on NASA's Solar Dynamics Observatory (SDO). In addition to the helioseismic waves (also observed with the SDO/AIA instrument), the flare caused a large expanding area of white-light emission and was accompanied by substantial restructuring of magnetic fields, leading to the rapid formation of a sunspot structure in the flare region. The flare produced no significant hard X-ray emission and no coronal mass ejection. This indicates that the flare energy release was mostly confined to the lower atmosphere. The absence of significant coronal mass ejection rules out magnetic rope eruption as a mechanism of helioseismic waves. We discuss the connectivity of the flare energy release with the electric currents dynamics and show the potential importance of high-speed plasma flows in the lower solar atmosphere during the flare energy release.

Energy Release and Initiation of Sunquake in C-class Flare

I.N. **Sharykin**, A.G. Kosovichev, I.V. Zimovets

2015 ApJ 807 102

http://arxiv.org/pdf/1405.5912v1.pdf

We present analysis of a C-class solar flare of **Febrary 17, 2013**, revealing a strong helioseismic response caused by a very compact impact in the photosphere. This is the first detection of sunquake in C-class flares. To investigate possible mechanisms of generation of this sunquake, and to understand the role of accelerated charged particles and photospheric electric currents, we use data from three space observatories: Ramaty High Energy Solar Spectroscopic Imager (RHESSI), Solar Dynamics Observatory (SDO) and Geostationary Operational Environmental Satellite (GOES). We find that the sunquake impulse does not spatially correspond to the HXR emission source, but both of these events are parts of the same energy release. Our analysis reveals a close association of the flare energy release with a rapid increase of the electric currents, and suggests that the sunquake initiation can be explained by a rapid current dissipation or by a localized impulsive Lorentz force.

Detection of coronal mass ejection associated shock waves in the outer corona.

Sheeley, N.R., Hakala, W.N., Wang, Y.,

2000. J. Geophys. Res. 105, 5081–5092.

White-light QFP wave train and the associated failed breakout eruption⋆

Yuandeng **Shen**1,2,3,5, Surui Yao1, Zehao Tang1,3, Xinping Zhou1,3, Zhining Qu4, Yadan Duan1,3, Chengrui Zhou1,3 and Song Tan1,3

A&A 665, A51 (**2022**)

https://arxiv.org/pdf/2207.08110.pdf

https://www.aanda.org/articles/aa/pdf/2022/09/aa43924-22.pdf

Quasi-periodic fast-propagating (QFP) magnetosonic wave trains are commonly observed in the low corona at extreme ultraviolet wavelength bands. Here, we report the first white-light imaging observation of a QFP wave train propagating outwardly in the outer corona ranging from 2 to 4 $R_\odot$. The wave train was recorded by the Large Angle Spectroscopic Coronagraph on board the Solar and Heliospheric Observatory (SOHO), and was associated with a GOES M1.5 flare in NOAA active region AR12172 at the southwest limb of the solar disk. Measurements show that the speed and period of the wave train were about 218 km s^{-1} and 26 min, respectively. The extreme ultraviolet imaging observations taken by the Atmospheric Imaging Assembly on board the Solar Dynamic Observatory reveal that in the low corona the QFP wave train was associated with the failed eruption of a breakout magnetic system consisting of three low-lying closed loop systems enclosed by a high-lying large-scale one. Data analysis results show that the failed eruption of the breakout magnetic system was mainly because of the magnetic reconnection that occurred between the two lateral low-lying closed-loop systems. This reconnection enhances the confinement capacity of the magnetic breakout system because the upward-moving reconnected loops continuously feed new magnetic fluxes to the high-lying large-scale loop system. For the generation of the QFP wave train, we propose that it could be excited by the intermittent energy pulses released by the quasi-periodic generation, rapid stretching, and expansion of the upward-moving, strongly bent reconnected loops. **2014 October 2**

Coronal Quasi-periodic Fast-mode Propagating (QFP) Wave Trains **Review**

Yuandeng **Shen**, Xinping Zhou, Yadan Duan, Zehao Tang, Chengrui Zhou, Song Tan

Solar Phys. **297**, Article number: 20 **2022**

https://arxiv.org/pdf/2112.14959.pdf

https://link.springer.com/content/pdf/10.1007/s11207-022-01953-2.pdf **File**

QFP wave trains in the corona have been studied intensively in the past decade, thanks to the full-disk, high spatiotemporal resolution, and wide-temperature coverage observations taken by the SDO/AIA. In AIA observations, QFP wave trains are seen to consist of multiple coherent and concentric wavefronts emanating successively near the epicenter of the accompanying flares; they propagate outwardly either along or across coronal loops at fast-mode magnetosonic speeds from several hundred to more than 2000 km/s, and their periods are in the range of tens of seconds to several minutes. Based on the distinct different properties of QFP wave trains, they might be divided into two distinct categories including narrow and broad ones. For most QFP wave trains, some of their periods are similar to those of quasi-periodic pulsations (QPPs) in the accompanying flares, indicating that they are probably different manifestations of the same physical process. Currently, candidate generation mechanisms for QFP wave trains include two main categories: pulsed energy excitation mechanism in association with magnetic

reconnection and dispersion evolution mechanism related to the dispersive evolution of impulsively generated broadband perturbations. In addition, the generation of some QFP wave trains might be driven by the leakage of three and five minute oscillations from the lower atmosphere. As one of the new discoveries of SDO, QFP wave trains provide a new tool for coronal seismology to probe the corona parameters, and they are also useful for diagnosing the generation of QPPs, flare processes including energy release and particle accelerations. This review aims to summarize the main observational and theoretical results of the spatially-resolved QFP wave trains in extreme ultraviolet observations, and states briefly a number of questions that deserve further investigations. **2010 September 08, 2011 February 14, 2011 May 30, 2012 April 24, 2013 May 22, 2014 November 03, 2015 April 16**
The occurrence of QFP wave trains is rather
common and is frequently associated with ***single pulsed global EUV waves****, ares and CMEs.*
Table *1. Physical parameters of the published QFP wave trains*

First Unambiguous Imaging of Large-Scale Quasi-Periodic Extreme-Ultraviolet Wave or Shock

Yuandeng **Shen**, P. F. Chen, Ying D. Liu, Kazunari Shibata, Zehao Tang, Yu Liu
ApJ **873** 22 **2019**
https://iopscience.iop.org/article/10.3847/1538-4357/ab01dd/pdf
https://arxiv.org/pdf/1901.08199.pdf
https://doi.org/10.3847/1538-4357/ab01dd
We report the first unambiguous quasi-periodic large-scale extreme-ultraviolet (EUV) wave or shock that was detected by the Atmospheric Imaging Assembly on board the Solar Dynamics Observatory. During the whip-like unwinding eruption of a small filament on **2012 April 24**, multiple consecutive large-scale wavefronts emanating from AR11467 were observed simultaneously along the solar surface and a closed transequatorial loop system. In the meantime, an upward propagating dome-shaped wavefront was also observed, whose initial speed and deceleration are about 1392 km/s and 1.78 km/s^2, respectively. Along the solar surface, the quasi-peridoic wavefronts had a period of about 163 +/- 21 seconds and propagated at a nearly constant speed of 747 +/- 26 km/s; they interacted with active region AR11469 and launched a sympathetic upward propagating secondary EUV wave. The wavefronts along the loop system propagated at a speed of 897 km/s, and they were reflected back at the southern end of the loop system at a similar speed. In addition to the propagating waves, a standing kink wave was also present in the loop system simultaneously. Periodicity analysis reveals that the period of the wavefronts was consistent with that of the unwinding helical structures of the erupting filament. Based on these observational facts, we propose that the observed quasi-periodic EUV wavefronts were most likely excited by the periodic unwinding motion of the filament helical structures. In addition, two different seismological methods are applied to derive the magnetic field strength of the loop system, and for the first time the reliability of these inversion techniques are tested with the same magnetic structure.

Coronal EUV, QFP, and kink waves simultaneously launched during the course of jet-loop interaction

Yuandeng **Shen**, Zehao Tang, Hongbo Li, Yu Liu
MNRAS Letters, Volume 480, Issue 1, p.L63-L67 **2018**
https://arxiv.org/pdf/1807.09533.pdf
https://watermark.silverchair.com/sly127.pdf
We present the observations of an extreme ultraviolet (EUV) wave, a quasi-periodic fast-propagating (QFP) magnetosonic wave, and a kink wave that were simultaneously associated with the impingement of a coronal jet upon a group of coronal loops. After the interaction, the coronal loop showed obvious kink oscillation that had a period of about 428 seconds. In the meantime, a large-scale EUV wave and a QFP wave are observed on the west of the interaction position. It is interesting that the QFP wave showed refraction effect during its passing through two strong magnetic regions. The angular extent, speed, and lifetime of the EUV (QFP) wave were about 140 (40) degree, 423 (322) km/s, and 6 (26) minutes, respectively. It is measured that the period of the QFP wave was about 390 +/- 100 second. Based on the observational analysis results, we propose that the kink wave was probably excited by the interaction of the jet; the EUV was probably launched by the sudden expansion of the loop system due to the impingement of the coronal jet; and the QFP wave was possibly formed through the dispersive evolution of the disturbance caused by the jet-loop interaction. **2011 February 14**

Homologous large-amplitude Nonlinear fast-mode Magnetosonic Waves Driven by Recurrent Coronal Jets

Yuandeng **Shen**, Yu Liu, Ying D. Liu, Jiangtao Su, Zehao Tang, Yuhu Miao
The Astrophysical Journal, 861:105 (13pp), **2018** July 10
http://iopscience.iop.org/article/10.3847/1538-4357/aac9be/pdf
https://arxiv.org/pdf/1805.12303.pdf

The detailed observational analysis of a homologous Extreme-ultraviolet (EUV) wave event is presented to study the driving mechanism and the physical property of the EUV waves, combining high resolution data taken by the Solar Dynamics Observatory and the Solar TErrestrial RElations Observatory. It is observed that four homologous EUV waves originated from the same active region AR11476 within about one hour, and the time separations between consecutive waves were of 8 - 20 minutes. The waves showed narrow arc-shaped wavefronts and propagated in the same direction along a large-scale transequatorial loop system at a speed of 648 - 712 km/s and a deceleration of 0.985 - 1.219 km/s2. The EUV waves were accompanied by weak flares, coronal jets, and radio type III bursts, in which the EUV waves were delayed with respect to the start times of the radio type III bursts and coronal jets about 2 - 13 and 4 - 9 minutes, respectively. Different to previous studies of homologous EUV waves, no coronal mass ejections were found in the present event. Based on the observational results and the close temporal the spatial relationship between the EUV waves and the coronal jets, for the first time, we propose that the observed homologous EUV waves were large-amplitude nonlinear fast-mode magnetosonic waves or shocks driven by the associated recurrent coronal jets, resemble the generation mechanism of a piston shock in a tube. In addition, it is found that the recurrent jets were tightly associated with the alternating flux cancellation and emergence in the eruption source region and radio type III bursts. **2010-04-28, 2010-11-11, 2012 May 14**

EUV Waves Driven by Sudden Expansion of Transequatorial Loops Caused by Solar Coronal Jets

Yuandeng **Shen**, Zehao Tang, Yuhu Miao, Jiangtao Su, Yu Liu

ApJL **860** L8 **2018**

https://arxiv.org/pdf/1805.12309.pdf

We present two events to study the driving mechanism of extreme-ultraviolet (EUV) waves that are not associated with coronal mass ejections (CMEs), by using high resolution observations taken by the Atmospheric Imaging Assembly (AIA) on board Solar Dynamics Observatory. Observational results indicate that the observed EUV waves were accompanied by ares and coronal jets, but without CMEs that were regarded as the driver of most EUV waves in previous studies. In the first case, it is observed that a coronal jet ejected along a transequatorial loop system at a plane-of-the-sky (POS) speed of 335±22 km/s, in the meantime, an arc-shaped EUV wave appeared on the eastern side of the loop system. In addition, the EUV wave further interacted with another interconnecting loop system and launched a fast propagating (QFP) magnetosonic wave along the loop system, which had a period of 200 s and a speed of 388±65 km/s, respectively. In the second case, we also observed a coronal jet ejected at a POS speed of 282±44 km/s along a transequatorial loop system and the generation of bright EUV wave on the eastern side of the loop system. Based on the observational results, we propose that the observed EUV waves on the eastern side of the transequatorial loop systems are fast-mode magnetosonic waves, and they were driven by the sudden lateral expansion of the transequatorial loop systems due to the direct impingement of the associated coronal jets, while the QFP wave in the first case formed due to the dispersive evolution of the disturbance caused by the interaction between the EUV wave and the interconnecting coronal loops. It is noted that EUV waves driven by sudden loop expansions have shorter lifetimes than those driven by CMEs**. 2011 February 15, 2014 August 21.**

Dispersively Formed Quasi-Periodic Fast Magnetosonic Wavefronts Due to the Eruption of a Nearby Mini-filament

Yuandeng **Shen**, Tengfei Song, Yu Liu

MNRAS **2018**

https://arxiv.org/pdf/1803.01125.pdf

The observational analysis is performed to study the excitation mechanism and the propagation properties of a quasi-periodic fast-propagating (QFP) magnetosonic wave. The QFP wave was associated with the eruption of a nearby mini-filament and a small B4 GOES flare, which may indicate that the generation of a QFP wave do not need too much flare energy. The propagation of the QFP wave was along a bundle of funnel-shaped open loops with a speed of about 1100+/-78, and an acceleration of -2.2+/-1.1. Periodicity analysis indicates that the periods of the QFP wave are 43+/-6, 79+/-18 second. For the first time, we find that the periods of the QFP wave and the accompanying flare are inconsistent, which is different from the findings as reported in previous studies. We propose that the present QFP wave was possibly caused by the mechanism of dispersive evolution of an initially broadband disturbance resulted from the nearby mini-filament eruption. **2015 July 12**

A quasi-periodic fast-propagating magnetosonic wave associated with the eruption of a magnetic flux rope

Yuandeng **Shen**, Yu Liu, Tengfei Song, Zhanjun Tian

2017

https://arxiv.org/pdf/1712.09045.pdf

Using high temporal and high spatial resolution observations taken by the Atmospheric Imaging Assembly onboard the Solar Dynamics Observatory, we present the detailed observational analysis of a high quality quasi-periodic fast-propagating (QFP) magnetosonic wave that was associated with the eruption of a magnetic flux rope and a GOES

C5.0 flare. For the first time, we find that the QFP wave lasted during the entire flare lifetime rather than only the rising phase of the accompanying flare as reported in previous studies. In addition, the propagation of the different parts of the wave train showed different kinematics and morphologies. For the southern (northern) part, the speed, duration, intensity variation are about 875 +/- 29 (1485 +/- 233) km/s, 45 (60) minutes, and 4% (2%), and the pronounced periods of them are 106 +/- 12 and 160 +/- 18 (75 +/- 10 and 120 +/- 16) seconds, respectively. It is interesting that the northern part of the wave train showed obvious refraction effect when they pass through a region of strong magnetic field. Periodicity analysis result indicates that all the periods of the QFP wave can be found in the period spectrum of the accompanying flare, suggesting their common physical origin. We propose that the quasi-periodic nonlinear magnetohydrodynamics process in the magnetic reconnection that produces the accompanying flare should be important for exciting of QFP wave, and the different magnetic distribution along different paths can account for the different speeds and morphology evolution of the wave fronts. **2014 March 23**

Observations of a Quasi-periodic, Fast-Propagating Multiple Wavelengths and Its Interaction with Other Magnetic Structures

Y.-D. **Shen**, Y. Liu, J.-T. Su, H. Li, X.-F. Zhang, Z.-J. Tian, R.-J. Zhao, A. Elmhamdi

Solar Phys (**2013**) 288:585–602

We present observations of a quasi-periodic fast-propagating (QFP) magnetosonic wave on **23 April 2012**, with high-resolution observations taken by the Atmospheric Imaging Assembly onboard the Solar Dynamics Observatory. Three minutes after the start of a C2.0 flare, wave trains were first observed along an open divergent loop system in 171 Å observations at a distance of 150 Mm from the footpoint of the guiding loop system and with a speed of 689 km s−1, then they appeared in 193 Å observations after their interaction with a perpendicular, underlaying loop system on the path; in the meantime; their speed decelerated to 343 km s−1 within a short time. The sudden deceleration of the wave trains and their appearance in 193 Å observations are interpreted through a geometric effect and the density increase of the guiding loop system, respectively. We find that the wave trains have a common period of 80 seconds with the flare. In addition, a few low frequencies are also identified in the QFP wave. We propose that the generation of the period of 80 seconds was caused by the periodic releasing of energy bursts through some nonlinear processes in magnetic reconnection, while the low frequencies were possibly the leakage of pressure-driven oscillations from the photosphere or chromosphere, which could be an important source for driving coronal QFP waves. Our results also indicate that the properties of the guiding magnetic structure, such as the distributions of magnetic field and density as well as geometry, are crucial for modulating the propagation behaviors of QFP waves.

On a small-scale EUV wave: the driving mechanism and the associated oscillating filament

Yuandeng **Shen**, Yu Liu, Zhanjun Tian, Zhining Qu

ApJ **851** 101 **2017**

https://arxiv.org/pdf/1711.04905.pdf

We present observations of a small-scale Extreme-ultraviolet (EUV) wave that was associated with a mini-filament eruption and a GOES B1.9 micro-fare in the quiet Sun region. The initiation of the event was due to the photospheric magnetic emergence and cancellation in the eruption source region, which first caused the ejection of a small plasma ejecta, then the ejecta impacted on a nearby mini-filament and thereby led to the filament's eruption and the associated fare. During the filament eruption, an EUV wave at a speed of 182 { 317 km/s was formed ahead of an expanding coronal loop, which propagated faster than the expanding loop and showed obvious deceleration and refection during the propagation. In addition, the EUV wave further resulted in the transverse oscillation of a remote filament whose period and damping time are 15 and 60 minutes, respectively. Based on the observational results, we propose that the small-scale EUV wave should be a fast-mode magnetosonic wave that was driven by the the expanding coronal loop. Moreover, with the application of filament seismology, it is estimated that the radial magnetic field strength is about 7 Gauss. The observations also suggest that small-scale EUV waves associated with miniature solar eruptions share similar driving mechanism and observational characteristics with their large-scale counterparts. **March 21, 2016**

Simultaneous Transverse Oscillations of a Prominence and a Filament and Longitudinal Oscillation of another Filament Induced by a Single Shock Wave

Yuandeng **Shen**, Ying D. Liu, P. F. Chen, Kiyoshi Ichimoto

ApJ, **2014**

http://arxiv.org/pdf/1409.1304v1.pdf

We present the first stereoscopic and Doppler observations of simultaneous transverse oscillations of a prominence and a filament and longitudinal oscillation of another filament launched by a single shock wave. Using H-alpha Doppler observations, we derive the three-dimensional oscillation velocities at different heights along the prominence axis. The results indicate that the prominence has a larger oscillation amplitude and damping time at higher altitude, but the periods at different heights are the same (i.e., 13.5 minutes). This suggests that the prominence oscillates like a linear vertical rigid body with one end anchored on the Sun. One of the filaments shows weak transverse oscillation after the passing of the shock, which is possibly due to the low altitude of the filament and the weakening (due to reflection) of the shock wave before the interaction. Large amplitude longitudinal oscillation is observed in the other filament after the passing of the shock wave. The velocity amplitude and period are about 26.8 km/s and 80.3 minutes, respectively. We propose that the orientation of a filament or prominence relative to the normal vector of the incoming shock should be an important factor for launching transverse or longitudinal filament oscillations. In addition, the restoring forces of the transverse prominence are most likely due to the coupling of gravity and magnetic tension of the supporting magnetic field, while that for the longitudinal filament oscillation is probably the resultant force of gravity and magnetic pressure. **August 09, 2011**

A Chain of Winking (Oscillating) Filaments Triggered by an Invisible Extreme-Ultraviolet Wave

Yuandeng **Shen**, Kiyoshi Ichimoto, Takako T. Ishii, Zhanjun Tian, Ruijuan Zhao, Kazunari Shibata
ApJ, **2014**
http://arxiv.org/pdf/1403.7705v1.pdf
Winking (oscillating) filaments have been observed for many years. However, observations of successive winking filaments in one event have not been reported yet. In this paper, we present the observations of a chain of winking filaments and a subsequent jet that are observed right after the X2.1 are in AR11283. The event also produced an Extreme-ultraviolet (EUV) wave that has two components: upward dome-like wave (850 km/s) and lateral surface wave (554 km/s) which was very weak (or invisible) in imaging observations. By analyzing the temporal and spatial relationships between the oscillating filaments and the EUV waves, we propose that all the winking filaments and the jet were triggered by the weak (or invisible) lateral surface EUV wave. The oscillation of the filaments last for two or three cycles, and their periods, Doppler velocity amplitudes, and damping times are 11 - 22 minutes, 6 - 14 km/s, and 25 - 60 minutes, respectively. We further estimate the radial component magnetic field and the maximum kinetic energy of the filaments, and they are 5 - 10 Gauss and ~ 10^19 J, respectively. The estimated maximum kinetic energy is comparable to the minimum energy of ordinary EUV waves, suggesting that EUV waves can efficiently launch filament oscillations on their path. Based on our analysis results, we conclude that the EUV wave is a good agent for triggering and connecting successive but separated solar activities in the solar atmosphere, and it is also important for producing solar sympathetic eruptions. **2011-09-06**

Diffraction, Refraction, and Reflection of An Extreme-Ultraviolet Wave Observed during Its Interactions with Remote Active Regions

Shen, Yuandeng; Liu, Yu; Su, Jiangtao; Li, Hui; Zhao, Ruijuan; Tian, Zhanjun; Ichimoto, Kiyoshi; Shibata, Kazunari
E-print, July **2013, File**; **2013** ApJ 773 L33
We present observations of the diffraction, refraction, and reflection of a global extreme-ultraviolet (EUV) wave propagating in the solar corona. These intriguing phenomena are observed when the wave interacts with two remote active regions, and they together exhibit the wave property of this EUV wave. When the wave approached AR11465, it became weaker and finally disappeared in the active region, but a few minutes latter a new wavefront appeared behind the active region, and it was not concentric with the incoming wave. In addition, a reflected wave was also observed simultaneously on the wave incoming side. When the wave approached AR11459, it transmitted through the active region directly and without reflection. The formation of the new wavefront and the transmission could be explained with diffraction and refraction effects, respectively. We propose that the different behaviors observed during the interactions may caused by different speed gradients at the boundaries of the two active regions. For the origin of the EUV wave, we find that it formed ahead of a group of expanding loops a few minutes after the start of the loops' expansion, which represents the initiation of the associated coronal mass ejection (CME). Based on these results, we conclude that the EUV wave should be a nonlinear magnetosonic wave or shock driven by the associated CME, which propagated faster than the ambient fast-mode speed and gradually slowed down to an ordinary linear wave. Our observations support the hybrid model that includes both fast wave and slow non-wave components. **2012 April 23**

Observations of a Quasi-periodic, Fast-Propagating Multiple Wavelengths and Its Interaction with Other Magnetic Structures

Y.-D. **Shen**, Y. Liu, J.-T. Su, H. Li, X.-F. Zhang, Z.-J. Tian, R.-J. Zhao, A. Elmhamdi
Solar Phys (**2013**) 288:585–602
We present observations of a quasi-periodic fast-propagating (QFP) magnetosonic wave on **23 April 2012**, with high-resolution observations taken by the Atmospheric Imaging Assembly onboard the Solar Dynamics Observatory. Three minutes after the start of a C2.0 flare, wave trains were first observed along an open divergent

loop system in 171 Å observations at a distance of 150 Mm from the footpoint of the guiding loop system and with a speed of 689 km s−1, then they appeared in 193 Å observations after their interaction with a perpendicular, underlaying loop system on the path; in the meantime; their speed decelerated to 343 km s−1 within a short time. The sudden deceleration of the wave trains and their appearance in 193 Å observations are interpreted through a geometric effect and the density increase of the guiding loop system, respectively. We find that the wave trains have a common period of 80 seconds with the flare. In addition, a few low frequencies are also identified in the QFP wave. We propose that the generation of the period of 80 seconds was caused by the periodic releasing of energy bursts through some nonlinear processes in magnetic reconnection, while the low frequencies were possibly the leakage of pressure-driven oscillations from the photosphere or chromosphere, which could be an important source for driving coronal QFP waves. Our results also indicate that the properties of the guiding magnetic structure, such as the distributions of magnetic field and density as well as geometry, are crucial for modulating the propagation behaviors of QFP waves.

OBSERVATIONAL STUDY OF THE QUASI-PERIODIC FAST-PROPAGATING MAGNETOSONIC WAVES AND THE ASSOCIATED FLARE ON 2011 MAY 30

Yuandeng **Shen**1,2 and Yu Liu

2012 ApJ 753 53

https://iopscience.iop.org/article/10.1088/0004-637X/753/1/53/pdf

On **2011 May 30**, quasi-periodic fast-propagating (QFP) magnetosonic waves accompanied by a C2.8 flare were directly imaged by the Atmospheric Imaging Assembly instrument on board the Solar Dynamics Observatory. The QFP waves successively emanated from the flare kernel, they propagated along a cluster of open coronal loops with a phase speed of ~834 km s–1 during the flare's rising phase, and the multiple arc-shaped wave trains can be fitted with a series of concentric circles. We generate the k - ω diagram of the Fourier power and find a straight ridge that represents the dispersion relation of the waves. Along the ridge, we find a lot of prominent nodes which represent the available frequencies of the QFP waves. On the other hand, the frequencies of the flare are also obtained by analyzing the flare light curves using the wavelet technique. The results indicate that almost all the main frequencies of the flare are consistent with those of the QFP waves. This suggests that the flare and the QFP waves were possibly excited by a common physical origin. On the other hand, a few low frequencies (e.g., 2.5 mHz (400 s) and 0.7 mHz (1428 s)) revealed by the k - ω diagram cannot be found in the accompanying flare. We propose that these low frequencies were possibly due to the leakage of the pressure-driven p-mode oscillations from the photosphere into the low corona, which should be a noticeable mechanism for driving the QFP waves observed in the corona.

