Flares as seen in the Lower Solar Atmosphere

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

Relevant Lectures I'm Sorry I Missed!

Week 0	MONDAY 02	TUESDAY 03	WEDNESDAY 04	THURSDAY 05	FRIDAY 06
9:00 - 10:15		Reception	**Giovanni Pinzón** Fundamentals in Stellar Structure	**Giovanni Pinzón** Fundamentals in Stellar Structure	**Gustavo Guerrero** Solar Dynamo
10:15 - 10:30		Break	Break	Break	Break
10:30 - 11:30		**Giovanni Pinzón** Fundamentals in Stellar Structure	**Leonardo Castañeda** Emission Process	**Benjamín Calvo-Mozo** Introduction to radiative transfer	**Leonardo Castañeda** Emission Process
11:30 - 11:45		Break	Break	Break	Break
11:45 - 12:45		**Leonardo Castañeda** Emission Process	**Cristina Mandrini** Solar Activity and Structure: Magnetic Field	**Gustavo Guerrero** Solar Dynamo	**Benjamín Calvo-Mozo** Introduction to radiative transfer
12:45 - 14:00		LUNCH	LUNCH	LUNCH	LUNCH
14:00 - 15:15		**Cristina Mandrini** Solar Activity and Structure: Generalities	**Santiago Vargas** Introduction to IDL	**Cristina Mandrini** Solar Activity and Structure: Magnetic Field	**Juan Carlos Martínez-Oliveros** Sunpy, the future of solar physics
15:15 - 15:30		Break	Break	Break	Break
15:30 - 16:45		**Santiago Vargas** Introduction to IDL	**Dominik Utz** Introduction to SolarSoft	**Dominik Utz** Introduction to SolarSoft	**Dominik Utz** Introduction to SolarSoft
16:45 - 17:00		Discussion	Discussion	Discussion	Discussion

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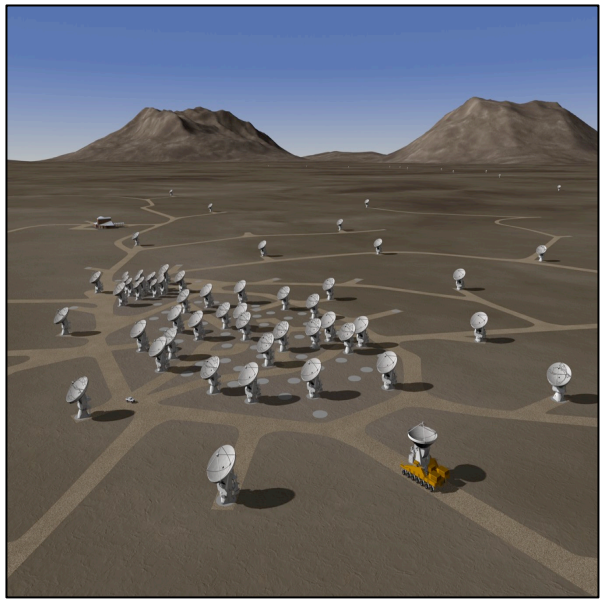
Why the lower solar atmosphere?

1) It is where the energy of a flare appears
2) It is near where we think the energy is stored
3) It presents many challenging observational and theoretical problems



ALMA (Chile)

ATST (Hawai'i)

Outline of presentation

- Flare morphology
- White-light flares
- Understanding the radiation
- What happens in the impulsive phase

The Carrington flare of 1859

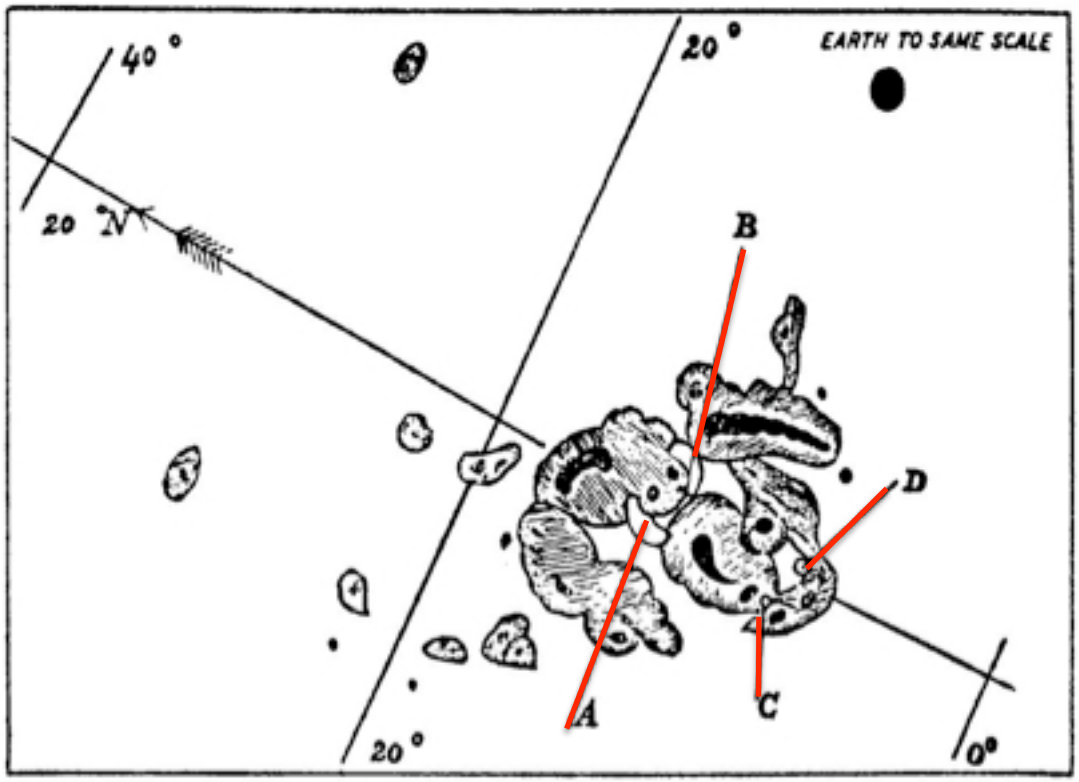
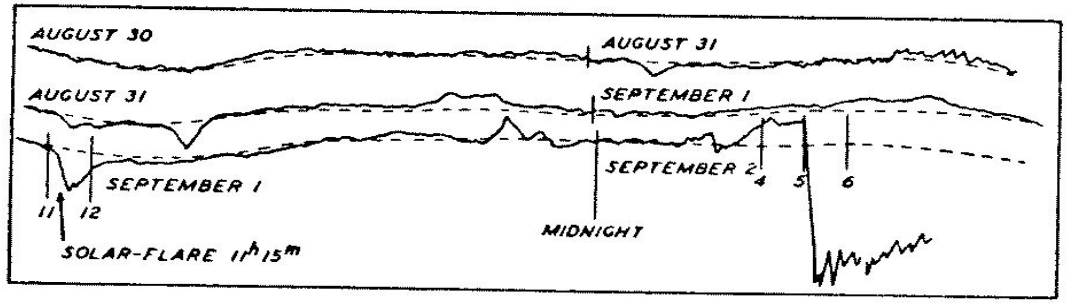


