CMEs and Space Weather from a Flare Perspective

Hugh Hudson

UC Berkeley and University of Glasgow

Scope of the Hudson sessions

1) Basic principles, language familiarization
2) Flares as seen in the lower solar atmosphere
3) CMEs and space weather from a flare perspective
4) Practicum: EUV spectroscopy with EVE

How X-ray astronomy began

3 days

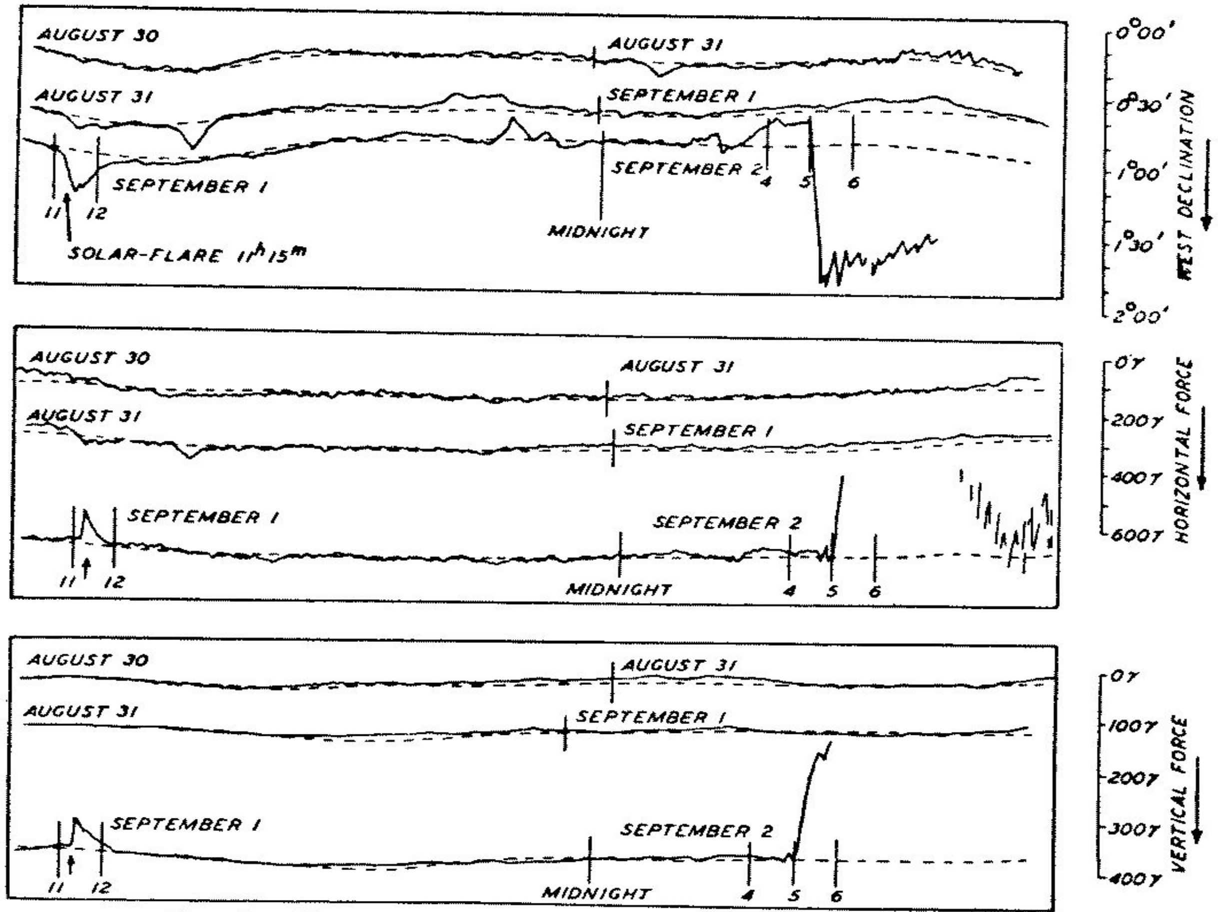


Fig. 35. Magnetograms, Kew, August 30 to September 2, 1859

Three **B** components

Crochet

Sudden Commencement

Geomagnetic storm

Solar-terrestrial effects

- Quotes from Lord Kelvin

  - "It seems as if we may also be forced to conclude that the supposed connection between magnetic storms and sunspots is unreal, and that the seeming agreement between the periods has been mere coincidence.”

Solar-terrestrial effects

- Quotes from Lord Kelvin

  - "It seems as if we may also be forced to conclude that the supposed connection between magnetic storms and sunspots is unreal, and that the seeming agreement between the periods has been mere coincidence.”

  - "X-rays will prove to be a hoax.”

  - "Radio has no future."

How "Space Weather" began

3 days

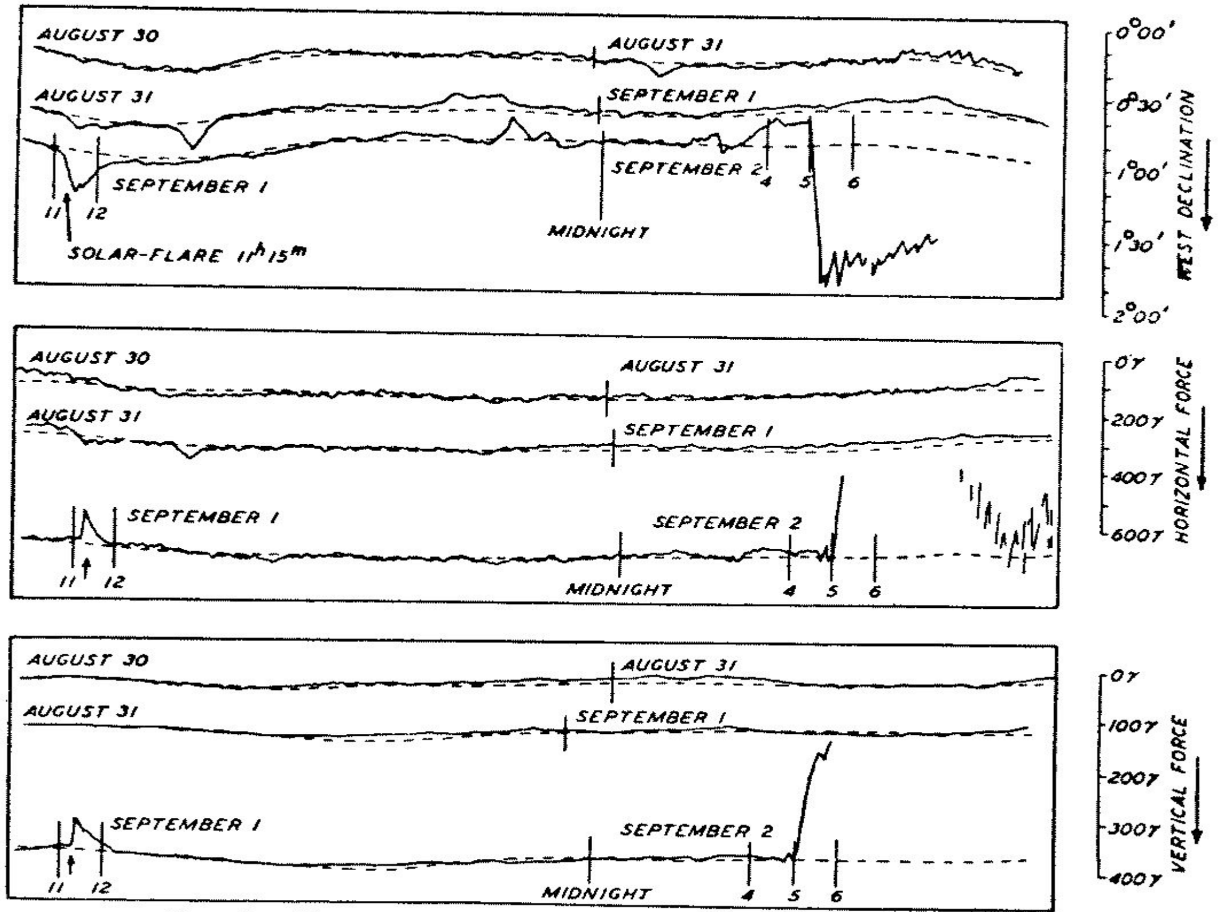


Fig. 35. Magnetograms, Kew, August 30 to September 2, 1859

Three **B** components

Crochet

Sudden Commencement

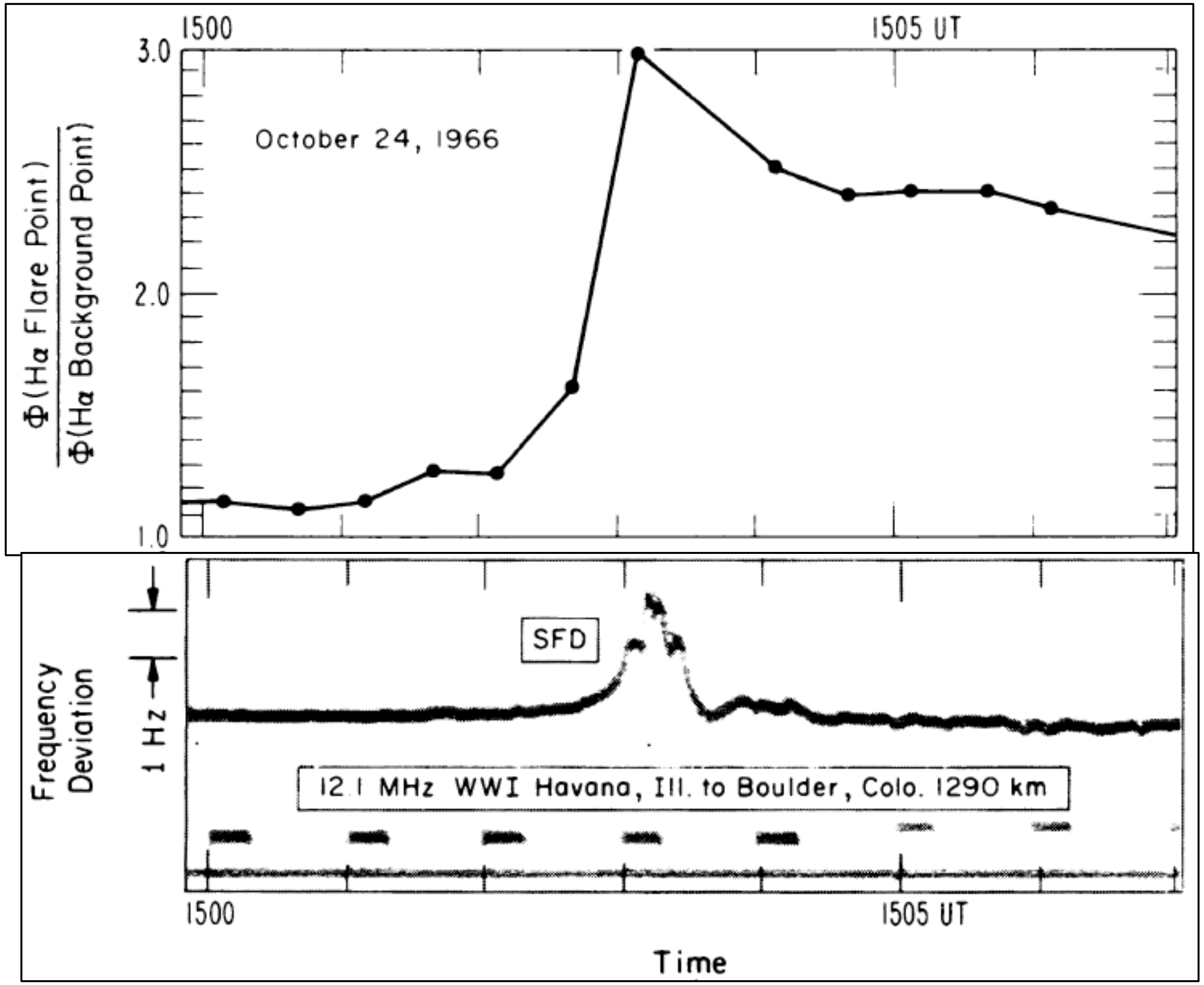
Geomagnetic storm

♩ The SFE* (= "crochet") ♩

- The flare emits EUV and X-rays (Röntgen's discovery was yet to be made)
- The ionospheric electron density increases (Heaviside hadn't recognized the ionosphere yet)
- Induced currents flow, and deflect terrestrial compasses (Maxwell's equations didn't appear until 1861, but Gauss had already shown how to locate geomagnetic disturbances)

* "Solar Flare Effect," or SFE. I prefer "crochet."