EVIDENCE FOR THE WAVE NATURE OF AN EXTREME ULTRAVIOLET WAVE OBSERVED BY THE ATMOSPHERIC IMAGING ASSEMBLY ON BOARD THE SOLAR DYNAMICS OBSERVATORY

Yuandeng **Shen**1,2 and Yu Liu

2012 ApJ 754 7, **File**

Extreme-ultraviolet (EUV) waves have been found for about 15 years. However, significant controversy remains over their physical natures and origins. In this paper, we report an EUV wave that was accompanied by an X1.9 flare and a partial halo coronal mass ejection (CME). Using high temporal and spatial resolution observations taken by the Solar Dynamics Observatory and the Solar-TErrestrial RElations Observatory, we are able to investigate the detailed kinematics of the EUV wave. We find several arguments that support the fast-mode wave scenario. (1) The speed of the EUV wave (570 km s–1) is higher than the sound speed of the quiet-Sun corona. (2) Significant deceleration of the EUV wave (–130 m s–2) is found during its propagation. (3) The EUV wave resulted in the oscillations of a loop and a filament along its propagation path, and a reflected wave from the polar coronal hole is also detected. (4) Refraction or reflection effect is observed when the EUV wave was passing through two coronal bright points. (5) The dimming region behind the wavefront stopped to expand when the wavefront started to become diffuse. (6) The profiles of the wavefront exhibited a dispersive nature, and the magnetosonic Mach number of the EUV wave derived from the highest intensity jump is about 1.4. In addition, triangulation indicates that the EUV wave propagated within a height range of about 60-100 Mm above the photosphere. We propose that the EUV wave observed should be a nonlinear fast-mode magnetosonic wave that propagated freely in the corona after it was driven by the CME expanding flanks during the initial period. **2011 September 24**,

SIMULTANEOUS OBSERVATIONS OF A LARGE-SCALE WAVE EVENT IN THE SOLAR ATMOSPHERE: FROM PHOTOSPHERE TO CORONA

Yuandeng **Shen**1,2 and Yu Liu

2012 ApJ 752 L23, **File**

For the first time, we report a large-scale wave that was observed simultaneously in the photosphere, chromosphere, transition region, and low corona layers of the solar atmosphere. Using the high temporal and high spatial resolution

observations taken by the Solar Magnetic Activity Research Telescope at Hida Observatory and the Atmospheric Imaging Assembly (AIA) on board Solar Dynamic Observatory, we find that the wave evolved synchronously at different heights of the solar atmosphere, and it propagated at a speed of 605 km s–1 and showed a significant deceleration (–424 m s–2) in the extreme-ultraviolet (EUV) observations. During the initial stage, the wave speed in the EUV observations was 1000 km s–1, similar to those measured from the AIA 1700 Å (967 km s–1) and 1600 Å (893 km s–1) observations. The wave was reflected by a remote region with open fields, and a slower wave-like feature at a speed of 220 km s–1 was also identified following the primary fast wave. In addition, a type-II radio burst was observed to be associated with the wave. We conclude that this wave should be a fast magnetosonic shock wave, which was first driven by the associated coronal mass ejection and then propagated freely in the corona. As the shock wave propagated, its legs swept the solar surface and thereby resulted in the wave signatures observed in the lower layers of the solar atmosphere. The slower wave-like structure following the primary wave was probably caused by the reconfiguration of the low coronal magnetic fields, as predicted in the field-line stretching model.
2011-08-09

Observational and numerical characterization of a recurrent arc-shaped front propagating along a coronal fan

M.V. **Sieyra**, S. Krishna Prasad, G. Stenborg, E. Khomenko, T. Van Doorsselaere, A. Costa, A. Esquivel, J.M. Riedl
A&A 667, A21 **2022**
https://arxiv.org/pdf/2208.10857.pdf
https://www.aanda.org/articles/aa/pdf/2022/11/aa44454-22.pdf
Recurrent, arc-shaped intensity disturbances were detected by EUV channels in an active region. The fronts were observed to propagate along a coronal loop bundle rooted in a small area within a sunspot umbra. Previous works have linked these intensity disturbances to slow magnetoacoustic waves that propagate from the lower atmosphere to the corona along the magnetic field. The slow magnetoacoustic waves propagate at the local cusp speed. However, the measured propagation speeds from the intensity images are usually smaller as they are subject to projection effects due to the inclination of the magnetic field with respect to the line-of-sight. Here, we aim to understand the effect of projection by comparing observed speeds with those from a numerical model. Using multi-wavelength data we determine the periods present in the observations at different heights of the solar atmosphere through Fourier analysis. We calculate the plane-of-sky speeds along one of the loops from the cross-correlation time lags obtained as a function of distance along the loop. We perform a 2D ideal MHD simulation of an active region embedded in a stratified atmosphere. We drive slow waves from the photosphere with a 3 minutes periodicity. Synthetic time-distance maps are generated from the forward-modelled intensities in coronal wavelengths and the projected propagation speeds are calculated. The intensity disturbances show a dominant period between [2-3] minutes at different heights of the atmosphere. The apparent propagation speeds calculated for coronal channels exhibit an accelerated pattern with values increasing from 40 to 120 km/s as the distance along the loop rises. The propagation speeds obtained from the synthetic time-distance maps also exhibit accelerated profiles within a similar range of speeds. We conclude that the accelerated propagation in our observations is due to the projection effect. **2011 July 6**

A Study of the Observational Properties of Coronal Mass Ejection Flux Ropes near the Sun*

G. **Sindhuja**1 and N. Gopalswamy2
2020 ApJ 889 104
https://doi.org/10.3847/1538-4357/ab620f
We present the observational properties of coronal mass ejection (CME) flux ropes (FRs) near the Sun based on a set of 35 events from solar cycle 24 (2010–2017). We derived the CME FR properties using the Flux Rope from Eruption Data technique. According to this technique, the geometrical properties are obtained from a flux-rope fit to CMEs and the magnetic properties from the reconnected flux in the source region. In addition, we use the magnetic flux in the dimming region at the eruption site. Geometric properties like radius of the FR and the aspect ratio are derived from the FR fitting. The reconnected flux exhibits a positive correlation with flare fluence in soft X-rays (SXRs), peak flare intensity in SXRs, CME speed, and kinetic energy, with correlation coefficients (cc) 0.78, 0.6, 0.48, and 0.55, respectively. We found a moderate positive correlation between magnetic flux in the core dimming regions and the toroidal flux obtained from the Lundquist solution for a force-free FR (cc = 0.43). Furthermore, we correlate the core dimming flux and CME mass (cc = 0.34). The area of the core dimming region shows a moderate correlation with the radius of the FR (cc = 0.4). Thus, we infer that greater magnetic content (poloidal and toroidal fluxes) indicates a more energetic eruption in terms of flare size, CME speed, kinetic energy, mass, and radius of the FR, suggesting important implications for space weather predictions.

Observational Effects of Flare-Associated Waves,

Smith, S.F., Harvey, K.L.,

1971. in: Macris, C. J. (Ed.), Physics of the Solar Corona, p. 156.

Inference of Magnetic Field in the Coronal Streamer Invoking Kink Wave Motions generated by Multiple EUV Waves

A.K. **Srivastava**, Talwinder Singh, Leon Ofman, B.N. Dwivedi

Mon. Not. R. Astron. Soc. **2016   File**

http://arxiv.org/pdf/1606.00337v1.pdf

Using MHD seismology by observed kink waves, the magnetic field profile of a coronal streamer has been investigated. STEREO-B/EUVI temporal image data on **7 March 2012** shows an evolution of two consecutive EUV waves that interact with the footpoint of a coronal streamer evident in the co-spatial and co-temporal STEREO-B/COR-I observations. The evolution of EUV waves is clearly evident in STEREO-B/EUVI, and its energy exchange with coronal streamer generates kink oscillations. We estimate the phase velocities of the kink wave perturbations by tracking it at different heights of the coronal streamer. We also estimate the electron densities inside and outside the streamer using SSI of polarized brightness images in STEREO-B/COR-1 observations. Taking into account the MHD theory of kink waves in a cylindrical waveguide, their observed properties at various heights, and density contrast of the streamer, we estimate the radial profile of magnetic field within this magnetic structure. Both the kink waves diagnose the exponentially decaying radial profiles of the magnetic field in coronal steamer upto 3 solar radii. Within the limit of uncertainties in the measurements, it is indicated that coronal magnetic field of the streamer varies slowly in time at various heights, although its nature always remains exponentially decaying. It is seen that during the evolution of second kink motion in the streamer, it increases in brightness, and also in areal extent slightly, which may be associated with the decreased photospheric magnetic flux at its footpoint. As a result, the magnetic field profile produced by the second kink wave is reduced within the streamer compared to the one diagnosed by the first one. The precisely estimated magnetic field profiles with the uncertainty less than 10% match well with the empirical profile and various observational estimations of the outer coronal magnetic field.

X6.9-class Flare Induced Vertical Kink Oscillations in a Large-Scale Plasma Curtain as Observed by SDO/AIA

A.K. **Srivastava**, M. Goossens

E-print, Sept **2013**; ApJ

We present rare observational evidence of vertical kink oscillations in a laminar and diffused large-scale plasma curtain as observed by the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO). The X6.9 class flare in the Active Region 11263 on **09 August 2011**, induces a global large-scale disturbance that propagates in a narrow lane above the plasma curtain and creates a low density region that appears as a dimming in the observational image data. This large-scale propagating disturbance acts as a non-periodic driver that interacts asymmetrically and obliquely with the top of the plasma curtain, and triggers the observed oscillations. In the deeper layers of the curtain, we find evidence of vertical kink oscillations with two periods (795 s and 530 s). On the magnetic surface of the curtain where the density is inhomogeneous due to the coronal dimming, non-decaying vertical oscillations are also observed (period approx 763-896 s). We infer that the global large-scale disturbance triggers vertical kink oscillations in the deeper layers as well as on the surface of the large-scale plasma curtain. The properties of the excited waves strongly depend on the local plasma and magnetic field conditions.

Magnetohydrodynamic models of coronal transients in the meridional plane.

Steinolfson, R.S., Wu, S.T., Dryer, M., Tandberg-Hanssen, E., **1978**.

I- The effect of the magnetic field. Astrophys. J. 225, 259–274.

Multi-instrument observations and tracking of a coronal mass ejection front from low to middle corona

Oleg **Stepanyuk*** and Kamen Kozarev

J. Space Weather Space Clim. **2024**, 14, 2

https://www.swsc-journal.org/articles/swsc/pdf/2024/01/swsc230003.pdf

The shape and dynamics of coronal mass ejections (CMEs) vary significantly based on the instrument and wavelength used. This has led to significant debate about the proper definitions of CME/shock fronts, pile-up/compression regions, and core observations in projection in optically thin vs. optically thick emission. Here we present an observational analysis of the evolving shape and kinematics of a large-scale CME that occurred on **May 7, 2021** on the eastern limb of the Sun as seen from 1 AU. The eruption was observed continuously, consecutively by the Atmospheric Imaging Assembly (AIA) telescope suite on the Solar Dynamics Observatory (SDO), the ground-based COronal Solar Magnetism Observatory (COSMO) K-coronagraph (K-Cor) on Mauna Loa, and the C2 and C3 telescopes of the Large Angle Solar Coronagraph (LASCO) on the Solar and Heliospheric Observatory (SoHO). We apply the updated multi-instrument version of the recently developed Wavetrack Python suite for automated detection and tracking of coronal eruptive features to evaluate and compare the evolving shape of the CME front as it propagated from the solar surface out to 20 solar radii. Our tool allows tracking features beyond just the leading edge and is an important step towards semi-automatic manufacturing of training sets for training data-driven image segmentation models for solar imaging. Our findings confirm the expected strong connection between EUV waves and CMEs. Our novel, detailed analysis sheds observational light on the details of EUV wave-shock-CME relations that lacking for the gap region between the low and middle corona.

YOHKOH SXT Observations of X-Ray ”Dimming” Associated with a Halo Coronal Mass Ejection.

Sterling, A.C., Hudson, H.S.,
1997. Astrophys. J. 491, L55–L58.

OBSERVATIONS AND MAGNETIC FIELD MODELING OF THE FLARE/CORONAL MASS EJECTION EVENT ON 2010 APRIL 8

Yingna **Su**1, Vincent Surges1,2, Adriaan van Ballegooijen1, Edward DeLuca1 and Leon Golub
2011 ApJ 734 53, **File**
We present a study of the flare/coronal mass ejection event that occurred in Active Region 11060 on **2010 April 8**. This event also involves a filament eruption, EIT wave, and coronal dimming. Prior to the flare onset and filament eruption, both SDO/AIA and STEREO/EUVI observe a nearly horizontal filament ejection along the internal polarity inversion line, where flux cancellations frequently occur as observed by SDO/HMI. Using the flux-rope insertion method developed by van Ballegooijen, we construct a grid of magnetic field models using two magneto-frictional relaxation methods. We find that the poloidal flux is significantly reduced during the relaxation process, though one relaxation method preserves the poloidal flux better than the other. The best-fit pre-flare NLFFF model is constrained by matching the coronal loops observed by SDO/AIA and Hinode/XRT. We find that the axial flux in this model is very close to the threshold of instability. For the model that becomes unstable due to an increase of the axial flux, the reconnected field lines below the X-point closely match the observed highly sheared flare loops at the event onset. The footpoints of the erupting flux rope are located around the coronal dimming regions. Both observational and modeling results support the premise that this event may be initiated by catastrophic loss of equilibrium caused by an increase of the axial flux in the flux rope, which is driven by flux cancellations.

Cross-loop propagation of a quasi-periodic extreme-ultraviolet wave train triggered by successive stretching of magnetic field structures during a solar eruption

Zheng **Sun**, Hui Tian, P. F. Chen, Shuo Yao, Zhenyong Hou, Hechao Chen, Linjie Chen
ApJL **939** L18 **2022**
https://arxiv.org/pdf/2210.06769.pdf
https://iopscience.iop.org/article/10.3847/2041-8213/ac9aff/pdf
Solar extreme-ultraviolet (EUV) waves generally refer to large-scale disturbances propagating outward from sites of solar eruptions in EUV imaging observations. Using the recent observations from the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO), we report a quasi-periodic wave train propagating outward at an average speed of ∼308 km s−1. At least five wavefronts can be clearly identified with the period being ∼120 s. These wavefronts originate from the coronal loop expansion, which propagates with an apparent speed of ∼95 km s−1, about 3 times slower than the wave train. In the absence of a strong lateral expansion, these observational results might be explained by the theoretical model of Chen et al. (2002), which predicted that EUV waves may have two components: a faster component that is a fast-mode magnetoacoustic wave or shock wave and a slower apparent front formed as a result of successive stretching of closed magnetic field lines. In this scenario, the wave train and the successive loop expansion we observed likely correspond to the fast and slow components in the model, respectively. **2021 November** 2

Shock-Cloud Interaction in the Solar Corona

Takuya **Takahashi**
ApJ **836** 178 **2017**
https://arxiv.org/pdf/1701.07001v1.pdf
Flare associated coronal shock waves sometimes interact with solar prominences leading to large amplitude prominence oscillations. Such prominence activation gives us unique opportunity to track time evolution of shock-cloud interaction in cosmic plasmas. Although the dynamics of interstellar shock-cloud interaction is extensively studied, coronal shock-solar prominence interaction is rarely studied in the context of shock-cloud interaction. Associated with X5.4 class solar flare occurred on **7 March, 2012**, a globally propagated coronal shock wave interacted with a polar prominence leading to large amplitude prominence oscillation. In this paper, we studied bulk acceleration and excitation of internal flow of the shocked prominence using three-dimensional MHD simulations. We studied eight magnetohydrodynamic (MHD) simulation runs with different mass density structure of the

prominence, and one hydrodynamic simulation run, and compared the result. In order to compare observed motion of activated prominence with corresponding simulation, we also studied prominence activation by injection of triangular shaped coronal shock. We found that magnetic tension force mainly accelerate (and then decelerate) the prominence. The internal flow, on the other hand, is excited during the shock front sweeps through the the prominence and damps almost exponentially. We construct phenomenological model of bulk momentum transfer from shock to the prominence, which agreed quantitatively with all the simulation results. Based on the phenomenological prominence-activation model, we diagnosed physical parameters of coronal shock wave. The estimated energy of the coronal shock is several percent of total energy released during the X5.4 flare.

Prominence Activation by Coronal Fast Mode Shock

Takuya **Takahashi**, Ayumi Asai, Kazunari Shibata

2015 *ApJ* **801** 37

http://arxiv.org/pdf/1501.01592v1.pdf

An X5.4 class flare occurred in active region (AR) NOAA11429 on **2012 March 7**. The flare was associated with very fast coronal mass ejection (CME) with its velocity of over 2500 km/s. In the images taken with STEREO-B/COR1, a dome-like disturbance was seen to detach from expanding CME bubble and propagated further. A Type-II radio burst was also observed at the same time. On the other hand, in EUV images obtained by SDO/AIA, expanding dome-like structure and its foot print propagating to the north were observed. The foot print propagated with its average speed of about 670 km/s and hit a prominence located at the north pole and activated it. While the activation, the prominence was strongly brightened. On the basis of some observational evidence, we concluded that the foot print in AIA images and the ones in COR1 images are the same, that is MHD fast mode shock front. With the help of a linear theory, the fast mode mach number of the coronal shock is estimated to be between 1.11 and 1.29 using the initial velocity of the activated prominence. Also, the plasma compression ratio of the shock is enhanced to be between 1.18 and 2.11 in the prominence material, which we consider to be the reason of the strong brightening of the activated prominence. The applicability of linear theory to the shock problem is tested with nonlinear MHD simulation.

The Wave-Driver System of the Off-Disk Coronal Wave 17 January 2010

M. **Temmer**, B. Vrsnak, A. M. Veronig

E-print, July **2012**; Solar Phys. **2013,** Volume 287, Issue 1-2, pp 441-454, **File**

http://arxiv.org/pdf/1207.2857v1.pdf

We study the **17 January 2010** flare-CME-wave event by using STEREO/SECCHI EUVI and COR1 data. The observational study is combined with an analytic model which simulates the evolution of the coronal-wave phenomenon associated with the event. From EUV observations, the wave signature appears to be dome shaped having a component propagating on the solar surface (v~280 km s-1) as well as off-disk (v~600 km s-1) away from the Sun. The off-disk dome of the wave consists of two enhancements in intensity, which conjointly develop and can be followed up to white-light coronagraph images. Applying an analytic model, we derive that these intensity variations belong to a wave-driver system with a weakly shocked wave, initially driven by expanding loops, which are indicative of the early evolution phase of the accompanying CME. We obtain the shock standoff distance between wave and driver from observations as well as from model results. The shock standoff distance close to the Sun (<0.3 Rs above the solar surface) is found to rapidly increase with values of ~0.03-0.09 Rs which give evidence of an initial lateral (over-)expansion of the CME. The kinematical evolution of the on-disk wave could be modeled using input parameters which require a more impulsive driver (t=90 s, a=1.7 km s-2) compared to the off-disk component (t=340 s, a=1.5 km s-2).

Relation between the 3D-geometry of the coronal wave and associated CME during the 26 April 2008 event

M. **Temmer**1· A.M. Veronig1 N. Gopalswamy2 · S. Yashiro2

E-print, March **2011**; Solar Phys., Volume 273, Number 2, 421-432, **2011, File**

We study the kinematical characteristics and 3D geometry of a largescale coronal wave that occurred in association with the **26 April 2008** flare-CME event. The wave was observed with the EUVI instruments aboard both STEREO spacecraft (STEREO-A and STEREO-B) with a mean speed of _240 km s^{-1}. The wave is more pronounced in the eastern propagation direction, and is thus, better observable in STEREO-B images. From STEREO-B observations we derive two separate initiation centers for the wave, and their locations fit with the coronal dimming regions. Assuming a simple geometry of the wave we reconstruct its 3D nature from combined STEREO-A and STEREO-B observations. We find that the wave structure is asymmetric with an inclination towards East. The associated CME has a deprojected speed of _750±50 km s^{-1}, and shows a non-radial outward motion towards the East with respect to the underlying source region location. Applying the forward fitting model developed by Thernisien, Howard, and

Vourlidas (2006), we derive the CME flux rope position on the solar surface to be close to the dimming regions. We conclude that the expanding flanks of the CME most likely drive and shape the coronal wave.

ANALYTIC MODELING OF THE MORETON WAVE KINEMATICS

M. **Temmer**1, B. Vrˇsnak2, T. ˇ Zic2, and A. M. Veronig1

Astrophysical Journal, 702:1343–1352, **2009, File** September

The issue whether Moreton waves are flare-ignited or coronal mass ejection (CME)-driven, or a combination of both, is still a matter of debate. We develop an analytical model describing the evolution of a large-amplitude coronal wave emitted by the expansion of a circular source surface in order to mimic the evolution of a Moreton wave. The model results are confronted with observations of a strong Moreton wave observed in association with the X3.8/3B flare/CME event from **2005 January 17.** Using different input parameters for the expansion of the source region, either derived from the real CME observations (assuming that the upward moving CME drives the wave), or synthetically generated scenarios (expanding flare region, lateral expansion of the CME flanks), we calculate the kinematics of the associated Moreton wave signature. Those model input parameters are determined which fit the observed Moreton wave kinematics best. Using the measured kinematics of the upward moving CME as the model input, we are not able to reproduce the observed Moreton wave kinematics. The observations of the Moreton wave can be reproduced only by applying a strong and impulsive acceleration for the source region expansion acting in a piston mechanism scenario. Based on these results we propose that the expansion of the flaring region or the lateral expansion of the CME flanks is more likely the driver of the Moreton wave than the upward moving CME front.

Analysis of the Flare Wave Associated with the 3B/X3.8 Flare of January 17, 2005

Thalmann, J. K.; Veronig, A. M.; Temmer, M.; Vršnak, B.; Hanslmeier, A.

Central European Astrophysical Bulletin, 2007CEAB...31..187T; **File**

The flare wave associated with the 3B/X3.8 flare and coronal mass ejection (CME) of **January 17, 2005** are studied using imaging data in the Hα and EUV spectral channels. Due to the high-cadence Hα observations from Kanzelhöhe Solar Observatory (KSO), a distinct Moreton wave can be identified in ˜40 Hα frames over a period of ˜7 minutes. The associated coronal EIT wave is identifiable in only one EUV frame and appears close to the simultaneously observed Moreton wave front, indicating that they are closely associated phenomena. Beside the morphology of the wave across the solar disc (covering an angular extend of ˜130°), the evolution in different directions is studied to analyse the influence of a coronal hole (CH) on the wave propagation. The Moreton wave shows a decelerating character which can be interpreted in terms of a freely propagating fast-mode MHD shock. The parts of the wave front moving towards the CH show a lower initial and mean speed, and a greater amount of deceleration than the segments moving into the undisturbed direction. This is interpreted as the tendency of high Alfvén velocity regions to influence the propagation of wave packets.

The Mean Temperatures of CME-Related Dimming Masses

Emily **Thomson**, Hugh Hudson

Solar Phys. 298, Article number: 130 (**2023**)

https://link.springer.com/content/pdf/10.1007/s11207-023-02222-6.pdf

Sun-as-a-star EUV spectroscopy from EVE (the Extreme-ultraviolet Variability Experiment, on board SDO, the Solar Dynamics Observatory) frequently shows striking irradiance reductions following major solar flares. These coincide with dimming events as seen in EUV and X-ray images, involving the evacuation of large volumes of the corona by the associated coronal mass ejections. The EVE view of the dimming process is precise and quantitative, whereas difference imaging in the EUV reveals the structures to be full of complicated detail due most likely to unrelated activity. We have studied a sample of **11 events, mostly GOES X-class flares**, all of which were associated with coronal mass ejections. For a set of nine lines of Fe ions at stages VIII – XIII, corresponding to nominal peak formation temperatures below $\log_{10}(T/K)=6.3$, we have compared the emission-measure-weighted temperature of the preflare global corona and that of the dimming mass, defined by the deficit at the time of greatest dimming. We find similar temperatures by this measure, but with a distinctly narrower variation in the preflare samples. For higher ionization states, weak emission commonly appears during the dimming intervals, consistent with residual late-phase flare development. The dimming depths do not appear to correlate with the preflare state of the global corona. **2012-03-07, 2013-11-05**

Table 2 List of dimming events and their properties. 2010-2013

PERSISTENCE MAPPING USING EUV SOLAR IMAGER DATA

B. J. **Thompson**1 and C. A. Young2

2016 ApJ 825 27

We describe a simple image processing technique that is useful for the visualization and depiction of gradually evolving or intermittent structures in solar physics extreme-ultraviolet imagery. The technique is an application of image segmentation, which we call "Persistence Mapping," to isolate extreme values in a data set, and is particularly useful for the problem of capturing phenomena that are evolving in both space and time. While integration or "time-lapse" imaging uses the full sample (of size N), Persistence Mapping rejects (N − 1)/N of the data set and identifies the most relevant 1/N values using the following rule: if a pixel reaches an extreme value, it retains that value until that value is exceeded. The simplest examples isolate minima and maxima, but any quantile or statistic can be used. This paper demonstrates how the technique has been used to extract the dynamics in long-term evolution of comet tails, erupting material, and **EUV dimming** regions.

A CATALOG OF CORONAL "EIT WAVE" TRANSIENTS

B. J. **Thompson**1 and D. C. Myers2

Astrophysical Journal Supplement Series, 183:225–243, **2009** August; **File**

Solar and Heliospheric Observatory (*SOHO*) Extreme ultraviolet Imaging Telescope (EIT) data have been visually searched for coronal "EIT wave" transients over the period beginning **from 1997 March 24 and extending through 1998 June 24.** The dates covered start at the beginning of regular high-cadence (more than 1 image every 20minutes) observations, ending at the four-month interruption of *SOHO* observations in mid-1998. One hundred and seventy six events are included in this catalog. The observations range from "candidate" events, which were either weak or had insufficient data coverage, to events which were well defined and were clearly distinguishable in the data. Included in the catalog are times of the EIT images in which the events are observed, diagrams indicating the observed locations of the wave fronts and associated active regions, and the speeds of the wave fronts. The measured speeds of the wave fronts varied from less than 50 to over 700 km s^{-1} with "typical" speeds of 200–400 km s^{-1}.

OBSERVATIONS OF THE 24 SEPTEMBER 1997 CORONAL FLARE WAVES

B. J. **THOMPSON**[1], B. REYNOLDS[2], H. AURASS[3], N. GOPALSWAMY[4], J. B. GURMAN[5], H. S. HUDSON[6], S. F. MARTIN[7] andO. C. ST. CYR[8]

Solar Physics **193:** 161–180, **2000, File**.

We report coincident observations of coronal and chromospheric 'flare wave' transients in association with a flare, large-scale coronal dimming, metric radio activity and a coronal mass ejection. The two separate eruptions occurring on 24 September 1997 originate in the same active region and display similar morphological features. The first wave transient was observed in EUV and H_ data, corresponding to a wave disturbance in both the chromosphere and the solar corona, ranging from 250 to approaching 1000 km s_1 at different times and locations along the wavefront. The sharp wavefront had a similar extent and location in both the EUV and H_ data. The data did not show clear evidence of a driver, however. Both events display a coronal EUV dimming which is typically used as an indicator of a coronal mass ejection in the inner corona.White-light coronagraph observations indicate that the first event was accompanied by an observable coronal mass ejection while the second event did not have clear evidence of a CME. Both eruptions were accompanied by metric type II radio bursts propagating at speeds in the range of 500–750 km s_1, and neither had accompanying interplanetary type II activity. The timing and location of the flare waves appear to indicate an origin with the flaring region, but several signatures associated with coronal mass ejections indicate that the development of the CME may occur in concert with the development of the flare wave.

Coronal Dimmings and Energetic CMEs in April-May 1998

Thompson, B. J.; Cliver, E. W.; Nitta, N.; Delannée, C.; Delaboudinière, J.-P.

Geophysical Research Letters, Volume 27, Issue 10, p. 1431-1434, **2000, File**

We have analyzed the coronal dimmings for seven fast (>600 km/s) coronal mass ejections (CMEs) occurring between 23 April and 9 May which were associated with flares from NOAA active region (AR) 8210. Each of these CMEs had at least one group of interplanetary radio bursts associated with them. These dimming regions were identified by their strong depletion in coronal EUV emission within a half hour of the estimated time of CME lift-off. They included areas which were as dark as quiescent coronal holes as well as other regions with weaker brightness depletions. While the location of the active region and the associated flare did not correspond well with the coronagraph observations, we found that the extended dimming areas in these events generally mapped out the apparent ``foot-print" of the CME as observed by white-light coronagraph. We briefly discuss the implications of these results on models of CME topology.

[Erratum: 2000GeoRL..27.1865T]

SOHO/EIT Observations of the 1997 April 7 Coronal Transient: Possible Evidence of Coronal Moreton Waves.

Thompson, B.J., Gurman, J.B., Neupert, W.M., Newmark, J.S., Delaboudini`re, J.P., St. Cyr, O.C., Stezelberger, S., Dere, K.P., Howard, R.A.,
Michels, D.J.,
1999. Astrophys. J. 517, L151–L154.

Upflows in the upper solar atmosphere **Review**

Hui **Tian**, Louise Harra, Deborah Baker, David H. Brooks, Lidong Xia

Solar Phys. **2021**

https://arxiv.org/pdf/2102.02429.pdf

Spectroscopic observations at extreme and far ultraviolet wavelengths have revealed systematic upflows in the solar transition region and corona. These upflows are best seen in the network structures of the quiet Sun and coronal holes, boundaries of active regions, and dimming regions associated with coronal mass ejections. They have been intensively studied in the past two decades because they are highly likely to be closely related to the formation of the solar wind and heating of the upper solar atmosphere. We present an overview of the characteristics of these upflows, introduce their possible formation mechanisms, and discuss their potential roles in the mass and energy transport in the solar atmosphere. Though past investigations have greatly improved our understanding of these upflows, they have left us with several outstanding questions and unresolved issues that should be addressed in the future. New observations from the Solar Orbiter mission, the Daniel K. Inouye Solar Telescope and the Parker Solar Probe will likely provide critical information to advance our understanding of the generation, propagation and energization of these upflows.

3.4. Connection to the solar wind

4. Upflows from CME-induced dimmings

EIS Observations of Solar Mass Eruptions

Hui **Tian**

EIS Science Nugget, Jan **2013**

http://msslxr.mssl.ucl.ac.uk:8080/SolarB/nuggets/nugget_2013jan.jsp

Plasma properties and dynamics of the CME ejecta and EUV jets:

Plasma properties and dynamics of coronal dimmings:

14-15 Dec, 2006

What can we learn about solar coronal mass ejections, coronal dimmings, and Extreme-Ultraviolet jets through spectroscopic observations?