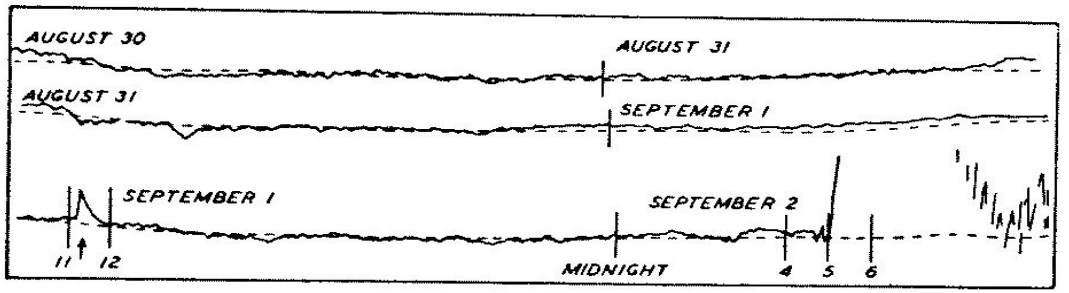
FIG. 36. Solar sketch, September 1, 1859, by R. C. Carrington

~5 min/35,000 miles
(50 Mm)

How X-ray astronomy began

3 days





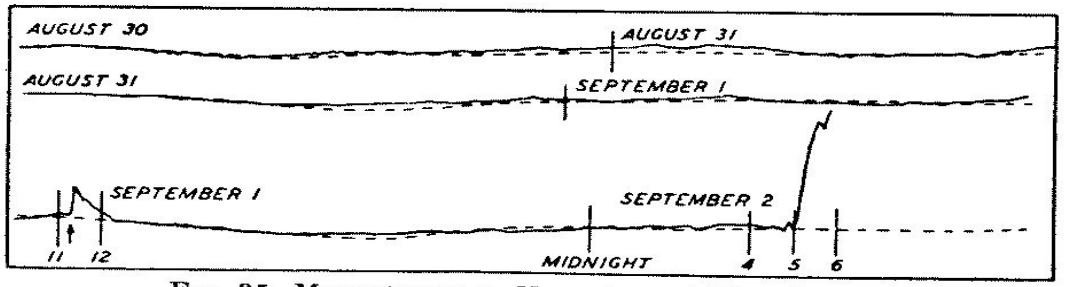


FIG. 35. Magnetograms, Kew, August 30 to September 2, 1859

Three **B** components

Crochet

Sudden Commencement

Geomagnetic storm

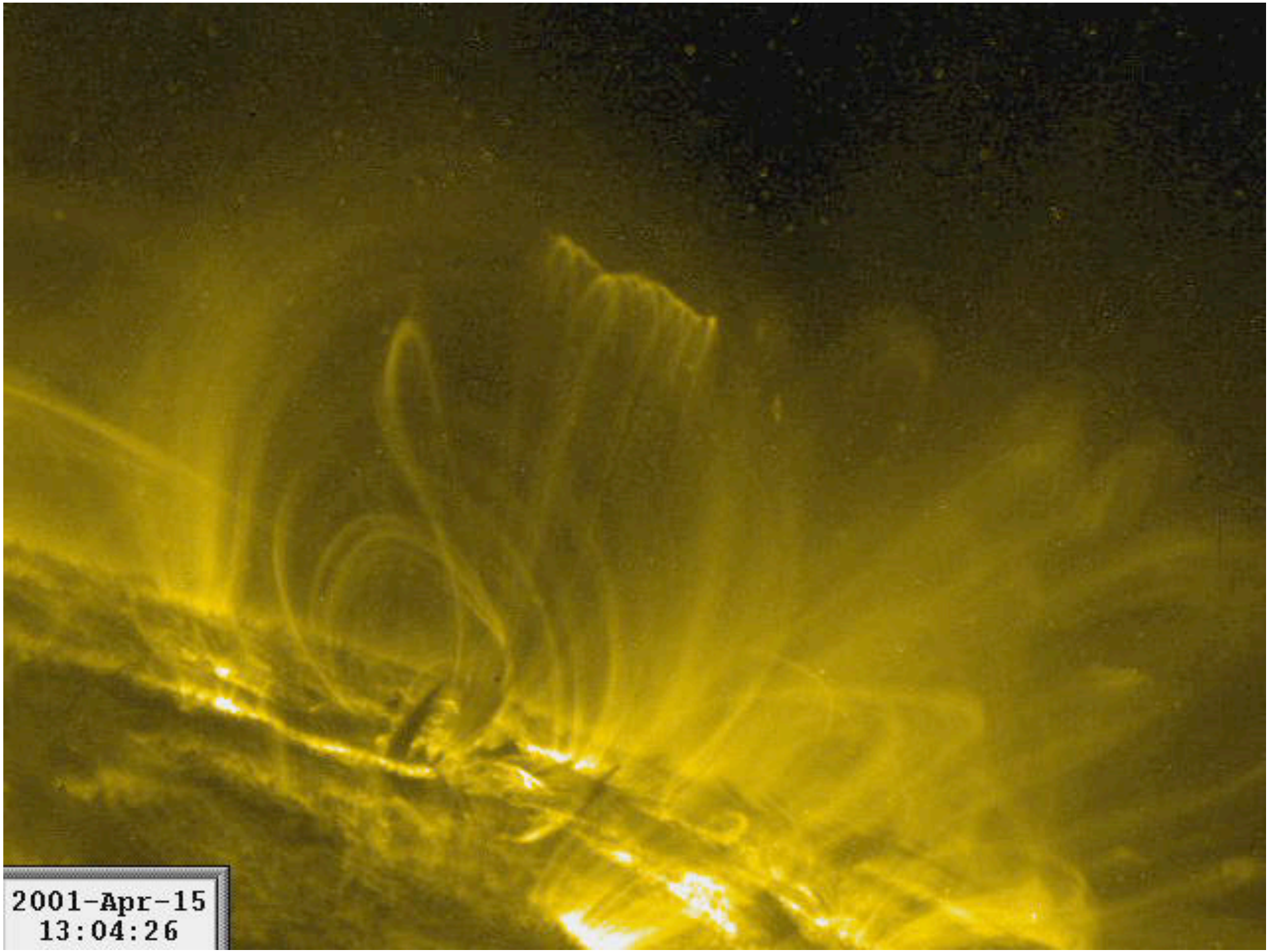
♩ The SFE* (= “crochet”) ♩

- 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.”

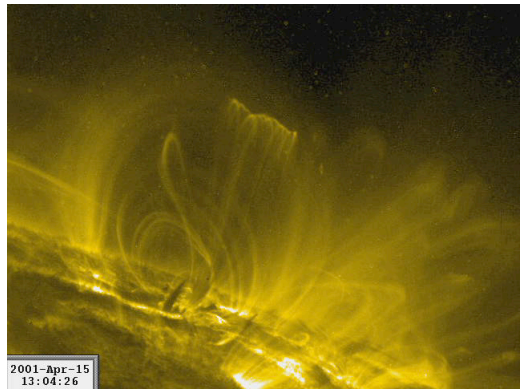
Why study solar flares?

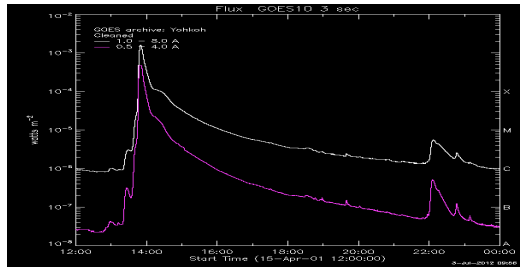
1) Flare-like and jet phenomena occur plentifully elsewhere around the Universe, and we can study them uniquely well on the Sun
2) There are several important plasma-physics problems that are not well understood
3) Flares lead to CMEs that lead to practical matters ("space weather")
