Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 44 (2009) 446–450

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Review

# On-disk signatures of eruptive activity from the Hinode mission

Louise K. Harra *

*UCL-Mullard Space Science Laboratory, Holmbury St. Mary, Dorking, Surrey RH5 6NT, UK*

Received 11 September 2008; received in revised form 15 April 2009; accepted 19 April 2009

**Abstract**

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.

*Keywords:* Solar physics; CMEs; Flares

## 1. Introduction

Coronal mass ejections (CMEs) consist of plasma and magnetic field that are ejected from the Sun into interplanetary space. CMEs are observed by using an occulting disk to block out the bright disk emission from the Sun. However much work has been carried out to determine the on-disk source regions. An excellent review was carried out by Hudson and Cliver (2001), particularly encompassing filament eruptions, flares, coronal 'waves' and coronal dimmings as signatures of CMEs. This paper is a review of recent observations of on-disk signatures of CMEs, in particular from the Hinode spacecraft. Recent observations in the areas of flares, filament eruptions, coronal dimming and coronal waves will be highlighted.

The Hinode spacecraft (Kosugi et al., 2007) was launched in September 2006. There are three instruments onboard Hinode – the Solar Optical Telescope (SOT), the X-ray Telescope (XRT) and the EUV Imaging Spectrometer (EIS). SOT measures the magnetic field and lower atmosphere dynamics, XRT measure the X-ray corona and EIS measures flows and dynamics through the transition region and corona. The STEREO mission (Kaiser et al., 2008) was launched one month after Hinode. It has two identical observatories, one ahead of the Earth's orbit and one behind.

## 2. Flares

Flares and CMEs have had a controversial relationship over the years (see Gosling (1993); Hudson et al. (1995)) when it was hotly debated whether flares or CMEs are the most important element when studying magnetic storms. It is now accepted that flares and CMEs can be closely related, but it is not always necessary to have a flare and a CME together. An aspect that is of particular interest is the build-up phase to large flares and CMEs. In the commissioning phase of Hinode a large complex sunspot group appeared. This region has been extensively studied by a number of authors. A positive polarity sunspot emerges to the south of a dominantly negative polarity preexisting sunspot. As the new sunspot emerged it rotated creating enormous shear in the active region (Kubo et al., 2006). The coronal response to the dramatic photospheric changes can be seen in Fig. 1. The coronal loops develop more shear

---

* Tel.: +44 1483 204141; fax: +44 1483 278312.
*E-mail address:* lkh@mssl.ucl.ac.uk.

0273-1177/$36.00 © 2009 COSPAR. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.asr.2009.04.020

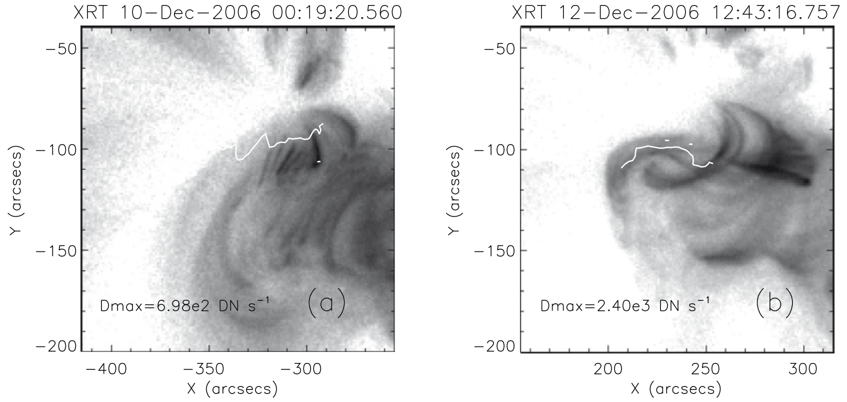

Fig. 1. This figure shows the evolution of active region NOAA 10930 as observed by Hinode XRT in the days before the large X-class flare on the 13th December. The white line overlaid on the images illustrates the location of the polarity inversion line. The image on the left shows the coronal loops lying perpendicular to the inversion line, whereas the image on the right (only ≈12 h before the flare) shows a highly sheared configuration with the coronal loops lying nearly parallel to the inversion line. From Su et al. (2007), Fig. 1.

as the new sunspot emerges and rotates (Su et al., 2007). The loops are highly sheared the day before the large X-class flare that took place on the 13th December.