Hui **Tian**, Scott W. McIntosh, Lidong Xia, Jiansen He, Xin Wang

E-print, Jan 2012; **2012** ApJ 748 106, **File**

Solar eruptions, particularly coronal mass ejections (CMEs) and extreme-ultraviolet (EUV) jets, have rarely been investigated with spectroscopic observations. We analyze several data sets obtained by the EUV Imaging Spectrometer onboard Hinode and find various types of flows during CMEs and jet eruptions. CME-induced dimming regions are found to be characterized by significant blueshift and enhanced line width by using a single Gaussian fit. While a red-blue (RB) asymmetry analysis and a RB-guided double Gaussian fit of the coronal line profiles indicate that these are likely caused by the superposition of a strong background emission component and a relatively weak (~10%) high-speed (~100 km s−1) upflow component. This finding suggests that the outflow velocity in the dimming region is probably of the order of 100 km s−1, not ~20 km s−1 as reported previously. Density and temperature diagnostics of the dimming region suggest that dimming is primarily an effect of density decrease rather than temperature change. The mass losses in dimming regions as estimated from different methods are roughly consistent with each other and they are 20%-60% of the masses of the associated CMEs. With the guide of RB asymmetry analysis, we also find several temperature-dependent outflows (speed increases with temperature) immediately outside the (deepest) dimming region. These outflows may be evaporation flows which are caused by the enhanced thermal conduction or nonthermal electron beams along reconnecting field lines, or induced by the interaction between the opened field lines in the dimming region and the closed loops in the surrounding plage region. In an erupted CME loop and an EUV jet, profiles of emission lines formed at coronal and transition region temperatures are found to exhibit two well-separated components, an almost stationary component accounting for the background emission and a highly blueshifted (~200 km s−1) component representing emission from the erupting material. The two components can easily be decomposed through a double Gaussian fit and we can diagnose the electron density, temperature and mass of the ejecta. Combining the speed of the blueshifted component and the projected speed of the erupting material derived from simultaneous imaging observations, we can calculate the real speed of the ejecta.

1997 MAY 12 CORONAL MASS EJECTION EVENT.
I. A SIMPLIFIED MODEL OF THE PREERUPTIVE MAGNETIC STRUCTURE
V. S. **Titov**, Z. Mikic, J. A. Linker, and R. Lionello
http://www.journals.uchicago.edu/doi/pdf/10.1086/527280
The Astrophysical Journal, 675:1614Y1628, 2008 March 10
A simple model of the coronal magnetic field prior to the coronal mass ejection (CME) eruption on 1997May 12 is developed. First, the magnetic field is constructed by superimposing a large-scale background field and a localized bipolar field to model the active region (AR) in the current-free approximation. Second, this potential configuration is quasi-statically sheared by photospheric vortex motions applied to two flux concentrations of the AR. Third, the resulting force-free field is then evolved by canceling the photospheric magnetic flux with the help of an appropriate tangential electric field applied to the central part of the AR. To understand the structure of the modeled configuration, we use the field linemapping technique by generalizing it to spherical geometry.We demonstrate that the initial potential configuration contains a hyperbolic flux tube (HFT) which is a union of two intersecting quasi-separatrix layers. This HFT provides a partition of the closed magnetic flux between the AR and the global solar magnetic field. Such a partition is approximate since the entire flux distribution is perfectly continuous. The vortex motions applied to the AR interlock the field lines in the coronal volume to form additionally two newHFTs pinched into thin current layers.Reconnection in these current layers helps to redistribute the magnetic flux and current within the AR in the flux-cancellation phase. In this phase, a magnetic flux rope is formed together with a bald patch separatrix surface wrapping around the rope. Other important implications of the identified structural features of the modeled configuration are also discussed.

On the relationship between coronal waves associated with a CME on 5 March 2000

D. **Tripathi** and N.-E.Raouafi
E-print, Aug. 2007, A&A 473 (**2007**) 951-957, **File**
Spatial and temporal correlations show that the deflection and the propagation of the kink in the streamer (based on the LASCO data), and plasma heating and spectral line broadening (based on the UVCS data), are basically due to a CME-driven shock wave. The spatial and temporal correlations between the EIT wave and the shock wave provide strong evidence in favor of the interpretation that the EIT waves are indeed the counterpart of CME-driven shock waves in the lower corona. Although, we cannot rule out the possibility that the EIT waves are just a manifestation of the stretching of the field lines due to the outward propagation of the CMEs.
Корональные волны при эрупции волокна вне АО.

The basic characteristics of EUV post-eruptive arcades and their role as tracers of coronal mass ejection source regions.

D. **Tripathi**, V. Bothmer and H. Cremades,
Astron. Astrophys. vol. 422, pp. 337-349, **2004, File**.
An almost one to one correspondence is found between EUV PEAs and white-light CMEs. Based on this finding, PEAs can be considered as reliable tracers of CME events even without simultaneous coronagraph observations. A detailed comparison of the white-light, soft X-ray and EUV observation for some of the events shows, that PEAs form in the aftermath of CMEs likely in the course of the magnetic restructurings taking place at the coronal source sites.

Oscillations in the wake of a flare blast wave_

D. **Tothova**1, D. E. Innes1, and G. Stenborg2
A&A 528, L12 (**2011**), **File**;
Context. Oscillations of coronal loops in the Sun have been reported in both imaging and spectral observations at the onset of flares. Images reveal transverse oscillations, whereas spectra detect line-of-sight velocity or Doppler-shift oscillations. The Doppler-shift oscillations are commonly interpreted as longitudinal modes.
Aims. Our aim is to investigate the relationship between loop dynamics and flows seen in TRACE 195 Å images and Doppler shifts observed by SUMER in Siiii 1113.2 Å and FeXIX 1118.1 Å at the time of a C.8-class limb flare and an associated CME.
Methods. We carefully co-aligned the sequence of TRACE 195 Å images to structures seen in the SUMER Siiii, CaX, and FeXIX emission lines. Additionally, Hα observations of a lifting prominence associated with the flare and the coronal mass ejection (CME) are available in three bands around 6563.3 Å. They give constraints on the timing and geometry.

Results. Large-scale Doppler-shift oscillations in FeXIX and transverse oscillations in intensity images were observed over a large region of the corona after the passage of a wide bright extreme-ultraviolet (EUV) disturbance, which suggests ionization, heating, and acceleration of hot plasma in the wake of a blast wave.
9 April 2002

Behavior of the flare produced coronal MHD wavefront and the occurrence of type II radio bursts.
Uchida, Y.,
1974. Solar Phys. 39, 431–449.

Flare-Produced Coronal MHD-Fast-Mode Wavefronts and Moreton's Wave Phenomenon.
Uchida, Y., Altschuler, M.D., Newkirk, G.J.,
1973. Solar Phys. 28, 495–516.

Diagnosis of Coronal Magnetic Structure by Flare-Associated Hydromagnetic Disturbances.
Uchida, Y.,
1970. Pub. Astron. Soc. Japan 22, 341–364.

Propagation of Hydromagnetic Disturbances in the Solar Corona and Moreton's Wave Phenomenon.
Uchida, Y.,
1968. Solar Phys. 4, 30–44.

Modeling Arrival Time of Coronal Mass Ejections to Near-Earth Orbit Using Coronal Dimming Parameters
Vakhrusheva, AA ; Kaportseva, KB ; Shugay, YS ; Eremeev, VE ; Kalegaev, VV
COSMIC RESEARCH Volume 62 Issue 4 Page 350-358 APR **2024**
DOI 10.1134/S0010952524600422
The paper demonstrates results of modeling arrival time of coronal mass ejections (CME) to near-Earth space with parameters of coronal dimmings in 2010-2018. We use drag-based model (DBM) for CME propagation and empirical model for quasi-stationary solar wind streams. We compared the ICME arrival time and speed forecast for events with coronal source in the central region of the solar disk based on the CME initial speed using (1) CACTus database; (2) dimming maximum intensity drop from Solar Demon database to calculate the initial speed of the CME. Results show that the methods result in similar errors. To study the possibility of predicting ICME, for which a CME may not be observed in the coronagraph for some reason, modeling of ICME was carried out using dimming parameters. In 43% of cases, ICME arrival time were forecasted with an accuracy of 24 h using parameters of dimmings in the central region of solar disk that could not be associated with any CMEs.

Parameters of Coronal Dimmings and Their Variations during Solar Cycle 24
Vakhrusheva, A. A. ; Shugai, Yu. S. ; Kaportseva, K. B. ; Eremeev, V. E. ; Kalegaev, V. V.
Geomagnetism and Aeronomy, Volume 64, Issue 1, p.1-10 **2024**
https://doi.org/10.1134/S0016793223600868
The parameters of dimmings and their relation to coronal mass ejections (CMEs) are studied to determine the location of possible sources of ejections on the solar disk during solar cycle 24. We used the Solar Demon database, which contains information on flares and dimmings obtained by processing images from the SDO/AIA space observatory. Of all the analyzed dimmings, 16% are associated with CMEs from the CACTus database using SOHO/LASCO coronagraph data for 2010-2018. Based on the parameter distribution, it is found that dimmings related with CMEs are on average events with large absolute parameter values. The correlation coefficient between the position angle of the dimmings and the position angle of the CME associated with them is 0.96. For dimmings observed in the central part of the solar disk, we obtained correlation coefficients between the CME velocity and dimming parameters that are close to 0.5. The results can be used to model the propagation of CMEs and to refine the probability of their arrival to the near-Earth orbit.

Why are CMEs large-scale coronal events: nature or nurture?
L. **van Driel-Gesztelyi**, G. D. R. Attrill, P. D´emoulin, C. H. Mandrini4, and L. K. Harra

E-print, March **2008**, **File** ; Annales. Geophys.

The apparent contradiction between small-scale source regions of, and large-scale coronal response to, coronal mass ejections (CMEs) has been a long-standing puzzle. For some, CMEs are considered to be inherently large-scale events - eruptions in which a number of flux systems participate in an unspecified manner, while others consider magnetic reconnection in special global topologies to be responsible for the large-scale response of the lower corona to CME events. Some of these ideas may indeed be correct in specific cases. However, what is the key element which makes CMEs large-scale? Observations show that the extent of the coronal disturbance matches the angular width of the CME – an important clue, which does not feature strongly in any of the above suggestions. We review observational evidence for the large-scale *nature* of CME source regions and find them lacking. Then we compare different ideas regarding how CMEs *evolve* to become large-scale. The large-scale magnetic topology plays an important role in this process. There is amounting evidence, however, that the key process is *magnetic reconnection* between the CME and other magnetic structures. We outline a CME evolution model, which is able to account for all the key observational signatures of large-scale CMEs and presents a clear picture *how* large portions, of the Sun become constituents of the CME. In this model reconnection is *driven* by the expansion of the CME core resulting from an over-pressure relative to the pressure in the CME's surroundings. This implies that the extent of the lower coronal signatures match the final angular width of the CME.

Plasma diagnostics of coronal dimming events

Kamalam **Vanninathan**, Astrid M. Veronig, Karin Dissauer, Manuela Temmer

ApJ **857** 62 **2018**

https://arxiv.org/pdf/1802.06152.pdf

https://iopscience.iop.org/article/10.3847/1538-4357/aab09a/pdf

Coronal mass ejections (CMEs) are often associated with coronal dimmings, i.e. transient dark regions that are most distinctly observed in Extreme Ultra-violet (EUV) wavelengths. Using Atmospheric Imaging Assembly (AIA) data, we apply Differential Emission Measure (DEM) diagnostics to study the plasma characteristics of six coronal dimming events. In the core dimming region, we find a steep and impulsive decrease of density with values up to 50-70%. Five of the events also reveal an associated drop in temperature of 5-25%. The secondary dimming regions also show a distinct decrease in density, but less strong, decreasing by 10-45%. In both the core and the secondary dimming the density changes are much larger than the temperature changes, confirming that the dimming regions are mainly caused by plasma evacuation. In the core dimming, the plasma density reduces rapidly within the first 20-30 min after the flare start, and does not recover for at least 10 hrs later, whereas the secondary dimming tends to be more gradual and starts to replenish after 1-2 hrs. The pre-event temperatures are higher in the core dimming (1.7-2.6 MK) than in the secondary dimming regions (1.6-2.0 MK). Both core and secondary dimmings are best observed in the AIA 211 \AA\ and 193 \AA\ filters. These findings suggest that the core dimming corresponds to the footpoints of the erupting flux rope rooted in the AR, while the secondary dimming represents plasma from overlying coronal structures that expand during the CME eruption. **01 August 2010, 21 June 2011, 06 September 2011, 19 January 2012, 09 March 2012, 14 March 2012**

Coronal response to an EUV wave from DEM analysis

K. **Vanninathan**, A.M. Veronig, K. Dissauer, M.S. Madjarska, I.G. Hannah, E.P. Kontar

ApJ **812 173 2015**

http://arxiv.org/pdf/1509.05269v1.pdf

EUV (Extreme-Ultraviolet) waves are globally propagating disturbances that have been observed since the era of the SoHO/EIT instrument. Although the kinematics of the wave front and secondary wave components have been widely studied, there is not much known about the generation and plasma properties of the wave. In this paper we discuss the effect of an EUV wave on the local plasma as it passes through the corona. We studied the EUV wave, generated during the **2011 February 15** X-class flare/CME event, using Differential Emission Measure diagnostics. We analyzed regions on the path of the EUV wave and investigated the local density and temperature changes. From our study we have quantitatively confirmed previous results that during wave passage the plasma visible in the Atmospheric Imaging Assembly (AIA) 171A channel is getting heated to higher temperatures corresponding to AIA 193A and 211A channels. We have calculated an increase of 6 - 9% in density and 5 - 6% in temperature during the passage of the EUV wave. We have compared the variation in temperature with the adiabatic relationship and have quantitatively demonstrated the phenomenon of heating due to adiabatic compression at the wave front. However, the cooling phase does not follow adiabatic relaxation but shows slow decay indicating slow energy release being triggered by the wave passage. We have also identified that heating is taking place at the front of the wave pulse rather than at the rear. Our results provide support for the case that the event under study here is a compressive fast-mode wave or a shock.

Coronal Signatures of Flare Generated Fast Mode Wave at EUV and Radio wavelengths

V. **Vasanth**

Solar Phys. **299**, 63 **2024**

https://arxiv.org/pdf/2404.00135.pdf
https://link.springer.com/content/pdf/10.1007/s11207-024-02293-z.pdf
This paper presents a detailed study of the type II solar radio burst that occurred on **06 March 2014** using combined data analysis. It is a classical radio event consisting of type III radio burst and a following type II radio burst in the dynamic spectrum. The type II radio burst is observed between 235 - 130 MHz (120 - 60 MHz) in harmonic (fundamental) bands with the life time of 5 minutes between 09:26 UT - 09:31 UT. The estimated speed of type II burst by applying twofold Saito model is 650 km/s. An extreme ultraviolet (EUV) wave is observed with Atmospheric Imaging Assembly (AIA) onboard the Solar Dynamics Observatory (SDO) pass bands. The very close temporal onset association of EUV wave and flare energy release indicates that the EUV wave is likely produced by a flare pressure pulse. The eruption is also accompanied by a weak coronal mass ejection (CME) observed with the coronagraphs onboard Solar and Heliospheric Observatory (SOHO) and the twin Solar Terrestrial Relations Observatory (STEREO). The plane of sky speed of the CME was 252 km/s at SOHO/LASCO-C2 and 280 km/s at STEREO-B/SECCHI-COR1 FOV. The EUV wave has two wave fronts, one expanding radially outward, and the other one moving along the arcade. The source position of the type II burst imaged by the Nancay Radio Heliograph (NRH) shows that it was associated with the outward moving EUV wave. The CME is independent of the shock wave as confirmed by the location of NRH radio sources below the CME's leading edge. Therefore the type II radio burst is probably ignited by the flare. This study shows the possibility of EUV wave and coronal shock triggered by flare pressure pulse, generating the observed type II radio burst.

Spectroscopy and Differential Emission Measure diagnostics of a coronal dimming associated with a fast halo CME

Astrid M. **Veronig**, Peter Gömöry, Karin Dissauer, Manuela Temmer, Kamalam Vanninathan
ApJ 879:85 **2019**
https://arxiv.org/pdf/1906.01517.pdf
https://iopscience.iop.org/article/10.3847/1538-4357/ab2712/pdf
We study the coronal dimming caused by the fast halo CME (deprojected speed v =1250 km s −1) associated with the C3.7 two-ribbon flare on **2012 September 27**, using Hinode/EIS spectroscopy and SDO/AIA Differential Emission Measure (DEM) analysis. The event reveals bipolar core dimmings encompassed by hook-shaped flare ribbons located at the ends of the flare-related polarity inversion line, and marking the footpoints of the erupting filament. In coronal emission lines of logT[K]=5.8−6.3, distinct double component spectra indicative of the superposition of a stationary and a fast up-flowing plasma component with velocities up to 130 km s−1 are observed at regions, which were mapped by the scanning EIS slit close in time of their impulsive dimming onset. The outflowing plasma component is found to be of the same order and even dominant over the stationary one, with electron densities in the upflowing component of 2×109cm−3 at logT[K]=6.2. The density evolution in core dimming regions derived from SDO/AIA DEM analysis reveals impulsive reductions by 40−50% within ≲10 min, and remains at these reduced levels for hours. The mass loss rate derived from the EIS spectroscopy in the dimming regions is of the same order than the mass increase rate observed in the associated white light CME (1×1012gs−1), indicative that the CME mass increase in the coronagraphic field-of-view results from plasma flows from below and not from material piled-up ahead of the outward moving and expanding CME front.

Genesis and impulsive evolution of the 2017 September 10 coronal mass ejection

Astrid M. **Veronig**, Tatiana Podladchikova, Karin Dissauer, Manuela Temmer, Daniel B. Seaton, David Long, Jingnan Guo, Bojan Vrsnak, Louise Harra, Bernhard Kliem
ApJ **2018**
https://arxiv.org/pdf/1810.09320.pdf
The X8.2 event of **10 September 2017** provides unique observations to study the genesis, magnetic morphology and impulsive dynamics of a very fast CME. Combining GOES-16/SUVI and SDO/AIA EUV imagery, we identify a hot (T≈10−15 MK) bright rim around a quickly expanding cavity, embedded inside a much larger CME shell (T≈1−2 MK). The CME shell develops from a dense set of large AR loops (≳0.5 Rs), and seamlessly evolves into the CME front observed in LASCO C2. The strong lateral overexpansion of the CME shell acts as a piston initiating the fast EUV wave. The hot cavity rim is demonstrated to be a manifestation of the dominantly poloidal flux and frozen-in plasma added to the rising flux rope by magnetic reconnection in the current sheet beneath. The same structure is later observed as the core of the white light CME, challenging the traditional interpretation of the CME three-part morphology. The large amount of added magnetic flux suggested by these observations explains the extreme accelerations of the radial and lateral expansion of the CME shell and cavity, all reaching values of 5−10 km s−2. The acceleration peaks occur simultaneously with the first RHESSI 100−300 keV hard X-ray burst of the associated flare, further underlining the importance of the reconnection process for the impulsive CME evolution. Finally, the much higher radial propagation speed of the flux rope in relation to the CME shell causes a distinct deformation of the white light CME front and shock.

Plasma diagnostics of an EIT wave observed by Hinode/EIS and SDO/AIA

A.M. **Veronig**, P. Gomory, I.W. Kienreich, N. Muhr, B. Vrsnak, M. Temmer, H.P. Warren
E-print, 16 Nov **2011**; ApJ Lett **2011** 743 L10**, File**

We present plasma diagnostics of an EIT wave observed with high cadence in Hinode/EIS sit-and-stare spectroscopy and SDO/AIA imagery obtained during the HOP-180 observing campaign on **2011 February 16**. At the propagating EIT wave front, we observe downward plasma flows in the EIS Fe XII, Fe XIII, and Fe XVI spectral lines (log T ~ 6.1-6.4) with line-of-sight (LOS) velocities up to 20 km/s. These red-shifts are followed by blue-shifts with upward velocities up to -5 km/s indicating relaxation of the plasma behind the wave front. During the wave evolution, the downward velocity pulse steepens from a few km/s up to 20 km/s and subsequently decays, correlated with the relative changes of the line intensities. The expected increase of the plasma densities at the EIT wave front estimated from the observed intensity increase lies within the noise level of our density diagnostics from EIS XIII 202/203 AA line ratios. No significant LOS plasma motions are observed in the He II line, suggesting that the wave pulse was not strong enough to perturb the underlying chromosphere. This is consistent with the finding that no Halpha Moreton wave was associated with the event. The EIT wave propagating along the EIS slit reveals a strong deceleration of a ~ -540 m/s2 and a start velocity of v0 ~ 590 km/s. These findings are consistent with the passage of a coronal fast-mode MHD wave, pushing the plasma downward and compressing it at the coronal base.

STEREO observations of a dome-shaped large-scale coronal EUV wave

Astrid **Veronig**, Ines Kienreich, Nicole Muhr, Manuela Temmer, Bojan Vršnak
CESRA**_2010, Presentation file**

FIRST OBSERVATIONS OF A DOME-SHAPED LARGE-SCALE CORONAL EXTREME-ULTRAVIOLET WAVE

A. M. **Veronig**[1], N. Muhr[1], I. W. Kienreich[1], M. Temmer[1,2], and B. Vrˇsnak[3]
Astrophysical Journal Letters, 716:L57–L62, **2010** June; **File**

We present first observations of a dome-shaped large-scale extreme-ultraviolet coronal wave, recorded by the Extreme Ultraviolet Imager instrument on board *STEREO-B* on **2010 January 17**. The main arguments that the observed structure is the wave dome (and not the coronal mass ejection, CME) are (1) the spherical form and sharpness of the dome's outer edge and the erupting CME loops observed inside the dome; (2) the low-coronal wave signatures above the limb perfectly connecting to the on-disk signatures of the wave; (3) the lateral extent of the expanding dome which is much larger than that of the coronal dimming; and (4) the associated high-frequency type II burst indicating shock formation low in the corona. The velocity of the upward expansion of the wave dome ($v \sim 650$ km s^{-1}) is larger than that of the lateral expansion of the wave ($v \sim 280$ km s^{-1}), indicating that the upward dome expansion is driven all the time, and thus depends on the CME speed, whereas in the lateral direction it is freely propagating after the CME lateral expansion stops. We also examine the evolution of the perturbation characteristics: first the perturbation profile steepens and the amplitude increases. Thereafter, the amplitude decreases with $r^{-2.5\pm0.3}$, the width broadens, and the integral below the perturbation remains constant. Our findings are consistent with the spherical expansion and decay of a weakly shocked fast-mode MHD wave.

Large-scale Coronal Waves Observed with EUVI/STEREO

Veronig, A.1; Temmer, M.1; Vrsnak, B.
Freiburg ESP Meeting **2008, Poster**

We report first observations and analysis of flare/CME associated large-scale coronal waves (so-called "EIT waves") observed with high time cadence by the EUVI instruments onboard the recent STEREO mission. The EIT instrument onboard SOHO for the first time directly imaged global disturbances in the solar corona, but the observations are severely hampered by the low cadence of EIT (12-15 min). Thus, the nature and origin of these large-scale disturbances are still not sufficiently constraint by observations, and it is an intense matter of debate whether EIT waves: a) are the coronal counterparts of Moreton waves observed in the chromosphere; b) are caused by the flare explosive energy release or by the erupting CME; c) are waves at all or rather propagating disturbances related to magnetic field line opening and restructuring associated with the CME lift-off. The high cadence full-disk coronal imaging by the EUVI instruments on the twin STEREO spacecraft provide us with the unprecedented opportunity to study the *dynamics* and origin of flare/CME associated coronal waves. We present first studies of global coronal waves observed with EUVI finding wave deceleration, indicative of an MHD blast wave (Veronig et al. 2008, ApJ Lett., in press).

High cadence observations of a global coronal wave by EUVI/STEREO

Astrid M. **Veronig**, Manuela Temmer, Bojan Vrˇsnak

E-print, June 2008 **;** ApJ Letters, Vol. 681, No. 2: L113-L116, **2008, File**.

We report a large-scale coronal wave (so-called 'EIT wave') observed with high cadence by EUVI onboard STEREO in association with the GOES B9.5 flare and double CME event on **19 May 2007**. The EUVI instruments provide us with the unprecedented opportunity to study the dynamics of flare/CME associated coronal waves. The coronal wave under study reveals deceleration, indicative of a freely propagating MHD wave. Complementary analysis of the associated flare and erupting filament/CME hint at wave initiation by the CME expanding flanks, which drive the wave only over a limited distance. The associated flare is very weak and occurs too late to account for the wave initiation.

INTERACTION OF A MORETON/EIT WAVE AND A CORONAL HOLE

Astrid M. **Veronig**, Manuela Temmer, Bojan Vrsˇnak, and Julia K. Thalmann

The Astrophysical Journal, 647:1466–1471, **2006 File**

We report high-cadence H_ observations of a distinct Moreton wave observed at Kanzelho¨he Solar Observatory associated with the 3B/X3.8 flare and coronal mass ejection (CME) event of **2005 January 17**. The Moreton wave can be identified in about 40 H_ frames over a period of 7 minutes. The EIT wave is observed in only one frame, but the derived propagation distance is close to that of the simultaneously measured Moreton wave fronts, indicating that they are closely associated phenomena. The large angular extent of the Moreton wave allows us to study the wave kinematics in different propagation directions with respect to the location of a polar coronal hole (CH). In particular, we find that the wave segment whose propagation direction is perpendicular to the CH boundary (‘‘frontal encounter’’) is stopped by the CH, which is in accordance with observations reported from EIT waves. However, we also find that at a tongue-shaped edge of the coronal hole, where the front orientation is perpendicular to the CH boundary (the wave ‘‘slides along’’ the boundary), the wave signatures can be found up to 100 Mm inside the CH. These findings are briefly discussed in the frame of recent modeling results.

Identification of a Peculiar Radio Source in the Aftermath of Large Coronal Mass Ejection Events

Angelos **Vourlidas**, Monique Pick, Sang Hoang, and Pascal Demoulin

The Astrophysical Journal Letters, Volume 656, Number 2, Page L105, **2007, File**

[http://www.journals.uchicago.edu/cgi-bin/resolve?ApJL21380]

We report the discovery of a new radio feature associated with coronal mass ejection (CME) events. The feature is a low-frequency (<1 MHz), relatively wide (~300 kHz) continuum that appears just after the main phase of the eruptive event, lasts for several hours, and exhibits a slow negative frequency drift.
We interpret this radio continuum as the lateral interaction of the CME with magnetic structures. Another possibility is that this continuum traces the reconfiguration of large-scale loop systems, such as streamers. In other words, it could be the large-scale counterpart of the post-CME arcades seen over active region neutral lines after big CME events.

Formation of Coronal Large-Amplitude Waves and the Chromospheric Response

B. **Vršnak**, T. Žic, S. Lulić, M. Temmer, A. M. Veronig

Solar Phys. January **2016**, Volume 291, Issue 1, pp 89-115

An in-depth analysis of numerical simulations is performed to obtain a deeper insight into the nature of various phenomena occurring in the solar atmosphere as a consequence of the eruption of unstable coronal structures. Although the simulations take into account only the most basic characteristics of a flux-rope eruption, the simulation analysis reveals important information on various eruption-related effects. It quantifies the relation between the eruption dynamics and the evolution of the large-amplitude coronal magnetohydrodynamic wave and the associated chromospheric downward-propagating perturbation. We show that the downward propagation of the chromospheric Moreton-wave disturbance can be approximated by a constant-amplitude switch-on shock that moves through a medium of rapidly decreasing Alfvén velocity. The presented analysis reveals the nature of secondary effects that are observed as coronal upflows, secondary shocks, various forms of wave-trains, delayed large-amplitude slow disturbances, transient coronal depletions, etc. We also show that the eruption can cause an observable Moreton wave and a secondary coronal front only if it is powerful enough and is preferably characterized by significant lateral expansion. In weaker eruptions, only the coronal and transition-region signatures of primary waves are expected to be observed. In powerful events, the primary wave moves at an Alfvén Mach number significantly larger than 1 and steepens into a shock that is due to the nonlinear evolution of the wavefront. After the eruption-driven phase, the perturbation evolves as a freely propagating simple wave, characterized by a significant deceleration, amplitude decrease, and wave-profile broadening. In weak events the coronal wave does not develop into a shock and propagates at a speed close to the ambient magnetosonic speed.

Origin of Coronal Shock Waves

Invited Review

Bojan **Vršnak** · Edward W. Cliver

Solar Phys, 253: 215–235, **2008**, DOI 10.1007/s11207-008-9241-5; **File**

The basic idea of the paper is to present transparently and confront two different views on the origin of large-scale coronal shock waves, one favoring coronal mass ejections (CMEs), and the other one preferring flares. For this purpose, we first review the empirical aspects of the relationship between CMEs, flares, and shocks (as manifested by radio type II bursts and Moreton waves). Then, various physical mechanisms capable of launching MHD shocks are presented. In particular, we describe the shock wave formation caused by a three-dimensional piston, driven either by the CME expansion or by a flare-associated pressure pulse. Bearing in mind this theoretical framework, the observational characteristics of CMEs and flares are revisited to specify advantages and drawbacks of the two shock formation scenarios. Finally, we emphasize the need to document clear examples of flare-ignited large-scale waves to give insight on the relative importance of flare and CME generation mechanisms for type II bursts/Moreton waves.