4) A flare provides an impulse with which to study the structure of the Sun


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).



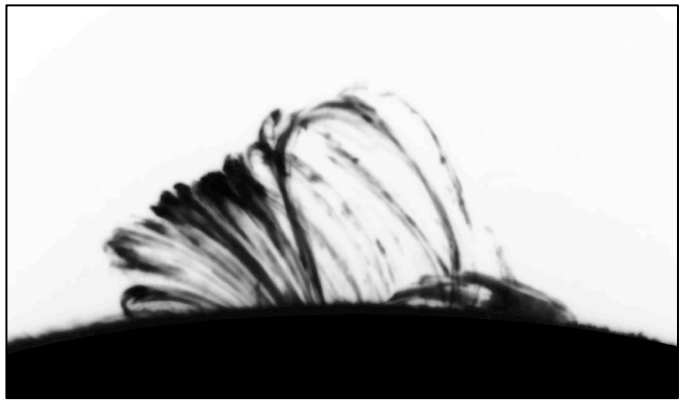


- The ribbons, heavily foreshortened because it's near the limb
- The saturation patterns, which show the most intense areas and are quite interesting diagnostically
- The striking "dimming" signature, showing the release of CME mass
- The "shrinking" preceding the main explosion
- The coupled oscillations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

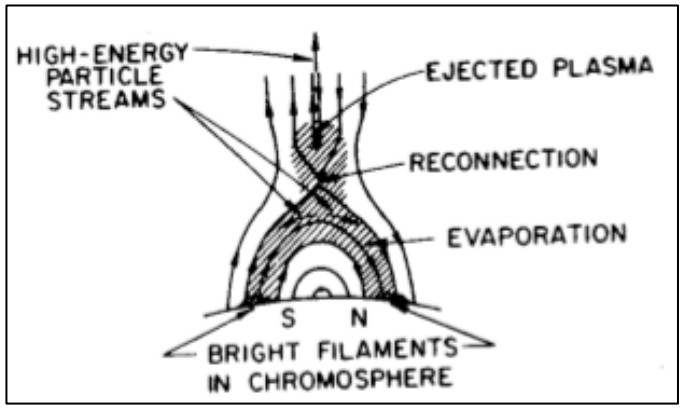
Flare morphology

- Ribbons and arcades
- The Neupert effect
- Soft-hard-soft and soft-hard-harder spectral patterns

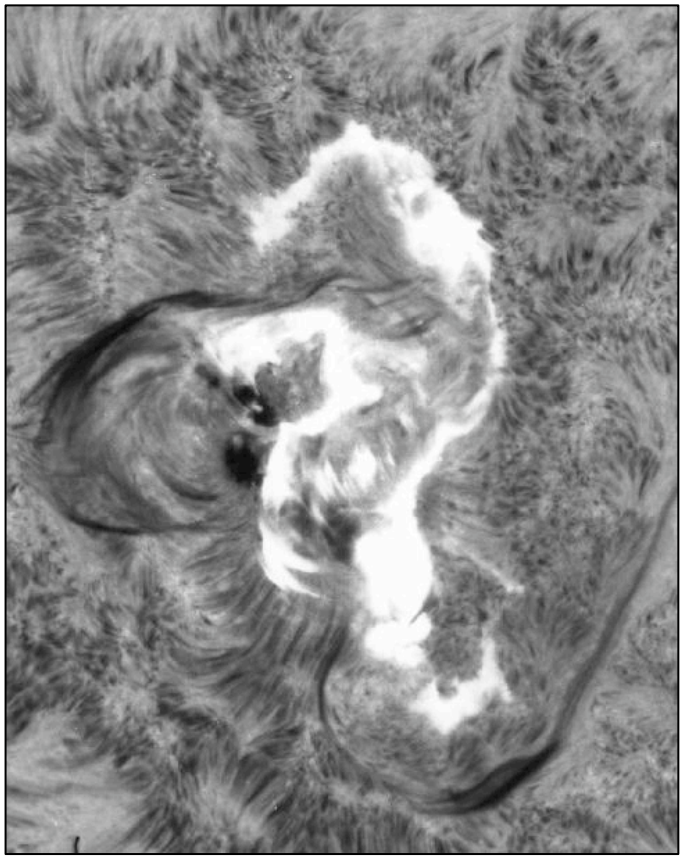
Ribbons and Arcades



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)