Helicity is a measure of twist and shear in a region. The helicity injection rate was determined for the same time period by Magara and Tsuneta (2008) using Hinode SOT. They found the helicity injection rate to reach a peak 24 h before the flare occurred. Their interpretation of this result is that the saturation is reached after the flux tube emerges to the surface. Following on from this work, the

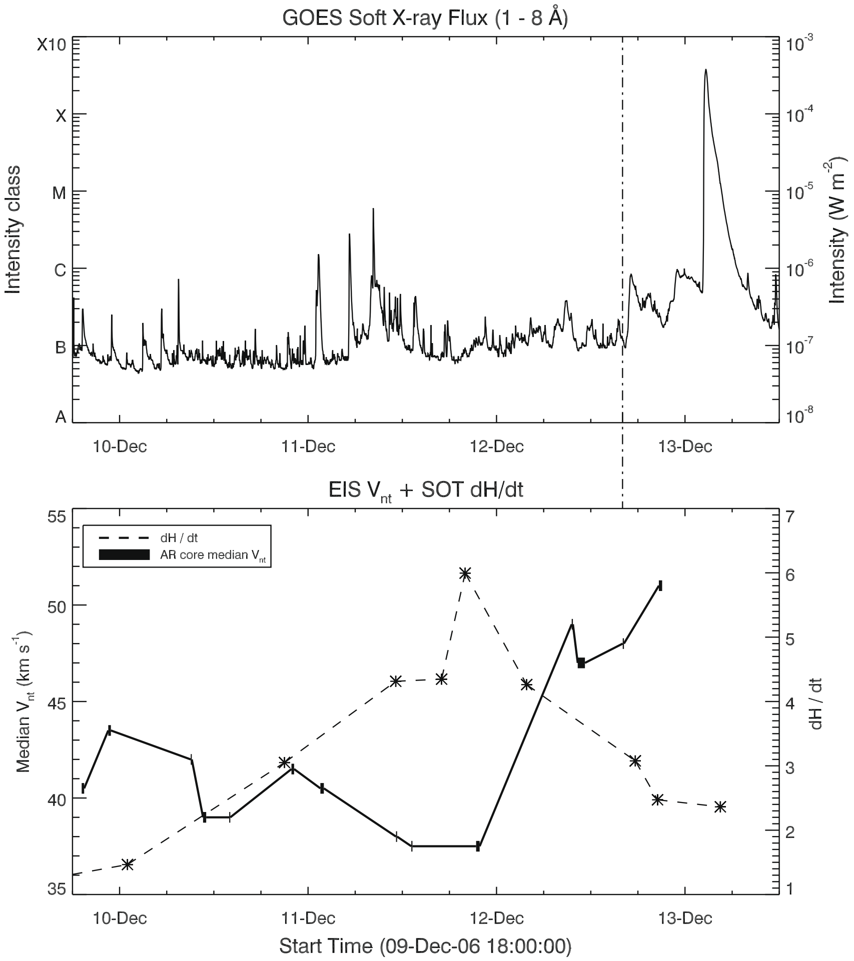

Fig. 2. Top image: the GOES lightcurve for 4 days before the X-class flare. Bottom image: the helicity injection rate determined from Magara and Tsuneta (2008), the non-thermal line widths for the active region and the surrounding area. From Harra et al. (2009), Fig. 4.

response in the corona was measured by analysing the EUV emission line widths from Hinode EIS. The non-thermal line widths of the Fe XII ion were found to increase following the saturation in the helicity injection. In particular the region surrounding the active region showed a rapid increase in the non-thermal widths many hours before the flare began as shown in Fig. 2. This could not be observed before Hinode and will provide us with an important insight to the trigger process. They interpret this as the magnetic flux emerging to a certain stage that allows interaction in the corona, producing flows or turbulence that is observed as line broadening. In addition some small eruptions occurred 12 h before the flare began away from the flare site in the plage region. These show strong outflows and turbulence. Another way to measure the changes in the pre-event stages is to analyse the intermittency. Abramenko et al. (2008) found that the peak of the photospheric intermittency occurred, followed by a gradual increase in the coronal intermittency hours before the flare.