BROADBAND METRIC-RANGE RADIO EMISSION ASSOCIATED WITH A MORETON/EIT WAVE

B. **Vrsˇnak**, J. Magdalenic´, M. Temmer, A. Veronig, A. Warmuth, G. Mann, H. Aurass, and W. Otruba
The Astrophysical Journal, 625:L67–L70, **2005**

We present the evolution and kinematics of a broadband radio source that propagated collaterally with an Hα/ EIT wave, linking it with the type II burst that was excited higher up in the corona. The NRH wave emission extended from the frequency to MHz and was considerably weaker than the flare-related type $f \approx 327$ f ! 151 IV burst. The emission centroid propagated at a height of 0–200 Mm above the solar limb and was intensified when the disturbance passed over enhanced coronal structures. We put forward the ad hoc hypothesis that the NRH wave signature is optically thin gyrosynchrotron emission excited by the passage of the coronal MHD fastmode shock. The identification of radio emission associated with the coronal wave front is important since it offers us new diagnostic information that could provide us with better insight into the physical conditions in the disturbance itself.

Multi-wavelength study of coronal waves associated with the CME-flare event of 3 November 2003

Vrsnak, B., Warmuth, A., Temmer, Veronig, A., Magdaleniˇc, J., Hillaris, A., Karlicky, M.:
Astron. Astrophys. 448(2), 739-752 **2006**, (e-print, 2005)

The large flare/CME event that occurred close to the west solar limb on 3 November 2003 launched a large-amplitude large-scale coronal wave that was observed in Hα and Fe xii 195 Å spectral lines, as well as in the soft X-ray and radio wavelength ranges. The wave also excited a complex decimeter-to-hectometer type II radio burst, revealing the formation of coronal shock(s). The back-extrapolation of the motion of coronal wave signatures and the type II burst sources distinctly marks the impulsive phase of the flare (the hard X-ray peak, drifting microwave burst, and the highest type III burst activity), favoring a flare-ignited wave scenario. On the other hand, comparison of the kinematics of the CME expansion with the propagation of the optical wave signatures and type II burst sources shows a severe discrepancy in the CME-driven scenario. However, the CME is quite likely associated with the formation of an upper-coronal shock revealed by the decameter-hectometer type II burst. Finally, some six minutes after the launch of the first coronal wave, another coronal disturbance was launched, exciting an independent (weak) decimeter-meter range type II burst. The back-extrapolation of this radio emission marks the revival of the hard X-ray burst, and since there was no CME counterpart, it was clearly ignited by the new energy release in the flare.

Flare waves observed in Helium I 10 830 °A. A link between Halpha Moreton and EIT waves.

Vrˇsnak, B., Warmuth, A., Brajˇsa, R., Hanslmeier, A.,
2002. Astron. Astrophys. 394, 299–310.

Formation of coronal MHD shock waves - II. The Pressure Pulse Mechanism.

Vrˇsnak, B., Luli´c, S.,
2000b. Solar Phys. 196, 181–197.

Formation Of Coronal Mhd Shock Waves - I. The Basic Mechanism.

Vrˇsnak, B., Luli´c, S.,
2000a. Solar Phys. 196, 157–180.

The Formation and Early Evolution of a Coronal Mass Ejection and its Associated Shock Wave on 2014 January 8

Linfeng **Wan**, Xin Cheng, Tong Shi, Wei Su, M. D. Ding

ApJ **2016 File**

http://arxiv.org/pdf/1605.01132v1.pdf

In this paper, we study the formation and early evolution of a limb coronal mass ejection (CME) and its associated shock wave that occurred on 2014 January 8. The extreme ultraviolet (EUV) images provided by the Atmospheric Imaging Assembly (AIA) on board \textit{Solar Dynamics Observatory} disclose that the CME first appears as a bubble-like structure. Subsequently, its expansion forms the CME and causes a quasi-circular EUV wave. Interestingly, both the CME and the wave front are clearly visible at all of the AIA EUV passbands. Through a detailed kinematical analysis, it is found that the expansion of the CME undergoes two phases: a first phase with a strong but transient lateral over-expansion followed by a second phase with a self-similar expansion. The temporal evolution of the expansion velocity coincides very well with the variation of the 25--50 keV hard X-ray flux of the associated flare, which indicates that magnetic reconnection most likely plays an important role in driving the expansion. Moreover, we find that, when the velocity of the CME reaches ∼600 km s−1, the EUV wave starts to evolve into a shock wave, which is evidenced by the appearance of a type II radio burst. The shock's formation height is estimated to be ∼0.2Rsun, which is much lower than the height derived previously. Finally, we also study the thermal properties of the CME and the EUV wave. We find that the plasma in the CME leading front and the wave front has a temperature of ∼2 MK, while that in the CME core region and the flare region has a much higher temperature of ≥8 MK.

Observations of Mini Coronal Dimmings Caused by Small-scale Eruptions in the Quiet Sun

Rui **Wang**, Ying D. Liu, Xiaowei Zhao, Huidong Hu

ApJL **952** L29 **2023**

https://arxiv.org/pdf/2307.11406.pdf

https://iopscience.iop.org/article/10.3847/2041-8213/ace437/pdf

Small-scale eruptions could play an important role in coronal heating, generation of solar energetic particles (SEPs), and mass source of the solar wind. However, they are poorly observed, and their characteristics, distributions, and origins remain unclear. Here a mini coronal dimming was captured by the recently launched Solar Orbiter spacecraft. The observations indicate that a minifilament eruption results in the dimming and takes away approximately (1.65±0.54)×1013 g of mass, which also exhibits similar features as the sources of SEP events. The released magnetic free energy is of the order of ∼1027 erg. Our results suggest that weak constraining force makes the flux rope associated with the minifilament easily enter a torus-unstable domain. We discuss that weak magnetic constraints from low-altitude background fields may be a general condition for the quiet-Sun eruptions, which provide a possible mechanism for the transport of coronal material and energy from the lower to the middle or even higher corona. **2020 May 20-21**

Solar Orbiter nugget #19 2023 *https://www.cosmos.esa.int/web/solar-orbiter/-/science-nugget-observations-of-mini-coronal-dimmings-caused-by-small-scale-eruptions-in-the-quiet-sun*

Investigating pre-eruptive magnetic properties at the footprints of erupting magnetic flux ropes

Wensi **Wang**, Jiong Qiu, Rui Liu, Chunming Zhu, Kai E Yang, Qiang Hu, Yuming Wang

ApJ **2022**

https://arxiv.org/pdf/2211.15909.pdf

It is well established that solar eruptions are powered by free magnetic energy stored in current-carrying magnetic field in the corona. It has also been generally accepted that magnetic flux ropes (MFRs) are a critical component of many coronal mass ejections (CMEs). What remains controversial is whether MFRs are present well before the eruption. Our aim is to identify progenitors of MFRs, and investigate pre-eruptive magnetic properties associated with these progenitors. Here we analyze 28 MFRs erupting within 45 deg from the disk center from 2010 to 2015. All MFRs'feet are well identified by conjugate **coronal dimmings**. We then calculate magnetic properties at the feet of the MFRs, prior to their eruptions, using Helioseismic and Magnetic Imager (HMI) vector magnetograms. Our results show that only 8 erupting MFRs are associated with significant non-neutralized electric currents, 4 of which also exhibit pre-eruptive dimmings at the foot-prints. Twist and current distributions are asymmetric at the two feet of these MFRs. The presence of pre-eruption dimmings associated with non-neutralized currents suggests the pre-existing MFRs. Furthermore, evolution of conjugate **dimmings** and electric currents within the foot-prints can provide clues about the internal structure of MFRs and their formation mechanism. **7 Mar 2011, 21 Jun 2011, 2 Aug 2011, 30 Sep 2011, 10 Mar 2012, 14 Jun 2012, 12 Aug 2013, 30 Aug 2013, 12 Oct 2013, 21 Sep 2014,**

Table 1. Overview of Eruptions 2010-2015

A High-resolution Study of Magnetic Field Evolution and Spicular Activity around the Boundary of a Coronal Hole

Jiasheng **Wang**1,2,3, Jeongwoo Lee1,2,3, Chang Liu1,2,3, Wenda Cao1,2,3, and Haimin Wang1,2,3
2022 ApJ 924 137
https://iopscience.iop.org/article/10.3847/1538-4357/ac374e/pdf

In this study, we analyze high-spatial-resolution (0.″24) magnetograms and high-spatial-resolution (0.″10) Hα off-band (± 0.8 Å) images taken by the 1.6 m Goode Solar Telescope to investigate the magnetic properties associated with small-scale ejections in a coronal hole boundary region from a statistical perspective. With one and a half hours of optical observations under excellent seeing, we focus on the magnetic structure and evolution by tracking the magnetic features with the Southwest Automatic Magnetic Identification Suite (SWAMIS). The magnetic field at the studied coronal hole boundary is dominated by negative polarity with flux cancellations at the edges of the negative unipolar cluster. In a total of 1250 SWAMIS-detected magnetic cancellation events, ~39% are located inside the coronal hole with an average flux cancellation rate of 2.0 × 1018 Mx Mm−2 hr−1, and ~49% are located outside the coronal hole with an average flux cancellation rate of 8.8 × 1017 Mx Mm−2 hr−1. We estimated that the magnetic energy released due to flux cancellation inside the coronal hole is six times more than that outside the coronal hole. Flux cancellation accounts for ~9.5% of the total disappearance of magnetic flux. Other forms of its disappearance are mainly due to fragmentation of unipolar clusters or merging with elements of the same polarity. We also observed a number of significant small-scale ejections associated with magnetic cancellations at the coronal hole boundary that have corresponding EUV brightenings. **2018 July 29**

Exploring the Nature of EUV Waves in a Radiative Magnetohydrodynamic Simulation

Can **Wang**, Feng Chen, Mingde Ding
ApJL **911** L8 **2021**
https://arxiv.org/pdf/2103.10326.pdf
https://doi.org/10.3847/2041-8213/abefe6

Coronal extreme-ultraviolet (EUV) waves are large-scale disturbances propagating in the corona, whose physical nature and origin have been discussed for decades. We report the first three dimensional (3D) radiative magneto-hydrodynamic (RMHD) simulation of a coronal EUV wave and the accompanying quasi-periodic wave trains. The numerical experiment is conducted with the MURaM code and simulates the formation of solar active regions through magnetic flux emergence from the convection zone to the corona. The coronal EUV wave is driven by the eruption of a magnetic flux rope that also gives rise to a C-class flare. It propagates in a semi-circular shape with an initial speed ranging from about 550 to 700 km s−1, which corresponds to an average Mach number (relative to fast magnetoacoustic waves) of about 1.2. Furthermore, the abrupt increase of the plasma density, pressure and tangential magnetic field at the wavefront confirms fast-mode shock nature of the coronal EUV wave. Quasi-periodic wave trains with a period of about 30 s are found as multiple secondary wavefronts propagating behind the leading wavefront and ahead of the erupting magnetic flux rope. We also note that the true wavefront in the 3D space can be very inhomogeneous, however, the line-of-sight integration of EUV emission significantly smoothes the sharp structures in 3D and leads to a more diffuse wavefront.

A small-scale filament eruption inducing Moreton Wave, EUV Wave and Coronal Mass Ejection

Jincheng **Wang**, Xiaoli Yan, Defang Kong, Zhike Xue, Liheng Yang, Qiaoling Li
ApJ **894** 30 **2020**
https://arxiv.org/pdf/2004.07488.pdf
https://doi.org/10.3847/1538-4357/ab8565

With the launch of SDO, many EUV waves were observed during solar eruptions. However, the joint observations of Moreton and EUV waves are still relatively rare. We present an event that a small-scale filament eruption simultaneously results in a Moreton wave, an EUV wave and a Coronal Mass Ejection in active region NOAA 12740. Firstly, we find that some dark elongate lanes or filamentary structures in the photosphere existed under the small-scale filament and drifted downward, which manifests that the small-scale filament was emerging and lifting from subsurface. Secondly, combining the simultaneous observations in different Extreme UltraViolet (EUV) and Hα passbands, we study the kinematic characteristics of the Moreton and EUV waves. The comparable propagating velocities and the similar morphology of Moreton and different passbands EUV wavefronts were obtained. We deduce that Moreton and different passbands EUV waves were the perturbations in different temperature-associated layers induced by the coronal magneto-hydrodynamic shock wave. We also find the refracted, reflected and diffracted phenomena during the propagation of the EUV wave. By using power-law fittings, the kinematic characteristics of unaffected, refracted and diffracted waves were obtained. The extrapolation field derived by the potential field source surface (PFSS) model manifests that the existence of an interface of different magnetic system (magnetic separatrix) result in refraction, reflection and deviation of the EUV wave. **2019 May 06**

Contribution of Velocity Vortices and Fast Shock Reflection and Refraction to the Formation of EUV Waves in Solar Eruptions

Hongjuan **Wang**, Siqing Liu, Jiancun Gong, Ning Wu, Jun Lin

ApJ **805** 114 **2015**

http://arxiv.org/pdf/1506.00328v1.pdf

We numerically study the detailed evolutionary features of the wave-like disturbance and its propagation in the eruption. This work is a follow-up to Wang et al., using significantly upgraded new simulations. We focus on the contribution of the velocity vortices and the fast shock reflection and refraction in the solar corona to the formation of the EUV waves. Following the loss of equilibrium in the coronal magnetic structure, the flux rope exhibits rapid motions and invokes the fast-mode shock forward of the rope, which then produces the type II radio burst. The expansion of the fast shock, which is associated with outward motion, takes place in various directions, and the downward expansion shows the reflection and the refraction as a result of the non-uniform background plasma. The reflected component of the fast shock propagates upward and the refracted component propagates downward. As the refracted component reaches the boundary surface, a weak echo is excited. The Moreton wave is invoked as the fast shock touches the bottom boundary, so the Moreton wave lags the type II burst. A secondary echo occurs in the area where reflection of the fast shock encounters the slow-mode shock, and the nearby magnetic field lines are further distorted because of the interaction between the secondary echo and the velocity vortices. Our results indicate that the EUV wave may arise from various processes that are revealed in the new simulations.

NUMERICAL EXPERIMENTS OF WAVE-LIKE PHENOMENA CAUSED BY THE DISRUPTION OF AN UNSTABLE MAGNETIC CONFIGURATION

Hongjuan **Wang**[1,2], Chengcai Shen[1,2], and Jun Lin[1,3]

Astrophysical Journal, 700:1716–1731, **2009, File**

The origin of the Moreton wave observed in the chromosphere and the EIT wave observed in the corona during the eruption remains an active research subject. We investigate numerically in this work the evolutionary features of the magnetic configuration that includes a current-carrying flux rope, which is used to model the filament, after the loss of equilibrium in the system takes place in a catastrophic fashion. Rapid motions of the flux rope following the catastrophe invoke the velocity vortices behind the rope, and may also invoke slow- and fast-mode shocks in front of the rope. The velocity vortices at each side of the flux rope propagate roughly horizontally away from the area where they are produced, and both shocks expand toward the flank of the flux rope. The fast shock may eventually reach the bottom boundary and produce two echoes moving back into the corona, but the slow one and the vortices totally decay somewhere in the lower corona before arriving of the bottom boundary. The interaction of the fast shock with the boundary leads to disturbance that accounts for the Moreton wave observed in H*α*, and the disturbance in the corona caused by the slow shock and the velocity vortices should account for the EIT wave whose speed is about 40 % that of the Moreton wave. The implication of these results to the observed correlation of the type II radio burst to the fast- and the slow-mode shocks and that of EIT waves to coronal mass ejections and flares has also been discussed.

ENDPOINT BRIGHTENINGS IN ERUPTING FILAMENTS

Y.-M. **Wang**[1], K. Muglach[1,2], and B. Kliem

Astrophysical Journal, 699:133–142, **2009, File**

http://www.iop.org:80/EJ/toc/-alert=43190/0004-637X/699/1

Two well known phenomena associated with erupting filaments are the transient coronal holes that form on each side of the filament channel and the bright post-event arcade with its expanding double row of footpoints. Here we focus on a frequently overlooked signature of filament eruptions: the spike- or fan-shaped brightenings that appear to mark the far endpoints of the filament. From a sample of non-active-region filament events observed with the Extreme-Ultraviolet Imaging Telescope on the *Solar and Heliospheric Observatory*, we find that these brightenings usually occur near the outer edges of the transient holes, in contrast to the post-event arcades, which define their inner edges. The endpoints are often multiple and are rooted in and around strong network flux well outside the filament channel, a result that is consistent with the axial field of the filament being much stronger than the photospheric field inside the channel. The extreme ultraviolet brightenings, which are most intense at the time of maximum outward acceleration of the filament, can be used to determine unambiguously the direction of the axial field component from longitudinal magnetograms. Their location near the outer boundary of the transient holes suggests that we are observing the footprints of the current sheet formed at the leading edge of the erupting filament, as distinct from the vertical current sheet behind the filament which is the source of the post-event arcade.

COMPARISON OF THE 1998 APRIL 29 M6.8 AND 1998 NOVEMBER 5 M8.4 FLARES

HAIMIN **WANG**, PHILIP R. GOODE, CARSTEN DENKER, GUO YANG, VASYL YURCHISHIN. NARIAKI NITTA, JOSEPH B. GURMAN, CHRIS ST. CYR, AND ALEXANDER G. KOSOVICHEV
ASTROPHYSICAL JOURNAL, 536:971И981, **2000, File**
We combined, and analyzed in detail, the Ha and magnetograph data from Big Bear Solar Observatory (BBSO), full-disk magnetograms from the Michelson Doppler Imager (MDI) on board Solar and Heliospheric Observatory (SOHO), coronagraph data from the Large Angle Spectrometric Coronagraph (LASCO) of SOHO, Fe XII 195 data from the Extreme ultraviolet Imaging Telescope (EIT) of SOHO, A_ and Yohkoh soft X-ray telescope (SXT) data of the M6.8 Care of 1998 April 29 in National Oceanic and Atmospheric Administration (NOAA) region 8375 and the M8.4 Care of 1998 November 5 in NOAA region 8384. These two Cares have remarkable similarities :
1. Partial halo coronal mass ejections (CMEs) were observed for both events. For the 1998 April 29 event, even though the Care occurred in the southeast of the disk center, the ejected material moved predominantly across the equator, and the central part of the CME occurred in the northeast limb. The direction in which the cusp points in the postCare SXT images determines the dominant direction of the CMEs.
2. Coronal dimming was clearly observed in EIT Fe XII 195 for both but was not observed in A_ Yohkoh SXT for either event. Dimming started 2 hr before the onset of the Cares, indicating large-scale coronal restructuring before both Cares.
3. No global or local photospheric magnetic Peld change was detected from either event ; in particular, no magnetic Peld change was found in the dimming areas.
4. Both events lasted several hours and, thus, could be classiPed as long duration events (LDEs). However, they are di†erent in the following important aspects. For the 1998 April 29 event, the Care and the CME are associated with an erupting Plament in which the two initial ribbons were well connected and then gradually separated. SXT preCare images show the classical S-shape sheared conPguration (sigmoid structure). For the 1998 November 5 event, two initial ribbons were well separated, and the SXT preCare image shows the interaction of at least two loops. In addition, no Plament eruption was observed. We conclude that even though these two events resulted in similar coronal consequences, they are due to two distinct physical processes : eruption of sheared loops and interaction of two loops.

EIT Waves and Fast-Mode Propagation in the Solar Corona.
Wang, Y.M.,
2000. Astrophys. J. 543, L89–L93.

Microwave observations of a large-scale coronal wave with the Nobeyama radioheliograph
A. **Warmuth**1, K. Shibasaki2, K. Iwai3 and G. Mann
A&A 593, A102 (**2016**) **File**
http://www.aanda.org/articles/aa/pdf/2016/09/aa28591-16.pdf
Context. Large-scale globally propagating waves in the solar corona have been studied extensively, mainly using extreme ultraviolet (EUV) observations. In a few events, corresponding wave signatures have been detected in microwave radioheliograms provided by the Nobeyama radioheliograph (NoRH). Several aspects of these observations seem to contradict the conclusions drawn from EUV observations.
Aims. We investigate whether the microwave observations of global waves are consistent with previous findings.
Methods. We revisited the wave of **1997 Sep. 24**, which is still the best-defined event in microwaves. We obtained radioheliograms at 17 and 34 GHz from NoRH and studied the morphology, kinematics, perturbation profile evolution, and emission mechanism of the propagating microwave signatures.
Results. We find that the NoRH wave signatures are morphologically consistent with both the associated coronal wave as observed by SOHO/EIT and the Moreton wave seen in Hα. The NoRH wave is clearly decelerating, which is typically found for large-amplitude coronal waves associated with Moreton waves, and its kinematical curve is consistent with the EIT wavefronts. The perturbation profile shows a pronounced decrease in amplitude. Based on the derivation of the spectral index of the excess microwave emission, we conclude that the NoRH wave is due to optically thick free-free bremsstrahlung from the chromosphere.
Conclusions. The wavefronts seen in microwave radioheliograms are chromospheric signatures of coronal waves, and their characteristics support the interpretation of coronal waves as large-amplitude fast-mode MHD waves or shocks.

Large-scale Globally Propagating Coronal Waves **Review**
Warmuth, Alexander
Living Reviews in Solar Physics, PUB.NO. lrsp-2015-3, **2015**
http://solarphysics.livingreviews.org/Articles/lrsp-2015-3/ **File**
Large-scale, globally propagating wave-like disturbances have been observed in the solar chromosphere and by inference in the corona since the 1960s. However, detailed analysis of these phenomena has only been conducted

since the late 1990s. This was prompted by the availability of high-cadence coronal imaging data from numerous spaced-based instruments, which routinely show spectacular globally propagating bright fronts. Coronal waves, as these perturbations are usually referred to, have now been observed in a wide range of spectral channels, yielding a wealth of information. Many findings have supported the “classical” interpretation of the disturbances: fast-mode MHD waves or shocks that are propagating in the solar corona. However, observations that seemed inconsistent with this picture have stimulated the development of alternative models in which “pseudo waves” are generated by magnetic reconfiguration in the framework of an expanding coronal mass ejection. This has resulted in a vigorous debate on the physical nature of these disturbances. This review focuses on demonstrating how the numerous observational findings of the last one and a half decades can be used to constrain our models of large-scale coronal waves, and how a coherent physical understanding of these disturbances is finally emerging.

Kinematical evidence for physically different classes of large-scale coronal EUV waves

A. **Warmuth** and G. Mann

A&A 532, A151 (**2011**), **File**

Context. Large-scale wavelike disturbances have been observed in the solar corona in the EUV range since more than a decade. The physical nature of these so-called “EIT waves” is still being debated controversially. The two main contenders are on the one hand MHD waves and/or shocks, and on the other hand magnetic reconfiguration in the framework of an expanding CME. There is a lot of observational evidence backing either one or the other scenario, and no single model has been able to reproduce all observational constraints, which are partly even contradictory. This suggests that there may actually exist different classes of coronal waves that are caused by distinct physical processes. Then, the problems in interpreting coronal waves would be mainly caused by mixing together different physical processes.
Aims. We search for evidence for physically different classes of large-scale coronal EUV waves.
Methods. Kinematics is the most important characteristic of any moving disturbance, hence we focus on this aspect of coronal waves. Identifying distinct event classes requires a large event sample, which is up to now only available from SOHO/EIT. We analyze the kinematics of a sample of 176 EIT waves. In order to check if the results are severely affected by the low cadence of EIT, we complement this with high-cadence data for 17 events from STEREO/EUVI. In particular, we focus on the wave speeds and their evolution.
Results. Based on their kinematical behavior, we find evidence for three distinct populations of coronal EUV waves: initially fast waves ($v \geq$ 320 kms-1) that show pronounced deceleration (class 1 events), waves with moderate ($v \approx$ 170−320 kms-1) and nearly constant speeds (class 2), and slow waves ($v \leq$ 130 kms-1) showing a rather erratic behavior (class 3).
Conclusions. The kinematical behavior of the fast decelerating disturbances is consistent with nonlinear large-amplitude waves or shocks that propagate faster than the ambient fast-mode speed and subsequently slow down due to decreasing amplitude. The waves with moderate speeds are consistent with linear waves moving at the local fast-mode speed. Thus both populations can be explained in terms of the wave/shock model. The slow perturbations with erratic behavior, on the other hand, are not consistent with this scenario. These disturbances could well be due to magnetic reconfiguration.

Large-scale waves in the solar corona: The continuing debate

Alexander **Warmuth**, a,

Advances in Space Research, Volume 45, Issue 4, 15 February **2010**, Pages 527-536, **File**

Ten years after the first observation of large-scale wave-like coronal disturbances with the EIT instrument aboard SOHO, the most crucial questions concerning these “EIT waves” are still being debated controversially – what is their actual physical nature, and how are they launched? Possible explanations include MHD waves or shocks, launched by flares or driven by coronal mass ejections (CMEs), as well as models where coronal waves are not actually waves at all, but generated by successive “activation” of magnetic fieldlines in the framework of a CME. Here, we discuss recent observations that might help to discriminate between the different models. We focus on strong coronal wave events that do show chromospheric Moreton wave signatures. It is stressed that multiwavelength observations with high time cadence are particularly important, ideally when limb events with CME observations in the low corona are available. Such observations allow for a detailed comparison of the kinematics of the wave, the CME and the associated type II radio burst. For Moreton-associated coronal waves, we find strong evidence for the wave/shock scenario. Furthermore, we argue that EIT waves are actually generated by more than one physical process, which might explain some of the issues which have made the interpretation of these phenomena so controversial.

Large-scale waves and shocks in the solar corona

Warmuth, A.:

2007, Springer Lecture Notes in Physics (in press), **File**

in: L. Klein & A. L. MacKinnon (Ed.), Lecture Notes in Physics, Berlin Springer Verlag, pp. 107–138.

Large-scale waves and shocks in the solar corona are **reviewed**. The emphasis is on globally propagating wave-like disturbances that are observed in the low corona which have become known as "coronal transient waves" or "coronal Moreton waves". These phenomena have recently come back into focus prompted by the observation of wave-like perturbations in several spectral ranges, particularly in the extreme ultraviolet (with the SOHO/EIT instrument). The different observational signatures of coronal waves are discussed with the aim of providing a coherent physical explanation of the phenomena. In addition to imaging observations, radiospectral data are considered in order to point out the relation between coronal waves and metric type II radio bursts. Briefly, potential generation mechanisms of coronal waves are examined. Finally, the relevance of coronal waves to other areas of solar physics is reviewed.

FIRST SOFT X-RAY OBSERVATIONS OF GLOBAL CORONAL WAVES WITH THE *GOES* SOLAR X-RAY IMAGER

A. **Warmuth**, G. Mann, and H. Aurass

The Astrophysical Journal, 626:L121–L124, **2005, File**

We present the first observations of global coronal waves obtained with the Solar X-Ray Imager (SXI) aboard the *GOES-12* satellite. Focusing on six events, the basic morphological and kinematic characteristics of the waves observed in soft X-rays are derived. Taking advantage of SXI's high temporal cadence and comparing the wave signatures with extreme-UV, Hα, and He i data, we prove that both chromospheric and coronal signatures of waves can be created by a single decelerating disturbance, presumably a large-amplitude simple wave or shock. We stress that SXI is a very useful tool for studying coronal waves and other transients because of its high cadence and duty cycle.

A multiwavelength study of solar flare waves
II. Perturbation characteristics and physical interpretation

A. **Warmuth**1, B. Vrˇsnak2, J. Magdaleni´c2, A. Hanslmeier3, and W. Otruba4

A&A 418, 1117–1129 (**2004**)

The study of solar flare waves – globally propagating wave-like disturbances usually observed in Hα as Moreton waves – has recently come back into focus prompted by the observation of coronal waves in the EUV with the *SOHO*/EIT instrument
("EIT waves"), and in several additional wavelength channels. We study 12 flare wave events in order to determine their physical nature, using Hα, EUV, heliumI, SXR and radioheliographic data. In the companion Paper I, we have presented the observational data and have discussed the morphology, spatial characteristics and the kinematics of the different flare wave signatures. The wavefronts observed in the various spectral bands were found to follow kinematical curves that are closely associated, implying that they are signatures of the same physical disturbance. In the present paper, we continue the study with a close examination of the evolution of the common perturbation that causes the different wave signatures, and with a detailed analysis of the metric type II radio bursts that were associated with all flare wave events. The basic characteristics of the waves are deceleration, perturbation profile broadening, and perturbation amplitude decrease. This behavior can be interpreted in terms of a freely propagating fast-mode MHD shock formed from a large-amplitude simple wave. It is shown that this scenario can account for all observed properties of the flare waves in the various spectral bands, as well as for the associated metric type II radio bursts.

