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Wednesday 08:30-09:00

CMEs, Shocks and their Radio Signatures

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Coronal mass ejections (CMEs) are large-scale transients that can be observed at a multitude of wavelengths. The dynamics of CMEs are not known in detail. In the low corona, this is partly due to the lack of imaging data and partly because other processes can mask the CME initiation and liftoff phase. Flares, filament eruptions, waves, and wave-like features often occur simultaneously with CMEs. For example, a debate exists on coronal shock waves, whether they are CME-driven or due to flares, or both. With radio emission we can trace propagating shocks, electron beams, and rising structures, and the emission source locations can reveal their origin. With radio emission we can also follow CMEs to large distances in the interplanetary space and thus obtain their full kinematics.

This overview describes some of the most recent findings from the radio signatures during CME liftoff and propagation, and discusses how well the current models on CME and shock formation agree with the observations.

CMEs, Shocks and their Radio Signatures

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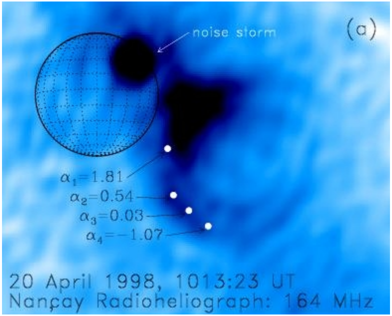
ESPM Freiburg 2008

Coronal mass ejection

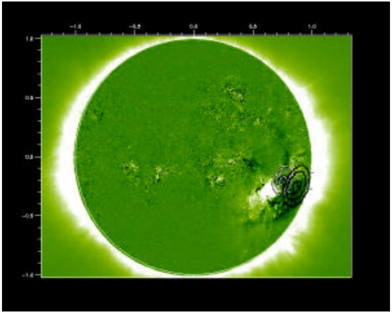


Direct radio imaging of a CME

- Faint emission from trapped electrons (synchrotron)
- Only part of the CME illuminated

(Bastian et al., ApJ 2001)

Flare and CME-related radio emission



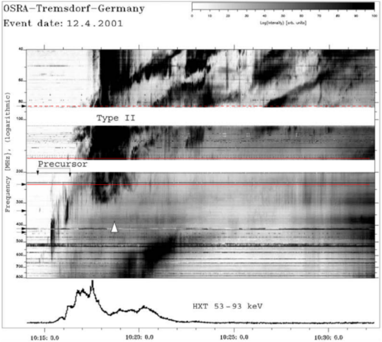
Black contours 164 MHz
White contours 236 MHz

More "typical" radio emission

- Single or a few separate sources
- Moving sources
- Shock-related emission

(Event of 12 April 2001)

Radio spectral features

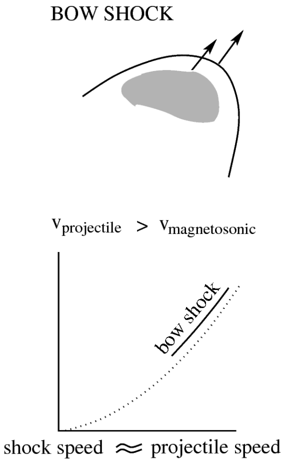


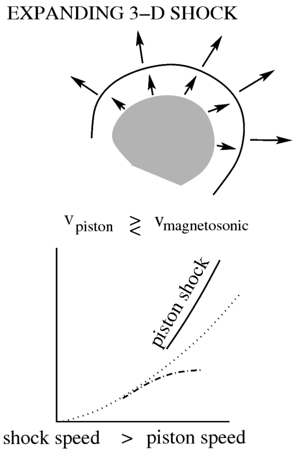
Dynamic spectrum (40 – 800 MHz):

- Several type II burst lanes
- Fundamental + second harmonics, plasma emission
- Electrons accelerated at the shock front
- Precursor structures
- Electron beams / reconnection processes

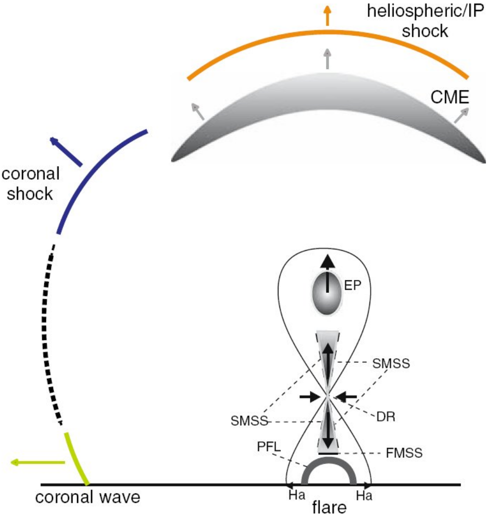
(Klassen et al., Solar Phys. 2003)