Twisted structures, known as sigmoids, have been known to have a strong correlation with CMEs (Canfield et al., 2007) and hence are important in understanding the source region of CMEs. A sigmoid was observed by Hinode XRT for a period of 66 h. The 'S-shape' of the sigmoid was comprised of two J shaped structures with many individual loops. Around 80 min before any increase in the soft X-rays a diffuse linear structure lifts off from the middle of the structure. The sigmoid structure disappears hours after the flare (McKenzie and Canfield (2008)). The observations support the model of Titov and Démoulin (1999) where a flux tube is embedded in a potential magnetic field. The flux tube becomes unstable and an eruption occurs. The sigmoid observed by XRT is long-lasting and stable before the eruption, and the diffuse linear structure has been suggested to be consistent with twisted flux tube in the model.

Measurements of magnetic helicity have been made close to the start time of the flare on the 13th December and correlated with microwave bursts by Zhang et al. (2008). They found a sharp rise in the transport rate of magnetic helicity (dH/dt) close in time to a microwave burst. The microwave burst indicates non-thermal particles originating from magnetic reconnection in the impulsive phase of flares. A rapid change in dH/dt may indicate a change in the twist and linkage of the magnetic field lines following reconnection. Near the end of the flare dH/dt returned to its original sign suggesting that the transport of magnetic helicity plays an important role in solar eruptions.

## 3. Filament eruptions

Filaments are cool, magnetic structures that lie high in the corona and when they erupt the material often leaves the gravitational pull of the Sun to form part of a CME. The early stages of filament eruptions are critical to understanding the trigger process. Sterling et al. (2007) measured a rise in a filament for 20 min before the flare itself began. Measurements from Hinode SOT show opposite directed fields moving together causing magnetic cancellation for around 6 h before the main eruption. A small percentage of the flux was cancelled during this time (only 5%), but this was enough to trigger an eruption.

Outflows are always found in active regions. The outflows from a small active region that was surrounded by a coronal hole was studied by Baker et al. (2009). They found that the outflows intensified hours before an eruption took place. They interpreted this as a expansion of the flux rope containing the filament which increased the compressive forces. Examination of the magnetograms found a drop of $0.41 \times 10^{21}$ Mx ($\approx$33% of the flux) due to flux cancellation, allowing expansion to take place. Quantitative measurements of such outflow may well provide critical information for prediction of the CME trigger.

The famous 13th December flare had a filament eruption which was observed with Hinode EIS. Doppler shifts of 20 km/s were observed in the He II emission line – these were red-shifted on one side of the filament length and blue-shifted on the opposite side. This indicates a rotation of the filament, and this occurred minutes before the flare began. This is consistent with either a torus instability or an MHD helical kink of a twisted flux rope (Williams et al., 2009).

## 4. Coronal 'waves'

Waves have also been observed to propagate across the disk associated with flares – these are known as Moreton waves as described by Moreton and Ramsey (1960). These are thought to be consistent with MHD fast-mode shock waves. Asai et al. (2008) found evidence of a weak emission region that showed broadened spectral lines with speeds of hundreds km/s. These were only observed in the very hot emission lines of Fe XV and Ca XVII and correspond to the propagation of a coronal wavelike feature seen in the XRT images. This is thought to be the first spectroscopic measurement of such waves in the corona.

Coronal 'waves' are also seen that are associated with CMEs (Biesecker et al., 2002). These are sometimes associated with flares, but certainly not always. There is huge debate about what the source of these so-called 'waves' are – whether they actually waves or if they are actually part of the CME as it expands and erupts. An excellent review of the latest debate on the topic is available in Attrill (2008). STEREO has observed an example of a coronal wave with excellent time cadence. The wave shows a strong reflection away from a coronal hole which is consistent with some kind of wave propagation (Long et al., 2008). The same event was analysed by Veronig et al. (2008) suggesting wave initiation at the expanding CME flanks. In this case the flare was very weak so could not have induced a wave. Activity on the Sun has been very low so more examples have yet to be found to take advantage of STEREO's good time resolution and wavelength coverage.