About cartoons

- In the absence of a comprehensive theory, people often resort to sketches.
- At best, these are like interpolation functions – how do you link what you know, to what you observe?
- At worst they represent incorrect preconceptions that do a disservice to research
- I maintain a Web archive on

http://solarmuri.ssl.berkeley.edu/~hhudson/cartoons/

The cartoon archive

Grand Archive of Flare and CME Cartoons

June 21, 2012

Why an archive? Why a cartoon?

Cartoons play an important role in discussions of how solar flares and CMEs work. These discussion may take place in august forums, or in pubs at any point around the solar world (see bar bets). In place of a self-consistent theory, a cartoon is often the only way to guess how different features of an event might be related. At the bottom of this page we have a random selection from each of three categories of cartoons. To scroll through the Archive randomly, simply use the "refresh" button on the browser. To view it systematically, click on the names below or look at the (chronological) overview or the matrix-style displays of thumbnail images. These are large pages and require broadband access to load properly. Each cartoon page should have some (often loose) information about its origin and a link to the published paper. Here are links to the gaudiest cartoon and to my favorite.

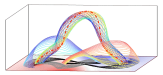
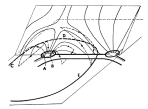
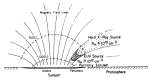
If you have contributions, preferably with nice digital versions of published cartoons, please send them to me at hhudson@ssl.berkeley.edu. This Archive grows with time, and you help this accretion by pointing out omissions of colorful, influential, or timely cartoons. Note that as the years have passed there has been some mission creep, such that there are some items only tangentially related to flares as such. Of course if you see errors in what I've written about any of these, please let me hear.

Direct links to the toons individually by author's name

Giovanelli	Alfvén	Dungey	Sweet	Piddington	Ellison
Gold-Hoyle	Gold	Anderson-Winckler	Gold_CME	De_Jager_62	Carmichael
De_Jager-Kundu	Byrne	Kundu	Sturrock	Alfven-Carlqvist	Hyder
Krivsky	Newkirk-Harvey	Jokipii-Parker	Najita-Orrall	Lin	Chiu
Kane-Donnelly	Wild-Smerd	Palmer-Smerd	Strauss-Papagiannis	McLean	Tindo
Yoppahl	Elliot	Hirayama	Piddington_74	Bratenahl-Baum	Obayashi
Svalgaard-Wilcox	Brown-Hoyng	Kopp-Pneuman	Hoyng	Spicer	Kosugi
Syrovatskii	Anzer-Pneuman	Cliver	Parker	Cargill-Priest	De_Jager_83
Sprangle-Vlahos	Nakajima	Ionson	Uchida-Sakurai	Heyvaerts	Pikelner-Livshits
Colgate	Melrose-White	Akasofu	Emslie-Vlahos	Priest-Milne	Svestka
Moore-Labonte	De Jager	Batchelor	Dowdy	Somov	Forbes-Malherbe
Tanaka	Anderson-Dougherty	Schmieder	Tsuneta-Naito	Wang	Uchida-Shibata
Cane	Machado	Martens-Kuin	Van Ballegooijen-Martens	Sakurai	Sturrock_90
Martinell	Raoult	Morris	Reames	Simnett-Haines	Bespalov
Winglee	Melrose_92	Podgornyi-Podgornyi	LaRosa-Moore	Vlahos	Wheatland-Melrose
Haerendel	Song-Lysak	Gosling, Birn and Hesse	Forbes-Acton	Melrose	Somov-Kosugi
Neidig	Li_97	Magara	Canfield-Reardon	Shibata	Duncan
Canfield	Tsuneta	Klimchuk	Aschwanden-Benz	Moore	Hanaoka
Antiochos	Jakimiec	McKenzie-Hudson	Titov-Demoulin	Sturrock_99	Berger
Fisk	Cecatto	Orlando	Hudson	Longcope-Welsch	Aschwanden
Lin-Forbes	Forbes	Gilbert	Longcope	Shimojo-Shibata	Delannee
Wygant	Aulanier	Montmerle	Lindsey-Braun	Sturrock 01	Fletcher et al.

Shimojo	Low	Crooker	McKenzie (CHSKP)	Kurokawa	Wang et al.
Ergun	Vrsnak et al.	Simnett	Chee & Cheng	DePontieu et al.	Chen-Krall
Buchlin	Sterling-Moore	Gary-Moore	Gurman	Karlicky	Asai
Karlicky-Kosugi	Benz	Barlaga	Kusano et al.	Georgoulis et al.	Smith
Cliver (II)	Uralov	Li et al.	Takasaki	Fletcher_2004	Aschwanden_04
Poulton	Nakariakov-Verwichte	Vainio-Khan	Kliem	Sakai-Kakimoto	Pollock
Lin	Mikic-Lee	Spicer_06	Williams	Dombeck	Droge
Tripathi	Attrill	Ryutova	Tan-Huang	Drake	Takasaki_07
Masdemi	Sakurai_07	Kouzvichev	Pevtsov	Ugai	Schmieder_EER
Xu	Aulanier_06	Hiragama_07	Ing	Jaube	Fletcher-Hudson
Ji	Liu W	Freedman-Kaufmann	Lee-Gary	Kostar	Lehtinen
Wedemeyer-Bohm	Pomoell	Nishio	Temmer	Bemporad	Welsch
Borovsky	Crooker-Pagel	Sakamoto	Birn	Benz_08	Imada
Magara-Tsuneta	Zhao	Getmon	Kahler-Ragot	Liu-Alexander	McKenzie-Savage
Tokiaari	Tsurutani	Saeva	Tevmassian	Schrijver	Chollet
VanBallegooijen-Cranmer	Liu_Wei	McIntosh-DePontieu	Haerendel_00	Mann	Ma
Selhorst	Kitiinaradom	Tsurutani_09	Longcope-Bradshaw	Tripathi-Gekelman	Balasubramaniam
Wang-Liu	Lobzin	Kamio	Chen	Masson	Tanvyan
Cliver-12	Takasao	Kowalski	Liu_Wei_12	Fisher	