The SFD* ionospheric effect



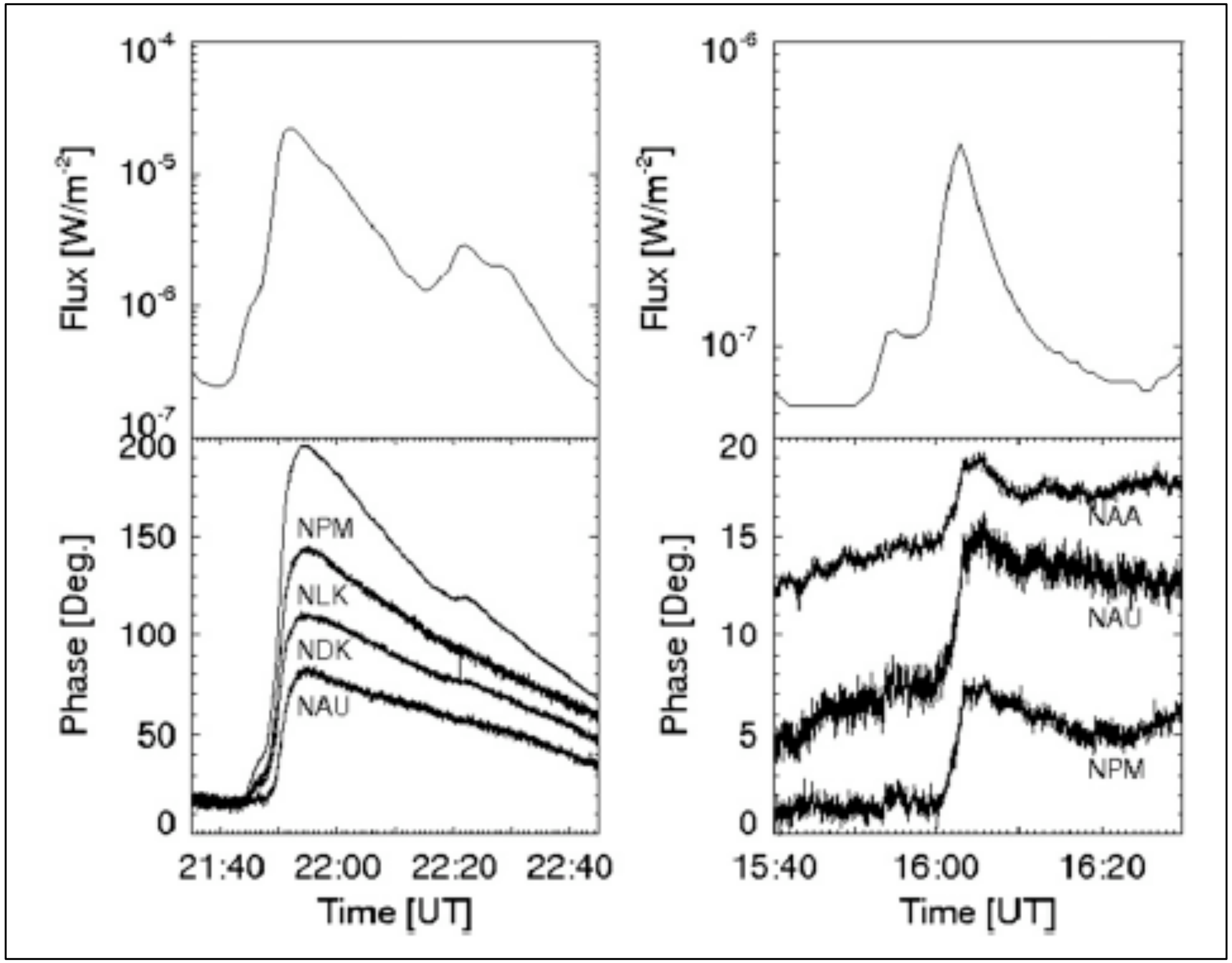
Ha: Impulsive + gradual phases

SFD: Impulsive phase via the EUV flash

Donnelly, 1971

* “Sudden Frequency Deviation”

The SPA* ionospheric effect



GOES signals for an M-class and a C-class flare

Phase variations for several VLF radio propagation paths

Raulin et al., 2011

*Sudden Phase Anomaly

Prompt ionospheric effects of flares

- The ionizing radiation from a flare (EUV and soft X-rays) produces a wide variety of ionospheric disturbances (SIDs): SFDs, SPAs, SCNAs, SWFs, SESs, … not to be defined here! All of these are diagnostically interesting TLAs*
- These prompt examples of flare *geoeffectiveness* cannot be predicted in detail, since they appear on the time scale of light travel from the Sun
- The prompt effects include those due to solar energetic particles (SEPs), which may persist for hours or days

* TLA = “three letter acronym”

Prompt geoeffectiveness

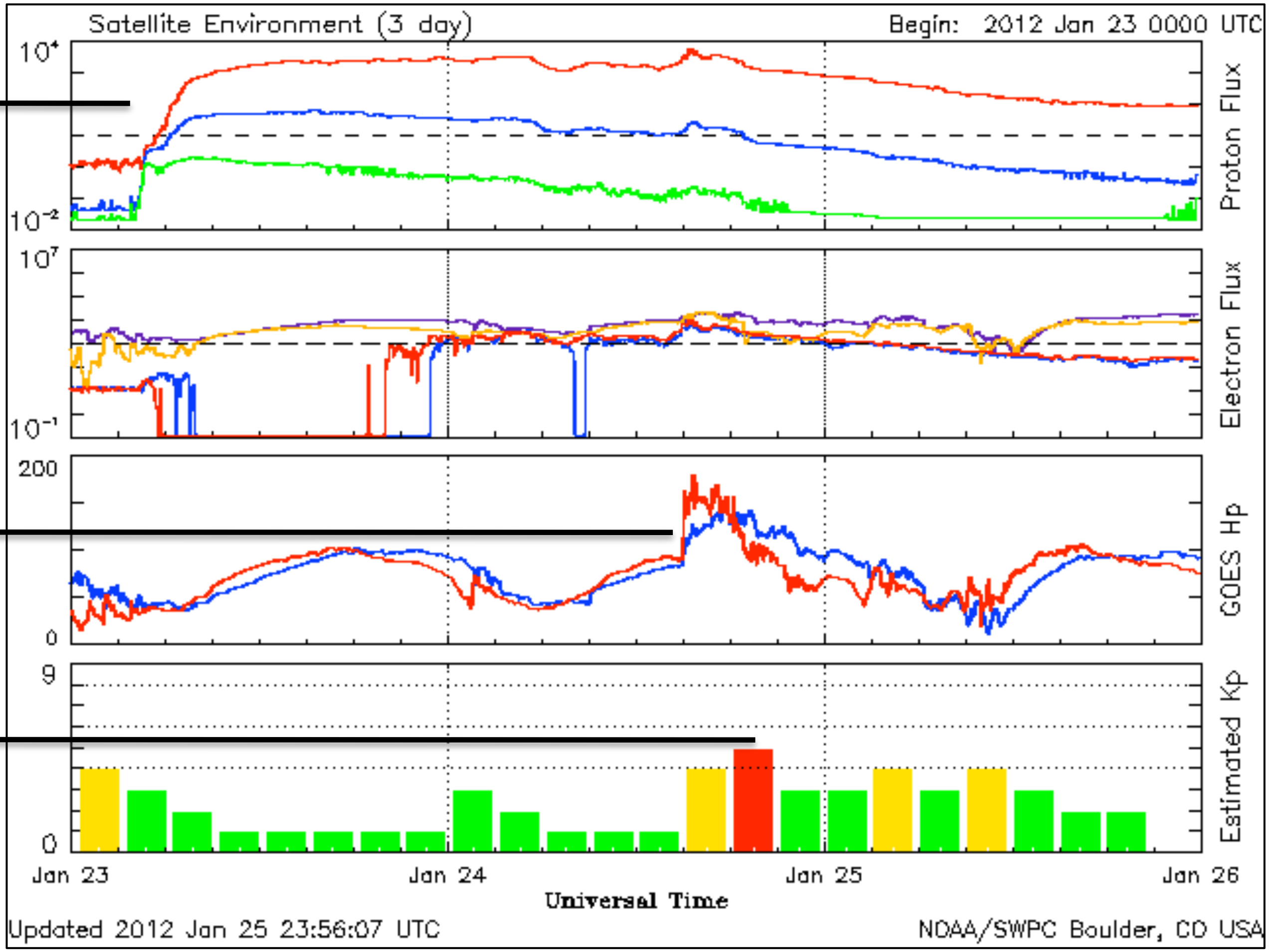
- The solar energetic particles have fluxes sufficient to
  - be lethal for unprotected astronauts
  - damage spacecraft and terrestrial power systems
- The transit times of these near-relativistic particle don’t leave much room for a warning based on flare occurrence

Prompt particles (SEPs)

“Protons” arrive at one AU

Shock arrives at one AU (SSC)

Geomagnetic storm ensues

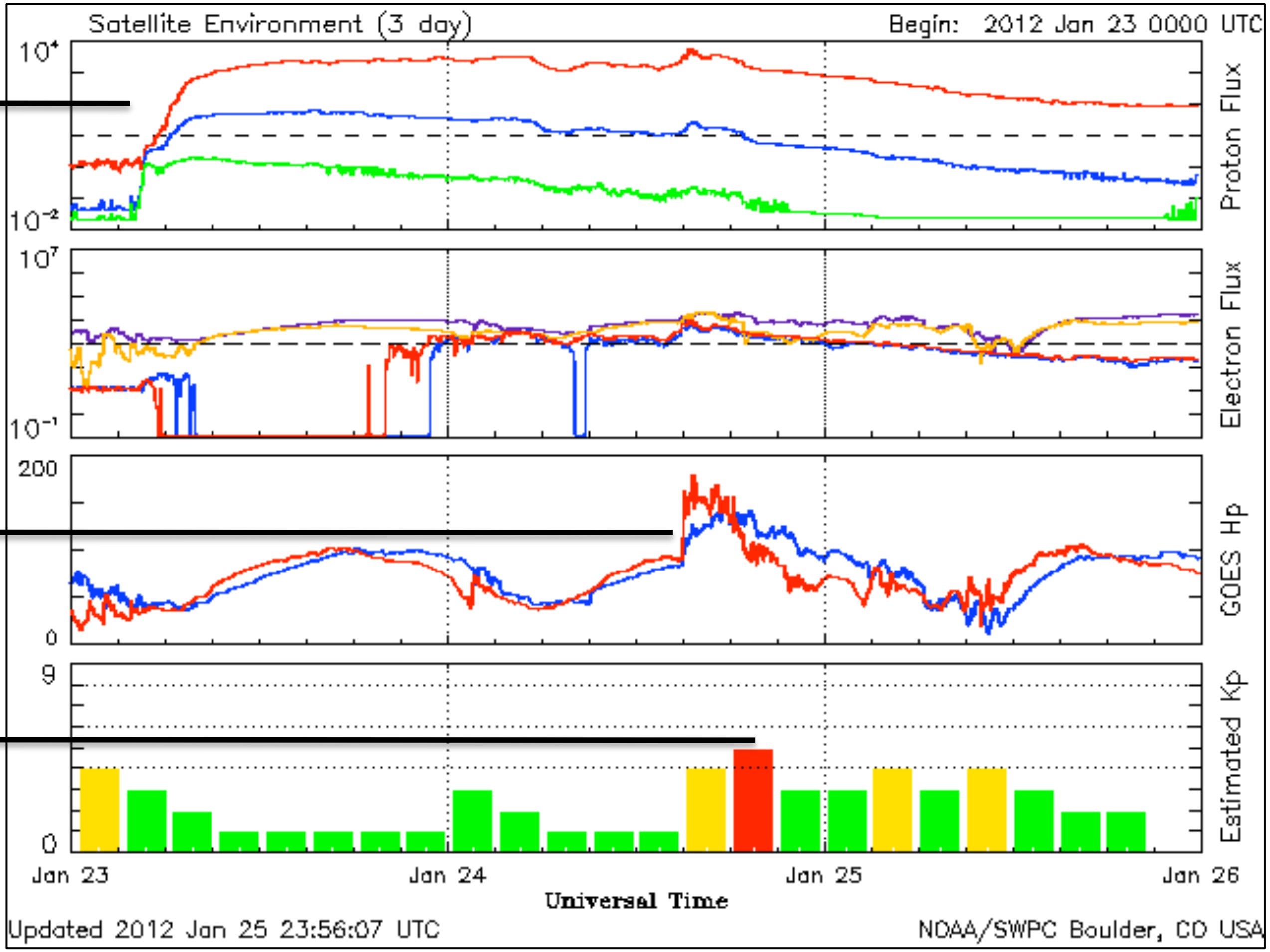


ICME (IP shock and "driver gas")

Protons arrive at one AU

Shock arrives at one AU (SSC)