A multiwavelength study of solar flare waves
I. Observations and basic properties

A. **Warmuth**1, B. Vrˇsnak2, J. Magdaleni´c2, A. Hanslmeier3, and W. Otruba4

A&A 418, 1101–1115 (**2004**), **File**

Propagating wave-like disturbances associated with solar flares – commonly observed in the chromosphere as Moreton waves – have been known for several decades. Recently, the phenomenon has come back into focus prompted by the observation of coronal waves with the *SOHO*/EIT instrument ("EIT waves"). It has been suggested that they represent the anticipated coronal counterpart to Moreton waves, but due to some pronounced differences, this interpretation is still being debated. We study 12 flare wave events in order to determine their physical nature, using Hα, EUV, He I 10 830 Å SXR and radioheliographic data. The flare wave signatures in the various spectral bands are found to lie on closely associated kinematical curves, implying that they are signatures of the same physical disturbance. In all events, and at all wavelengths, the flare waves are decelerating, which explains the apparent "velocity discrepancy" between Moreton and EIT waves which has been reported by various authors. In this paper, the focus of the study is on the morphology, the spatial characteristics and the kinematics of the waves. The characteristics of the common perturbation which causes the wave signatures, as well as the associated type II radio bursts, will be studied in companion Paper II, and a consistent physical interpretation of flare waves will be given.

Evolution of Two EIT/Hα Moreton Waves.

Warmuth, A., Vrˇsnak, B., Aurass, H., Hanslmeier, A.,
2001. Astrophys. J. 560, L105–L109.

On the plasma flow inside magnetic tornadoes on the Sun

Sven **WEDEMEYER**1,∗ and Oskar STEINER2,3
Publ. Astron. Soc. Japan (**2014**) 66 (SP1), S10 (1–8)
http://pasj.oxfordjournals.org/content/66/SP1/S10.full.pdf+html

High-resolution observations with the Swedish 1-m Solar Telescope (SST) and the Solar Dynamics Observatory (SDO) reveal rotating magnetic field structures that extend from the solar surface into the chromosphere and the corona. These so-called magnetic tornadoes are primarily detected as rings or spirals of rotating plasma in the Ca II 854.2nm line core (also known as chromospheric swirls). Detailed numerical simulations show that the observed chromospheric plasma motion is caused by the rotation of magnetic field structures, which again are driven by photospheric vortex flows at their footpoints. Under the right conditions, two vortex flow systems are stacked on top of each other.We refer to the lower vortex, which extends from the low photosphere into the convection zone, as intergranular vortex flow (IVF). Once amagnetic field structure is co-located with an IVF, the rotation is mediated into the upper atmospheric layers and an atmospheric vortex flow (AVF, or magnetic tornado) is generated. In contrast to the recent work by Shelyag et al. (2013, ApJ, 776, L4), we demonstrate that particle trajectories in a simulated magnetic tornado indeed follow spirals and argue that the properties of the trajectories decisively depend on the location in the atmosphere and the strength of the magnetic field.

SPATIAL AND TEMPORAL SCALES OF CORONAL MAGNETIC RESTRUCTURING IN THE DEVELOPMENT OF CORONAL MASS EJECTIONS

YAYUAN **WEN**, JINGXIU WANG, DALMIRO JORGE FILIPE MAIA,
YUZONG ZHANG, HUI ZHAO, and GUIPING ZHOU
Solar Physics (2006) 239: 257–276

Four events: December 18 2000, April 7 1997, April 6 2004, and June 24 1999.

We analyzed four CME events using Nan¸cay Radioheliograph (NRH) images and the experiments onboard the Solar and Heliospheric Observatory (SOHO) spacecraft to understand the coronal restructuring leading to CME initiation. The general process of coronal restructuring and reconfiguring takes place at a speed slower than either the Alvfenic or acoustic speed in the corona. This is a type of speed of **"topology waves,"** *i.e.*, the speed of successive topology changes from closed to open field configuration.

CORONAL SEISMOLOGY USING EIT WAVES: ESTIMATION OF THE CORONAL MAGNETIC FIELD STRENGTH IN THE QUIET SUN

M.J. **West**, A. N. Zhukov, L. Dolla, and L. Rodriguez
E-print March, 2011; Astrophysical Journal, 730:122 (10pp), **2011** April, **File**

Coronal EIT waves have been observed for many years. The nature of EIT waves is still contentious, however, there is strong evidence that some of them might be fast magnetosonic waves, or at least have a fast magnetosonic wave component. The fast magnetosonic wave speed is formed from two components; the Alfv?en speed (magnetic) and the sound speed (thermal). By making measurements of the wave speed, coronal density and temperature it is possible to calculate the quiet-Sun coronal magnetic field strength through coronal seismology. In this paper, we investigate an EIT wave observed on **2009 February 13** by the SECCHI/EUVI instruments on board the STEREO satellites. The wave epicenter was observed at disk center in the STEREO B (Behind) satellite. At this time, the STEREO satellites were separated by approximately 90◦, and as a consequence the STEREO A (Ahead) satellite observed the wave on the solar limb. These observations allowed us to make accurate speed measurements of the wave. The background coronal density was derived through Hinode/Extreme-ultraviolet Imaging Spectrometer observations of the quiet Sun and the temperature was estimated through the narrow temperature response in the EUVI bandpasses. The density, temperature, and speed measurements allowed us to estimate the quiet-Sun coronal magnetic field strength to be approximately 0.7 ? 0.7 G.

HIGH-CADENCE RADIO OBSERVATIONS OF AN EIT WAVE
S. M. **White**1 and B. J. Thompson2
The Astrophysical Journal, 620:L63–L66, **2005**
Sensitive radio observations of the **1997 September 24** EIT wave show its velocity to be 830 km s_{-1}. The wave first appears a short distance from the flare site, and its trajectory projects back to the flare site at the peak of the impulsive phase. The radio spectrum appears to be consistent with optically thin coronal emission rather than chromospheric emission. The observed radio brightness temperatures are consistent with the EIT fluxes if the temperature of the emitting gas is not at the peak formation temperature of the Fe xii 195 line or if °A abundances are closer to photospheric than coronal. An important result is that no deceleration is observed during the 4 minutes that the wave is visible in the radio images: the discrepancy between EIT wave and Hα Moreton wave speeds requires that EIT waves slow substantially as they propagate, if they are the same disturbance

EIT Waves: A Changing Understanding over a Solar Cycle
Wills-Davey, M. J., & Attrill, G. D. R.
Space Sci. Rev., Volume 149, Issue 1-4, pp. 325-353, **2009, a review; File**
We present here a review of observations and the current theories that attempt to explain coronal EIT waves. EIT waves were first observed by SOHO-EIT in 1996. Since then, careful analysis has shown that they are related to various other phenomena, such as: CMEs, coronal dimming regions, Moreton waves, and transverse coronal loop oscillations. Over the years, myriad theories have been proposed to explain EIT waves. Early attempts, while elegant, relied heavily on theories based on pre-coronal observations. More recent work, which tends to consider a larger data pool, has led to two competing theoretical camps: wave vs. non-wave models; in many cases, proposed hypotheses flatly contradict each other. Sifting through these seemingly-incongruous models requires a thorough understanding of the available data, as some observations make certain theories more difficult to justify. However, some questions still do not appear resolvable with current data and will likely require help from the next generation of coronal telescopes.
Despite much work, a satisfactory understanding of coronal waves continues to elude researchers, and many diverse possibilities exist for a plausible physical explanation

Are ``EIT Waves'' Fast-Mode MHD Waves?
M. J. **Wills-Davey**, C. E. DeForest, J. O. Stenflo
E-print, April 2007; Astrophys. J., 664, :556-562, **2007**
We examine the nature of large-scale, coronal, propagating wave fronts (``EIT waves") and find they are incongruous with solutions using fast-mode MHD plane-wave theory. Specifically, we consider the following properties: non-dispersive single pulse manifestions, observed velocities below the local Alfven speed, and different pulses which travel at any number of constant velocities, rather than at the ``predicted" fast-mode speed. We discuss the possibility of a soliton-like explanation for these phenomena, and show how it is consistent with the above-mentioned aspects.

Tracking Large-Scale Propagating Coronal Wave Fronts (EIT Waves) using Automated Methods.
Wills-Davey, M.J.,
2006. Astrophys. J. 645, 757–765.

Propagating disturbances in the lower solar corona.
Wills-Davey, M.J.,
2003. Ph.D. thesis. Montana State University.

Observations of a Propagating Disturbance in TRACE.
Wills-Davey, M.J., Thompson, B.J.,
1999. Solar Phys. 190, 467–483.

CORONAL MASS EJECTIONS
A Personal Workshop Summary
R. F. **WIMMER-SCHWEINGRUBER**
Space Science Reviews (2006) 123: 471–480

Magnetically Induced Current Piston for Generating Extreme-ultraviolet Fronts in the Solar Corona
Pakorn **Wongwaitayakornkul**1,3, Magnus A. Haw1,3, Hui Li2, and Paul M. Bellan1
2019 ApJ 874 137
sci-hub.se/10.3847/1538-4357/ab09f2
Single-pulse, globally propagating coronal fronts, called Extreme-ultraviolet (EUV) waves, were first observed in 1995 by the Extreme-ultraviolet Imaging Telescope and every observed EUV wave since has been associated with a coronal mass ejection (CME). The physical mechanism underlying these waves has been debated for two decades with wave or pseudo-wave theories being advocated. We propose a hybrid model where EUV waves are compressional fronts driven by a reverse electric current layer induced by the time-dependent CME core current. The reverse current layer flows in a direction opposite to the CME core current and is an eddy current layer necessary to maintain magnetic flux conservation above the layer. Repelled by the core current, the reverse current layer accelerates upward so it acts as a piston that drives a compressional perturbation in the coronal regions above. Given a sufficiently fast piston speed, the compressional perturbation becomes a shock that separates from the piston when the piston slows down. Since the model relates the motion of the EUV front to CME properties, the model provides a bound for the core current of an erupting CME. The model is supported and motivated by detailed results from both laboratory experiments and ideal 3D magnetohydrodynamic simulations. Overlaps and differences with other models and spacecraft observations are discussed. **2010 June 13**

NEW SOLAR EXTREME-ULTRAVIOLET IRRADIANCE OBSERVATIONS DURING FLARES
Thomas N. **Woods**1,9, Rachel Hock1, Frank Eparvier1, Andrew R. Jones1, Phillip C. Chamberlin2, James A. Klimchuk2, Leonid Didkovsky3, Darrell Judge3, John Mariska4, Harry Warren4, Carolus J. Schrijver5, David F. Webb6, Scott Bailey7 and W. Kent Tobiska
2011 ApJ 739 59**, File**
New solar extreme-ultraviolet (EUV) irradiance observations from the NASA Solar Dynamics Observatory (SDO) EUV Variability Experiment provide full coverage in the EUV range from 0.1 to 106 nm and continuously at a cadence of 10 s for spectra at 0.1 nm resolution and even faster, 0.25 s, for six EUV bands. These observations can be decomposed into four distinct characteristics during flares. First, the emissions that dominate during the flare's impulsive phase are the transition region emissions, such as the He II 30.4 nm. Second, the hot coronal emissions above 5 MK dominate during the gradual phase and are highly correlated with the GOES X-ray. A third flare characteristic in the EUV is coronal **dimming**, seen best in the cool corona, such as the Fe IX 17.1 nm. As the post-flare loops reconnect and cool, many of the EUV coronal emissions peak a few minutes after the GOES X-ray peak. One interesting variation of the post-eruptive loop reconnection is that warm coronal emissions (e.g., Fe XVI 33.5 nm) sometimes exhibit a second large peak separated from the primary flare event by many minutes to hours, with EUV emission originating not from the original flare site and its immediate vicinity, but rather from a volume of higher loops. We refer to this second peak as the EUV late phase. The characterization of many flares during the SDO mission is provided, including quantification of the spectral irradiance from the EUV late phase that cannot be inferred from GOES X-ray diagnostics.

A three-dimensional analysis of global propagation of magnetohydrodynamic (MHD) waves in a structured solar atmosphere.
Wu, S.T., Li, B., Wang, S., Zheng, H.,
2005. Journal of Geophysical Research (Space Physics) 110, A11102.

Three-dimensional numerical simulation of MHD waves observed by the Extreme Ultraviolet Imaging Telescope.
Wu, S.T., Zheng, H., Wang, S., Thompson, B.J., Plunkett, S.P., Zhao, X.P., Dryer, M.,
2001. J. Geophys. Res. 106, 25089–25102.

Evolution of the Toroidal Flux of CME Flux Ropes during Eruption
C. **Xing**, X. Cheng, M. D. Ding
The Innovation **2020**
https://arxiv.org/pdf/2011.10750.pdf
Coronal mass ejections (CMEs) are large-scale explosions of the coronal magnetic field. It is believed that magnetic reconnection significantly builds up the core structure of CMEs, a magnetic flux rope, during the eruption. However, the quantitative evolution of the flux rope, particularly its toroidal flux, is still unclear. In this paper, we study the evolution of the toroidal flux of the CME flux rope for four events. The toroidal flux is estimated as the magnetic flux in the footpoint region of the flux rope, which is identified by a method that simultaneously takes *the coronal*

dimming and the hook of the flare ribbon into account. We find that the toroidal flux of the CME flux rope for all four events shows a two-phase evolution: a rapid increasing phase followed by a decreasing phase. We further compare the evolution of the toroidal flux with that of the Geostationary Operational Environmental Satellites soft X-ray flux and find that they are basically synchronous in time, except that the peak of the former is somewhat delayed. The results suggest that the toroidal flux of the CME flux rope may be first quickly built up by the reconnection mainly taking place in the sheared overlying field and then reduced by the reconnection among the twisted field lines within the flux rope, as enlightened by a recent 3D magnetohydrodynamic simulation of CMEs. **2012/3/5, 2012/3/27, August 21, 2015, 2015/11/4**

Sun-as-a-star observations of obscuration dimmings caused by filament eruptions

Yu **Xu**, Hui Tian, Astrid M. Veronig, Karin Dissauer

ApJ **2024**

https://arxiv.org/pdf/2405.13671

Filament eruptions often lead to coronal mass ejections (CMEs) on the Sun and are one of the most energetic eruptive phenomena in the atmospheres of other late-type stars. However, the detection of filament eruptions and CMEs on stars beyond the solar system is challenging. Here we present six filament eruption cases on the Sun and show that filament material obscuring part of the solar disk can cause detectable dimming signatures in sun-as-a-star flux curves of He II 304 A. Those filament eruptions have similar morphological features, originating from small filaments inside active regions and subsequently strongly expanding to obscure large areas of the solar disk or the bright flare regions. We have tracked the detailed evolution of six obscuration dimmings and estimated the dimming properties, such as dimming depths, dimming areas, and duration. The largest dimming depth among the six events under study is 6.2% accompanied by the largest dimming area of 5.6\% of the solar disk area. Other events have maximum dimming depths in a range of around 1% to 3% with maximum areas varying between about 3% to 4% of the solar disk area. The duration of the dimming spans from around 0.4 hours to 7.0 hours for the six events under study. A positive correlation was found between the dimming depth and area, which may help to set constraint on the filament sizes in stellar observations. **2011.08.04, 2012.01.11, 2013.02.05, 2014.04.15, 2022.04.11, 2023.07.14**
Table 1. Six cases of obscuration dimmings and their flare/CME information

EUV Wave Detection and Characterization Using Deep Learning

Long **Xu**, Sixuan Liu, Yihua Yan & Weiqiang Zhang

Solar Physics volume 295, Article number: 44 (**2020**)

https://link.springer.com/content/pdf/10.1007/s11207-020-01612-4.pdf

https://doi.org/10.1007/s11207-020-01612-4

Coronal Mass Ejections (CMEs) are the most violent solar bursts. They cause severe disturbances in the solar–terrestrial space and affect human activities in many aspects, especially causing damage to high-tech infrastructure. It usually takes few hours for a CME to arrive at the Earth after eruption. Therefore, many efforts have been devoted to CME arrival time prediction, so that we have enough time to take action before a CME arrives at the Earth. For predicting CME arrival time, it is vital to detect the CME origin, arrival and departure speed in a coronagraph. It has been widely accepted that Extreme Ultraviolet (EUV) waves are associated with CMEs, so EUV waves are the signatures of CMEs as CMEs originate and traverse the solar disk, specifically for front-side CMEs. In this paper, two deep neural networks are developed to first detect EUV waves and then outline their wavefronts, giving early signatures of CMEs. Usually, CMEs are recorded by coronagraphs as they transit the corona, so our proposed method can obtain a certain time ahead compared with conventional CME forecasting. In addition, the parameters for describing EUV waves can be more easily deduced, benefiting the subsequent statistical analysis of CMEs. The experimental results demonstrate the effectiveness of the proposed model for detecting EUV waves and generating their outlines. **2011-09-06**

Observations of a Coronal Shock Wave and the Production of Solar Energetic Particles

Z. G. **Xu**1,2, C. Li1,2, and M. D. Ding

2017 ApJ 840 38

http://sci-hub.cc/10.3847/1538-4357/aa6ba2

We present a study that clarifies the acceleration source/mechanism of the solar energetic particle (SEP) event on **2011 August 9**. Based on the assumption of scatter-free propagation of charged particles along the interplanetary magnetic field, the solar particle release times of the electrons and protons are derived and both found to be in the decay phase of the flare emission. Furthermore, we compare the peak-flux spectra of the in situ particles and the remote-sensing hard X-ray photons and find a weak correlation between them. In particular, we note that an extreme ultraviolet shock wave, presumed to be a signature of coronal mass ejection (CME) shock front on the solar surface, and an associated type II radio burst were observed alongside this event. Under the framework of diffusive shock acceleration, the derived shock compression ratio can accelerate particles with a theoretical spectral index , which is comparable to the observational index of ~2.0. Our results appear to support the notion that the coronal shock wave was most likely responsible for the SEP event. Specifically, we find that the electrons were released in a low coronal site at ~0.58 solar radii, and protons were released when the CME-driven shock propagated to ~1.38 solar radii. The multi-spacecraft observations, in addition, reveal the connection between the acceleration of shock waves and the release of SEPs.

Deformation and deceleration of coronal wave

Z. K. **Xue**1,3, Z. Q. Qu1, X. L. Yan1,2, L. Zhao4 and L. Ma

A&A 556, A152 (**2013**), **File**

Aims. We studied the kinematics and morphology of two coronal waves to better understand the nature and origin of coronal waves.
Methods. Using multi-wavelength observations of the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO) and the Extreme Ultraviolet Imager (EUVI) on board the twin spacecraft Solar-TErrestrial RElations Observatory (STEREO), we present morphological and dynamic characteristics of consecutive coronal waves on **2011 March 24**. We also show the coronal magnetic field based on the potential field source surface model.
Results. This event contains several interesting aspects. The first coronal wave initially appeared after a surge-like eruption. Its front was changed and deformed significantly from a convex shape to a line-shaped appearance, and then to a concave configuration during its propagation to the northwest. The initial speeds ranged from 947 km s-1 to 560 km s-1. The first wave decelerated significantly after it passed through a filament channel. After the deceleration, the final propagation speeds of the wave were from 430 km s-1 to 312 km s-1. The second wave was found to appear after the first wave in the northwest side of the filament channel. Its wave front was more diffused and the speed was around 250 km s-1, much slower than that of the first wave.
Conclusions. The deformation of the first coronal wave was caused by the different speeds along different paths. The sudden deceleration implies that the refraction of the first wave took place at the boundary of the filament channel. The event provides evidence that the first coronal wave may be a coronal MHD shock wave, and the second wave may be the apparent propagation of the brightenings caused by successive stretching of the magnetic field lines.

Solar Tornadoes Observed with the Interface Region Imaging Spectrograph: Rotating Motion of Prominence Materials

Zihao **Yang**, Hui Tian, Hardi Peter, Yang Su, Tanmoy Samanta, Jingwen Zhang, Yajie Chen

ApJ **2017**

https://arxiv.org/pdf/1711.08968.pdf

The barbs or legs of some prominences show an apparent motion of rotation, which are often termed solar tornadoes. It is under debate whether the apparent motion is a real rotating motion, or caused by oscillations or counter-streaming flows. We present analysis results from spectroscopic observations of two tornadoes by the Interface Region Imaging Spectrograph. Each tornado was observed for more than 2.5 hours. Doppler velocities are derived through a single Gaussian fit to the Mg~{\sc{ii}}~k~2796\AA{}~and Si~{\sc{iv}}~1393\AA{}~line profiles. We find coherent and stable red and blue shifts adjacent to each other across the tornado axes, favoring the interpretation of these tornadoes as rotating cool plasmas with temperatures of 10^4 K-10^5 K. This interpretation is further supported by simultaneous observations of the Atmospheric Imaging Assembly on board the Solar Dynamics Observatory, which reveal periodic motions of dark structures in the tornadoes. Our results demonstrate that spectroscopic observations can provide key information to disentangle different physical processes in solar prominences. **2014 April 9, 2017 March 12.**

Multi-label Learning for Detection of CME-Associated Phenomena

Y. H. **Yang**, H. M. Tian, B. Peng, T. R. Li, Z. X. Xie

Solar Physics September **2017**, 292:131

https://link.springer.com/content/pdf/10.1007%2Fs11207-017-1136-x.pdf

Coronal mass ejections (CMEs) are considered as one of the driving sources of space weather. They are usually associated with many physical phenomena, e.g. flares, coronal dimmings, and sigmoids. To detect these phenomena, traditional supervised-learning methods assumed that at most one event occurred in a CME; therefore each CME instance is associated with a single label and the phenomenon is processed in isolation. This simplifying assumption does not fit well, as CMEs might have multiple events simultaneously. We propose to detect multiple CME-associated events by multi-label learning methods. With the data available from the Atmospheric Imaging Assembly (AIA) and the Large Angle and Spectrometric Coronagraph (LASCO), texture features representing the events are extracted from all of the associated and not-associated CMEs and converted into feature vectors for multi-label learning use. Then a function is learned to predict the proper label sets for CMEs, such that eight events, i.e. coronal dimming, coronal hole, coronal jet, coronal wave, filament, filament eruption, flare, and sigmoid, are detected explicitly. To test the proposed detection algorithm, we adopt the four-fold cross-validation strategy on a set of 551 labeled CMEs from AIA. Experimental results demonstrate the good performance of the multi-label classification methods in terms of test error.

6 June 2012

Numerical Simulation of Fast-mode Magnetosonic Waves Excited by Plasmoid Ejections in the Solar Corona

Liping **Yang**1,2, Lei Zhang1, Jiansen He1, Hardi Peter3, Chuanyi Tu1, Linghua Wang1, Shaohua Zhang4, and Xueshang Feng

2015 ApJ 800 111

The Atmospheric Imaging Assembly instrument on board the Solar Dynamics Observatory has directly imaged the fast-propagating magnetosonic waves (FMWs) successively propagating outward along coronal magnetic funnels. In this study we perform a numerical investigation of the excitation of FMWs in the interchange reconnection scenario, with footpoint shearing flow being used to energize the system and drive the reconnection. The modeling results show that as a result of magnetic reconnection, the plasma in the current sheet is heated up by Joule dissipation to ~10 MK and is ejected rapidly, developing the hot outflows. Meanwhile, the current sheet is torn into plasmoids, which are shot quickly both upward and downward. When the plasmoids reach the outflow regions, they impact and collide with the ambient magnetic field there, which consecutively launches FMWs. The FMWs propagate outward divergently away from the impact regions, with a phase speed of the Alfv?n speed of ~1000 km s?1. In the k ? ? diagram of the Fourier wave power, the FMWs display a broad frequency distribution with a straight ridge that represents the dispersion relation. With the WKB approximation, at the distance of 15 Mm from the wave source region, we estimate the energy flux of FMWs to be E ~ 7.0 × 106 erg cm?2 s?1, which is ~50?times smaller than the energy flux related to the tube-channeled reconnection outflow. These simulation results indicate that energetically and dynamically the outflow is far more important than the waves.

SDO/AIA and Hinode/EIS Observations of Interaction Between an EUV Wave and Active Region Loops

Liheng **Yang**, Jun Zhang, Wei Liu, Ting Li and Yuandeng Shen

E-print, Aug **2013**, **File**; **2013** ApJ 775 39

We present detailed analysis of an extreme ultraviolet (EUV) wave and its interaction with active region (AR) loops observed by the Solar Dynamics Observatory/Atmospheric Imaging Assembly and the Hinode EUV Imaging Spectrometer (EIS). This wave was initiated from AR 11261 on **2011 August 4** and propagated at velocities of 430-910 km/s. It was observed to traverse another AR and cross over a filament channel on its path. The EUV wave perturbed neighboring AR loops and excited a disturbance that propagated toward the footpoints of these loops. EIS observations of AR loops revealed that at the time of the wave transit, the original redshift increased by about 3 km/s, while the original blueshift decreased slightly. After the wave transit, these changes were reversed. When the EUV wave arrived at the boundary of a polar coronal hole, two reflected waves were successively produced and part of them propagated above the solar limb. The first reflected wave above the solar limb encountered a large-scale loop system on its path, and a secondary wave rapidly emerged 144 Mm ahead of it at a higher speed. These findings can be explained in the framework of a fast-mode magnetosonic wave interpretation for EUV waves, in which observed EUV waves are generated by expanding coronal mass ejections.

Quadrupolar Dimmings During a Partial Halo Coronal Mass Ejection Event

J. **Yang**, Y. Jiang, R. Zheng, J. Hong, Y. Bi and L. Yang

Solar Physics, Volume 270, Number 2, 551-559, **2011, File**

We present detailed observations of the formations of four distinct coronal dimmings during a flare of **17 September 2002**, which was followed by an eruption of a huge coronal loop system, and then an over-and-out partial halo coronal mass ejection (CME), with the same direction as the loop system eruption but laterally far offset from the flare site. Among the four dimmings, two compact ones were symmetrically located in the opposite polarity regions immediately adjacent to the highly sheared magnetic polarity inversion line in the flare region, and hence were probably composed of bipolar double dimmings due to a flux-rope eruption and represented its evacuated footpoints. However, another nearby compact dimming and a remote diffuse one were formed in the opposite polarity footpoint regions of the eruptive loop system, and thus probably consisted of a pair of dimmings magnetically linked by the erupting loop system and also indicated its evacuated footpoints. The loop system might have played a role in guiding the erupting flare field and producing the over-and-out CME, but its eruption might simply have been pushed out by the erupting flare field, because there was no reconnection signature between them. From comparison with a derived potential-field source-surface (PFSS) magnetic configuration, our observations consistently suggest that the dimmings were formed in pairs and originated from the eruptions of the two different magnetic systems. We thus define them as “quadrupolar dimmings.”

The dependence of the EIT wave velocity on the magnetic field strength

H.Q. **Yang** · P.F. Chen

E-print, Feb., Solar Phys. 266: 59–69, **2010, File**; DOI 10.1007/s11207-010-9595-3
``EIT waves" are a wavelike phenomenon propagating in the corona, which were initially observed in the extreme ultraviolet (EUV) wavelength by the EUV Imaging Telescope (EIT). Their nature is still elusive, with the debate between fast-mode wave model and non-wave model. In order to distinguish between these models, we investigate the relation between the EIT wave velocity and the local magnetic field in the corona. It is found that the two parameters show significant negative correlation in most of the EIT wave fronts, i.e., EIT wave propagates more slowly in the regions of stronger magnetic field. Such a result poses a big challenge to the fast-mode wave model, which would predict a strong positive correlation between the two parameters. However, it is demonstrated that such a result can be explained by the fieldline stretching model, i.e., that ``EIT waves" are apparently-propagating brightenings, which are generated by successive stretching of closed magnetic field lines pushed by the erupting flux rope during coronal mass ejections (CMEs). **19 May 2007**

Coronal Wave Trains and Plasma Heating Triggered by Turbulence in the Wake of a CME

Jing **Ye**1,2, Qiangwei Cai3, Chengcai Shen4, John C. Raymond4, Zhixing Mei1,2, Yan Li1,2, and Jun Lin1,2,5
2021 ApJ 909 45
https://doi.org/10.3847/1538-4357/abdeb5
Magnetohydrodynamic (MHD) turbulence plays an important role for the fast energy release and wave structures related to coronal mass ejections (CMEs). The CME plasma has been observed to be strongly heated during solar eruptions, but the heating mechanism is not understood. In this paper, we focus on the hot, dense region at the bottom of the CME and the generation of coronal wave trains therein using a high-resolution 2.5D MHD simulation. Our results show that the interaction between the tearing current sheet and the turbulence, including the termination shocks (TSs) at the bottom of the CME, can make a significant contribution to heating the CME, and the heating rate in this region is found to be greater than the kinetic energy transfer rate. Also, the turbulence can be somewhat amplified by the TSs. The compression ratio of the TS under the CME can exceed 4 due to thermal conduction, but such a strong TS is hardly detectable in all Solar Dynamics Observatory/Atmospheric Imaging Assembly bands. And turbulence is an indispensable source for the periodic generation of coronal wave trains around the CME.