Basic shock types related to CMEs



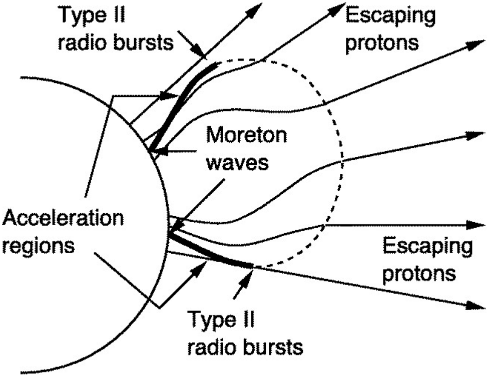


Schematic picture of a solar eruption



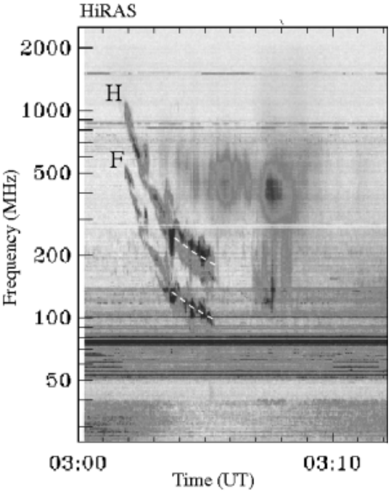
(Warmuth, LNP 2007/ Aurass et al., A&A 2002)

Shock at the CME flanks



(Vainio & Khan, ApJ 2004)

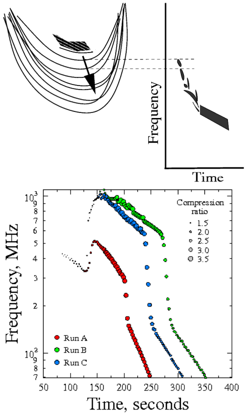
High-frequency type II emission



- F + H lanes = type II burst
- Emission lanes are fragmented at the beginning
- Emission starts at very high frequency

(Hiraiso radio spectrum)

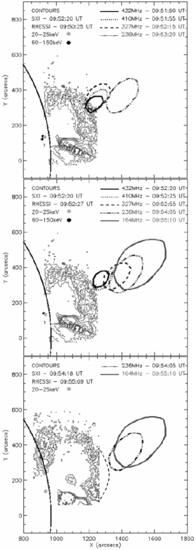
Type II emission through SXR loops



- Fragments are caused by shock crossing dense loops
- Yohkoh SXT loop densities agree with plasma emission densities
- MHD simulations produce curved radio emission lanes

(Pohjolainen, Pomoell & Vainio, A&A in press)

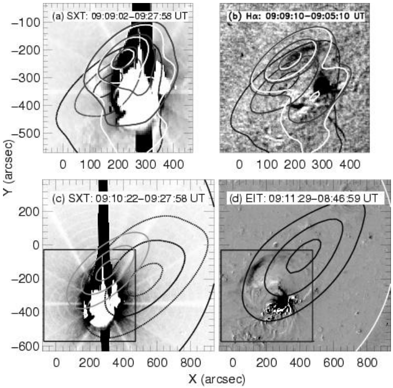
Type II emission above SXR loops



- Fast-accelerating coronal loop at low altitude
- High start frequency of the radio emission
- Type II shock driven by the X-ray rising loop
- X-ray coronal loop and CME structures related

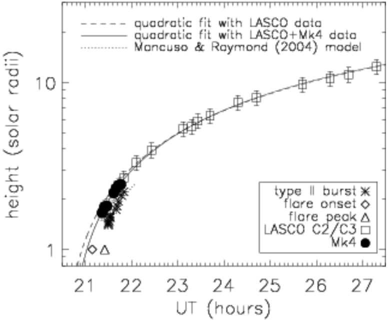
(Dauphin et al., A&A 2006;
also Klein et al. A&A 1999: flare ejecta as driver)

Type II emission at shock fronts



- Type II emission cospatial with SXT, EIT, and Moreton wave fronts
  (Khan & Aurass, A&A 2002)
- Similar EIT–Hα Moreton wave–type II cospatial events: May 2 1998
  (Pohjolainen et al., ApJ 2001)

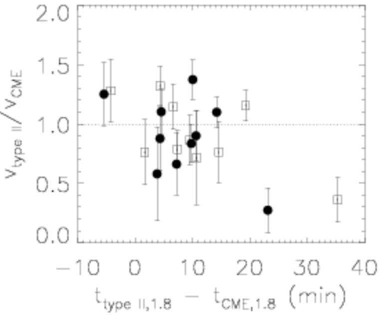
CME and type II heights (with no radio imaging)