Geomagnetic storm ensues



Disturbance speeds

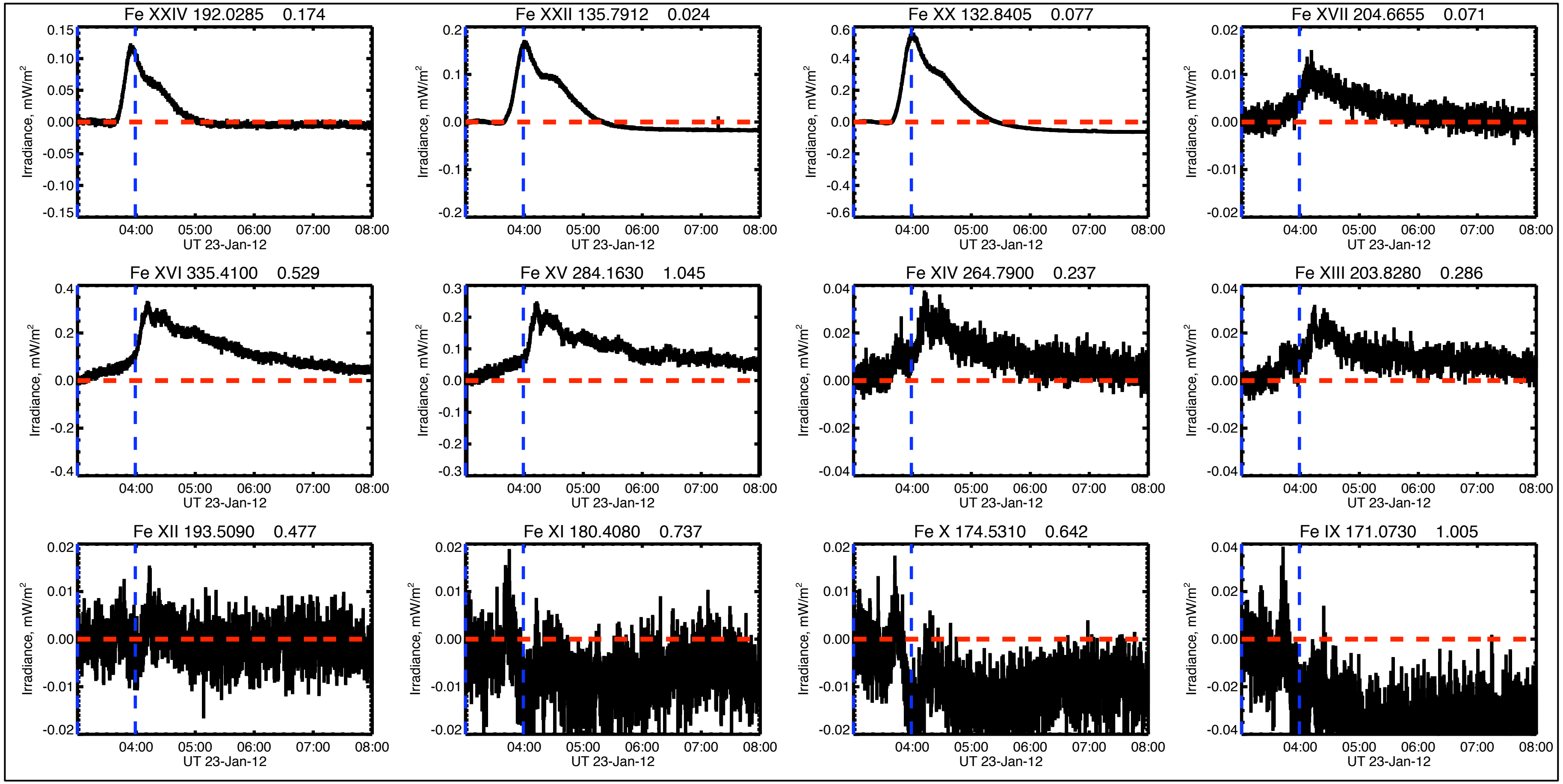
- SOL1859-09-01 (Carrington):

  18 hours ~ 2300 km/s => M_A ~ 40
- SOL2012-01-23 (This year):

  35 hours ~ 1200 km/s => M_A ~ 20

- If my numbers are right, these (Alfvenic) Mach numbers are comparable to those of supernovae

EUV signatures: The EVE "Fe cascade" plot



Fe-cascade plot

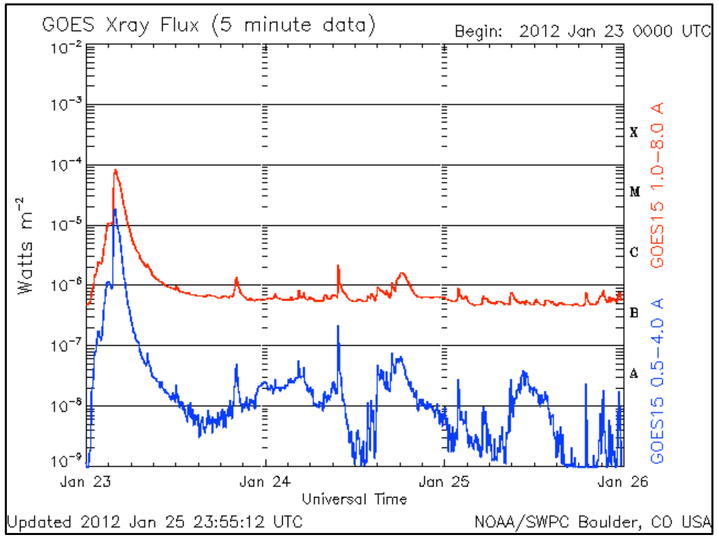
```
Fe IX   171.0730
Fe X    174.5310
Fe XI   180.4080
Fe XII  193.5090
Fe XIII 203.8280
Fe XIV  264.7900
Fe XV   284.1630
Fe XVI  335.4100
Fe XVII 204.6655
Fe XX   132.8405
Fe XXII 135.7912
Fe XXIV 192.0285
```

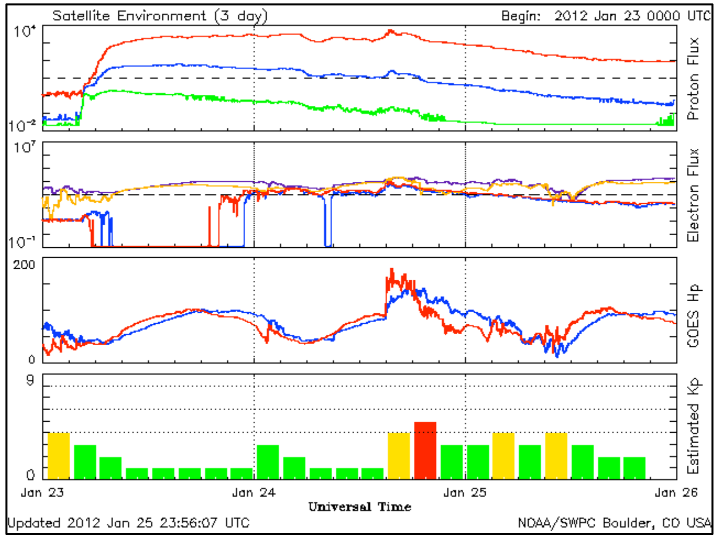
These lines, with full atomic information, are to be found in the CHIANTI database. In SolarSoft, an easy route into this code is

IDL> ch_ss

On the Web, http://www.chianti.rl.ac.uk/

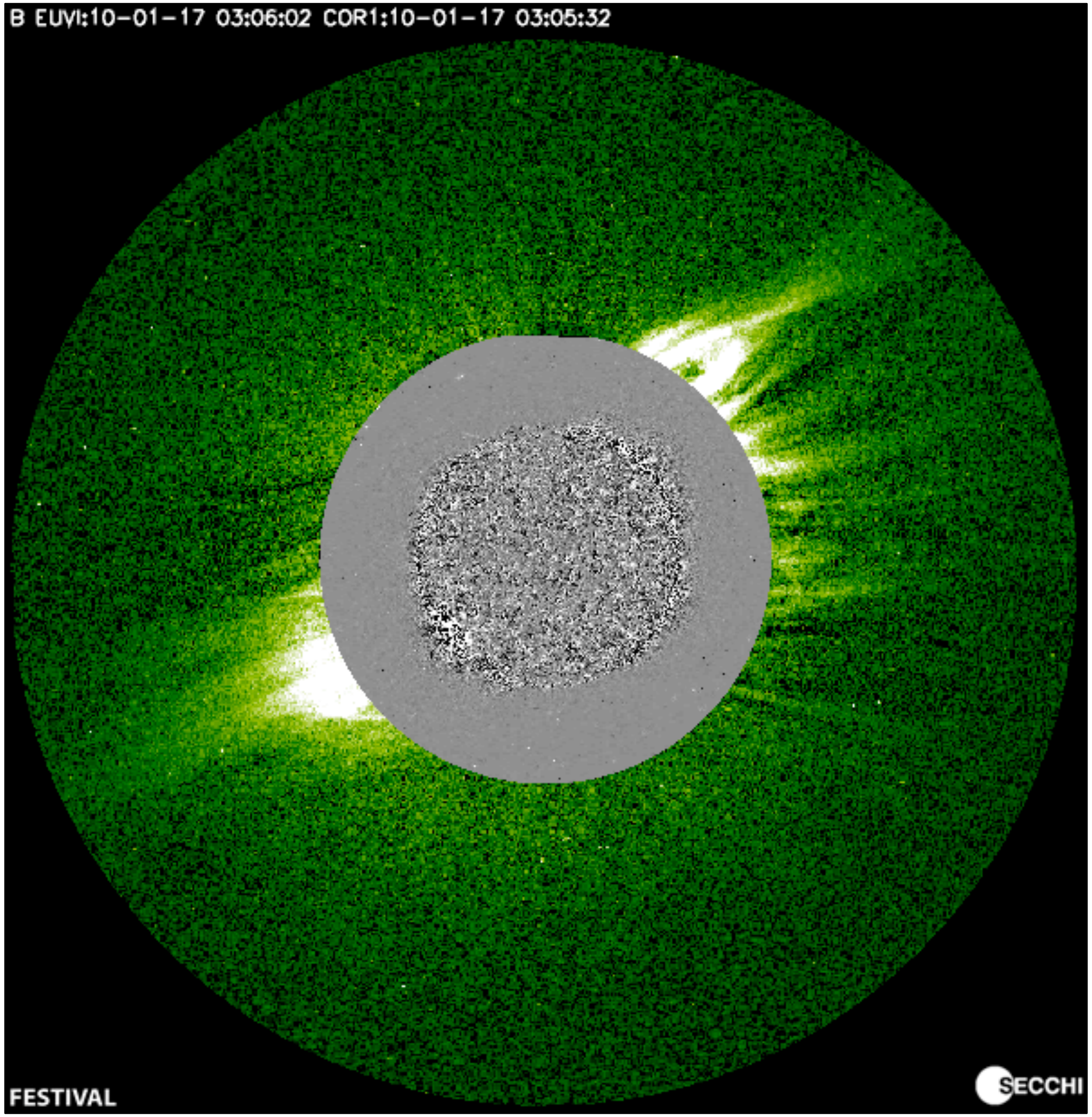
Delayed geoeffectiveness





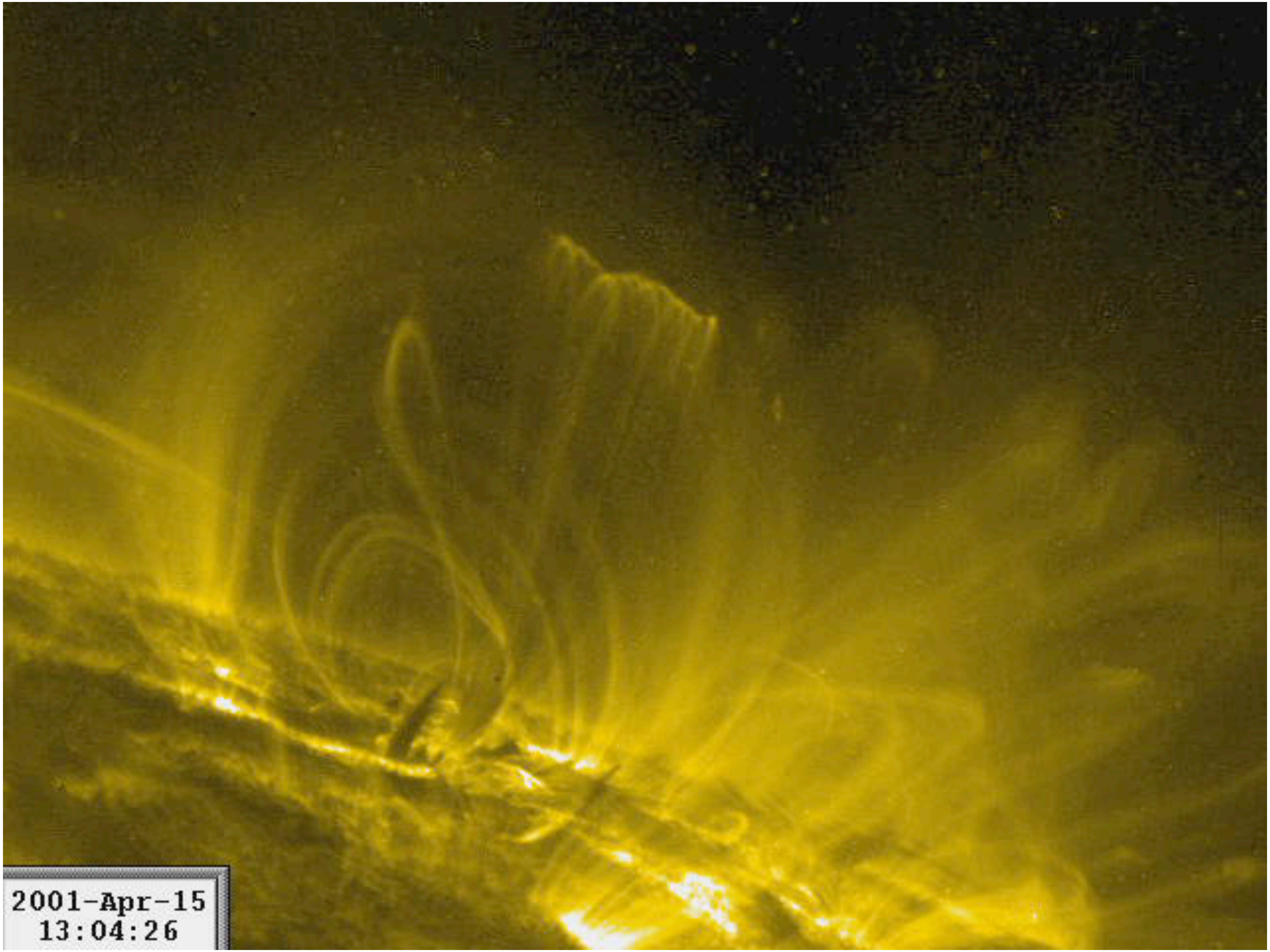
- The main terrestrial effects of flares come from (interplanetary) CMEs
- These effects are *delayed* by 1-5 days because the disturbances propagate not much faster than the solar wind itself.