Homologous Cyclones in the Quiet Sun

Xinting **Yu**1,2, Jun Zhang1, Ting Li1, Yuzong Zhang1, and Shuhong Yang
2014 ApJ 782 L15
Through observations with the Solar Dynamics Observatory Atmospheric Imaging Assembly (AIA) and Helioseismic and Magnetic Imager, we tracked one rotating network magnetic field (RNF) near the solar equator. It lasted for more than 100 hr, from **2013 February 23 to 28**. During its evolution, three cyclones were found to be rooted in this structure. Each cyclone event lasted for about 8 to 10 hr. While near the polar region, another RNF was investigated. It lasted for a shorter time (~70 hr), from 2013 July 7 to 9. There were two cyclones rooted in the RNF and each lasted for 8 and 11 hr, respectively. For the two given examples, the cyclones have a similar dynamic evolution, and thus we put forward a new term: homologous cyclones. The detected brightening in AIA 171 Å maps indicates the release of energy, which is potentially available to heat the corona.

Evolution of fast magnetoacoustic pulses in randomly structured coronal plasmas

D. **Yuan**, D.J. Pascoe, V.M. Nakariakov, B. Li, R. Keppens
2014
http://arxiv.org/pdf/1411.4152v1.pdf
Magnetohydrodynamic waves interact with structured plasmas and reveal the internal magnetic and thermal structures therein, thereby having seismological applications in the solar atmosphere. We investigate the evolution of fast magnetoacoustic pulses in randomly structured plasmas, in the context of large-scale propagating waves in the solar atmosphere. We perform one dimensional numerical simulations of fast wave pulses propagating perpendicular to a constant magnetic field in a low-β plasma with a random density profile across the field. Both linear and nonlinear regimes are considered. We study how the evolution of the pulse amplitude and width depends on their initial values and the parameters of the random structuring. A randomly structured plasma acts as a dispersive medium for a fast magnetoacoustic pulse, causing amplitude attenuation and broadening of the pulse width. After the passage of the main pulse, secondary propagating and standing fast waves appear in the plasma. Width evolution of both linear and nonlinear pulses can be well approximated by linear functions; however, narrow pulses may have zero or negative broadening. This arises because a narrow pulse is prone to splitting, while a broad pulse usually deviates less from their initial Gaussian shape and form ripple structures on top of the main pulse. A linear pulse decays at almost a constant rate, while a nonlinear pulse decays exponentially. A pulse interacts most efficiently with a random medium which has a correlation length of about half of its initial pulse width. The

development of a detailed model of a fast MHD pulse propagating in highly structured medium substantiates the interpretation of EIT waves as fast magnetoacoustic waves. Evolution of a fast pulse provides us with a novel method to diagnose the sub-resolution filamentation of the solar atmosphere.

The measurement of the apparent phase speed of the propagating EUV disturbances

D. **Yuan**1 and V. M. Nakariakov1,2

E-print, Apr **2012**, A&A 543, A9 (**2012**)

Context. Propagating disturbances of the EUV emission intensity are commonly observed over a variety of coronal structures. Parameters of these disturbances, particularly the observed apparent (image-plane projected) propagation speed, are important tools for MHD coronal seismology.
Aims. We design and test tools for reliable measurement of the apparent phase speed of propagating disturbances in imaging data sets.
Methods. We design Cross-Fitting Technique (CFT), 2D Coupled Fitting (DCF) and Best Similarity Match (BSM) for the measurements of the apparent phase speed of propagating EUV disturbances in the running differences of time-distance plots (*R*) and background-removed and normalised time-distance plots (*D*).
Results. The methods were applied to the analysis of quasi-periodic EUV disturbances propagating at a coronal fan-structure of active region NOAA11330 on **27-Oct-2011**, observed with the Atmospheric Imaging Assembly on SDO in the 171 A bandpass. The noise propagation in the AIA image processing was estimated, resulting in the preliminary estimation of the uncertainties in the AIA image flux. This information was utilised in the measurements of the apparent phase speed of the propagating disturbances with the CFT, DCF and BSM methods, which gave consistent results. The average projected speed is measured at 47.6 _0.6 km{s and 49.0 _0.7 km{s for *R* and *D*, with the corresponding periods at 179.7 _0.2 s and 179.7 _0.3 s respectively. We analysed the effects of the lag time and the detrending time in the running difference processing and the background-removed plot respectively, on the measurement of the speed, and found that they are fairly weak.
Conclusions. The CFT, DCF and BSM methods are found to be reliable techniques for measuring the apparent (projected) phase speed. The samples of larger effective spatial length are more suitable for these methods. Time-distance plots with background removal and normalisation allow for more robust measurements, with little effect of the choice of the detrending time. CFT provides reliable measurement on good samples (e.g. samples with large effective detection length and recurring features). DCF is found to be sensitive to the initial guess for parameters of the 2D fitting function. Thus DCF is only optimised in measuring one of the parameters (the phase speed in our application), while the period is poorly measured. BSM is robust for all kinds of samples and very tolerant to image pre-processing and regularisation (smoothing).

SOHO EIT Observations of Extreme-Ultraviolet "Dimming" Associated with a Halo Coronal Mass Ejection.

Zarro, D.M., Sterling, A.C., Thompson, B.J., Hudson, H.S., Nitta, N.,
1999. Astrophys. J. 520, L139–L142.

Two successive EUV waves and a transverse oscillation of a quiescent prominence

Q. M. **Zhang**, M. S. Lin, X. L. Yan, J. Dai, Z. Y. Hou, Y. Li, Y. Qiu

MNRAS Volume 533, Issue 3 Pages 3255–3262, **2024**

https://arxiv.org/pdf/2408.03634
https://doi.org/10.1093/mnras/stae1936
https://watermark.silverchair.com/stae1936.pdf

In this paper, we carry out multiwavelength observations of two successive extreme-ultraviolet (EUV) waves originating from active region (AR) NOAA 13575 and a transverse oscillation of a columnar quiescent prominence on **2024 February 9**. A hot channel eruption generates an X3.4 class flare and the associated full-halo coronal mass ejection (CME), which drives the first EUV wave front (WF1) at a speed of ∼835 km s−1. WF1 propagates in the southeast direction and interacts with the prominence, causing an eastward displacement of the prominence immediately. Then, a second EUV wave front (WF2) is driven by a coronal jet at a speed of ∼831 km s−1. WF2 follows WF1 and decelerates from ∼788 km s−1 to ∼603 km s−1 before arriving at and touching the prominence. After reaching the maximum displacement, the prominence turns back and swings for 1−3 cycles. The transverse oscillation of horizontal polarization is most evident in 304 Å. The initial displacement amplitude, velocity in the plane of the sky, period, and damping time fall in the ranges of 12−34 Mm, 65−143 km s−1, 18−27 minutes, and 33−108 minutes, respectively. There are strong correlations among the initial amplitude, velocity, period, and height of the prominence. Surprisingly, the oscillation is also detected in 1600 Å, which is totally in phase with that in 304 Å.

Transverse Oscillation of Prominence and Filament Induced by an Extreme-ultraviolet Wave from the Far Side of the Sun

Yanjie **Zhang**1, Qingmin Zhang1,2, De-chao Song1, and Haisheng Ji1

2024 ApJ 963 140

https://iopscience.iop.org/article/10.3847/1538-4357/ad206d/pdf

https://arxiv.org/pdf/2401.15858.pdf

In this paper, we report our multi-angle observations of the transverse oscillation of a prominence and a filament induced by an EUV wave originating from the far side of the Sun on **2014 September 1**. The prominence oscillation was simultaneously observed by both the Atmospheric Imaging Assembly on board the Solar Dynamics Observatory spacecraft and the Extreme-UltraViolet Imager on board the Behind Solar Terrestrial Relations Observatory spacecraft. The speed of the shock traveling in interplanetary space exceeds that of the EUV wave, and the coronal dimming area experiences minimal growth. ***This indicates that the shock wave is driven by the CME, while the EUV wave freely propagates after the lateral motion of the CME flanks has stopped***. The observed oscillation direction of the prominence, determined through three-dimensional reconstruction, further supports this point. Moreover, detailed investigation of the oscillations in the prominence and filament induced by the EUV wave reveals initial amplitudes of 16.08 and 2.15 Mm, periods of 1769 and 1863 s, damping timescales of 2640 and 1259 s, and damping ratios of 1.49 and 0.68, respectively. The radial component of the magnetic field, as derived from the prominence and filament oscillation measurements, was estimated to be 5.4 and 4.1 G, respectively. In turn, utilizing the onset times of both the prominence and filament oscillation, the average speeds of the EUV wave are determined to be 498 and 451 km s−1, respectively.

Transverse vertical oscillations during the contraction and expansion of coronal loops

Qingmin **Zhang**, Yuhao Zhou, Chuan Li, Qiao Li, Fanxiaoyu Xia, Ye Qiu, Jun Dai, Yanjie Zhang

ApJ **2023**

https://arxiv.org/pdf/2305.08338.pdf

In this paper, we carry out a detailed analysis of the M1.6 class eruptive flare occurring in NOAA active region 13078 on **2022 August 19**. The flare is associated with a fast coronal mass ejection (CME) propagating in the southwest direction with an apparent speed of ∼926 km s−1. Meanwhile, a shock wave is driven by the CME at the flank. The eruption of CME generates an extreme-ultraviolet (EUV) wave expanding outward from the flare site with an apparent speed of ≥200 km s−1. As the EUV wave propagates eastward, it encounters and interacts with the low-lying adjacent coronal loops (ACLs), which are composed of two loops. The compression of EUV wave results in contraction, expansion, and transverse vertical oscillations of ACLs. The commencements of contraction are sequential from western to eastern footpoints and the contraction lasts for ∼15 minutes. The speeds of contraction lie in the range of 13−40 km s−1 in 171 Å and 8−54 km s−1 in 193 Å. A long, gradual expansion follows the contraction at lower speeds. Concurrent vertical oscillations are superposed on contraction and expansion of ACLs. The oscillations last for 2−9 cycles and the amplitudes are ≤4 Mm. The periods are between 3 to 12 minutes with an average value of 6.7 minutes. The results show rich dynamics of coronal loops.

Birth places of extreme ultraviolet waves driven by impingement of solar jets upon coronal loops

Liang **Zhang**, Ruisheng Zheng, Huadong Chen, Yao Chen

ApJ **931** 162 **2022**

https://arxiv.org/pdf/2204.00522.pdf

https://iopscience.iop.org/article/10.3847/1538-4357/ac61db/pdf

Solar extreme ultraviolet (EUV) waves are large-scale propagating disturbances in the corona. It is generally believed that the vital key for the formation of EUV waves is the rapid expansion of the loops that overlie erupting cores in solar eruptions, such as coronal mass ejections (CMEs) and solar jets. However, the details of the interaction between the erupting cores and overlying loops are not clear, because that the overlying loops are always instantly opened after the energetic eruptions. Here, we present three typical jet-driven EUV waves without CME to study the interaction between the jets and the overlying loops that remained closed during the events. All three jets emanated from magnetic flux cancelation sites in source regions. Interestingly, after the interactions between jets and overlying loops, three EUV waves respectively formed ahead of the top, the near end (close to the jet source), and the far (another) end of the overlying loops. According to the magnetic field distribution of the loops extrapolated from Potential Field Source Surface method, it is confirmed that the birth places of three jet-driven EUV waves were around the weakest magnetic field strength part of the overlying loops. We suggest that the jet-driven EUV waves preferentially occur at the weakest part of the overlying loops, and the location can be subject to the magnetic field intensity around the ends of the loops. **2016 February 10, 2017 April 01, 2017 August 16**

Remote coronal dimmings related to a circular-ribbon flare

Q. M. **Zhang**, R. S. Zheng
A&A 633, A142 **2020**
https://arxiv.org/pdf/1912.09618.pdf
https://doi.org/10.1051/0004-6361/201937126
In this paper, multiwavelength observations of remote coronal dimmings related to an M1.1 circular-ribbon flare (CRF) in active region (AR) 12434 are reported. The confined flare without a CME was observed by AIA and HMI on board SDO on **2015 October 16**. Global three-dimensional (3D) magnetic fields before flare were obtained using the potential field source surface modeling. A few minutes before the flare hard X-ray peak time (06:13:48 UT), small-scale, weak dimming appeared ~240$\arcsec$ away from the flare site, which can be observed by AIA only in 131 and 171 Å. Afterwards, long and narrow dimmings became evident in all AIA EUV passbands except 304 Å, while localized core dimming was not clearly observed near the flare site. The large-area dimmings extended southeastward and the areas increased gradually. The total area of dimmings reaches (1.2±0.4)×104 Mm2 in 193 Å. The maximal relative intensity decreases in 171 and 193 Å reach 90\% and 80\%, respectively. Subsequently, the dimmings began to replenish and the area decreased slowly, lasting for ≥3 hr. The remote dimmings and AR 12434 were connected by large-scale coronal loops. The remote dimmings were associated with the southwest footpoints of coronal loops with weak negative polarities. Possible origins of remote dimmings are discussed.

Vertical oscillation of a coronal cavity triggered by an EUV wave

Q. M. **Zhang**, H. S. Ji
ApJ **860** 113 **2018**
https://arxiv.org/pdf/1805.01088.pdf
In this paper, we report our multiwavelength observations of the vertical oscillation of a coronal cavity on **2011 March 16**. The elliptical cavity with an underlying horn-like quiescent prominence was observed by the Atmospheric Imaging Assembly (AIA) on board the \textit{Solar Dynamics Observatory} (\textit{SDO}). The width and height of the cavity are 150$\arcsec$ and 240$\arcsec$, and the centroid of cavity is 128$\arcsec$ above the solar surface. At ~17:50 UT, a C3.8 two-ribbon flare took place in active region 11169 close to the solar western limb. Meanwhile, a partial halo coronal mass ejection (CME) erupted and propagated at a linear speed of ~682 km s−1. Associated with the eruption, a coronal extreme-ultraviolet (EUV) wave was generated and propagated in the northeast direction at a speed of ~120 km s−1. Once the EUV wave arrived at the cavity from the top, it pushed the large-scale overlying magnetic field lines downward before bouncing back. At the same time, the cavity started to oscillate coherently in the vertical direction and lasted for ~2 cycles before disappearing. The amplitude, period, and damping time are 2.4−3.5 Mm, 29−37 minutes, and 26−78 minutes, respectively. The vertical oscillation of the cavity is explained by a global standing MHD wave of fast kink mode. To estimate the magnetic field strength of the cavity, we use two independent methods of prominence seismology. It is found that the magnetic field strength is only a few Gauss and less than 10 G.

Pre-flare coronal dimmings

Q. M. **Zhang**, Y. N. Su, H. S. Ji
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https://arxiv.org/pdf/1611.08371v1.pdf
In this paper, we focus on the pre-flare coronal dimmings. We report our multiwavelength observations of the GOES X1.6 solar flare and the accompanying halo CME produced by the eruption of a sigmoidal magnetic flux rope (MFR) in NOAA active region (AR) 12158 on **2014 September 10**. The eruption was observed by the Atmospheric Imaging Assembly (AIA) aboard the Solar Dynamic Observatory (SDO). The photospheric line-of-sight magnetograms were observed by the Helioseismic and Magnetic Imager (HMI) aboard SDO. The soft X-ray (SXR) fluxes were recorded by the GOES spacecraft. The halo CME was observed by the white light coronagraphs of the Large Angle Spectroscopic Coronagraph (LASCO) aboard SOHO.} {About 96 minutes before the onset of flare/CME, narrow pre-flare coronal dimmings appeared at the two ends of the twisted MFR. They extended very slowly with their intensities decreasing with time, while their apparent widths (8−9 Mm) nearly kept constant. During the impulsive and decay phases of flare, typical fanlike twin dimmings appeared and expanded with much larger extent and lower intensities than the pre-flare dimmings. The percentage of 171 {\AA} intensity decrease reaches 40\%. The pre-flare dimmings are most striking in 171, 193, and 211 {\AA} with formation temperatures of 0.6−2.5 MK. The northern part of the pre-flare dimmings could also be recognized in 131 and 335 {\AA}.} To our knowledge, this is the first detailed study of pre-flare coronal dimmings, which can be explained by the density depletion as a result of the gradual expansion of the coronal loop system surrounding the MFR during the slow rise of the MFR.

Coexisting fast and slow propagating waves of the extreme-UV intensity in solar coronal plasma structures⋆

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A&A 581, A78 (**2015**)

Context. From 06:15 UT to 08:15 UT on **2011 June 2**, a toroidal filament located at the joint of two active regions, 11226 and 11227, appeared to perform two eruptions. During this phenomenon, fast and slow magnetoacoustic waves were detected to propagate simultaneously along a funnel coronal loop system of AR 11227.
Aims. We aim to understand the relationship between fast and slow magnetoacoustic waves during their propagations and measure their properties, such as the propagating speed, path, amplitude, and period observed in the extreme ultraviolet (EUV) wavebands.
Methods. We analyse time sequences of EUV images acquired by the Atmospheric Imaging Assembly onboard the Solar Dynamics Observatory. By creating time-distance maps along selected directions, we measure the speeds and localisation of EUV intensity waves in different EUV wavebands. We determine the periods of the waves with wavelet analysis.
Results. The fast and slow magnetoacoustic waves, apparently propagating along the same path, are found to have different properties. Their apparent propagation speeds, travel distances, and periods are about 900 km s-1 and 100 km s-1, 145 Mm and 36 Mm, and 2 min and 3 min, respectively.

EMERGING DIMMINGS OF ACTIVE REGIONS OBSERVED BY THE SOLAR DYNAMICS OBSERVATORY

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2012 ApJ 760 L29

Using the observations from the Atmospheric Imaging Assembly and the Helioseismic and Magnetic Imager on board the Solar Dynamics Observatory, we statistically investigate the emerging dimmings (EDs) of 24 isolated active regions (IARs) from 2010 June to 2011 May. All the IARs show EDs in lower-temperature lines (e.g., 171 Å) at their early emerging stages. Meanwhile, in higher temperature lines (e.g., 211 Å), the ED regions brighten continuously. There are two types of EDs: fan-shaped and halo-shaped. There are 19 fan-shaped EDs and 5 halo-shaped ones. The EDs appear to be delayed by several to more than ten hours relative to the first emergence of the IARs. The shortest delay is 3.6 hr and the longest is 19.0 hr. The EDs last from 3.3 hr to 14.2 hr, with a mean duration of 8.3 hr. Before the appearance of the EDs, the emergence rate of the magnetic flux of the IARs is between 1.2 × 1019 Mx hr–1 to 1.4 × 1020 Mx hr–1. The larger the emergence rate is, the shorter the delay time is. While the dimmings appear, the magnetic flux of the IARs ranges from 8.8 × 1019 Mx to 1.3 × 1021 Mx. These observations imply that the reconfiguration of the coronal magnetic fields due to reconnection between the newly emerging flux and the surrounding existing fields results in a new thermal distribution which leads to a dimming for the cooler channel (171 Å) and brightening in the warmer channels.

Propagation of Moreton Waves

Y.Z. **Zhang,** R. Kitai, N. Narukage, T. Matsumoto, S. Ueno, K. Shibata and J.X. Wang
E-print, April **2011,** PASJ **63**, 685–696, **2011, File**

With FMT and SMART telescopes at Hida Observatory of Kyoto University, 13 events of Moreton waves were captured at H-alpha center, +/-0.5A and +/-0.8A wavebands since 1997. With such samples, we have studied the statistical properties of the propagation of Moreton waves. Moreton waves were all restricted in sectorial zones with the mean value of 92 degree. However, their accompanied EIT waves, observed simultaneously with SOHO/EIT at Extreme-ultraviolet wavelength, were much isotropic with quite extended scope of 193 degree. The average propagation speed of the Moreton waves and the corresponding EIT waves were 664 km/s and 205 km/s, respectively. Moreton waves were propagating either under the large-scale close magnetic flux loops, or firstly in the sectorial region where two sets of magnetic loops separated each other and diverged, and then stopped before the open magnetic flux region. The location swept by Moreton waves had relatively weak magnetic field compared to the magnetic fields at their sidewalls. The ratio of magnetic flux density between the sidewalls and path falls in the range of 1.4 to 3.7 at the height of 0.01 solar radii. Additionally, we roughly estimated the distribution of fast magnetosonic speed between the propagating path and sidewalls in an event on 1997 November 3, and found the relatively low fast magnetosonic speed in the path. We also found that the propagating direction of Moreton waves coincided with the direction of filament eruption in a few well-observed events. This favors an interpretation of `Piston' model, although further studies are necessary for definitive conclusion. Key words: shock waves-Sun: chromosphere-Sun: corona-Sun: flares-Sun: magnetic flelds-Sun

Coronal Magnetic Topology and EUV Dimmings

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Solar Phys, Volume 241 Number 2, 329 – 349, **2007**; **File**

Coronal dimming can be considered to be a disk signature of front-side coronal mass ejections (CMEs) (Thompson *et al.*: 2000, *Geophys. Res. Lett.* **27**, 1431). The study of the magnetic connectivity associated with coronal dimming can shed new light on the magnetic nature of CMEs. In this study, four major flare-CME events on 14 July 2000, 28 October 2003, 7 November 2004, and 15 January 2005 are analyzed. They were all halo CMEs associated with major flare activity in complex active regions (ARs) and produced severe space weather consequences. To explore the magnetic connectivity of these CMEs, global potential-field extrapolations based on the composite synoptic magnetograms from the Michelson Doppler Imager onboard the *Solar and Heliospheric Observatory* are constructed, and their association with coronal dimming is revealed by the Extreme ultraviolet Imaging Telescope. It is found that each flare-CME event involved interaction of more than ten sets of magnetic-loop systems. These loop systems occupied over 50% of all identified loop systems in the visible hemisphere and covered a wide range of solar longitudes and latitudes. We categorize the loop systems as active-region loops (ARLs), AR-interconnecting loops (ARILs) including transequatorial loops (TLs), and long arcades (LAs) straddling filament channels. A recurring pattern, the saddle-field configuration (SFC), consisting of ARILs, is found to be present in all four major flare-CME events. The magnetic connectivity revealed by this work implies that intercoupling and interaction of multiple flux-loop systems are required for a major CME. For comparison, a simple flare-CME event of 12 May 1997 with a relatively simple magnetic configuration is chosen. Even for this simple flare-CME event, we find that multiple flux-loop systems are also present.
The dimmings of the CME appeared as an **octopus-like bundle of some magnetic ropes**, with the 'arms' being connected to some ARs, disposed over almost the whole visible solar surface.

Moreton wave and its source of disturbances in the X12/3B WLF of AR6659 in 1991 June 4
H. **Zhang**

A&A 372, 676{685 (2001); File

The Moreton wave that accompanied the X12/3B June 4 1991 white light flare (WLF) is analyzed. The wave, with a wavelength of 1:4 _ 10^4 km, propagated along the solar limb on the chromosphere, and the wavefronts were accelerated during the propagation: their velocity increased from 2500 kms^{-1} to 4000 kms^{-1}. The analyses show that the wave originated in the layers of the atmosphere between the photosphere and the upper chromosphere, and it is suggested that both a magneto-hydrodynamic (MHD) disturbance and a gasdynamic disturbance are coupled to induce the wave. The MHD disturbance is caused by a rapid variation of the magnetic _eld, which merges and alternatively emerges. A gas-dynamic disturbance is produced by a strong downward compression of the deep chromosphere and a spray upward ejection occurring simultaneously in the disturbance source region. In the disturbance source, the increase in the magnetic pressure is responsible for the wave acceleration. The photospheric (longitudinal) magnetic _eld of the source emerges continually during the wavefront propagation, and the corresponding magnetic pressure also increases. The wavefronts that are carried by the plasma around the disturbance source are accelerated, since the transverse pressure compresses the plasma. The observed results do not support the hypothesis that the Moreton wave is the "sweeping skirt" of the shock wavefront, as proposed by Uchida (1974).

UNCOVERING THE WAVE NATURE OF THE EIT WAVE FOR THE 2010 JANUARY 17 EVENT THROUGH ITS CORRELATION TO THE BACKGROUND MAGNETOSONIC SPEED
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2011 ApJ 742 131, **File**

An EIT wave, which typically appears as a diffuse brightening that propagates across the solar disk, is one of the major discoveries of the Extreme ultraviolet Imaging Telescope on board the Solar and Heliospheric Observatory. However, the physical nature of the so-called EIT wave continues to be debated. In order to understand the relationship between an EIT wave and its associated coronal wave front, we investigate the morphology and kinematics of the coronal mass ejection (CME)-EIT wave event that occurred on **2010 January 17**. Using the observations of the SECCHI EUVI, COR1, and COR2 instruments on board the Solar Terrestrial Relations Observation-B, we track the shape and movements of the CME fronts along different radial directions to a distance of about 15 solar radii (Rs); for the EIT wave, we determine the propagation of the wave front on the solar surface along different propagating paths. The relation between the EIT wave speed, the CME speed, and the local fast-mode characteristic speed is also investigated. Our results demonstrate that the propagation of the CME front is much faster than that of the EIT wave on the solar surface, and that both the CME front and the EIT wave propagate faster than the fast-mode speed in their local environments. Specifically, we show a significant positive correlation between the EIT wave speed and the local fast-mode wave speed in the propagation paths of the EIT wave. Our findings support that the EIT wave under study is a fast-mode magnetohydrodynamic wave.

Sunquake with a second bounce, other sunquakes, and emission associated with the X9.3 flare of 6 September 2017. I. Observations

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https://www.aanda.org/articles/aa/pdf/2020/07/aa36755-19.pdf
https://www.aanda.org/articles/aa/pdf/forth/aa36755-19.pdf

Aims. The 6 September 2017 X9.3 solar flare produced very unique observations of magnetic field transients and a few seismic responses, or sunquakes, detected by the Helioseismic and Magnetic Imager (HMI) instrument aboard Solar Dynamic Observatory (SDO) spacecraft, including the strongest sunquake ever reported. This flare was one of a few flares occurring within a few days or hours in the same active region. Despite numerous reports of the fast variations of magnetic field, and seismic and white light emission, no attempts were made to interpret the flare features using multi-wavelength observations. In this study, we attempt to produce the summary of available observations of the most powerful flare of the 6 September 2017 obtained using instruments with different spatial resolutions (this paper) and to provide possible interpretation of the flaring events, which occurred in the locations of some seismic sources (a companion Paper II).
Methods. We employed non-linear force-free field extrapolations followed by magnetohydrodynamic simulations in order to identify the presence of several magnetic flux ropes prior to the initiation of this X9.3 flare. Sunquakes were observed using the directional holography and time–distance diagram detection techniques. The high-resolution method to detect the Hα line kernels in the CRISP instrument at the diffraction level limit was also applied.
Results. We explore the available γ-ray (GR), hard X-ray (HXR), Lyman-α, and extreme ultra-violet (EUV) emission for this flare comprising two flaring events observed by space- and ground-based instruments with different spatial resolutions. For each flaring event we detect a few seismic sources, or sunquakes, using Dopplergrams from the HMI/SDO instrument coinciding with the kernels of Hα line emission with strong redshifts and white light sources. The properties of sunquakes were explored simultaneously with the observations of HXR (with KONUS/WIND and the Reuven Ramaty High Energy Solar Spectroscopic Imager payload), EUV (with the Atmospheric Imaging Assembly (AIA/SDO and the EUV Imaging Spectrometer aboard Hinode payload), Hα line emission (with the CRisp Imaging Spectro-Polarimeter (CRISP) in the Swedish Solar Telescope), and white light emission (with HMI/SDO). The locations of sunquake and Hα kernels are associated with the footpoints of magnetic flux ropes formed immediately before the X9.3 flare onset.
Conclusions. For the first time we present the detection of the largest sunquake ever recorded with the first and second bounces of acoustic waves generated in the solar interior, the ripples of which appear at a short distance of 5–8 Mm from the initial flare location. Four other sunquakes were also detected, one of which is likely to have occurred 10 min later in the same location as the largest sunquake. Possible parameters of flaring atmospheres in the locations with sunquakes are discussed using available temporal and spatial coverage of hard X-ray, GR, EUV, hydrogen H*α*-line, and white light emission in preparation for their use in an interpretation to be given in Paper II.