Thumbnails - random samples (clickable)

Random sample from those cartoons assuming bipolar magnetic configurations	Random sample from those cartoons assuming complex magnetic configurations	Random sample from the rest
Cartoon due to: Kliem 	Cartoon due to: Giovanelli 	Cartoon due to: Kane-Donnelly 

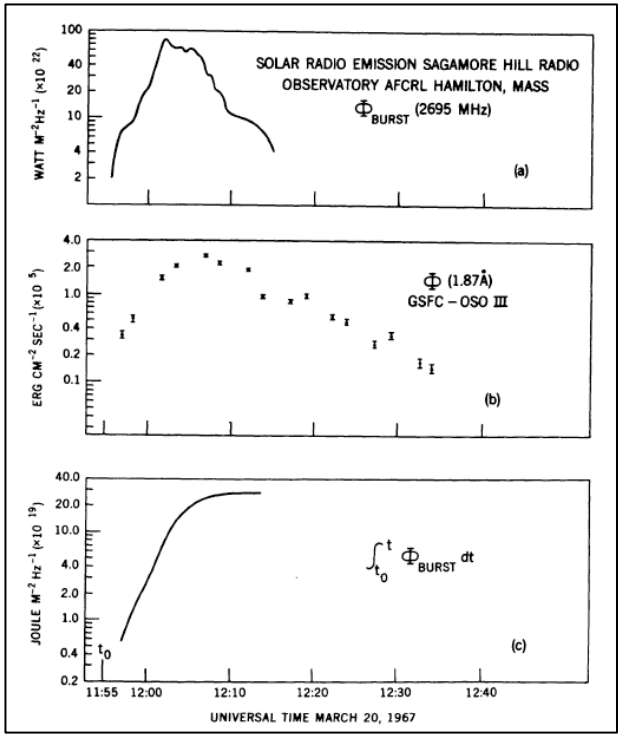
The full Grand Archive of Cartoons

Because of size, we've put the full collection of cartoons, in chronological order and with links to individual pages, on a separate page which should not be downloaded via modem.

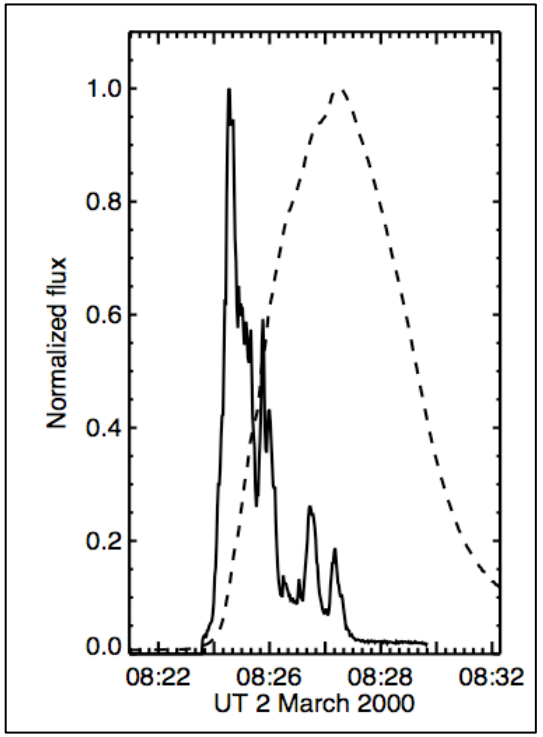
~250 entries at present

The Neupert Effect

The release of energy into a closed field structure will drive chromospheric material up into the corona, and the cooling time there is typically longer than the energy-release time scale. This produces a roughly integral relationship between the thermal and non-thermal signatures.



Neupert, 1968



RHESSI/GOES

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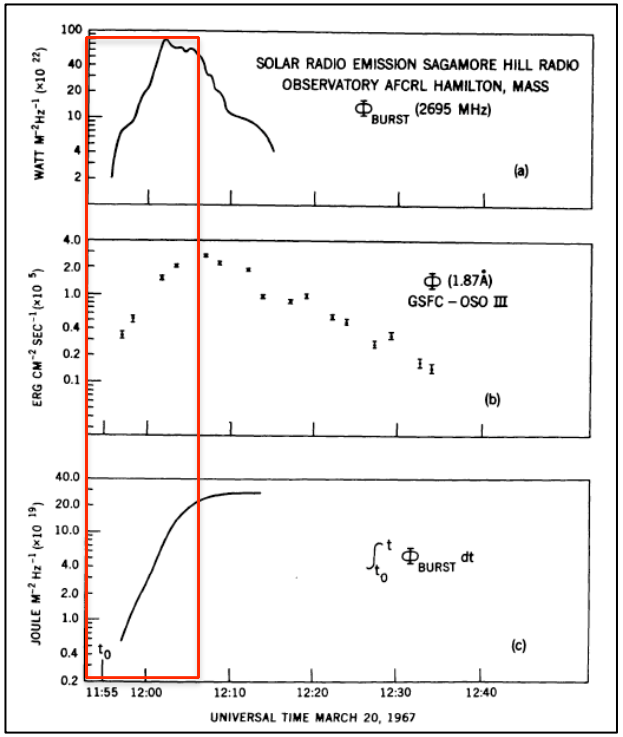
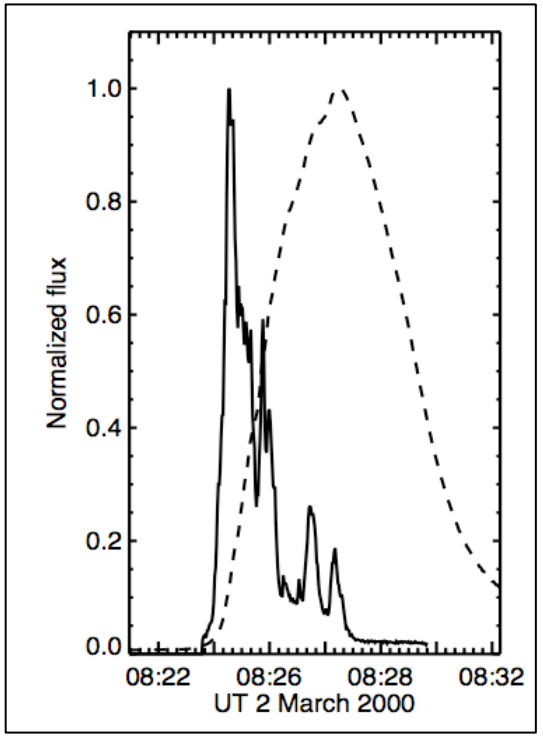