CME movie

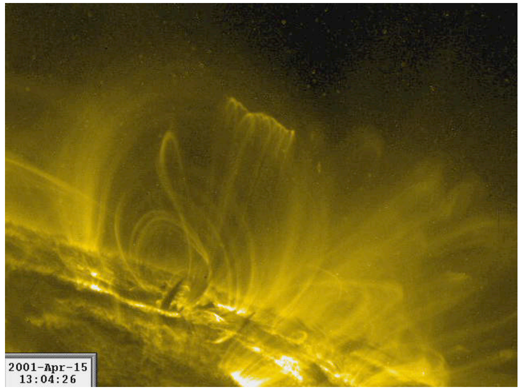


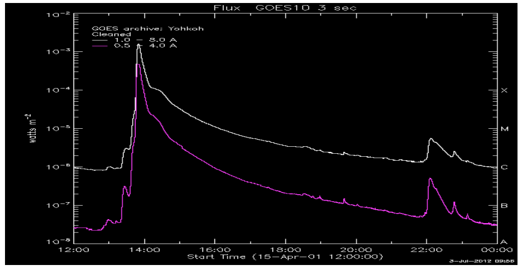
Moreton wave

- This movie showed a CME, for which the flare also launched a Moreton wave (a chromospheric effect)
- Best guess now is that the Moreton wave is the flank of the CME-driven bow wave


2001-Apr-15
13:04:26

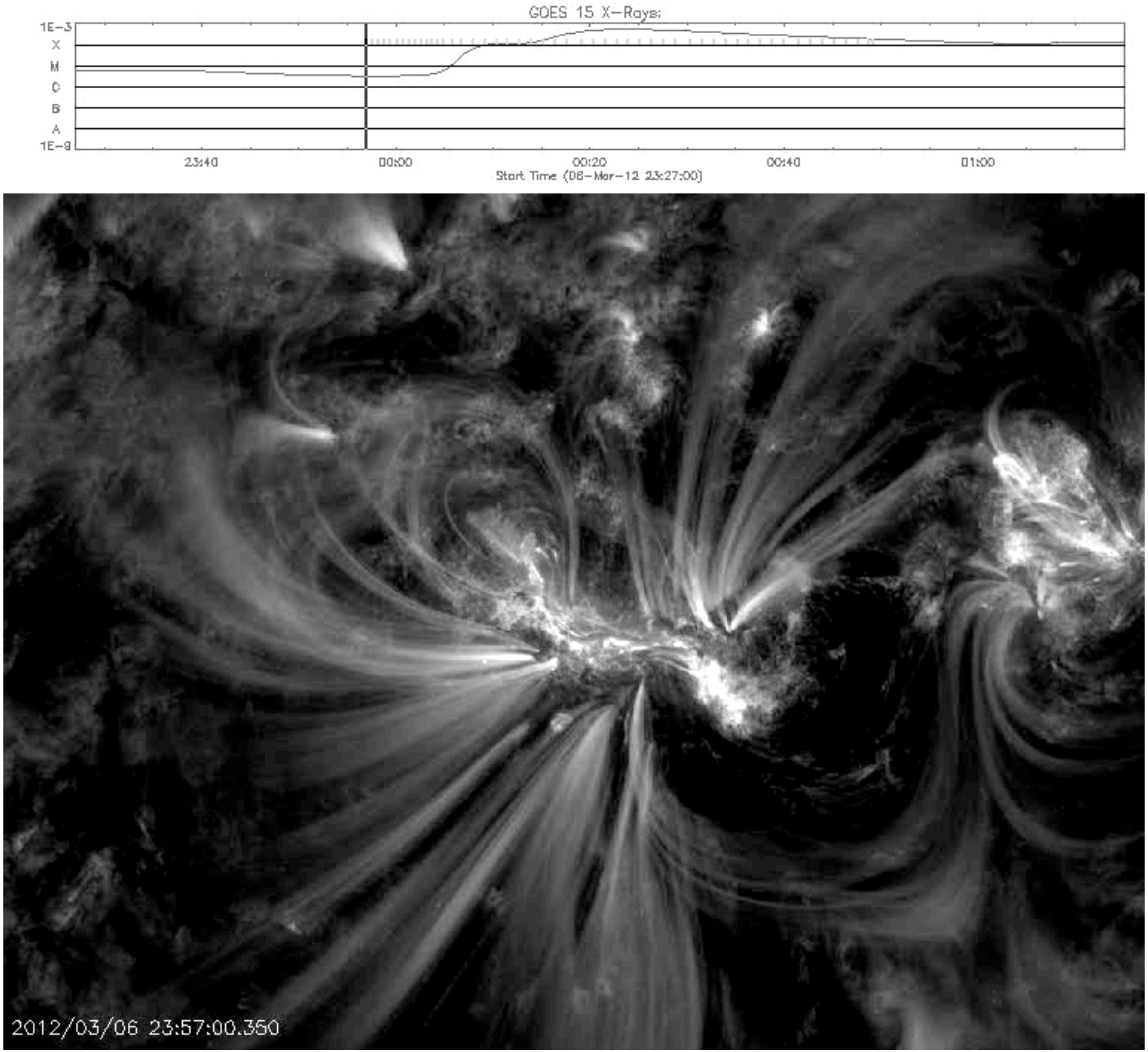
What should be noticed?



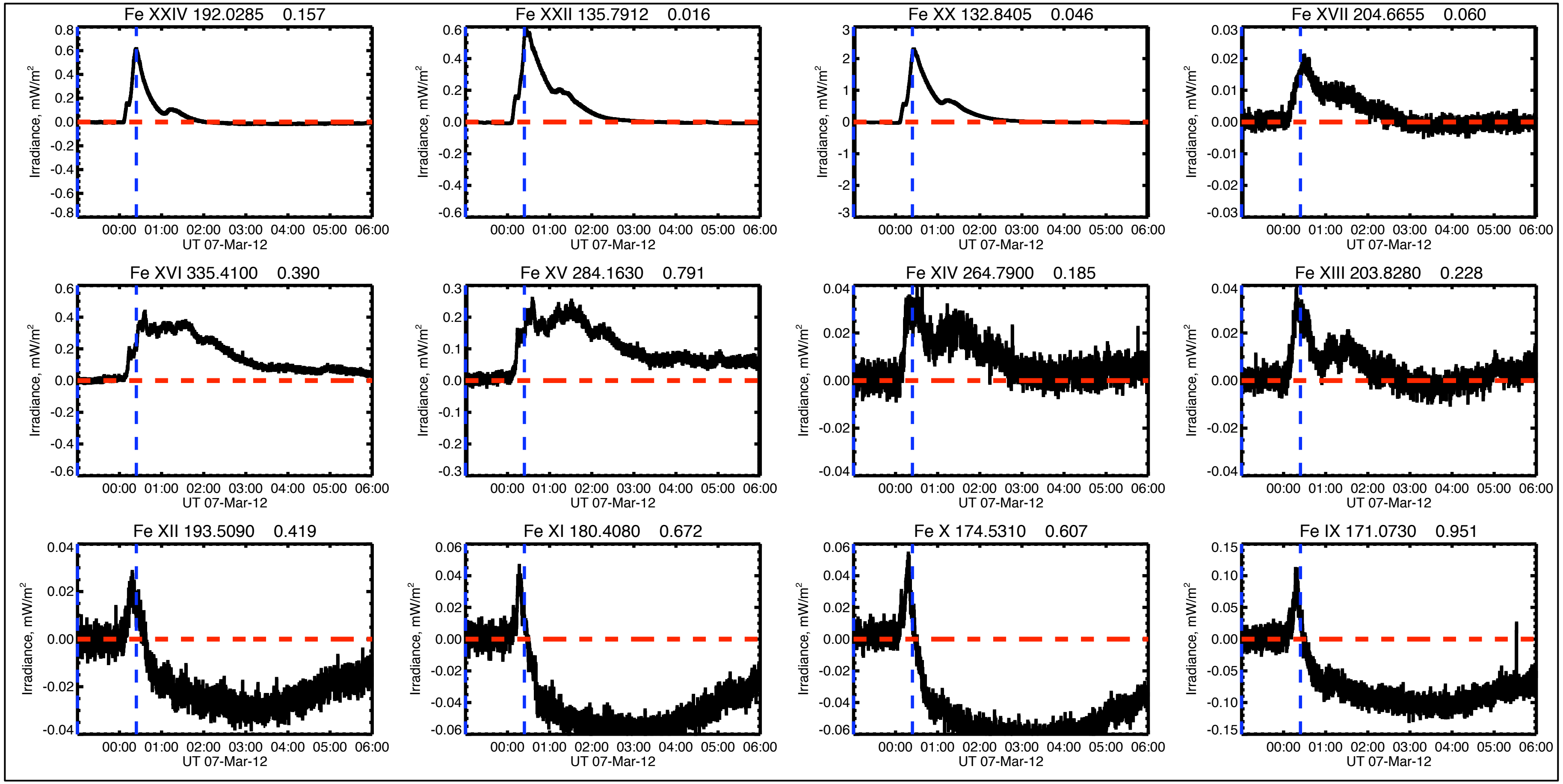


This TRACE movie shows coronal emission at 171 A, formed at a relatively low temperature as the new coronal structures cool and drain. The time span is about 10 hours (15 April 2001).

- The ribbons, heavily foreshortened because it's near the limb
- The saturation patterns, which show the most intense areas and are quite interesting diagnostically
- The striking "dimming" signature, showing the release of CME mass
- The "shrinking" preceding the main explosion
- The coupled oscillations within the arcade associated with a second flare
- etc.

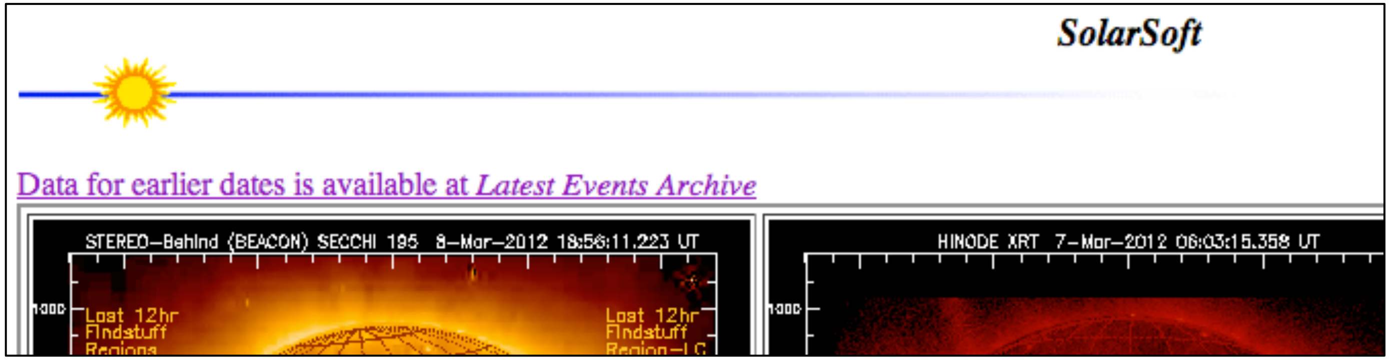

GOES 15 X-Rays:
1E-3
X
M
C
B
A
1E-9
23:40
00:00
00:20
00:40
01:00
Start Time (06-Mar-12 23:27:00)
2012/03/06 23:57:00.350

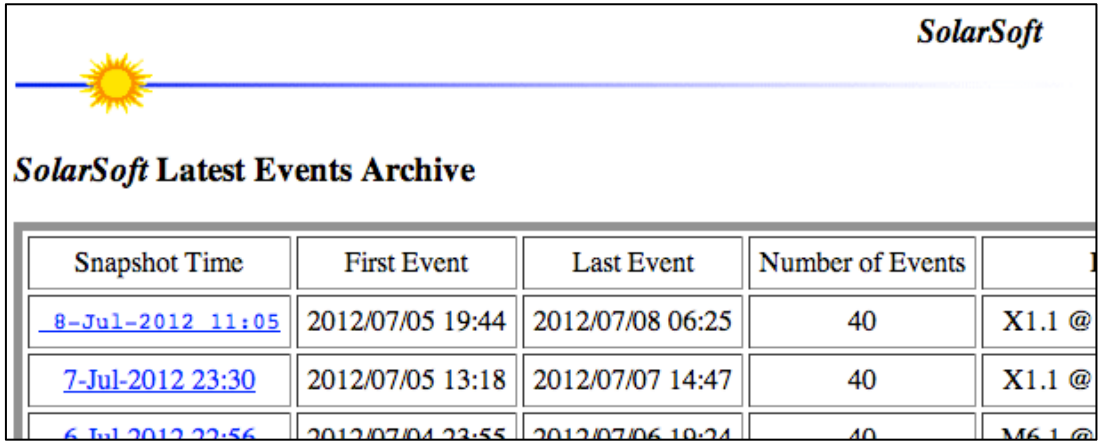
Dimming via EVE for SOL2012-03-07



Easy way to find movies

- Sam Freeland’s “latest events” pages: http://www.lmsal.com/solarsoft/latest_events_archive.html