## 5. Coronal dimming

Coronal dimming measurements have been made since the Skylab era (e.g. Rust, 1994). They are important as they potentially outline the source of CMEs. Most work on dimmings have been carried out using imaging data, until the Hinode EIS data. The flare on the 14th December was related to a CME. Fig. 3 shows the intensity before and after the flare and CME. There is a clear loss of coronal plasma in the intensity images at the east of the active region in a plage area. The Doppler velocity maps are also shown. These show strong blue-shifted plasma at the region of the coronal plasma loss. This outflow is persistent, lasting for many hours. In addition the structure of the outflow is in the form of long loops with the strongest blue shifts at the footpoints of these loops. An investigation into the magnetic structure of the outflowing region shows that the region is favourable for reconnection with the expanding loops in the active region following a filament eruption. The plage region becomes a constituent of the CME providing mass through the plasma upflows observed. This is consistent with the reconnection scenario described by Attrill et al. (2007) shown in Fig. 4. The expanding CME reconnects with the quiet-Sun magnetic loops displacing the footpoints of the expanding CME.

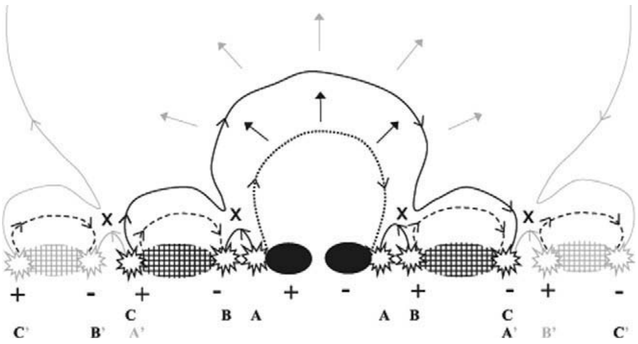

Fig. 4. Illustrates a model of an expanding CME front (dotted line) reconnecting with favourably orientated quiet-Sun magnetic loops (dashed line). The black line shows the result of the reconnections. From Attrill et al. (2007), Fig. 4.

Outflowing plasma was also observed following the flare and CME on the 13th December by Imada et al. (2007). The flows in this case were over 100 km/s, and were also seen in the plage region to the east of the active region. They found that the outflows have a strong temperature dependence in the corona, with the hotter temperatures having a stronger outflow. This information is critical for understanding the processes around solar wind and CME formation.