Neupert, 1968 (integral)



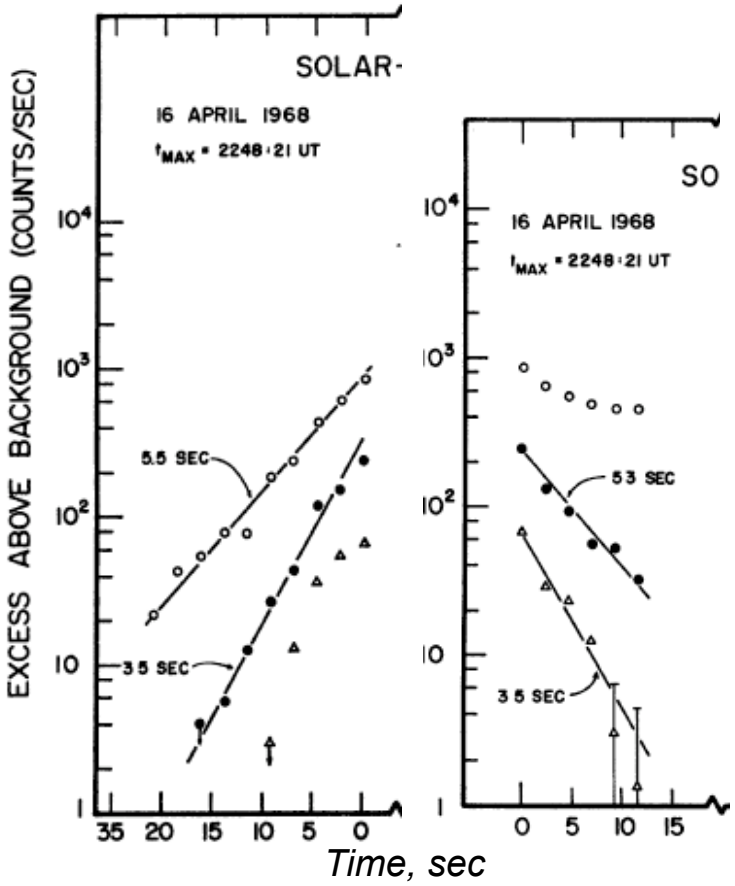
RHESSI/GOES (derivative)

Meaning of the Neupert Effect

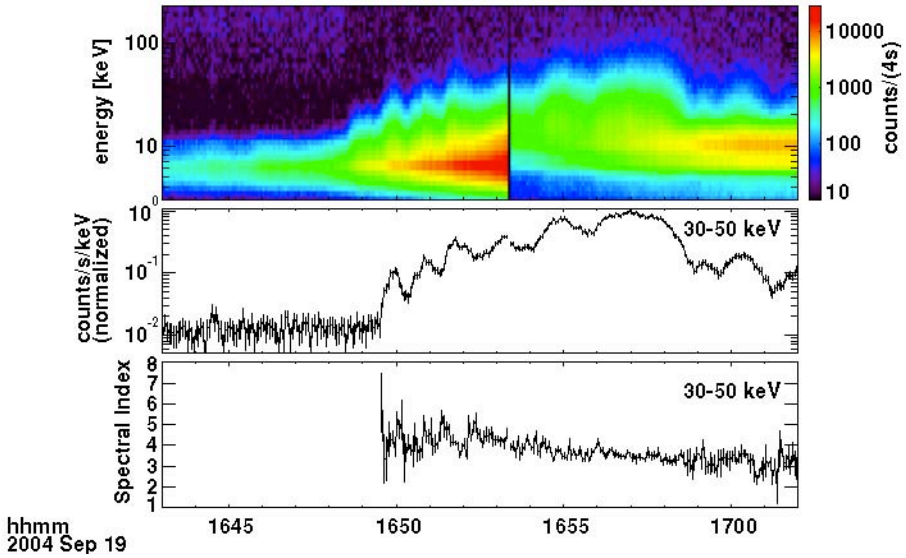
- The Neupert effect just means that there is a slow coronal reservoir for the fast flare dissipation in the interface region
- Specifically, it does not imply anything about the thick-target model, for example – almost any model would be consistent