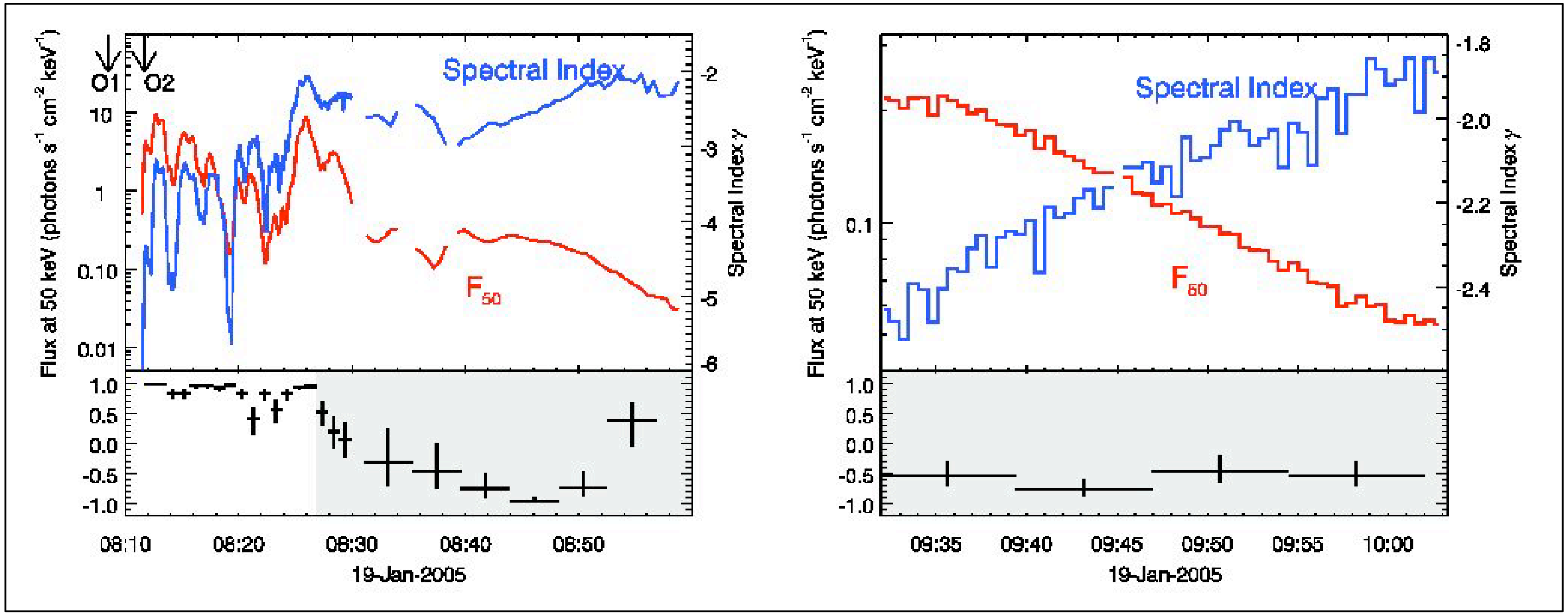




These are “stealth pages” – not well publicized!

Flare morphology

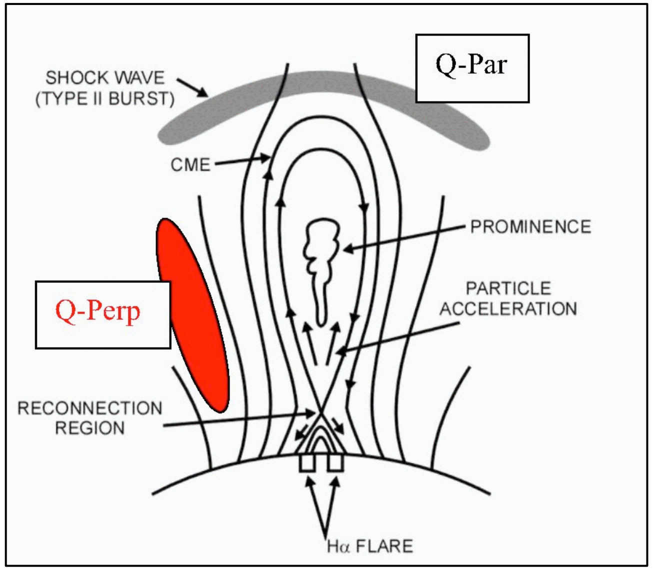
- Soft-hard-soft and soft-hard-harder spectral patterns



SHS…………….SHH………………..!.................. Grigis & Benz 2007

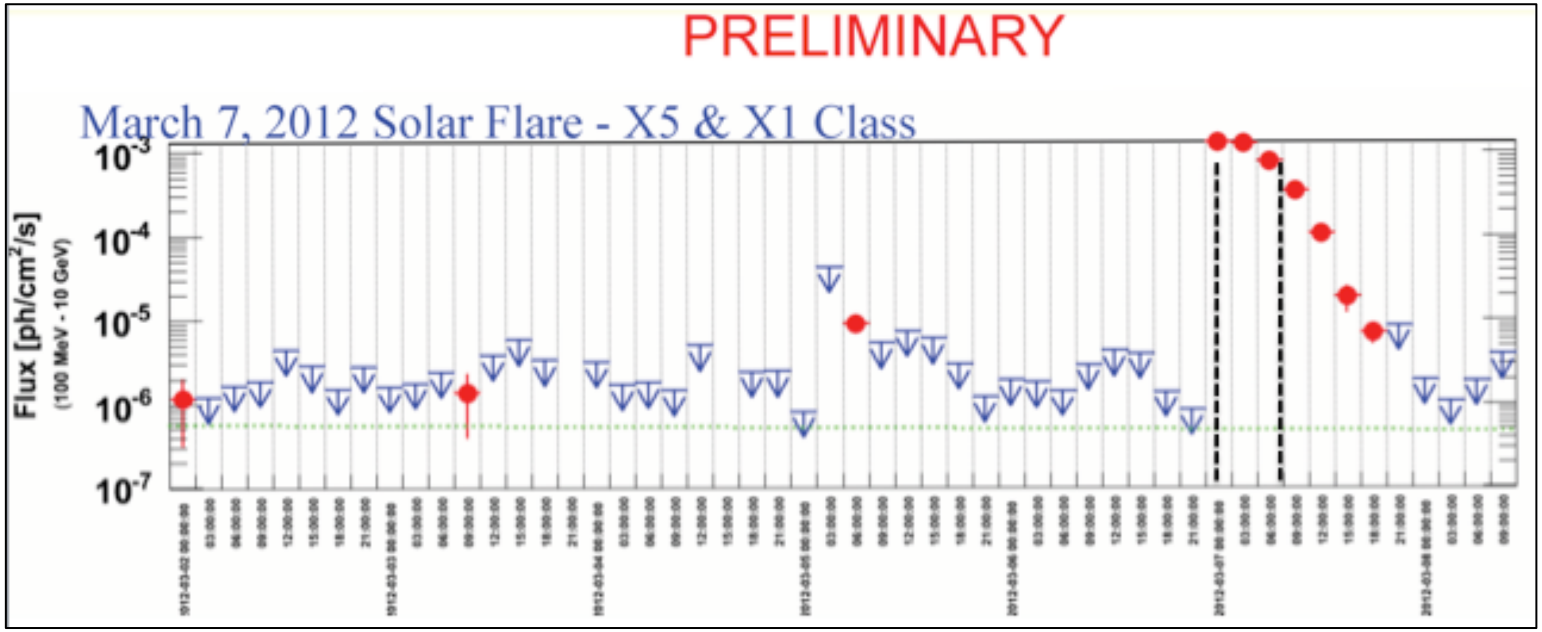
The Soft-Hard-Harder pattern

- This is a bit of a mystery, conceptually, because it is an explicit part of the flare that correlates strongly with SEP production (Kiplinger, 1995). How can shock-accelerated particles reside in the flare?



Cartoon by Cliver et al. (2004). Note the location of the shock wave; either as a bow wave, or a flank, it does not intersect closed magnetic fields and should not be relevant for the SHH sources

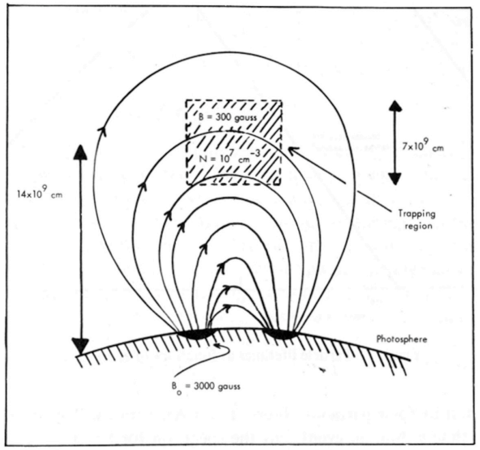
Related *Fermi* observations?



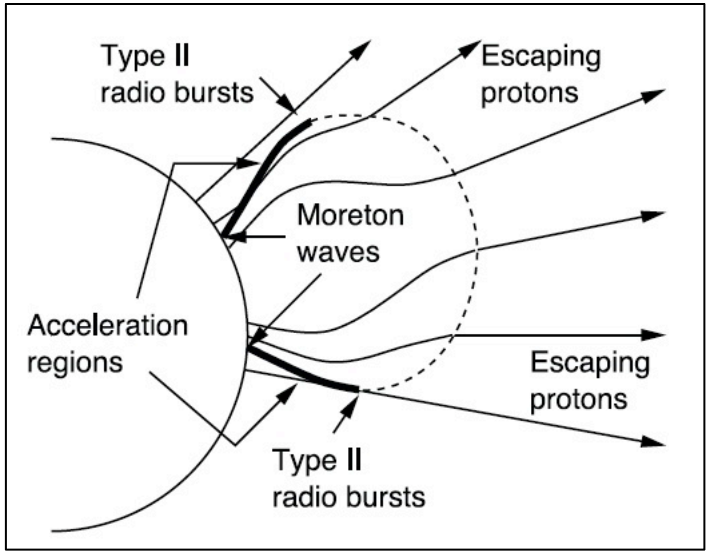
Fermi observations of long-lasting 20 MeV γ-ray fluxes from a major flare. Here the emissions lasted for ~20 hours, much longer than any flare effect except for the CME and interplanetary effects. The natural interpretation is that high-energy protons were trapped in closed fields near the flare site (N. Omodei, personal communication 2012)

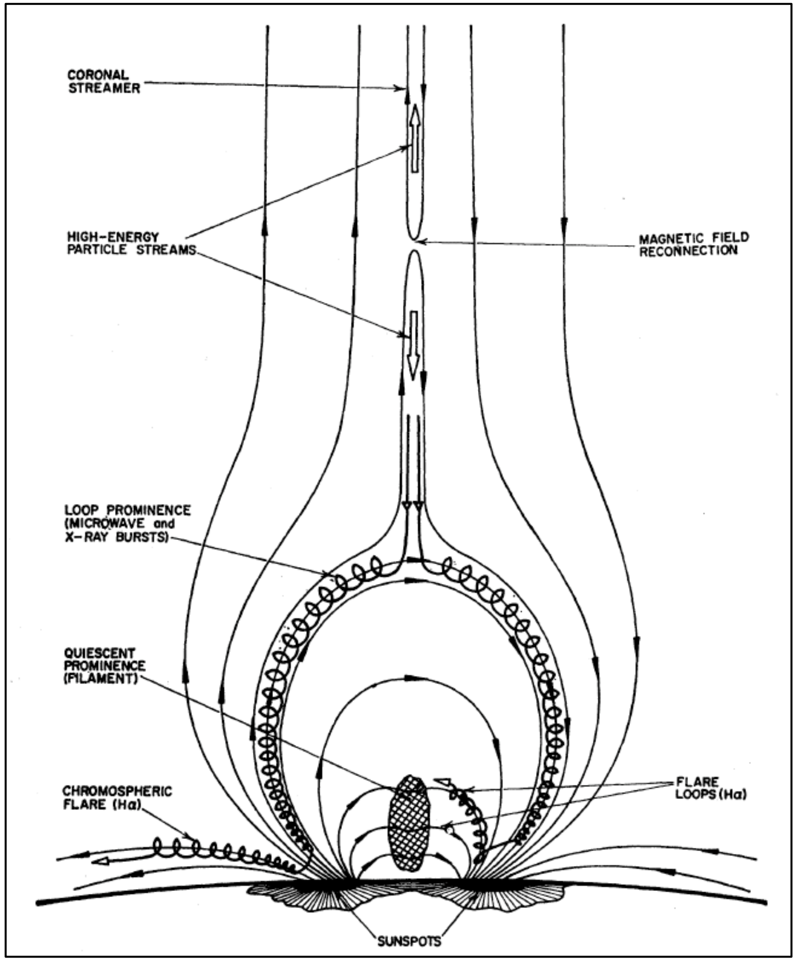
Fermi's remarkable "sustained γ-ray events"

Elliott (1973)



Vainio-Khan (2004)





Strauss & Papagiannis (1971)

Fermi's remarkable "sustained γ-ray events"

- Are the particles trapped for many hours (Elliot idea)?

  - collisional losses may stop the particles

  - particle drift motions may lead to precipitation
- Are the particles continually accelerated for many hours (CSHKP idea)?

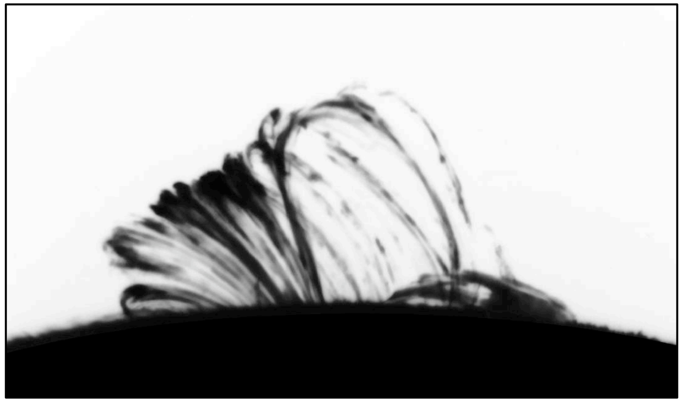
  - energetics sounds dodgy

  - fits in well with standard reconnection model
- Do SEPs themselves wander back to the Sun (Vainio-Khan idea, plus spin)?