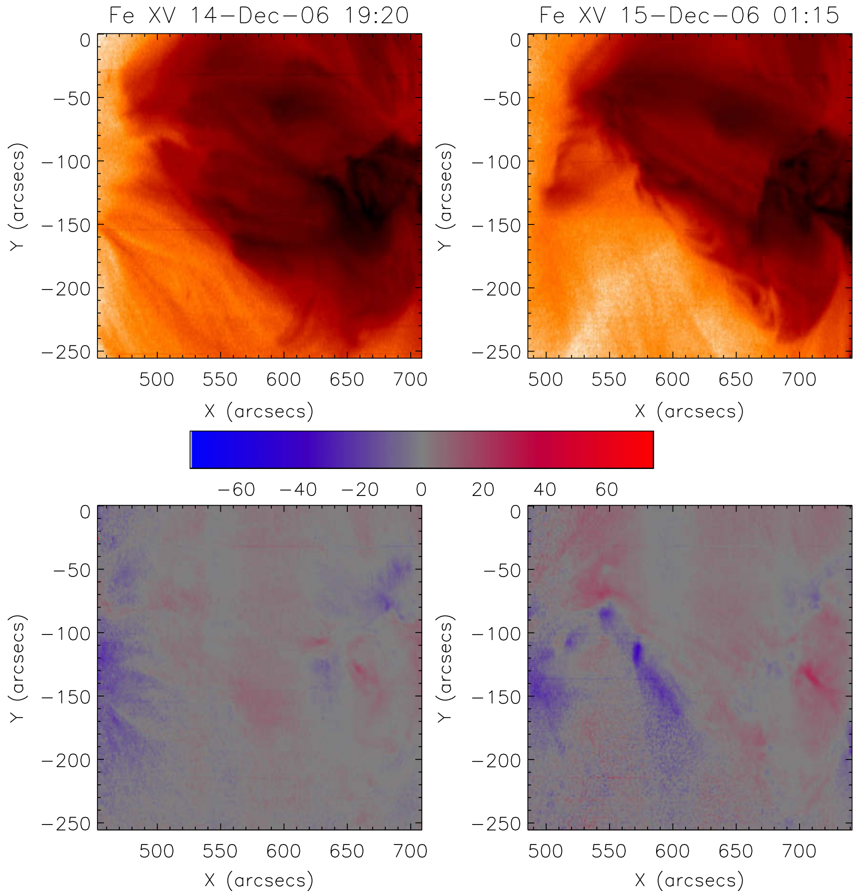

Fig. 3. Top images: the intensity in the corona before the eruption (left) and after the eruption (right). Bottom image: From Harra et al. (2007), Fig. 4.

## 6. Summary

Since the launch of the Hinode and STEREO missions the Sun has been in a period of extended solar minimum. In spite of this, observations have been made of large globla events, and smaller eruptions. We now have unprecedented information on the magnetic field shear and flows and the impact this has on the dynamics of the atmosphere above. Connecting up with information from Hinode and STEREO will provide information from the source of activity to its impact in interplanetary space. Observers are looking forward to the solar maximum!

## Acknowledgement

Hinode is a Japanese mission developed and launched by ISAS/JAXA, with NAOJ as domestic partner and NASA and STFC (UK) as international partners. It is operated by these agencies in co-operation with ESA and NSC (Norway).

## References

Abramenko, V., Yurchyshyn, V., Wang, H. Intermittency in the photosphere and corona above an active region. Astrophys. J. 681, 1669–1676, 2008.

Asai, A., Hara, H., Watanabe, T., Imada, S., Sakao, T., Narukage, N., Culhane, J.L., Doschek, G.A. Strongly blueshifted phenomena observed with Hinode EIS in the 2006 December 13 solar flare. Astrophys. J. 685, 622–629, 2008.

Attrill, G.D.R., Harra, L.K., van Driel-Gesztelyi, L., Démoulin, P. Coronal "Wave": magnetic footprint of a coronal mass ejection? Astrophys. J. 656 (2), L101–L104, 2007.

Attrill, G.D.R. Low Coronal Signatures of Coronal Mass Ejections. Ph.D. Thesis, University College, London, 2008.

Baker, D., van Driel-Gesztelyi, L., Murray, M., Green, L., Torok, T., Sun, J. Origin of plasma upflows in a coronal hole – active region complex. Solar Phys., ASJ Conference Series, accepted for publication, 2009.

Biesecker, D.A., Myers, D.C., Thompson, B.J., Hammer, D.M., Vourlidas, A. Solar phenomena associated with "EIT Waves". Astrophys. J. 569, 1009–1015, 2002.

Canfield, R.C., Kazachenko, M.D., Acton, L.W., et al. Yohkoh SXT full-resolution observations of sigmoids: structure formation and eruption. Astrophys. J. 671, L81–L84, 2007.

Gosling, J.T. The solar flare myth. J. Geophys. Res. 98, 18937–18950, 1993.

Harra, L.K., Williams, D.R., Wallace, A.J., Magara, T., Hara, H., Tsuneta, S., Sterling, A.C., Doschek, G.A. The coronal response to helicity injection building up to a large X-class flare. Astrophys. J. 691 (2), L99–L102, 2009.

Harra, L.K., Hara, H., Imada, S., Young, P.R., Williams, D.R., Sterling, A.C., Korendyke, C., Attrill, G.D.R. Coronal dimming observed with Hinode: outflows related to a coronal mass ejection. Pub. Astron. Soc. Jpn. 59, S801–S806, 2007.

Hudson, H.S., Cliver, E.W. Observing coronal mass ejections without coronagraphs. J. Geophys. Res 106, 25199–25214, 2001.