Properties of the 15 February 2011 Flare Seismic Sources

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Solar Physics, June **2013**, Volume 284, Issue 2, pp 315-327

The first near-side X-class flare of Solar Cycle 24 occurred in February 2011 (SOL2011-02-05T01:55) and produced a very strong seismic response in the photosphere. One sunquake was reported by Kosovichev (Astrophys. J. Lett. 734, L15, 2011), followed by the discovery of a second sunquake by Zharkov, Green, Matthews et al. (Astrophys. J. Lett. 741, L35, 2011). The flare had a two-ribbon structure and was associated with a flux-rope eruption and a halo coronal mass ejection (CME) as reported in the CACTus catalogue. Following the discovery of the second sunquake and the spatial association of both sources with the locations of the feet of the erupting flux rope (Zharkov, Green, Matthews et al., Astrophys. J. Lett. 741, L35, 2011), we present here a more detailed analysis of the observed photospheric changes in and around the seismic sources. These sunquakes are quite unusual, taking place early in the impulsive stage of the flare, with the seismic sources showing little hard X-ray (HXR) emission, and strongest X-ray emission sources located in the flare ribbons. We present a directional time–distance diagram computed for the second source, which clearly shows a ridge corresponding to the travelling acoustic-wave packet and find that the sunquake at the second source happened about 45 seconds to one minute earlier than the first source. Using acoustic holography we report different frequency responses of the two sources. We find strong downflows at both seismic locations and a supersonic horizontal motion at the second site of acoustic-wave excitation.

Sunquake with a second bounce, other sunquakes, and emission associated with the X9.3 flare of 6 September 2017. II. Proposed interpretation

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A&A 639, A79 **2020**

https://www.aanda.org/articles/aa/pdf/2020/07/aa37885-20.pdf

https://solargsm.com/wp-content/uploads/2020/05/Zharkova_et-al_6sept17_aa20.pdf

In this paper we present the interpretation of the observations of the flare from **6 September 2017** reported in Paper 1. These include gamma-ray (GR), hard X-ray (HXR), soft X-rays (SXR), Lyα line, extreme ultraviolet (EUV), Hα, and white light (WL) emission, which were recorded during the two flaring events 1 (FE1) and 2 (FE2) that occurred at 11:55:37 UT (FE1) and 12:06:40 UT (FE2). Paper 1 also reported the first detection of the sunquake with first and second bounces of seismic waves combined with four other sunquakes in different locations supported with the observations of HXR, GR, EUV, Hα, and WL emission with strongly varying spatial resolution and temporal coverage. In the current Paper 2, we propose some likely scenarios for heating of flaring atmospheres in the footpoints with sunquakes which were supported with EUV and Hα emission. We used a range of parameters derived from the HXR, EUV, and Hα line observations to generate hydrodynamic models, which can account for the blueshifts derived from the EUV emission and the redshifts observed with the EUV Imaging Spectrometer (EIS) in the He II line and by the CRisp Imaging Spectro-Polarimeter (CRISP) in the Swedish Solar Telescope (SST) in Hα line emission. The parameters of hydrodynamic shocks produced by different beams in flaring atmospheres were used as the initial conditions for another type of hydrodynamic models that were developed for acoustic wave propagation in the solar interior. These models simulate the sets of acoustic waves produced in the interior by the hydrodynamic shocks from atmospheres above deposited in different footpoints of magnetic loops. The Hα line profiles with large redshifts in three kernels (two in FE1 and one in FE2) were interpreted with the full non-local thermodynamic equilibrium (NLTE) radiative simulations in all optically thick transitions (Lyman lines and continuum Hα, Hβ, and Pα) applied for flaring atmospheres with fast downward motions while considering thermal and non-thermal excitation and ionisation of hydrogen atoms by energetic power-law electron beams. The observed Hα line profiles in three kernels were fit with the simulate blue wing emission of the Hα line profiles shifted significantly (by 4-6 Å) towards the line red wings, because of strong downward motions with velocities about 300 km s-1 by the shocks generated in flaring atmospheres by powerful beams. The flaring atmosphere associated with the largest sunquake (seismic source 2 in FE1) is found consistent with being induced by a strong hydrodynamic shock produced by a mixed beam deposited at an angle of -30◦ from the local vertical. We explain the occurrence of a second bounce in the largest sunquake by a stronger momentum delivered by the shock generated in the flaring atmosphere by a mixed beam and deeper depths of the interior where this shock was deposited. Indeed, the shock with mixed beam parameters is found deposited deeply into the interior beneath the flaring atmosphere under the angle to the local vertical that would allow the acoustic waves generated in the direction closer to the surface to conserve enough energy for the second bounces from the interior layers and from the photosphere. The wave characteristics of seismic sources 1 and 3 (in FE1) were consistent with those produced by the shocks generated by similar mixed beams deposited at the angles -(0 - 10)◦ (seismic source 1) and +30◦ (seismic source 3) to the local vertical. The differences of seismic signatures produced in the flares of **6 September 2011** and 2017 are also discussed.

Why "solar tsunamis" rarely leave their imprints in the chromosphere

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ApJ 949 L8 **2023**

https://arxiv.org/pdf/2304.14859.pdf

https://iopscience.iop.org/article/10.3847/2041-8213/acd0ac/pdf

Solar coronal waves frequently appear as bright disturbances that propagate globally from the eruption center in the solar atmosphere, just like the tsunamis in the ocean on Earth. Theoretically, coronal waves can sweep over the underlying chromosphere and leave an imprint in the form of Moreton wave, due to the enhanced pressure beneath their coronal wavefront. Despite the frequent observations of coronal waves, their counterparts in the chromosphere are rarely detected. Why the chromosphere rarely bears the imprints of solar tsunamis remained a mystery since their discovery three decades ago. To resolve this question, all coronal waves and associated Moreton waves in the last decade have been initially surveyed, though the detection of Moreton waves could be hampered by utilising the low-quality Hα data from Global Oscillations Network Group. Here, we present 8 cases (including 5 in Appendix) of the coexistence of coronal and Moreton waves in inclined eruptions where it is argued that the extreme inclination is key to providing an answer to address the question. For all these events, the lowest part of the coronal wavefront near the solar surface appears very bright, and the simultaneous disturbances in the solar transition region and the chromosphere predominantly occur beneath the bright segment. Therefore, evidenced by observations, we propose a scenario for the excitation mechanism of the coronal-Moreton waves in highly inclined eruptions, in which the lowest part of a coronal wave can effectively disturb the chromosphere even for a weak (e.g., B-class) solar flare.
2011-02-24, 2011-07-03, 2011-08-09, 2011-09-07, 2014-02-25, 2014-03-29, 2021-05-22, 2021-10-28, 2021-11-02

Twin extreme ultraviolet waves in the solar corona

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ApJL **929** L4 **2022**
https://arxiv.org/pdf/2203.15513.pdf
https://iopscience.iop.org/article/10.3847/2041-8213/ac61e3/pdf
Solar extreme ultraviolet (EUV) waves are spectacular propagating disturbances with EUV enhancements in annular shapes in the solar corona. These EUV waves carry critical information about the coronal magnetised plasma that can shed light on the elusive physical parameters (e.g. the magnetic field strength) by global solar coronal magneto-seismology. EUV waves are closely associated with a wide range of solar atmospheric eruptions, from violent flares and coronal mass ejections (CMEs) to less energetic plasma jets or mini-filament eruptions. However, the physical nature and driving mechanism of EUV waves is still controversial. Here, we report the unique discovery of twin EUV waves (TEWs) that were formed in a single eruption with observations from two different perspectives. In all earlier studies, a single eruption was associated at most with a single EUV wave. The newly found TEWs urge to re-visit our theoretical understanding about the underlying formation mechanism(s) of coronal EUV waves. Two distinct scenarios of TEWs were found. In the first scenario, the two waves were separately associated with a filament eruption and a precursor jet, while in another scenario the two waves were successively associated with a filament eruption. Hence, we label these distinguished scenarios as "fraternal TEWs" and "identical TEWs", respectively. Further, we also suggest that impulsive lateral expansions of two distinct groups of coronal loops are critical to the formation of TEWs in a single eruption. **2010 August 18**

An Extreme Ultraviolet Wave Associated with A Solar Filament Activation
Ruisheng **Zheng**, Yao Chen, Bing Wang, Hongqiang Song
ApJ **894** 139 **2020**
https://arxiv.org/pdf/2004.04904.pdf
https://doi.org/10.3847/1538-4357/ab863c
Extreme ultraviolet (EUV) waves are impressive coronal propagating disturbances. They are closely associated with various eruptions, and can used for the global coronal seismology and the acceleration of solar energetic particles. Hence, the study of EUV waves plays an important role in solar eruptions and Space Weather. Here we present an EUV wave associated with a filament activation that did not evolve into any eruption. Due to the continuous magnetic flux emergence and cancellation around its one end, the filament rose with untwisting motion, and the filament mass flowed towards another end along the rising fields. Intriguingly, following the filament activation, an EUV wave formed with a fast constant speed ($\sim$500 km s^{-1}) ahead of the mass flow, and the overlying coronal loops expanded both in lateral and radial directions. Excluding the possibility of a remote flare and an absent coronal mass ejection, we suggest that the EUV wave was only closely associated with the filament activation. Furthermore, their intimate spacial and temporal relationship indicates that the EUV wave was likely directly triggered by the lateral expansion of overlying loops. We propose that the EUV wave can be interpreted as linear fast-mode wave, and the most vital key for the successful generation of the EUV wave is the impulsive early-phase lateral expansion of overlying loops that was driven by the activated filament mass flow without any eruption. **2015 May 7**

The initial morphologies of the wavefronts of extreme ultraviolet waves
Ruisheng **Zheng**, Zhike Xue, Yao Chen, Bing Wang, Hongqiang Song
ApJL **871** 232 **2019**
https://arxiv.org/pdf/1812.08371.pdf
The morphologies of the wavefronts of extreme ultraviolet (EUV) waves can shed light on their physical nature and driving mechanism that are still strongly debated. In reality, the wavefronts always deform after interacting with ambient coronal structures during their propagation. Here, we focus on the initial wavefront morphologies of four selected EUV waves that are closely associated with jets or flux rope eruptions, using the high spatio-temporal resolution observations and different perspectives from the Solar Dynamics Observatory and the Solar-Terrestrial Relations Observatory. For the jet-driven waves, the jets originated from one end of the overlying closed loops, and the arc-shaped wavefront formed around the other far end of the expanding loops. The extrapolated field lines of the Potential Field Source Surface model show the close relationships between the jets, the wavefronts, and the overlying closed loops. For the flux-rope-driven waves, the flux ropes (sigmoids) lifted off beneath the overlying loops, and the circular wavefronts had an intimate spatio-temporal relation with the expanding loops. All the results suggest that the configuration of the overlying loops and their locations relative to the erupting cores are very important for the formation and morphology of the wavefronts, and both two jet-driven waves and two flux-rope-driven waves are likely triggered by the sudden expansion of the overlying closed loops. We also propose that the wavefront of EUV wave is possibly integrated by a chain of wave components triggered by a series of separated expanding loops. **2011 January 27, 2012 March 26, 2014 March 28, 2018 February 24**

An extreme ultraviolet wave generating upward secondary waves in a streamer-like solar structure
Ruisheng **Zheng**, Yao Chen, Shiwei Feng, Bing Wang, Hongqiang Song

ApJL 858 L1 **2018**
https://arxiv.org/pdf/1804.06997.pdf
http://sci-hub.tw/10.3847/2041-8213/aabe87
Extreme ultraviolet (EUV) waves, spectacular horizontally propagating disturbances in the low solar corona, always trigger horizontal secondary waves (SWs) when they encounter ambient coronal structure. We present a first example of upward SWs in a streamer-like structure after the passing of an EUV wave. The event occurred on **2017 June 1**. The EUV wave happened during a typical solar eruption including a filament eruption, a CME, a C6.6 flare. The EUV wave was associated with quasi-periodic fast propagating (QFP) wave trains and a type II radio burst that represented the existence of a coronal shock. The EUV wave had a fast initial velocity of ∼1000 km s−1, comparable to high speeds of the shock and the QFP wave trains. Intriguingly, upward SWs rose slowly (∼80 km s−1) in the streamer-like structure after the sweeping of the EUV wave. The upward SWs seemed to originate from limb brightenings that were caused by the EUV wave. All the results show the EUV wave is a fast-mode magnetohydrodynamic shock wave, likely triggered by the flare impulses. We suggest that part of the EUV wave was probably trapped in the closed magnetic fields of streamer-like structure, and upward SWs possibly resulted from the release of trapped waves in the form of slow-mode. It is believed that an interplay of the strong compression of the coronal shock and the configuration of the streamer-like structure is crucial for the formation of upward SWs.
CESRA nugget #1925 Aug **2018** http://cesra.net/?p=1925

AN EXTREME-ULTRAVIOLET WAVE ASSOCIATED WITH A SURGE
Ruisheng **Zheng**, Yunchun Jiang, Jiayan Yang, Yi Bi, Junchao Hong, Bo Yang, and Dan Yang
2013 ApJ 764 70
Taking advantage of the high temporal and spatial resolution observations from the Solar Dynamics Observatory, we present an extreme-ultraviolet (EUV) wave associated with a surge on **2010 November 13**. Due to the magnetic flux cancelation, some surges formed in the source active region (AR). The strongest surge produced our studied event. The surge was deflected by the nearby loops that connected to another AR, and disrupted the overlying loops that slowly expanded and eventually evolved into a weak coronal mass ejection (CME). The surge was likely associated with the core of the CME. The EUV wave happened after the surge deflected. The wave departed far from the flare center and showed a close location relative to the deflected surge. The wave propagated in a narrow angular extent, mainly in the ejection direction of the surge. The close timing and location relations between the EUV wave and the surge indicate that the wave was closely associated with the CME. The wave had a velocity of 310-350 km s–1, while the speeds of the surge and the expanding loops were about 130 and 150 km s–1, respectively. All of the results suggest that the EUV wave was a fast-mode wave and was most likely triggered by the weak CME.

AN EXTREME ULTRAVIOLET WAVE ASSOCIATED WITH A MICRO-SIGMOID ERUPTION
Ruisheng **Zheng**, Yunchun Jiang, Jiayan Yang, Yi Bi, Junchao Hong, Dan Yang, and Bo Yang
2012 ApJ 753 L29
Taking advantage of the high temporal and spatial resolution of the Solar Dynamics Observatory (SDO) observations, we present an extreme ultraviolet (EUV) wave associated with a micro-sigmoid eruption on **2010 October 21**. The micro-sigmoid underwent a typical "sigmoid-to-arcade" evolution via tether-cutting reconnection, accompanied by a B1.7 flare, a filament eruption, and coronal twin dimmings. In the eruption, the newly formed sigmoidal loops expanded quickly, and the expansion likely triggered an EUV wave. The wave onset was nearly simultaneous with the start of the eruption and the associated flare. The wave had a nearly circular front and propagated at a constant velocity of 270-350 km s–1 with very little angular dependence. Remarkably, in some direction, the wave encountered a small loop and refracted at a higher speed. All the results provide evidences that the wave was a fast-mode magnetohydrodynamic (MHD) wave. Owing to the close temporal and spatial relationship between the wave and the expanding loops, we believe that the wave was most likely triggered by the fast expansion of the newly formed sigmoidal loops, which evolved into the leading front of the invisible micro-coronal mass ejection.

A FAST PROPAGATING EXTREME-ULTRAVIOLET WAVE ASSOCIATED WITH A MINI-FILAMENT ERUPTION
Ruisheng **Zheng**, Yunchun Jiang, Jiayan Yang, Yi Bi, Junchao Hong, Dan Yang, and Bo Yang
2012 ApJ 753 112

The fast extreme-ultraviolet (EUV) waves (>1000 km s–1) in the solar corona were very rare in the past. Taking advantage of the high temporal and spatial resolution of the Solar Dynamics Observatory observations, we present a fast EUV wave associated with a mini-filament eruption, a C1.0 flare, and a coronal mass ejection (CME) on **2011 September 30**. The event took place at the periphery between two active regions (ARs). The mini-filament rapidly erupted as a blowout jet associated with a flare and a CME. The CME front was likely developed from the large-scale overlying loops. The wave onset was nearly simultaneous with the start of the jet and the flare. The wave departed far from the flare center and showed a close location relative to the rapid jet. The wave had an initial speed of about 1100 km s–1 and a slight deceleration in the last phase, and the velocity decreased to about 500 km s–1. The wave propagated in a narrow angle extent, likely to avoid the ARs on both sides. All the results provide evidence that the fast EUV wave was a fast-mode MHD wave. The wave resisted being driven by the CME, because it opened up the large-scale loops and its front likely formed later than the wave. The wave was most likely triggered by the jet, due to their close timing and location relations.

An extreme ultraviolet wave associated with a failed eruption observed by the Solar Dynamics Observatory⋆

R. **Zheng**, Y. Jiang, J. Yang, Y. Bi, J. Hong, B. Yang and D. Yang

A&A 541, A49 (**2012**)

Aims. Taking advantage of the high temporal and spatial resolution of the Solar Dynamics Observatory (SDO) observations, we present an extreme ultraviolet (EUV) wave associated with a failed filament eruption that generated no coronal mass ejection (CME) on **2011 March 1**. We aim at understanding the nature and origin of this EUV wave.

Methods. Combining the high-quality observations in the photosphere, the chromosphere, and the corona, we studied the characteristics of the wave and its relations to the associated eruption.

Results. The event occurred at an ephemeral region near a small active region. The continuous magnetic flux cancelation in the ephemeral region produced pre-eruption brightenings and two EUV jets, and excited the filament eruption, accompanying it with a microflare. After the eruption, the filament material appeared far from the eruption center, and the ambient loops seemed to be intact. It was evident that the filament eruption had failed and was not associated with a CME. The wave happened just after the north jet arrived, and apparently emanated ahead of the north jet, far from the eruption center. The wave propagated at nearly constant velocities in the range of 260−350 km s-1, with a slight negative acceleration in the last phase. Remarkably, the wave continued to propagate, and a loop in its passage was intact when wave and loop met.

Conclusions. Our analysis confirms that the EUV wave is a true wave, which we interpret as a fast-mode wave. In addition, the close temporal and spatial relationship between the wave and the jet provides evidence that the wave was likely triggered by the jet when the CME failed to happen.

HOMOLOGOUS EXTREME ULTRAVIOLET WAVES IN THE EMERGING FLUX REGION OBSERVED BY THE SOLAR DYNAMICS OBSERVATORY

Ruisheng **Zheng**, Yunchun Jiang, Jiayan Yang, Yi Bi, Junchao Hong, B. Yang and Dan Yang

2012 ApJ 747 67, **File**

Taking advantage of the high temporal and spatial resolution of the Solar Dynamics Observatory (SDO) observations, we present four homologous extreme ultraviolet (EUV) waves within 3 hr on **2010 November 11**. All EUV waves emanated from the same emerging flux region (EFR), propagated in the same direction, and were accompanied by surges, weak flares, and faint coronal mass ejections (CMEs). The waves had the basically same appearance in all EUV wavebands of the Atmospheric Imaging Assembly on SDO. The waves propagated at constant velocities in the range of 280-500 km s–1, with little angular dependence, which indicated that the homologous waves could be likely interpreted as fast-mode waves. The waves are supposed to likely involve more than one driving mechanism, and it was most probable that the waves were driven by the surges, due to their close timing and location relations. We also propose that the homologous waves were intimately associated with the continuous emergence and cancellation of magnetic flux in the EFR, which could supply sufficient energy and trigger the onsets of the waves.

A POSSIBLE DETECTION OF A FAST-MODE EXTREME ULTRAVIOLET WAVE ASSOCIATED WITH A MINI CORONAL MASS EJECTION OBSERVED BY THE SOLAR DYNAMICS OBSERVATORY

Ruisheng **Zheng**, Yunchun Jiang, Junchao Hong, Jiayan Yang, Yi Bi, Liheng Yang and Dan Yang

2011 ApJ 739 L39, **File**

"Extreme ultraviolet (EUV) waves" are large-scale wavelike transients often associated with coronal mass ejections (CMEs). In this Letter, we present a possible detection of a fast-mode EUV wave associated with a mini-CME observed by the Solar Dynamics Observatory. On **2010 December 1**, a small-scale EUV wave erupted near the disk center associated with a mini-CME, which showed all the low corona manifestations of a typical CME. The CME was triggered by the eruption of a mini-filament, with a typical length of about 30". Although the eruption was tiny, the wave had the appearance of an almost semicircular front and propagated at a uniform velocity of 220-250 km s–1 with very little angular dependence. The CME lateral expansion was asymmetric with an inclination toward north, and the southern footprints of the CME loops hardly shifted. The lateral expansion resulted in deep long-duration dimmings, showing the CME extent. Comparing the onset and the initial speed of the CME, the wave was likely triggered by the rapid expansion of the CME loops. Our analysis confirms that the small-scale EUV wave is a true wave, interpreted as a fast-mode wave.

Observations of a Flare-ignited broad Quasi-periodic Fast-propagating wave train

Xinping **Zhou**, Yuandeng Shen, Ying D. Liu, Huidong Hu, Jiangtao Su, Zehao Tang, Chengrui Zhou, Yadan Duan, Song Tan

ApJL **2022**

https://arxiv.org/pdf/2204.05603.pdf

Large-scale Extreme-ultraviolet (EUV) waves are frequently observed as an accompanying phenomenon of flares and coronal mass ejections (CMEs). Previous studies mainly focus on EUV waves with single wavefronts that are generally thought to be driven by the lateral expansion of CMEs. Using high spatio-temporal resolution multi-angle imaging observations taken by the Solar Dynamic Observatory and the Solar Terrestrial Relations Observatory, we present the observation of a broad quasi-periodic fast propagating (QFP) wave train composed of multiple wavefronts along the solar surface during the rising phase of a GOES M3.5 flare on **2011 February 24**. The wave train transmitted through a lunate coronal hole (CH) with a speed of 840 +/-67 km/s, and the wavefronts showed an intriguing refraction effect when they passed through the boundaries of the CH. Due to the lunate shape of the CH, the transmitted wavefronts from the north and south arms of the CH started to approach each other and finally collided, leading to the significant intensity enhancement at the collision site. This enhancement might hint the occurrence of interference between the two transmitted wave trains. The estimated magnetosonic Mach number of the wave train is about 1.13, which indicates that the observed wave train was a weak shock. Period analysis reveals that the period of wave train was ~90 seconds, in good agreement with that of the accompanying flare. Based on our analysis results, we conclude that the broad QFP wave train was a large-amplitude fast-mode magnetosonic wave or a weak shock driven by some non-linear energy release processes in the accompanying flare.

Total reflection of a flare-driven quasi-periodic EUV wave train at a coronal hole boundary

Xinping **Zhou**, Yuandeng Shen, Zehao Tang, Chengrui Zhou, Yadan Duan, Song Tang

A&A 659, A164 **2022**

https://arxiv.org/pdf/2112.15098.pdf

https://doi.org/10.1051/0004-6361/202142536

https://www.aanda.org/articles/aa/pdf/2022/03/aa42536-21.pdf

The reflection, refraction, and transmission of large-scale extreme ultraviolet (EUV) waves (collectively, secondary waves) have been observed during their interactions with coronal structures such as active regions (ARs) and coronal holes (CHs). However, the effect of the total reflection of EUV waves has not been reported in the literature. Here, we present the first unambiguous observational evidence of the total reflection of a quasi-periodic EUV wave train during its interaction with a polar CH. The event occurred in NOAA AR 12473, located close to the southeast limb of the solar disk, and was characterized by a jet-like CME. In this study, we focus in particular on the driving mechanism s of the quasi-periodic wave train and the total reflection effect at the CH boundary. We find that the periods of the incident and the reflected wave trains are both about 100 seconds. The excitation of the quasi-periodic wave train was possibly due to the intermittent energy release in the associated flare since its period is similar to that of the quasi-periodic pulsations in the associated flare. Our observational results showed that the reflection of the wave train at the boundary of the CH was a total reflection because the measured incidence and critical angles satisfy the theory of total reflection, i.e., the incidence angle is less than the critical angle. **2015 December 22**

CME-Driven and Flare-Ignited Fast Magnetosonic Waves Successively Detected in a Solar Eruption

Xinping **Zhou**, Yuandeng Shen, Jiangtao Su, Zehao Tang, Chengrui Zhou, Yadan Duan, Song Tan

Sola Phys. volume 296, Article number: 169 **2021**

https://arxiv.org/pdf/2109.02847.pdf

https://link.springer.com/content/pdf/10.1007/s11207-021-01913-2.pdf

https://doi.org/10.1007/s11207-021-01913-2

We present SDO/AIA observation of three types of fast-mode propagating magnetosonic waves in a GOES C3.0 flare on **2013 April 23**, which was accompanied by a prominence eruption and a broad coronal mass ejection (CME). During the fast rising phase of the prominence, a large-scale dome-shaped extreme ultraviolet (EUV) wave firstly formed ahead of the CME bubble and propagated at a speed of about 430 km/s in the CME's lateral direction. One can identify the separation process of the EUV wave from the CME bubble. The reflection effect of the on-disk counterpart of this EUV wave was also observed when it interacted with a remote active region. Six minutes after the first appearance of the EUV wave, a large-scale quasi-periodic EUV train with a period of about 120 seconds appeared inside the CME bubble, which emanated from the flare epicenter and propagated outward at an average speed up to 1100 km/s. In addition, another narrow quasi-periodic EUV wave train was observed along a closed-loop system connecting two adjacent active regions, which also emanated from the flare epicenter, propagated at a speed of about475 km/s and with a period of about 110 seconds. We propose that all the observed waves are fast-mode magnetosonic waves, in which the large-scale dome-shaped EUV wave ahead of the CME bubble was driven by the expansion of the CME bubble, while the large-scale quasi-periodic EUV train within the CME bubble and the narrow quasi-periodic EUV wave train along the closed-loop system were excited by the intermittent energy-releasing process in the flare. Coronal seismology application and energy carried by the waves are also estimated based on the measured wave parameters.

Magnetic Reconnection Invoked by Sweeping of the CME-Driven Fast-Mode Shock

Guiping **Zhou**, Guannan Gao, Jingxiu Wang, Jun Lin, Yingna Su, Chunlan Jin, Yuzong Zhang

ApJ **905** 150 **2020**

https://arxiv.org/pdf/2010.12957.pdf

https://doi.org/10.3847/1538-4357/abc5b2

Coronal waves exist ubiquitously in the solar atmosphere. They are important not only in their own rich physics but also essential candidates of triggering magnetic eruptions in the remote. However, the later mechanism has never been directly confirmed. By revisiting the successive eruptions on **2012 March 7**, fast-mode shocks are identified to account for the X5.4 flare-related EUV wave with a velocity of 550 km/s, and appeared faster than 2060±270 km/s at the front of the corresponding coronal mass ejection in the slow-rising phase. They not only propagated much faster than the local Alfven speed of about 260 km/s, but also simultaneously accompanied by type II radio burst, i.e., a typical feature of shock wave. The observations show that the shock wave disturbs the coronal loops C1 connecting active regions (ARs) 11429 and 11430, which is neighboring a null point region. Following a 40-min-oscillation, an external magnetic reconnection (EMR) occurred in the null point region. About 10 min later, a large-scale magnetic flux rope (MFR) overlaid by the C1 became unstable and erupted quickly. It is thought that the fast-mode shock triggered EMR in the null point region and caused the subsequent eruptions. This scenario is observed directly for the first time, and provides new hint for understanding the physics of solar activities and eruptions.

Large-Scale Source Regions of Earth-Directed Coronal Mass Ejections

Guiping **Zhou**, Jingxiu Wang and Jun Zhang

A&A, 445, No. 3, 1133-1141, **2006, File**

Table, description and illustrations including some filament eruptions

Large-scale Coronal Dimming Foreshadowing a Solar Eruption on 2011 October 1

Chunming **Zhu**1, C. Richard DeVore2, Joel T. Dahlin2,3, Jiong Qiu1, Maria D. Kazachenko4,5, Vadim M. Uritsky2,6, and Jackson S. Vandervelde2,7

2024 ApJ 961 218

https://iopscience.iop.org/article/10.3847/1538-4357/ad1603/pdf

Understanding large-scale solar eruptions requires detailed investigation of the entire system's evolution, including the magnetic environment enveloping the source region and searches for precursor activity prior to event onset. We combine stereoscopic observations from the Solar Dynamics Observatory (SDO) and STEREO-B spacecraft for several hours before a filament ejection, M1.2-class eruptive flare, and coronal mass ejection (CME) originating in NOAA active region (AR) 11305 on **2011 October 1**. Two episodes of significant preeruption coronal dimming that occurred well to the southeast of the ejected filament are identified. The CME subsequently took off with a substantial component of velocity toward the dimming, which became very pronounced during eruption. We used SDO/Helioseismic and Magnetic Imager (HMI) data to reconstruct the magnetic environment of the system and found that it contains a null point near the dimming region. AR 11305 had quite complex connections to nearby ARs 11302 and 11306, as well as to other regions of decayed AR flux. The intensifying and spatially expanding precursor dimming was accompanied by southeastward rising motions of loops toward the null point and northeastward and southwestward motions of loops retracting away. These motions and the dimming are consistent with persistent magnetic reconnection occurring at the null point as it moved upward and southeastward, thereby removing a strapping magnetic field high above AR 11305. Eventually, the filament was ejected explosively toward the null point. We conclude that the breakout model for solar eruptions provides a compelling account of this event. Furthermore, we conjecture that preeruption dimmings may be much more frequent than currently recognized.