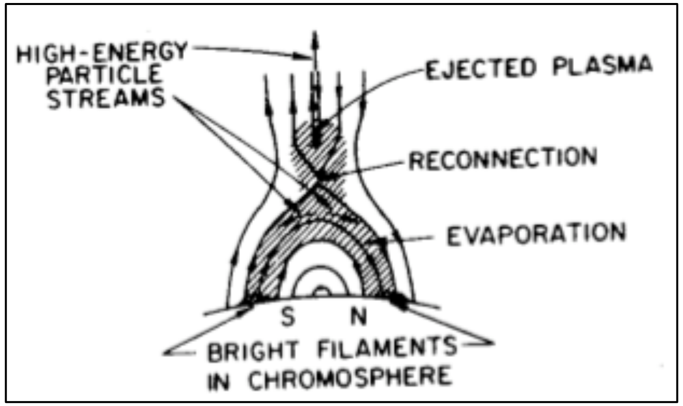
  - the mirror force would seem to prevent this

  - this idea would predict bright coronal holes

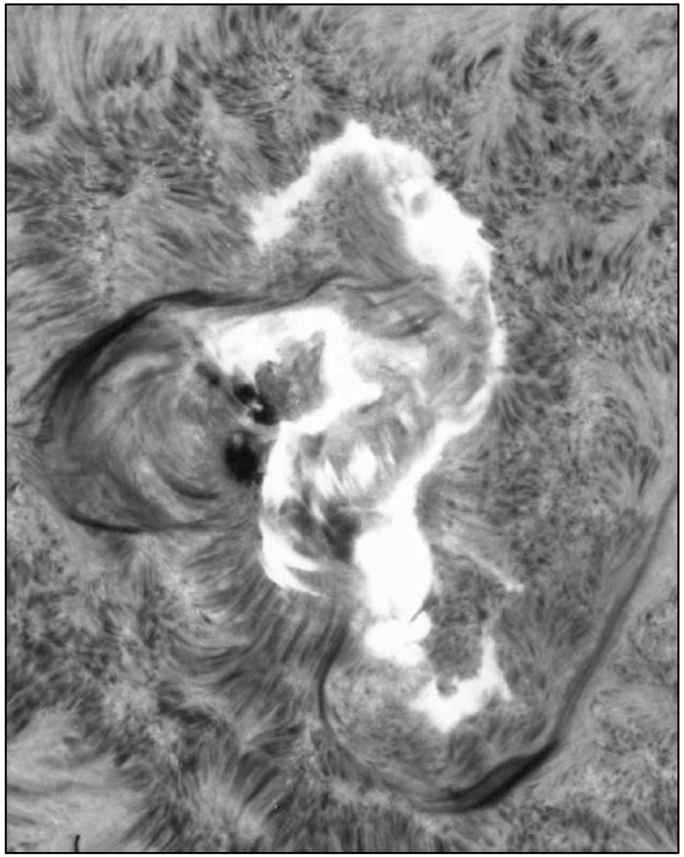
Ribbons and Arcades



An Ha loop prominence system seen at the limb (Białkow)

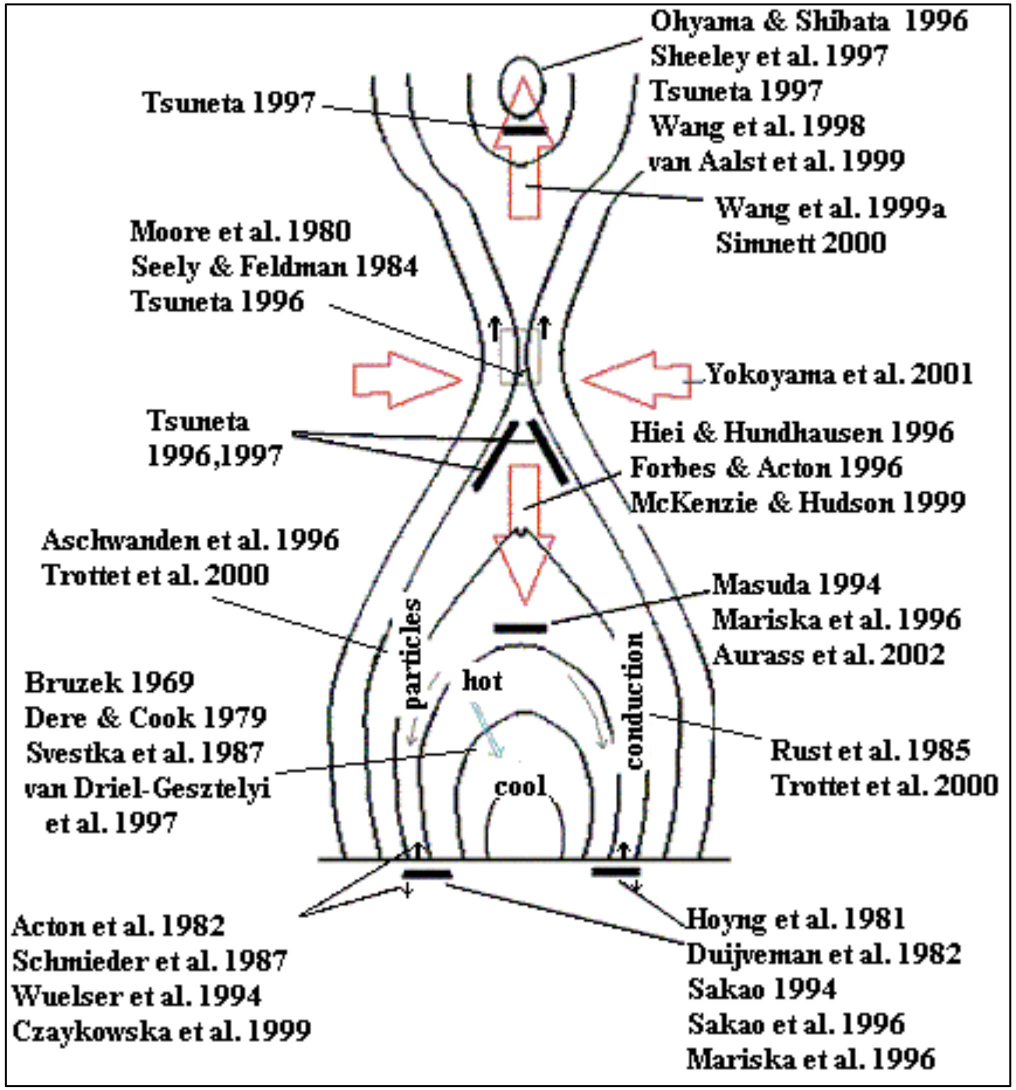


The resulting cartoon (Sturrock, 1976)



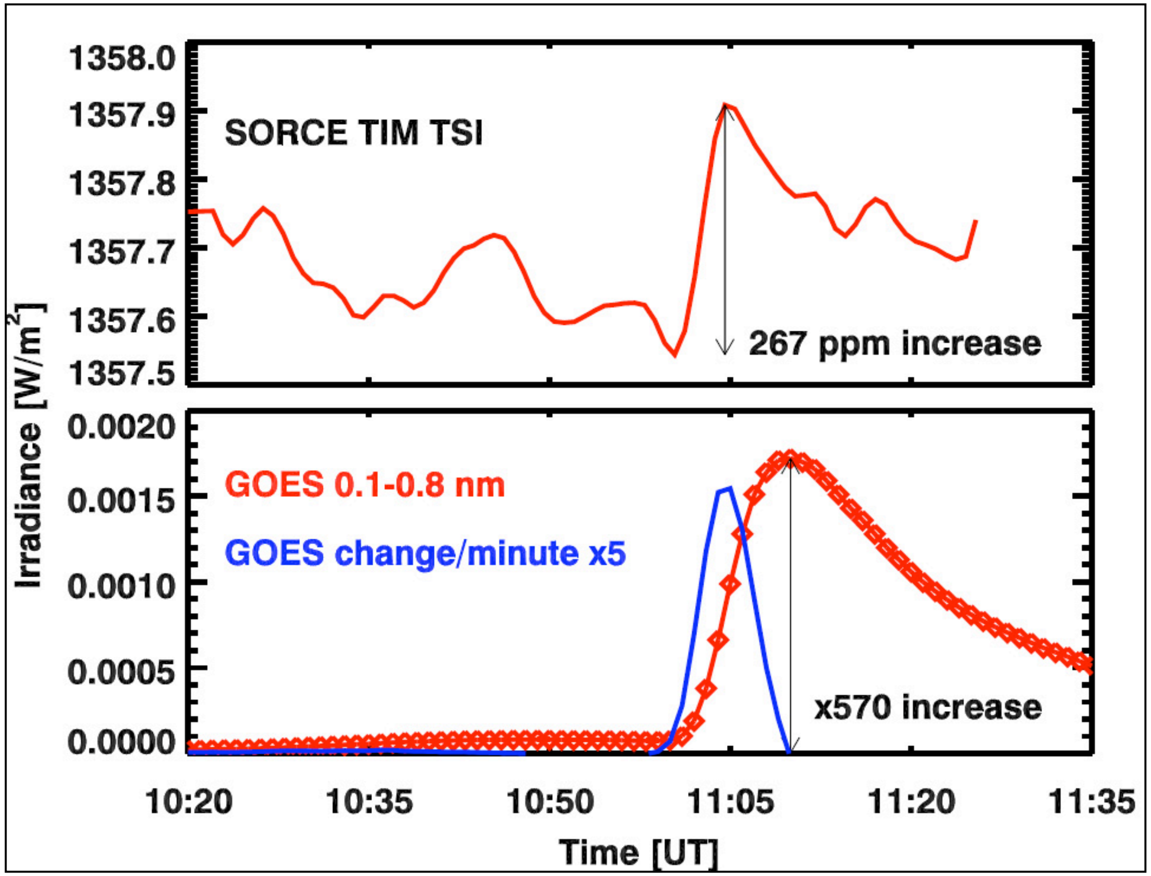
Another seen on the disk. Note the ribbons at the feet of the arcade loops (Big Bear)

Standard carton embellished



McKenzie, >2002

First bolometric observation of a solar flare



All of the flare radiant energy

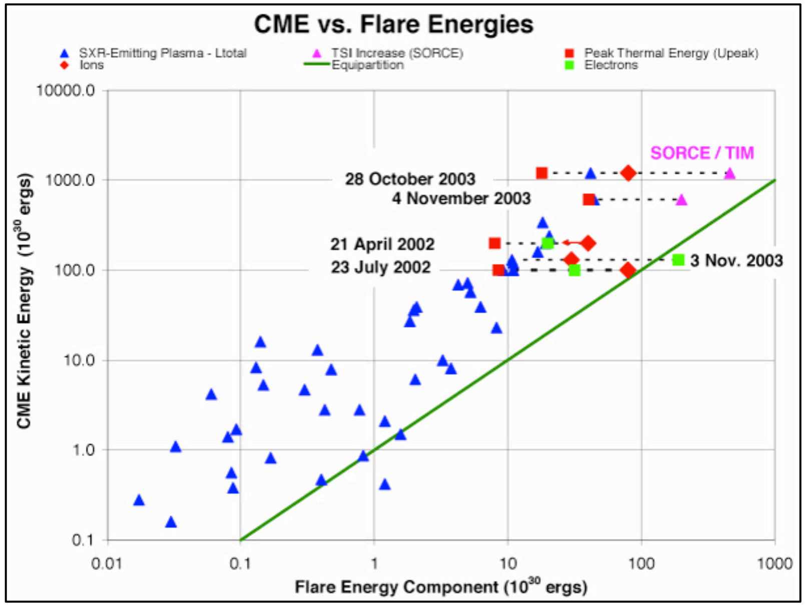
About 1% of the radiant energy

Woods et al. 2004

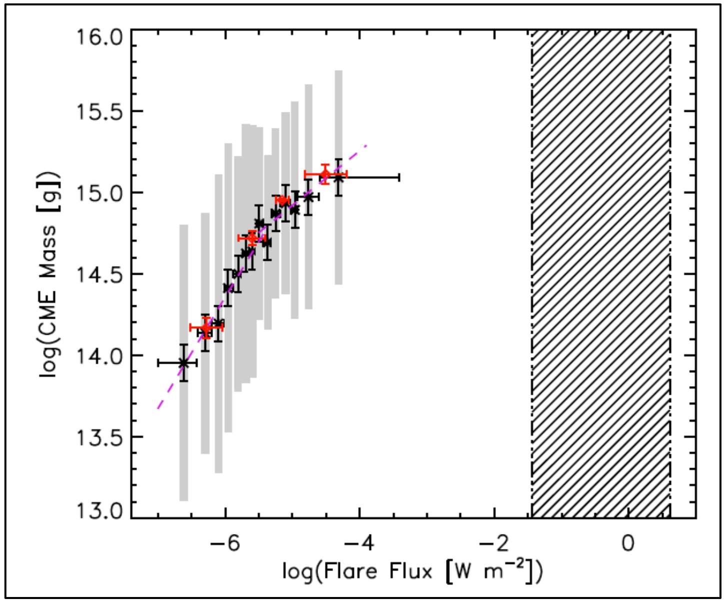
Comment on Relative Energies

- One often reads that CMEs have “far more” energy than flares.
- This is a misconception, probably based on assuming the GOES energy is the flare energy
- See Emslie et al. (2005) for quantitative details

Flare and CME Energy Scaling



Dennis 2005
(RHESSI Science Nugget)



Aarnio et al. 2011

It is often incorrectly claimed that flare and CME energies do not correlate well. This misconception may have been influenced by the “plane-of-the-sky” approximation, and the use of occulted flares http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/RHESSI_Science_Nuggets

RHESSI Science Nuggets

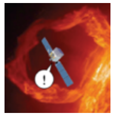
From RHESSI Wiki

Welcome to the **RHESSI Science Nuggets**: science notes from RHESSI. The following is a time-ordered list of the latest Nuggets added to the wiki. An alphabetical list of wiki Nuggets is also available. If you are looking for older Nuggets than please visit the **original series** of RHESSI Science Nuggets (http://sprg.ssl.berkeley.edu/~tohban/nuggets/) and use the search facilities there; for this new series of Nuggets in the Wiki format, use your browser's search facility for title words or authors. We welcome volunteer authors - please see our page of help for authors (http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/Help:For_Authors) .