Hudson, H.S., Haisch, B., Strong, K.T. Comment on 'The solar flare myth' by J.T. Gosling, J. Geophys. Res, 100, 3473–3477, 1995.

Imada, S., Hara, H., Watanabe, T., Kamio, S., Asai, A., Matsuzaki, K., Harra, L.K., Mariska, J.T. Discovery of a temperature-dependent upflow in the plage region during a gradual phase of the X-class flare. Pub. Astron. Soc. Jpn. 59 (45), S793–S799, 2007.

Kaiser, M.L., Kucera, T.A., Davila, J.M., Cyr, O.C.S., Guhathakurta, M., Christian, E. The STEREO mission: an introduction. Space Sci. Rev. 136, 5–16, 2008.

Kosugi, T., Matsuzaki, K., Sakao, T., Shimizu, T., Sone, Y., Tachikawa, S., Hashimoto, T., Minesugi, K., Ohnishi, A., Yamada, T., Tsuneta, S., Hara, H., Ichimoto, K., Suematsu, Y., Shimojo, M., Watanabe, T., Shimada, S., Davis, J.M., Hill, L.D., Owens, J.K., Title, A.M., Culhane, J.L., Harra, L.K., Doschek, G.A., Golub, L. The Hinode (Solar-B) mission: an overview. Solar Phys. 243, 3–17, 2007.

Kubo, M., Yokoyama, T., Katsukawa, Y., Lites, B., Tsuneta, S., Suematsu, Y., Ichimoto, K., Shimizu, T., Nagata, S., Tarbell, T.D., Shine, R.A., Title, A.M., Elmore, D. Hinode observations of a vector magnetic field change associated with a flare on 2006 December 13. Pub. Astron. Soc. Jpn., 59, S779–S784, 2007.

Long, D.M., Gallagher, P.T., McAteer, R.T.J., Bloomfield, D.S. The kinematics of a globally propagating disturbance in the solar corona. Astrophys. J. 680, L81–L84, 2008.

Magara, T., Tsuneta, S. Hinode's observational result on the saturation of magnetic helicity injected into the solar atmosphere and its relation to the occurrence of a solar flare. Pub. Astron. Soc. Jpn. 60(5), 1181–1189, 2008.

McKenzie, D.E., Canfield, R.C. Hinode XRT observations of a long-lasting coronal sigmoid. Astron. Astrophys. 481, L65–L68, 2008.

Moreton, G.E., Ramsey, H.E. Recent observations of dynamical phenomena associated with solar flares. Pub. Astron. Soc. Pacific 72, 357, 1960.

Rust, D.M. Spawning and shedding helical magnetic fields in the solar atmosphere. Geophys. Res. Lett. 21, 241–244, 1994.

Sterling, A.C., Moore, R.L., Berger, T.E., Bobra, M., Davis, J.M., Jibben, P., Kano, R., Lundquist, L.L., Myers, D., Narukage, N., Sakao, T., Shibasaki, K., Shine, R.A., Tarbell, T.D., Weber, M. Hinode observations of the onset stage of a solar filament eruption. Pub. Astron. Soc. Jpn. 59, S823–S829, 2007.

Su, Y., Golub, L., Van Ballegooijen, A., DeLuca, E.E., Reeves, K.K., Sakao, T., Kano, R., Narukage, N., Shibasaki, K. Evolution of the sheared magnetic fields of two X-class flares observed by Hinode/XRT. Pub. Astron. Soc. Jpn. 59, S785–S791, 2007.

Titov, V.S., Démoulin, P. Basic topology of twisted magnetic configurations in solar flares. Astron. Astrophys. 351, 707–720, 1999.

Veronig, A.M., Temmer, M., Vrsnak, B. High-cadence observations of a global coronal wave by STEREO EUVI. Astrophys. J. 681, L113–L116, 2008.

Williams, D.R., Brooks, D.H., Harra, L.K., Imada, S. Evidence from EIS for axial filament rotation before a large flare, Pub. Astron. Soc. Japan, 61(3), 2009, in press.

Zhang, Y., Tan, Baolin, Yan, Y. Correlation between the sharp variation of the transport rate of magnetic helicity and solar eruptive events. Astrophys. J. 682, L133–L136, 2008.