- Stellar flares show the same relationship

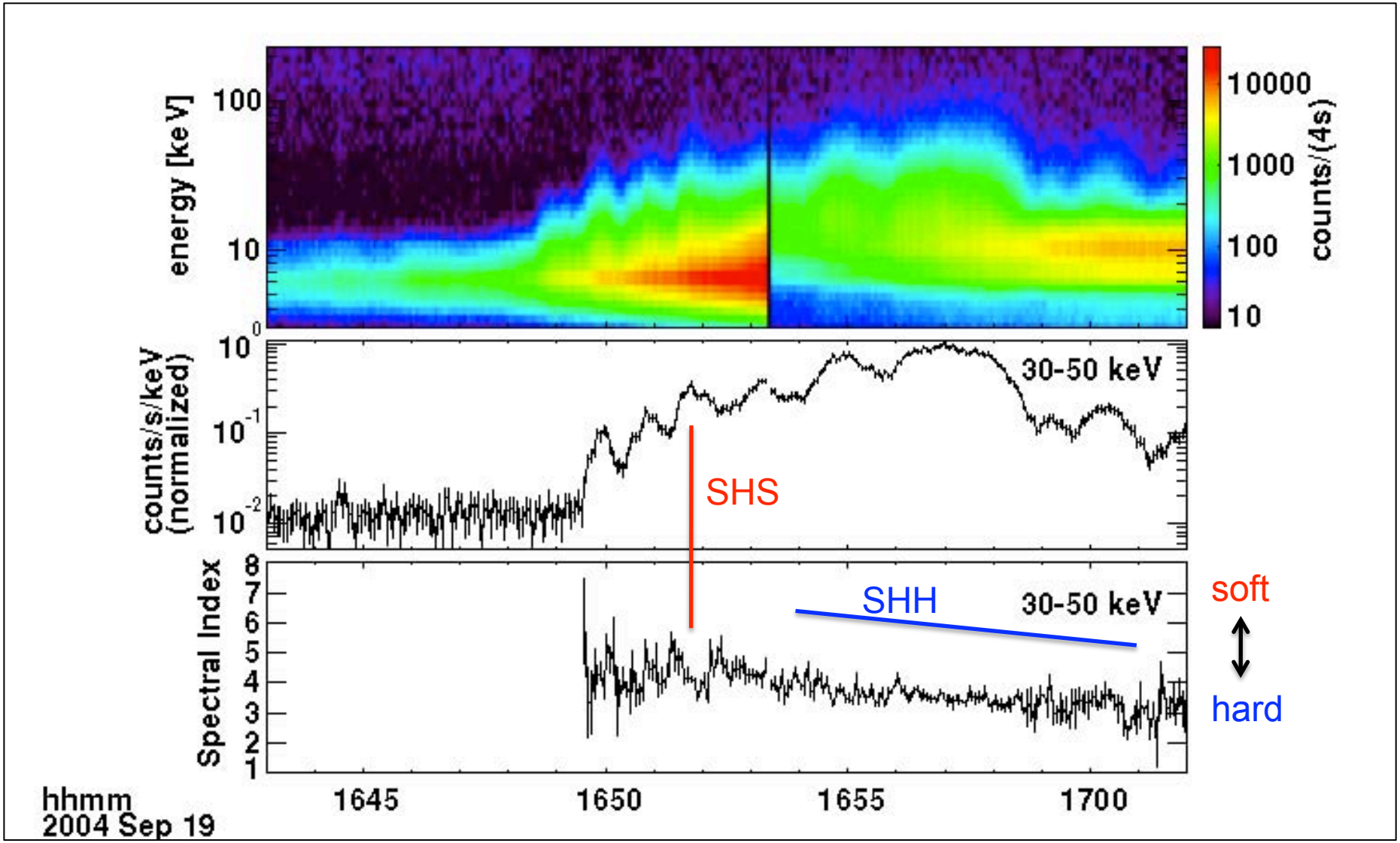
Soft-Hard-Soft pattern



Kane & Anderson, 1970. Note the faster rise and decay times at higher energies: **SHS**.



Grayson et al., 2009. Note the steadily decreasing spectral index following the impulsive peaks. This is a “soft-hard-harder” (**SHH**) event.

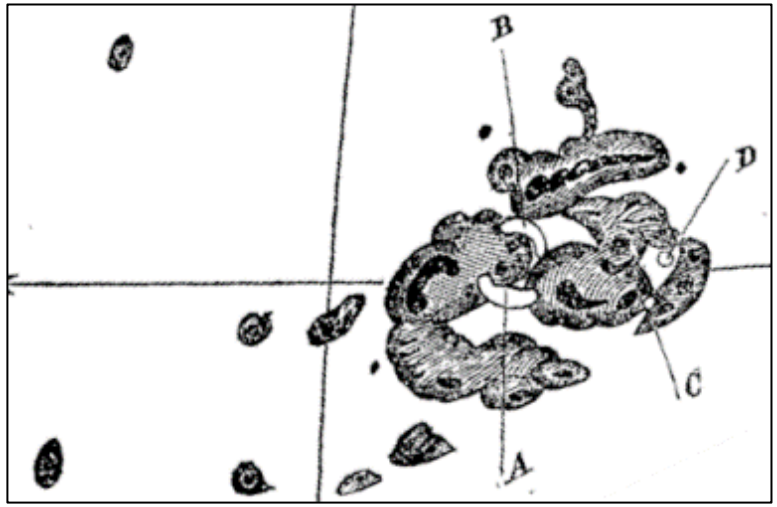

energy [keV]
100
10
0
10000
1000
100
10
counts/(4s)
counts/s/keV
(normalized)
10^{0}
10^{-1}
10^{-2}
30-50 keV
SHS
Spectral Index
8
7
6
5
4
3
2
1
SHH
30-50 keV
soft
hard
hhmm
2004 Sep 19
1645
1650
1655
1700

Significance of morphology

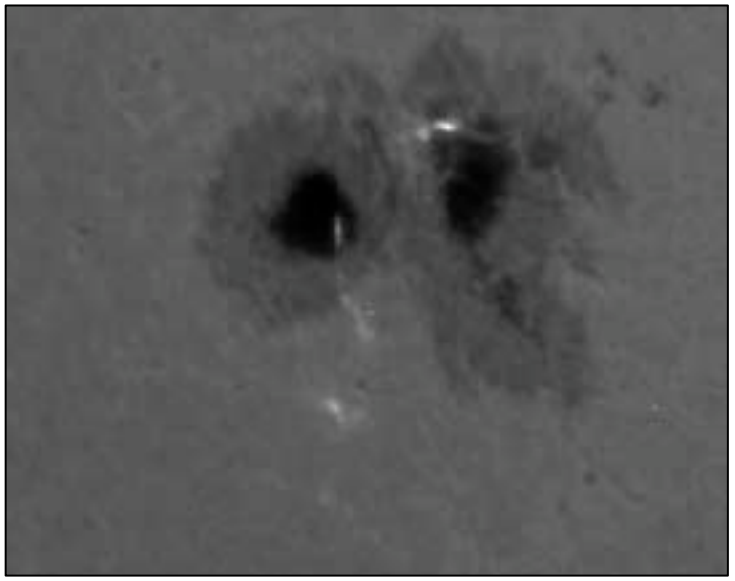
- The ribbons, Neupert effect, and soft-hard-soft spectral evolution create a paradigm that describes much of the behavior of solar flares
- This paradigm also works for some stellar flares, although observing ribbons is not so easy
- Other paradigms exist (SHH and others, such as jets), and these deserve particular interest
- The SHH spectral hardening correlates with CME eruption (Kiplinger, 1995) for reasons we don’t understand yet