Investigation of energetic particle release using multi-point imaging and in situ observations

Bei **Zhu**, Ying D. Liu, Ryun-Young Kwon, Rui Wang

ApJ **2018**

https://arxiv.org/pdf/1808.04934.pdf

The solar eruption on **2012 January 27** resulted in a wide-spread solar energetic particle (SEP) event observed by STEREO A and the near-Earth spacecraft (separated by 108\degree). The event was accompanied by an X-class flare, extreme-ultraviolet (EUV) wave and fast coronal mass ejection (CME). We investigate the particle release by comparing the release times of particles at the spacecraft and the times when magnetic connectivity between the source and the spacecraft was established. The EUV wave propagating to the magnetic footpoint of the spacecraft in the lower corona and the shock expanding to the open field line connecting the spacecraft in the upper corona are thought to be responsible for the particle release. We track the evolution of the EUV wave and model the propagation of the shock using EUV and white-light observations. No obvious evidence indicates that the EUV wave reached the magnetic footpoint of either STEREO A or L1-observers. Our shock modeling shows that the release time of the particles observed at L1 was consistent with the time when the shock first established contact with the magnetic field line connecting L1-observers. The release of the particles observed by STEREO A was delayed relative to the time when the shock was initially connected to STEREO A via the magnetic field line. We suggest that the particle acceleration efficiency of the portion of the shock connected to the spacecraft determines the release of energetic particles at the spacecraft.

Acceleration and Release of Solar Energetic Particles Associated with a Coronal Shock on 2021 September 28 Observed by Four Spacecraft

Bin **Zhuang**, Noé Lugaz, David Lario, Ryun-Young Kwon, Nicolina Chrysaphi, Jonathan Niehof, Tingyu Gou, Lulu Zhao

ApJ **2024**

https://arxiv.org/pdf/2401.10388.pdf

Extreme ultraviolet (EUV) waves are thought to be the propagating footprint of the shock on the solar surface. One of the key questions in SEP research is the timing of the SEP release with respect to the time when the EUV wave magnetically connects with an observer. Taking advantage of close-to-the-Sun measurements by Parker Solar Probe (PSP) and Solar Orbiter (SolO), we investigate an SEP event that occurred on **2021 September 28** and was observed at different locations by SolO, PSP, STEREO-A, and near-Earth spacecraft. During this time, SolO, PSP and STEREO-A shared similar nominal magnetic footpoints relative to the SEP source region but were at different heliocentric distances. We find that the SEP release times estimated at these four locations were delayed compared to the times when the EUV wave intercepted the footpoints of the nominal magnetic fields connecting to each spacecraft by around 30 to 60 minutes. Combining observations in multiple wavelengths of radio, white-light, and EUV, with a geometrical shock model, we analyze the associated shock properties, and discuss the acceleration and delayed release processes of SEPs in this event as well as the accuracy and limitations of using EUV waves to determine the SEP acceleration and release times.

EIT Wave Observations and Modeling in the STEREO Era **(Review)**

A.N. **Zhukov**

E-print, Feb 2011; JASTP, Volume 73, Issue 10, 20 June **2011**, Pages 1096-1116, **File**

``EIT waves'' are large-scale bright fronts observed propagating in the solar corona in association with coronal mass ejections (CMEs). An overview of the observed properties of large-scale wave-like fronts in the solar atmosphere (Moreton waves, EIT waves and similar phenomena observed in other wavelengths) is presented. The models proposed to explain these phenomena are reviewed. A particular emphasis is put on the recent EIT wave observations made by the STEREO mission (Solar-TErrestrial RElations Observatory) launched in October 2006. New key observational results and their implications for EIT wave models are discussed. It is concluded that no single model can account for the large variety of observed EIT wave properties. Prospects for future investigations of this complex phenomenon are outlined.

STEREO/SECCHI Observations on 8 December 2007: Evidence Against the Wave Hypothesis of the EIT Wave Origin

A.N. **Zhukov** · L. Rodriguez · J. de Patoul

Solar Phys (**2009**) 259: 73–85, **File**

The physical nature of EIT waves, large-scale bright fronts propagating in the solar corona, remains a subject of a continuing debate. Two main ways of interpreting this phenomenon have been suggested. One of them describes an EIT wave as a fast mode magnetosonic wave freely propagating in the corona. The other interpretation does not consider an EIT wave a true magnetohydrodynamic wave but instead invokes several possibilities linked to the magnetic field restructuring during the coronal mass ejection (CME) evolution in the low corona. We investigate an EIT wave observed by the SECCHI/EUVI telescopes onboard the STEREO spacecraft on **8 December 2007**. The wave front had a nearly symmetric shape and exhibited a peculiar velocity profile measured by two independent methods. After an initial short propagation at a speed of around 100 km s−1, the wave was moving at a very low velocity (around 20 – 40 kms−1) for about 30 minutes, and then was reaccelerated up to speeds of around 200 km s−1. It is difficult to envisage such a velocity change for a freely propagating coronal wave. However, such a behavior is possible, for example, for erupting prominences. We conclude that this event provides observational evidence that even EIT waves with a symmetric front can be produced by a magnetic field restructuring during the CME eruption.

Global Coronal Mass Ejections

A.N. **Zhukov** and I.S. Veselovsky

Astrophysical Journal, 664: L131–L134, **2007**, **File** .

We characterize a CME by the apparent angular extent of associated dimmings above the solar limb, and define a global CME as a CME with the total apparent extent of limb dimmings of more than 180◦. Several examples of global CMEs are discussed. All the global CMEs identified up to now are fast full halo CMEs associated with X-class flares (if they originate on the front side of the Sun). We demonstrate that global CMEs involve an eruption of several magnetic flux systems distributed on a large spatial scale comparable to a half of the solar disc (true angular width around 180◦). We discuss possible interpretations of the global CME phenomenon and challenges it presents to CME modeling. Our results suggest a non-local nature of the CME eruption mechanism.

Initiation of CMEs: EIT Waves and EUV Dimmings,

Zhukov, A.N.,

2004. in: T. Sakurai & T. Sekii (Ed.), The Solar-B Mission and the Forefront of Solar Physics, pp. 381–388.

On the nature of EIT waves, EUV dimmings and their link to CMEs.

Zhukov, A.N., Auch`ere, F.,

2004. Astron. Astrophys. 427, 705–716.

Cylindrical and Spherical Pistons as Drivers of MHD Shocks

Tomislav **Žic** · Bojan Vršnak · Manuela Temmer · Carla Jacobs

Solar Phys (**2008**) 253: 237–247

We consider an expanding three-dimensional (3-D) piston as a driver of an MHD shock wave. It is assumed that the source-region surface accelerates over a certain time interval to achieve a particular maximum velocity. Such an expansion creates a large-amplitude wave in the ambient plasma. Owing to the nonlinear evolution of the wave front, its profile steepens and after a certain time and distance a discontinuity forms, marking the onset of the shock formation. We investigate how the formation time and distance depend on the acceleration phase duration, the maximum expansion velocity (defining also acceleration), the Alfvén velocity (defining also Mach number), and the initial size of the piston. The model differs from the 1-D case, since in the 3-D evolution, a decrease of the wave amplitude with distance must be taken into account. We present basic results, focusing on the timing of the shock formation in the low- and high-plasma-beta environment. We find that the shockformation time and the shock-formation distance are (1) approximately proportional to the acceleration phase duration; (2) shorter for a higher expansion velocity; (3) larger in a higher Alfvén speed environment; (4) only weakly dependent on the initial source size; (5) shorter for a stronger acceleration; and (6) shorter for a larger Alfvén Mach number of the source surface expansion. To create a shock causing a high-frequency type II burst and the Moreton wave, the source region expansion should, according to our results, achieve a velocity on the order of 1000 km s^{-1} within a few minutes, in a low Alfvén velocity environment.

Mode-Conversion of a Solar Extreme-Ultraviolet Wave over a Coronal Cavity

Weiguo **Zong**, Yu Dai

ApJL 834 L15 **2017**

https://arxiv.org/pdf/1612.08574v1.pdf

We report on observations of an extreme-ultraviolet (EUV) wave event in the Sun on **2011 January 13** by \emph{Solar Terrestrial Relations Observatory} (\emph{STEREO}) and \emph{Solar Dynamics Observatory} (\emph{SDO}) in quadrature. Both the trailing edge and the leading edge of the EUV wave front in the north direction are reliably traced, revealing generally compatible propagation velocities in both perspectives and a velocity ratio about 1/3. When the wave front encounters a coronal cavity near the northern polar coronal hole, the trailing edge of the front stops while its leading edge just shows a small gap and extends over the cavity, meanwhile getting significantly decelerated but intensified. We propose that the trailing edge and the leading edge of the northward propagating wave front correspond to a non-wave coronal mass ejection (CME) component and a fast-mode magnetohydrodynamic (MHD) wave component, respectively. The interaction of the fast-mode wave and the coronal cavity may involve a mode conversion process, through which part of the fast-mode wave is converted to a slow-mode wave that is trapped along the magnetic field lines. This scenario can reasonably account for the unusual behavior of the wave front over the coronal cavity.

Coronal and Chromospheric Signatures of Large-Scale Disturbances Associated with a Major Solar Eruption

Weiguo **Zong**, Yu Dai
ApJ **2015**
http://arxiv.org/pdf/1507.05369v1.pdf

We present both coronal and chromospheric observations of large-scale disturbances associated with a major solar eruption on **2005 September 7**. In GOES/SXI, arclike coronal brightenings are recorded propagating in the southern hemisphere. The SXI front shows an initially constant speed of 730 km s−1 and decelerates later on, and its center is near the central position angle of the associated coronal mass ejection (CME) but away from flare site. Chromospheric signatures of the disturbances are observed in both MLSO/PICS Hα and MLSO/CHIP He I 10830 {\AA}, and can be divided into two parts. The southern signatures occur in regions where the SXI front sweeps over, with the Hα bright front coincident with the SXI front while the He I dark front lagging the SXI front but showing a similar kinematics. Ahead of the path of the southern signatures, oscillations of a filament are observed. The northern signatures occur near the equator, with the Hα and He I fronts coincident with each other. They first propagate westward, and then deflect to the north at the boundary of an equatorial coronal hole (CH). Based on these observational facts, we suggest that the global disturbances are associated with the CME lift-off, and show a hybrid nature: a mainly non-wave CME flank nature for the SXI signatures and the corresponding southern chromospheric signatures, and a shocked fast-mode coronal magnetohydrodynamics (MHD) wave nature for the northern chromospheric signatures.

Large-scale disturbances preceding a fast halo CME:

W.-G. **Zong**
A&A 479 (**2008**) 859-864; **File**

*Aims.*The nature of coronal waves, often termed "EIT waves" is still unclear. Therefore new efforts are needed to investigate large-scale disturbances during solar eruptions. In this paper, we present observations of an event occurring on **19 January 2005**, and study the large-scale disturbance during the event in detail.
*Methods.*Using the high cadence images from SXI onboard GOES-12, the large-scale disturbance is identified. Combined with EIT 195 Å images, TRACE UV 1600 Å images, RHESSI hard X-ray data and MDI/SOHO longitudinal magnetic field maps, the intrinsic process of the large-scale disturbance is discussed.
*Results.*The large-scale disturbance propagated over a distance about 3.8×10^5 km at a velocity of about 390 km s^{-1}. Along the trajectory of the disturbance, a brightening line was left behind, which was coincident with the dense structure in EIT intensity images. With the morphology and metric radio spectrum data, it was found that the disturbance was not a wave but the low-coronal signatures of the eruption.

An MHD Study of Large-Amplitude Oscillations in Solar Filaments

Ernesto **Zurbriggen**, Mariana Cécere, María Valeria Sieyra, Gustavo Krause, Andrea Costa & C. Guillermo Giménez de Castro
Solar Physics volume 296, Article number: 173 (**2021**)
https://link.springer.com/content/pdf/10.1007/s11207-021-01908-z.pdf
https://doi.org/10.1007/s11207-021-01908-z

Quiescent filaments are usually affected by internal and/or external perturbations triggering oscillations of different kinds. In particular, external large-scale coronal waves can perturb remote quiescent filaments leading to large-amplitude oscillations. Observational reports have indicated that the activation time of oscillations coincides with the passage of a large-scale coronal wavefront through the filament, although the disturbing wave is not always easily detected. Aiming to contribute to understanding how –and to what extent– coronal waves are able to excite filament oscillations, here we modelled with 2.5D magnetohydrodynamic simulations a filament floating in a gravitationally stratified corona disturbed by a coronal shock wave. This simplified scenario results in a two-coupled-oscillation pattern of the filament, which is damped in a few cycles, enabling a detailed analysis. A parametric study was carried out varying parameters of the scenario such as height, size, and mass of the filament. An oscillatory analysis reveals a general tendency for periods of oscillations, amplitudes, and damping times to increase with height, whereas filaments of larger radius exhibit shorter periods and smaller amplitudes. The calculation of forces exerted on the filament shows that the main restoring force is the magnetic tension.

Распространение быстрой магнитозвуковой ударной волны в магнитосфере активной области

А. Н. **Афанасьев**, А. М. Уралов, В. В. Гречнев

Астрономический журнал, 90(8) - 2013, С. 648-656

В рамках метода нелинейной геометрической акустики рассматривается проблема распространения быстрой магнитозвуковой ударной волны в магнитосфере активной области на Солнце. Магнитное поле моделируется подфотосферным магнитным диполем в окружении радиального поля спокойной короны. Начальные параметры волны задаются на сферической поверхности в глубине активной области. Волна распространяется асимметрично и испытывает отражение от областей сильного магнитного поля, что приводит к излучению энергии волны преимущественно вверх. Значительные градиенты альфвеновской скорости способствуют существенному возрастанию интенсивности волны. Нелинейное затухание волны и расходимость волнового фронта приводят к обратному эффекту. Анализ совместного действия этих факторов показал, что выходящее из активной области быстрое магнитозвуковое возмущение может представлять собой ударную волну умеренной интенсивности. Полученный результат поддерживает сценарий, согласно которому первичным источником корональной волны может быть эруптивное волокно, импульсно расширяющееся внутри магнитосферы активной области.

ПАРАМЕТРЫ КОРОНАЛЬНЫХ ДИММИНГОВ И ИХ ВАРИАЦИИ В ТЕЧЕНИЕ 24-ГО СОЛНЕЧНОГО ЦИКЛА

Вахрушева А.А., Шугай Ю.С., Капорцева К.Б., Еремеев В.Е., Калегаев В.В.

ГиА Том: **64**Номер: **1** Год: **2024,** 3-12 **File**

Исследованы параметры диммингов и их связь с корональными выбросами массы для определения расположения возможных источников выбросов на диске Солнца в ходе 24-го солнечного цикла. Использована база данных Solar Demon, в которой содержится информация по вспышкам и диммингам, полученная путем обработки изображений с космической обсерватории SDO/AIA. Из всех проанализированных диммингов 16% соотнесены с корональными выбросами массы из базы данных CACTus по данным коронографа SOHO/LASCO за 2010-2018 гг. По распределению параметров установлено, что димминги, связанные с корональными выбросами массы, в среднем являются событиями с большими абсолютными величинами параметров. Между центральным углом димминга и центральным углом соотнесенного с ним коронального выброса массы коэффициент корреляции равен 0.96. Для диммингов, наблюдаемых в центральной части диска Солнца, были получены коэффициенты корреляции между скоростью коронального выброса массы и параметрами димминга, близкие к 0.5. Полученные результаты могут быть использованы для моделирования распространения корональных выбросов массы и уточнения вероятности их прихода на околоземную орбиту

ИССЛЕДОВАНИЕ ПРОБЛЕМЫ ЛОКАЛИЗАЦИИ ВОЛНЫ МОРТОНА В СОЛНЕЧНОЙ АТМОСФЕРЕ

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АЖ Том: 92Номер: 2 Год: **2015** Страницы: 190

Рассмотрены два варианта объяснения наблюдаемой в солнечной атмосфере картины волны Мортона в линии H : при помощи модели облака, фронта волны, находящегося в верхней хромосфере и совершающего радиальные движения вверх-вниз, и путем смещения всей линии поглощения H . Показано, что ни при каких значениях оптических параметров облака, а именно: -функции источников, - оптической толщины, - допплеровской ширины и - допплеровского смещения облака внутри линии поглощения H (обусловленное радиальными движениями облака фронта волн
фронта внутри линии H . Показано, что наблюдаемую картину фронта волны можно получить исключительно путем смещения всей линии поглощения H . На основании этого сделан вывод о том, что эта волна распространяется в области формирования линии поглощения H , иными словами, в фотосфере и нижней хромосфере. Показано, что волна Мортона не наблюдается в верхней хромосфере, что также подтверждает вывод, приведенный выше. Далее показано, что эта волна не может распространяться в короне, так как время охлаждения коронального газа до температуры 100000 К на порядок превышает период волны. Показано, волна Мортона не является ударной волной, так как наблюдаемый профиль фронта не имеет характерного разрыва для случая ударной волны.

ВОЗБУЖДЕНИЕ И ЗАТУХАНИЕ СПЕКТРАЛЬНЫХ ЛИНИЙ МНОГОЗАРЯДНЫХ ИОНОВ И ДИНАМИКА ТЕМПЕРАТУРЫ КОРОНЫ

Подгорный1 И.М., Подгорный2 А.И.

Астрономия-**2018** Том 2 Солнечно-земная физика – современное состояние и перспективы С.198

http://www.izmiran.ru/library/eaas2018/eaas-2018-2.pdf

The active region AR12673 is appeared near the solar activity minimum. The dimming of the spectral line 193 Å (FeXII) is observed before and after the X9.3 flare. The dimming in emissions of other spectral lines is not observed. It is impossible to insist that dimming is created due to flare energy release. He dimming of the spectral line 193 Å can appear due to local ions FeXII density decreasing. Such decreasing can be result of the local electron temperature increasing or decreasing. **6 Sept 2017**

КРУПНОМАСШТАБНЫЕ ЯВЛЕНИЯ НА СОЛНЦЕ, СВЯЗАННЫЕ С ЭРУПЦИЕЙ ВОЛОКОН ВНЕ АКТИВНЫХ ОБЛАСТЕЙ: СОБЫТИЕ 12.09.1999

И. М. **Черток**1, В. В. Гречнев2, А.М.Уралов2

АСТРОНОМИЧЕСКИЙЖУРНАЛ, ***2009****, том 86,№4, с. 392–405*

На примере события **12.09.1999** проанализированы крупномасштабные возмущения, связанные с корональными выбросами массы при эрупции волокон вне активных областей. Анализ основан на H*α*-фильтрограммах, изображениях крайнего УФ- и мягкого рентгеновского диапазонов, и данных коронографов. Эрупция волокна происходила в относительно слабых магнитных полях, но сопровождалась более масштабными явлениями, чем вспышечные события. После эрупции в течение нескольких часов развивалась крупномасштабная аркада, основаниями которой были расходящиеся ленты, подобные вспышечным. Объем события был ограничен "волной EIT", квазистационарной на солнечной поверхности и расширяющейся над лимбом. Событие не имело импульсной компоненты, поэтому "волна EIT" над лимбом — магнитная структура, идентифицированная как фронтальная структура коронального выброса массы, в силу их совпадения по форме, структурным деталям и кинематике. В ареале события наблюдалось три типа диммингов, обусловленных (а) эвакуацией плазмы, (б) нагревом плазмы и ее последующей эвакуацией, (в) поглощением излучения в системе волокон, активизированных эрупцией. Факт возникновения димминга из-за нагрева плазмы был выявлен по данным мягкого рентгеновского диапазона, но он не обнаруживается по четырем каналам EIT. Это ставит вопрос о корректности некоторых выводов, сделанных ранее только по данным EIT. Обусловленные эрупцией трансформации магнитных полей имели место также в стационарной корональной дыре, примыкавшей к ареалу события. Расширение коронального выброса массы является автомодельным и характеризуется быстро уменьшающимся ускорением, что не учитывается широко используемой полиномиальной аппроксимацией.

КРУПНОМАСШТАБНАЯ АКТИВНОСТЬ В СОЛНЕЧНЫХ МОЩНЫХ ЭРУПТИВНЫХ СОБЫТИЯХ НОЯБРЯ 2004 г. ПО ДАННЫМ SOHO

И. М. **Черток**

АСТРОНОМИЧЕСКИЙЖУРНАЛ, ***2006****, том 83,№1, с. 76–87*

По данным УФ-телескопа SOHO/EIT и коронографа LASCO проанализированы крупномасштабные солнечные возмущения, связанные с серией мощных вспышек и корональных выбросов массы, которые произошли **3–10 ноября 2004** г., на поздней фазе спада 23-го цикла и вызвали сильные геомагнитные бури. С использованием деротированных фиксированных разностных гелиограмм в корональном канале 195 ˚A с 12-мин интервалом, а также в разнотемпературных каналах 171, 195, 284 и 304 ˚A с 6-ч интервалом показано, что эти возмущения имели глобальный характер и были гомологичными, т.е. обладали аналогичными характеристиками и затрагивали одни и те же структуры. Практически во всех 9 событиях данной серии наблюдались две повторяющиеся системы крупномасштабных диммингов (областей пониженной яркости с временем жизни порядка 10–15 ч): (а) трансэкваториальные димминги, соединяющие северный приэкваториальный центр эрупции с южной активной областью; (б) северные димминги, охватывающие значительный сектор между двумя корональными дырами. В этом же северном секторе перед расширяющимися диммингами наблюдались корональные волны — уярчения, распространявшиеся от центра эрупции со скоростью сотни км/с. В каждом событии наиболее яркая центральная часть коронального выброса массы типа гало соответствовала северной системе диммингов. На основе полученных результатов обсуждаются свойства диммингов и корональных волн, а также связь между ними, и показано, что в процесс эрупции крупных корональных выбросов массы оказываются вовлеченными структуры глобальной солнечной магнитосферы с пространственным масштабом, намного превосходящим размеры активных областей и обычных комплексов активности.

КРУПНОМАСШТАБНАЯ АКТИВНОСТЬ В СОЛНЕЧНЫХ ЭРУПТИВНЫХ СОБЫТИЯХ ОКТЯБРЯ–НОЯБРЯ 2003 г. ПО ДАННЫМ SOHO/EIT

И. М. **Черток**1, В. В. Гречн ев2

АСТРОНОМИЧЕСКИЙЖУРНАЛ, **2005***, том 82,№2, с. 180–192*

По данным УФ-телескопа SOHO/EIT анализируются крупномасштабные возмущения на Солнце, связанные с мощными вспышками и корональными выбросами массы (КВМ), которые произошли

в октябре–ноябре 2003 г. во время двух прохождений по диску грандиозного комплекса из трех активных областей. В частности, димминги (транзиентные корональные дыры) и, в меньшей степени, корональные волны (распространяющиеся излучающие фронты) исследуются на основе деротированных фиксированных разностных изображений, в которых предварительно компенсируется солнечное вращение и одна и та же гелиограмма перед событием вычитается из всех последующих гелиограмм. Такой метод позволяет изучать разностные гелиограммы как в линии 195 ˚A с 12-мин интервалом, так и в каналах разных температур 171, 195, 284, 304 ˚A с 6-ч интервалом. Анализ показывает, в частности, что практически во всех эруптивных событиях в течение двух оборотов возмущения, связанные с КВМ, имели глобальный характер и охватывали почти всю южную половину диска. При этом северная половина диска, где присутствовала обширная корональная дыра, затрагивалась возмущениями в гораздо меньшей степени. Преобладающие димминги на диске наблюдались как узкие протяженные образования, простирающиеся, в основном, между тремя главными удаленными областями комплекса, а также в виде протяженных структур, расположенных вдоль параллели в южном полярном секторе. В повторяющихся с небольшим временным интервалом событиях наблюдавшиеся основные димминги обнаружили явную гомологию по их форме и локализации. В ходе мощнейшего события 28 октября одна гомологическая глобальная димминговая система сменилась на другую. Многие димминги проявлялись одинаковым или сходным образом в трех корональных каналах и в линии переходного слоя. Из приведенных данных следует, что одни и те же быстро восстанавливающиеся глобальные структуры на высотах короны и переходного слоя были вовлечены в процесс эрупции последовательных КВМ и соответствующую перестройку крупномасштабных магнитных полей.

КРУПНОМАСШТАБНЫЕ “ДИММИНГИ”, ВЫЗЫВАЕМЫЕ КОРОНАЛЬНЫМИ ВЫБРОСАМИ МАССЫ НА СОЛНЦЕ, ПО ДАННЫМ SOHO/EIT В ЧЕТЫРЕХ ЛИНИЯХ КРАЙНЕГО УФ-ДИАПАЗОНА

И. М. **Черток**, В. В. Гречнев

АСТРОНОМИЧЕСКИЙЖУРНАЛ, ***2003****, том 80,№11, с. 1013–1025*

Димминги, или транзиентные корональные дыры (области пониженной интенсивности мягкого рентгеновского и крайнего ультрафиолетового излучения), которые наблюдаются на солнечном диске после корональных выбросов массы (КВМ) типа гало, анализируютсяпо данным SOHO/EIT одновременно в трех корональных линиях FeIX/X (171 ˚ A), FeXII (195 ˚ A) и FeIX (284 ˚A), чувствительных к температурам *Te* ≈ 1.2, 1.5 и 2.0 МК, соответственно, а также в линии переходного слояН eII (304 ˚ A; *Te* ≈ (0.02–0.08) МК). Анализ разностных изображений с 6-ч или 12-ч интервалами и предварительной компенсацией вращенияСо лнца показывает, что обычно димминги наиболее сильно проявляются и имеют аналогичную крупномасштабную структуру в корональных линиях с умеренной температурой возбуждения171 и 195 ˚ A, а в более высокотемпературной линии 284 ˚ A видны, в основном, наиболее глубокие участки диммингов. Во многих КВМ-событиях обнаруживаются также отчетливые, но сравнительно небольшие по площади димминги в линии переходного слоя304 ˚ A, в частности, в районах, примыкающих к источнику эрупции. Более того, есть события, в которых наблюдаютсядимминги в переходном слое, не имеющие корональных аналогов. Эти результаты свидетельствуют о том, что в процессе КВМ открытие магнитных силовых линий, приводящее к уменьшению плотности вещества, может затрагивать и холодную плазму переходного слоя. Эффекты вариаций температуры также нельзя исключить для некоторых димминговых структур.

КРУПНОМАСШТАБНЫЕ КАНАЛИЗИРОВАННЫЕ ДИММИНГИ, ВЫЗЫВАЕМЫЕ КОРОНАЛЬНЫМИ ВЫБРОСАМИ МАССЫ НА СОЛНЦЕ

И. М. **Черток**, В. В. Гречнев

АСТРОНОМИЧЕСКИЙЖУРНАЛ, ***2003****, том 80,№2, с. 162–174*

В результате анализа разностных изображений Солнца, полученных с помощью УФ-телескопа SOHO/EIT на волне 195 ˚ A, обнаружена новаяра зновидность “диммингов” или транзиентных корональных дыр (т.е. областей пониженной интенсивности мягкого рентгеновского и крайнего УФ-излучения), которые наблюдаются на солнечном диске после корональных выбросов массы (КВМ) типа гало. Установлено, что в крупных событиях при наличии на диске нескольких активных областей, волокон и других структур, наряду с относительно компактными диммингами, примыкающими к эруптивному центру, имеют место сильно анизотропные, сравнимые по контрасту канализированные димминги, которые простираютсяв доль нескольких узких протяженных структур (каналов) и могут охватывать почти весь видимый диск. При этом корональные волны, которые наблюдаются как фронты повышенной яркости, распространяющиеся в ряде КВМ-событий перед диммингами, также имеют анизотропный характер. Аргументируется, что указанные транзиентные явления тесно связаны с сильным возмущением и перестройкой крупномасштабных магнитных структур, вовлеченных в процесс КВМ, а канализированный характер диммингов отражает сложность глобальной солнечной магнитосферы, в частности, вблизи максимума цикла солнечной активности.