Please note that each Nugget page has a Discussion page, which sometimes has really interesting information.

179 Dimmings and Sustained Gamma-Ray Events

25 June 2012 by Hugh Hudson and Nicola Omodei



Coronal disruptions reveal themselves as depletions and gamma-ray emissions. Click the title to read more.

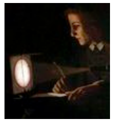
178 Flare Nimbus

14 June 2012 by Susan McKenna-Lawlor

The Flare Nimbus, its history and significance. Click the title to read more.

177 RHESSI and the Transit of Venus I

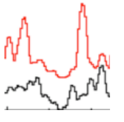
1 June 2012 by Hugh Hudson and Martin Fivian



RHESSI prepares for the June 5/6 Venus transit. Click the title to read more.

176 Time Profiles of Solar Flare Densities

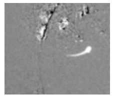
21 May 2012 by Ryan Milligan and Michael Kennedy



Density-diagnostic line ratios in EVE spectra. Click the title to read more.

175 Solar energetic electron events over one solar cycle

7 May 2012 by Linghua Wang

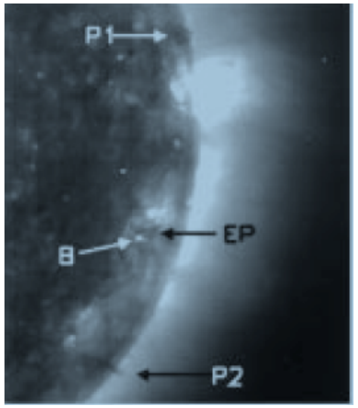


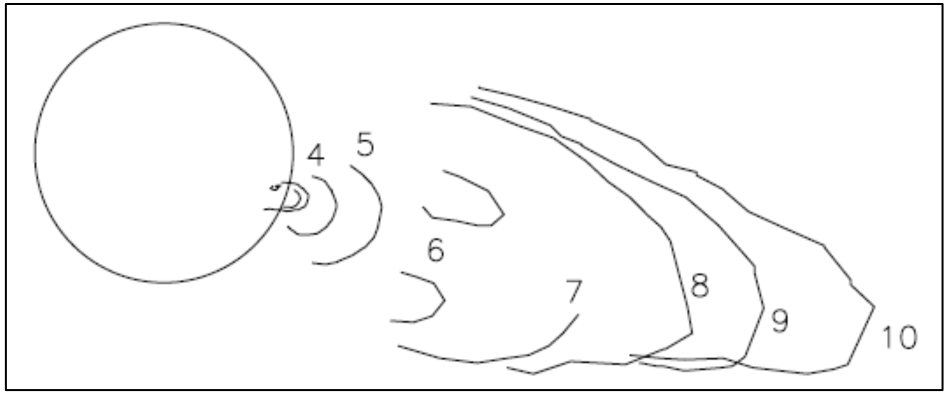
The statistics of SEP electrons. Click the title to read more.

A Shocking Type II

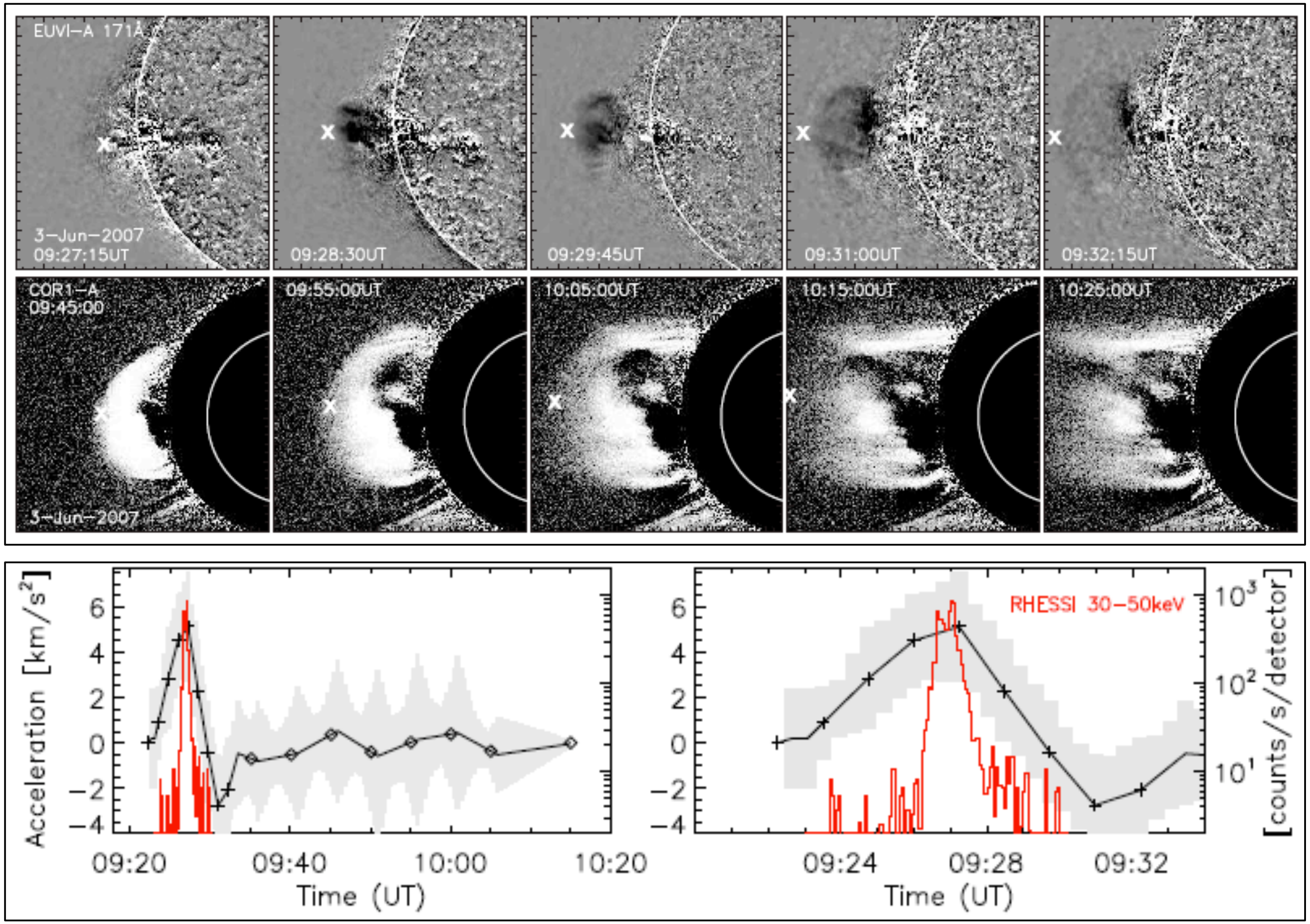
CME initiation and the impulsive phase

- There has been a widespread belief that CMEs are somehow independent of, and more energetic than, solar flares
- This belief is incorrect, even though it features in current literature (e.g., Webb & Howard, *Living Reviews* 2012)





Dere et al., 1997: the compact beginning of a (large-scale) CME from a compact source in the chromosphere (cf. Yohkoh observations of “dimmings”)



Temmer et al. 2010 (cf Zarro, Zhang): the compact beginning of a (large-scale) CME from a compact source, with an acceleration profile matching the hard X-ray impulsive phase

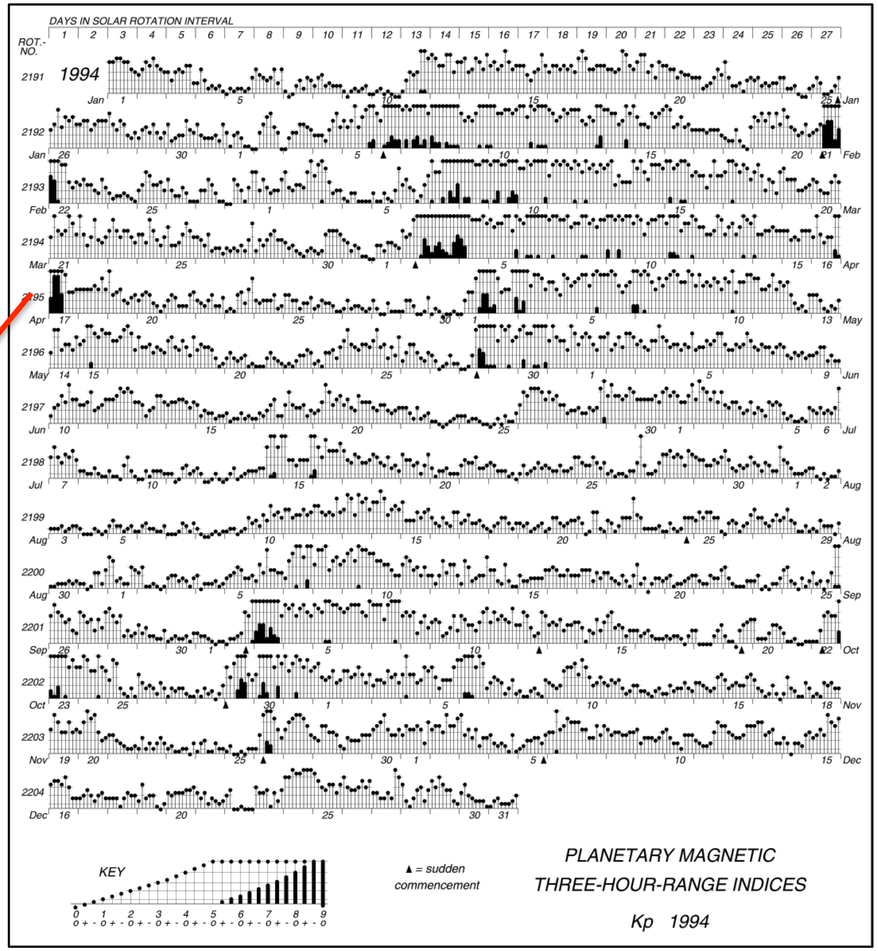
Stealth CMEs

- The examples show that fast CMEs, the ones responsible for major geoeffectiveness, have a close association with compact flares
- It is likely that much of the energy of such a CME comes from the low corona and correlates physically with the energy going into the flare
- BUT! What about the “stealth” CMEs? These are the ones typically arising in the polar-crown filament zone

Stealth CMEs

An early case confounding the "flare myth" idea. See also Robbrecht et al. (2009)

Yohkoh/SXT April 14, 1994 (Hudson et al., 1995)



The Bartels "Musical Diagram" for the geomagnetic Kp index

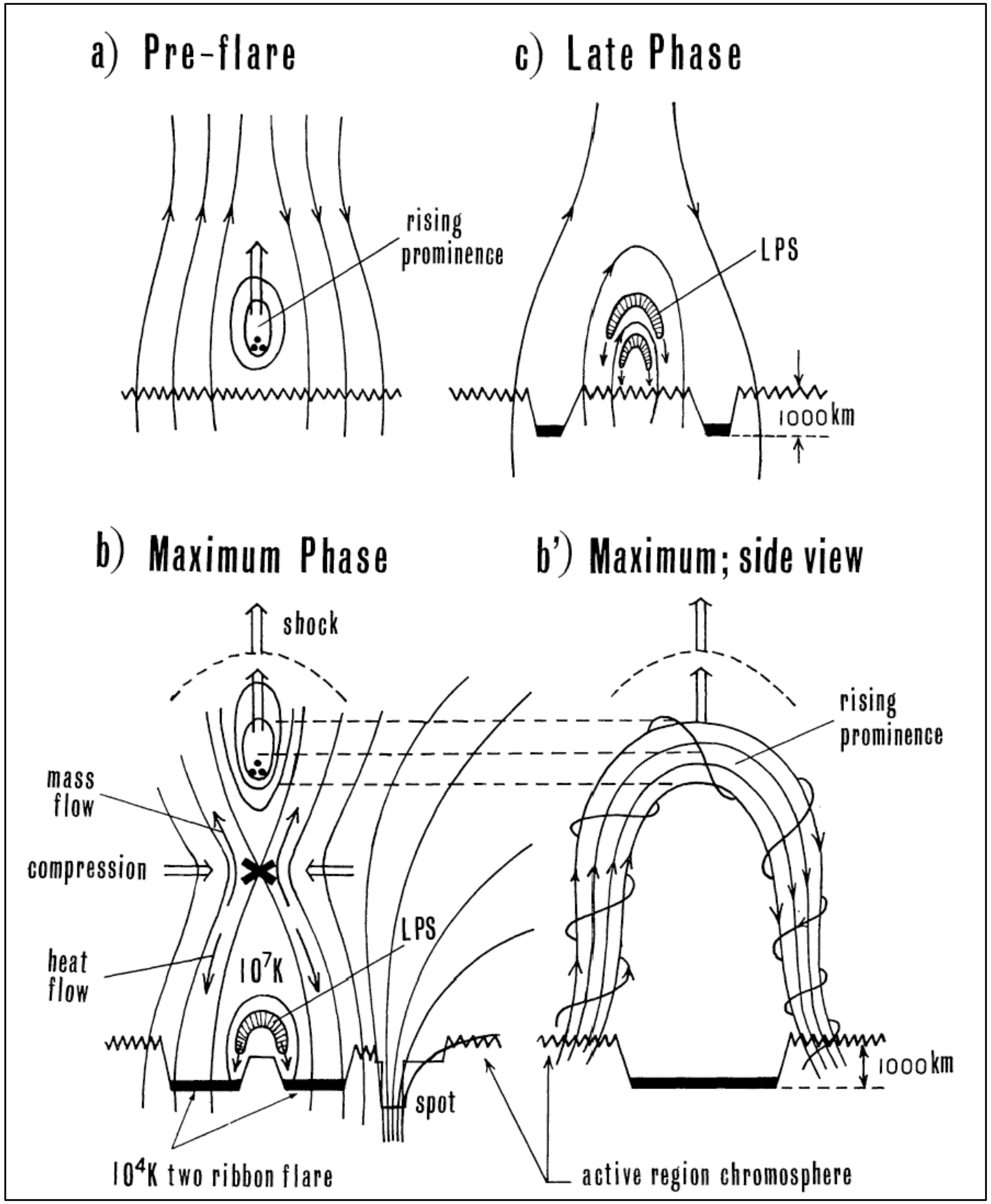
Stealth CMEs

- The stealth CMEs have a strong association with filament eruptions in the quiet Sun, but not flares listed as GOES X-ray events – GOES response bias is to blame
- These have all the earmarks of flares, except that they are larger, slower, and cooler (Hudson et al. 1995). Hence it is likely that ***All*** CMEs are associated with basic flare physics.
- The traditional nomenclature for this (Hyder, 1967) is the phenomenon termed