- Atmospheric densities from UVCS observations
- Type II heights from plasma frequency ($f_p \approx \sqrt{n_e}$)
- CME heights from Mauna Loa Mk4 coronameter + LASCO C2

(Mancuso, A&A 2007)

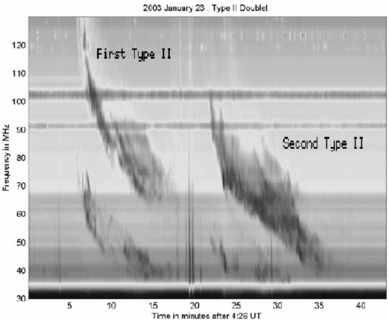
Speed difference and delay

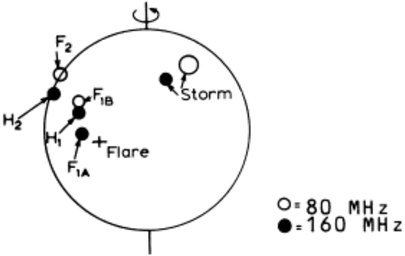


- In 9 out of 10 events CME leading edge is ahead of type II
- Differences in speed
- Acceleration effects still largely unknown
- Support for the CME-driven shock at flanks

(Mancuso, A&A 2007)

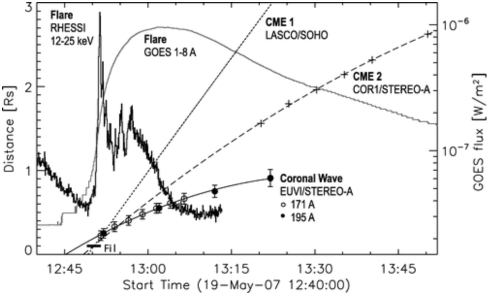
Doublet type II bursts: same shock, different location?





(Subramanian & Ebenezer A&A 451, 2006;
Robinson & Sheridan PASA 1982)

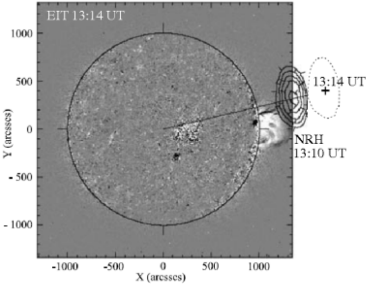
STEREO observations of EUV waves



Initiation of shock wave by CME expanding flanks
- wave is driven over a limited distance after which it decays into an ordinary MHD wave

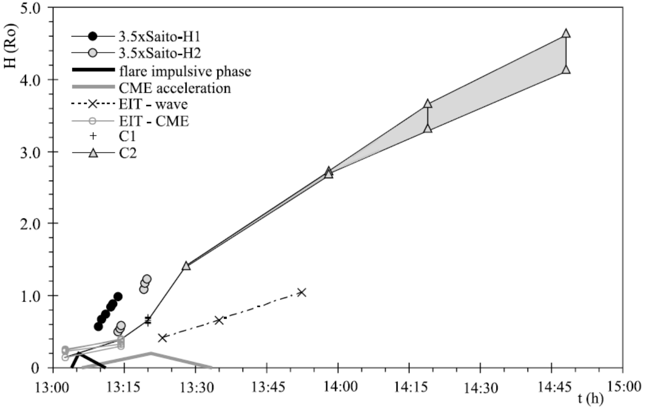
(Veronig et al., ApJ 2008)

Detailed analysis of single events



- Limb event on 24 Dec 1996
- EIT, LASCO C1, and radio imaging observations
- CME velocity subsonic (110... 235 km s^{-1})
- Identification of type II bursts from radio spectrum

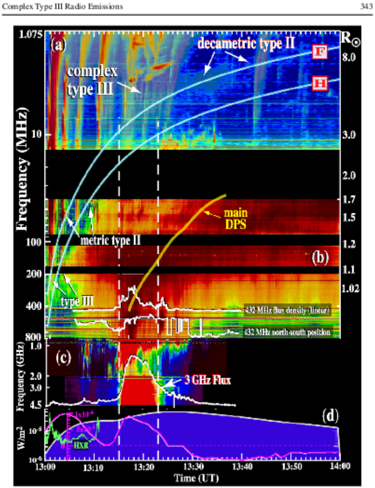
Detailed analysis of single events: A flare wave?



(Magdalenić et al., Solar Phys. 2008, in press)

1. Radio emission during solar eruptions
2. Radio observations of coronal shocks
3. **Radio observations of accelerated particles**
4. CME propagation

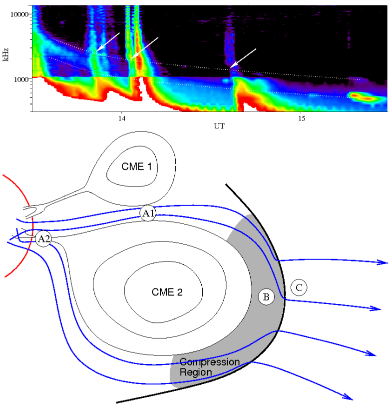
Complex type III bursts



- Complex type III bursts
- Particles accelerated in the low corona
- Particle beams through turbulent shock regions? Not SA (shock-accelerated) events

(Reiner et al., Solar Phys. 2008)

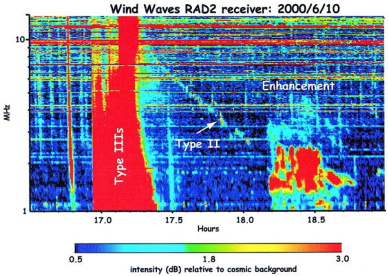
Tilted type III bursts



- Tilted type III bursts along the shock
- Later-accelerated particle beams travel through shock fronts?
- SEP-related?

(Lehtinen et al., Solar Phys. 2008)

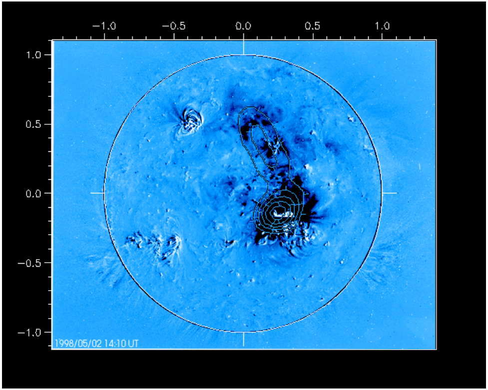
CME interaction and SEP acceleration



(Gopalswamy et al., ApJ 2001)

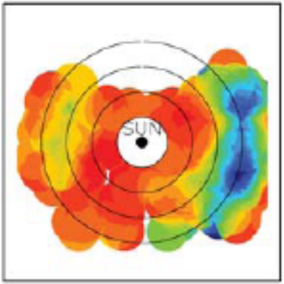
- SEP-rich CMEs when high densities from earlier events (Gopalswamy et al., ApJ 2002; Kahler & Vourlidas, JGR 2005)
- SEP-producing CMEs are preceded by fast and wide CMEs (Gopalswamy et al., JGR 2004)
- Radio signatures attributed to CME interaction occur after SEP acceleration has commenced (Richardson et al., GeoRL 2003)

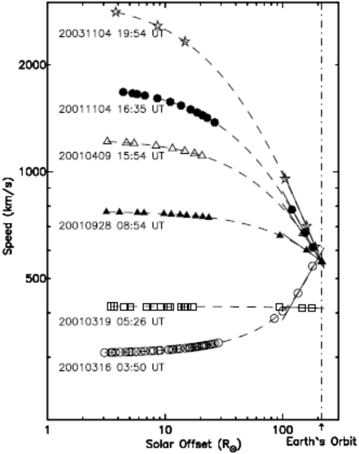
Type IV radio emission over dimmed regions



(May 2, 1998 event))

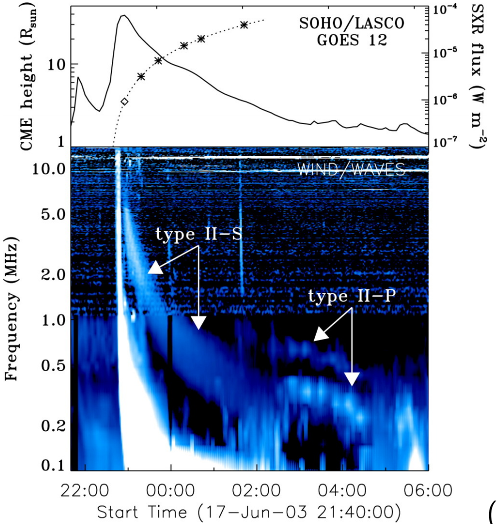
Radio scintillation observations





(Manoharan, Solar Phys. 2006)

Radio emission in IP space



(Bastian, ApJ 2007)

Constraints and Conclusions

- 7% of SMEI CMEs not detected at all by LASCO (Howard & Simnett, JGR 2008)
- Projection effects hit hard especially in acceleration phase (Howard et al., JGR 2008)
- Radio imaging also affected by projection effects (but heights can be checked with atmospheric density models)
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