“*Disparition brusque* -> Flare Brightening”

Global structures of flares

- A flare, or flare-like physics, invariably accompanies a CME.
- The converse is not true: Many flares below X class, and a few above X class, do not launch CMEs
- A “space weather” concept needs to incorporate both aspects of the disturbance – the eruption, for the interplanetary CME disturbance, and the flare, for the prompt ionospheric effects



Global dynamics

This is the Hirayama (1974) cartoon showing a filament eruption. It is an early form of the "standard model" that captures many features of the flare/CME process:

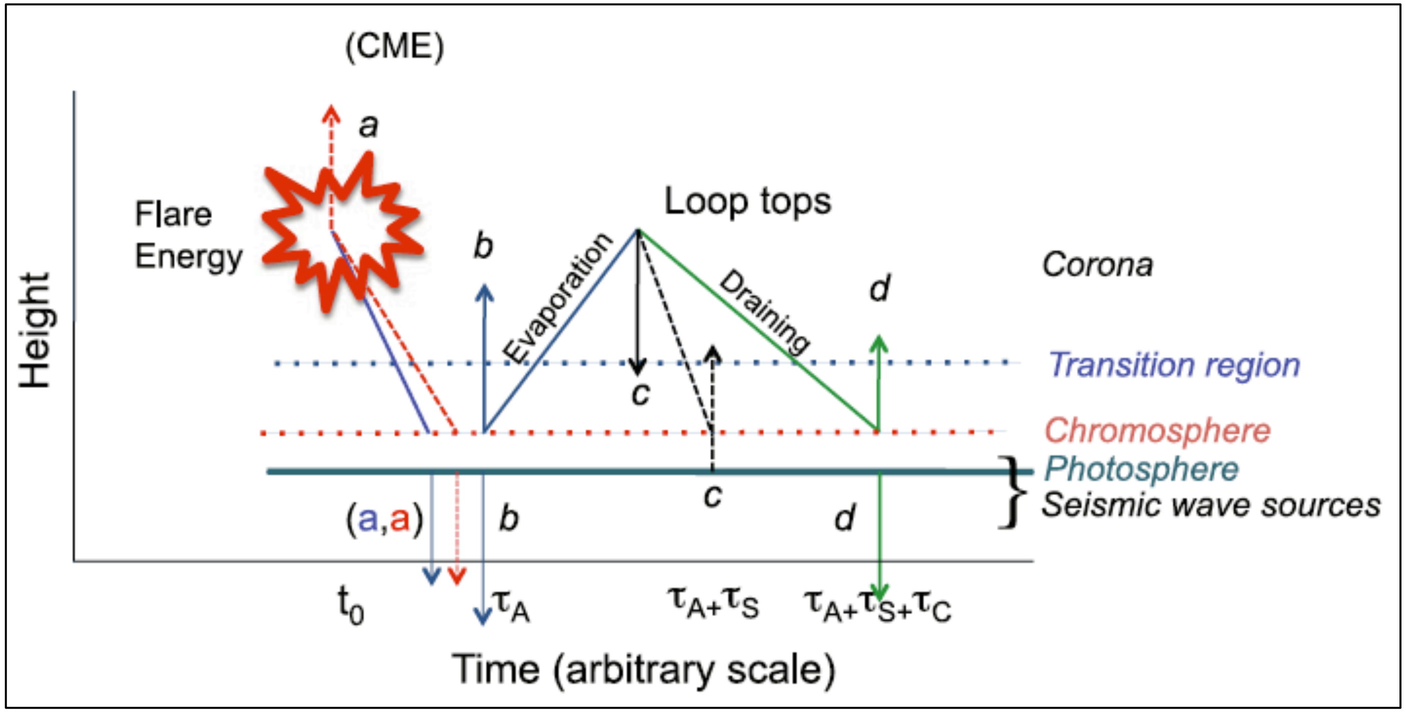
- Rising prominence
- Loop prominence system
- Reconnection
- Photospheric currents
- Coronal overpressure

And, unlike later versions, it actually has a chromosphere

Problems with the standard model

- The initial eruption is not explained from energy principles
- There is no fundamental role for particle acceleration, which the data strongly imply (ie, non-fluid behavior)
- The impulsive-phase radiation (the white-light flare) does not play a central role
- Not only is energy conservation not globally considered typically, neither is momentum conservation

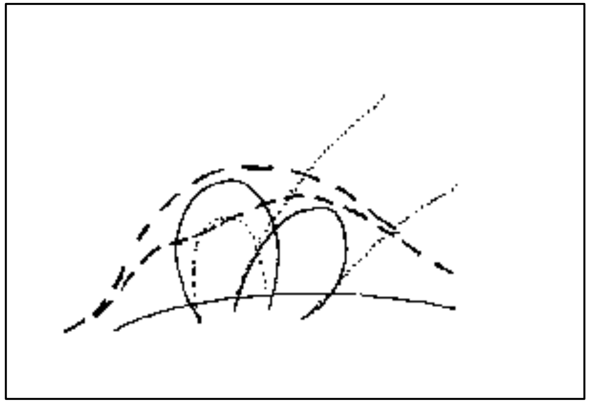
Conservation of momentum



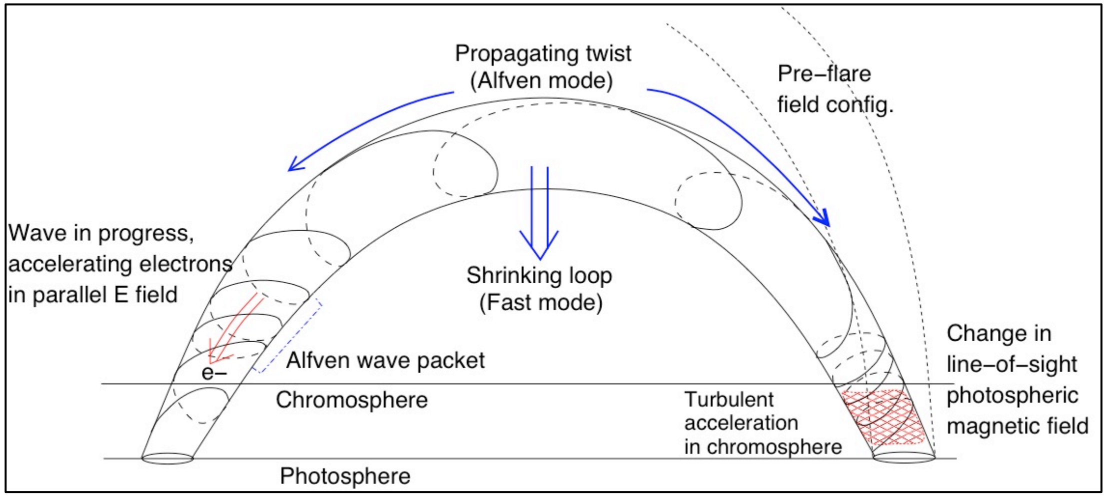
Hudson et al. 2011

- Flare energy release must conserve momentum
- The sketch shows possible sources and sinks of the vertical linear momentum
- Details upon request

Conservation of energy



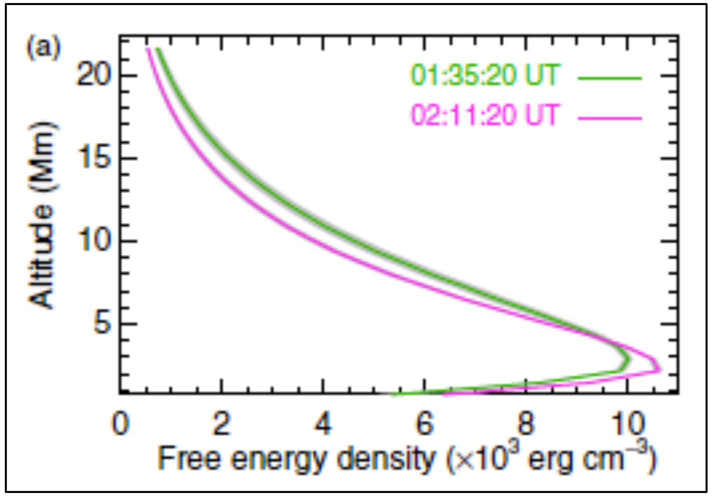
Hudson 2000. Dashed lines show magnetoisobars during flare-associated implosion



Fletcher & Hudson 2008

- implosion transports energy as Poynting flux
- field adjustment at photosphere matches observed stepwise changes
- the chromosphere is there, but remains a mystery

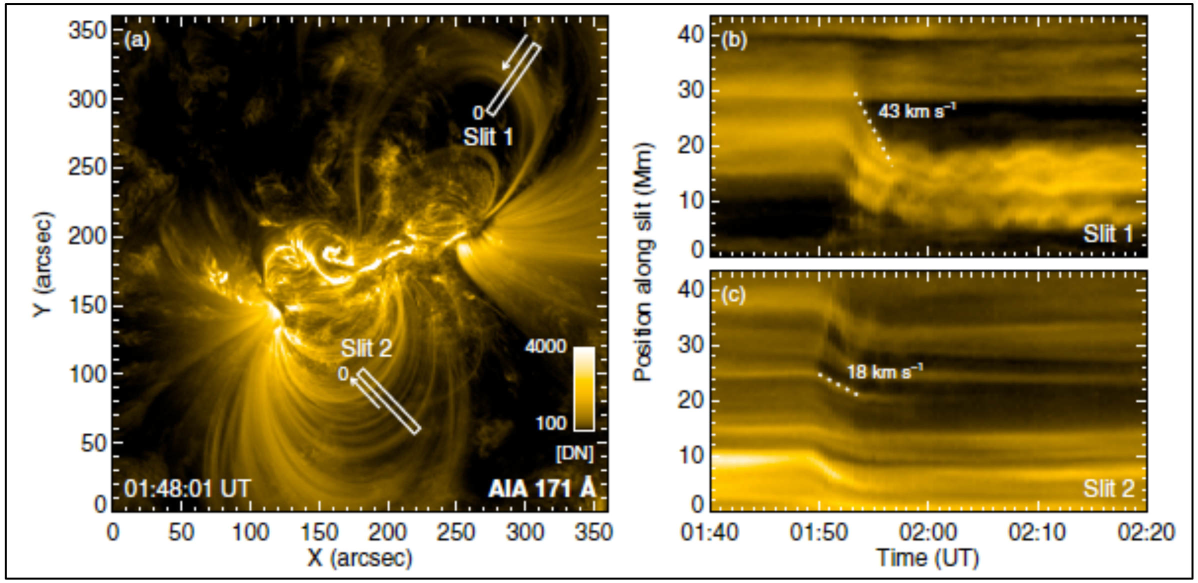
Conservation of energy



Sun et al. (2012), SOL2011-02-15

• The NLFFF model shows the free energy to be concentrated at the base of the corona

• An implosion happens, consistent with energy release



Resources

- M. Stix, 1989 “The Sun, an Introduction” (basic material on quiet Sun)
- D. Billings, 1966 “A Guide to the Solar Corona” (background on solar corona)
- A. Hundhausen, 1972, “Coronal Expansion and the Solar Wind” (basic theory of solar wind)
- A.G. Emslie et al. 2012, “High-Energy Aspects of Solar Flares,” (overview of flares): SSR vol. 159
- F. Chen 1984, “Introduction to Plasma Physics and Controlled Fusion (plasma physics text)
- Web resources

  - Living Reviews http://solarphysics.livingreviews.org/

  - Nugget collections
  http://sprg.ssl.berkeley.edu/~tohban/wiki/index.php/RHESSI_Science_Nuggets et al.

  - Stephanie’s plasma pages
  http://sprg.ssl.berkeley.edu/~hhudson/plasma/webpage/plasma.html