White-light flares

- A white-light flare is one that can be observed in the visible continuum, as in Carrington's 1859 discovery
- Because the Sun is so bright, this means that the lower solar atmosphere contains much of the flare energy

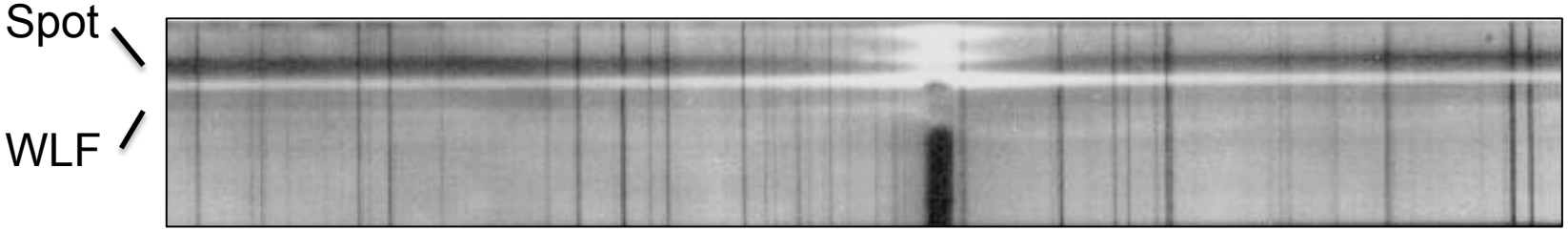


Carrington et al., 1859



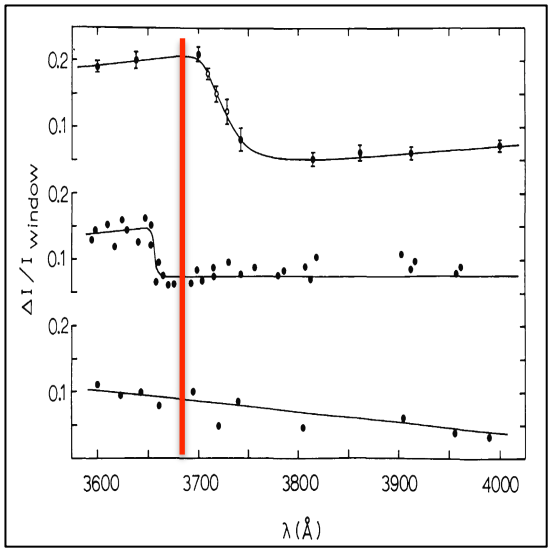
Metcalf et al., 2003

Spectra

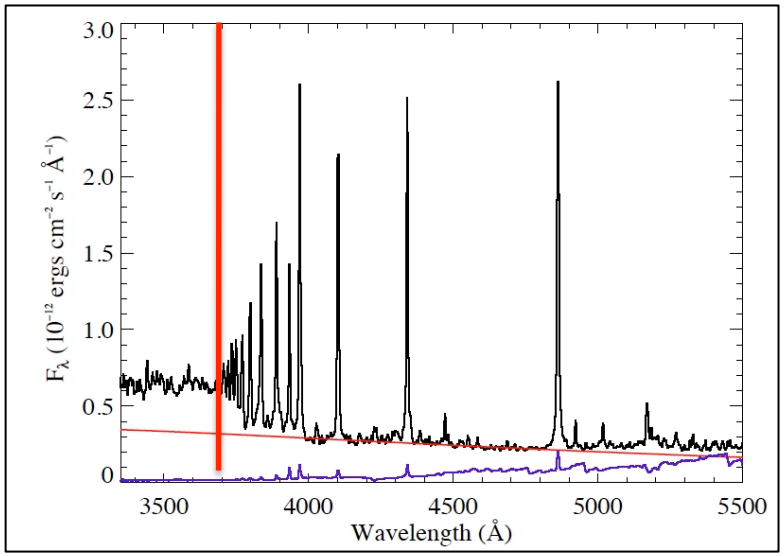


Babin & Koval 2007

Is there a Balmer jump, implying recombination radiation?

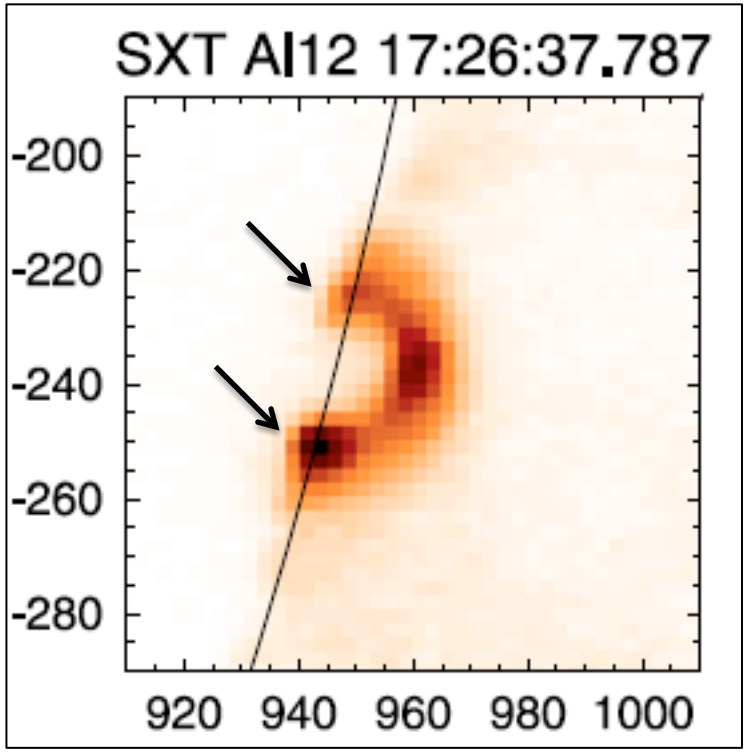


Solar: Neidig, Hiei, and Machado & Rust

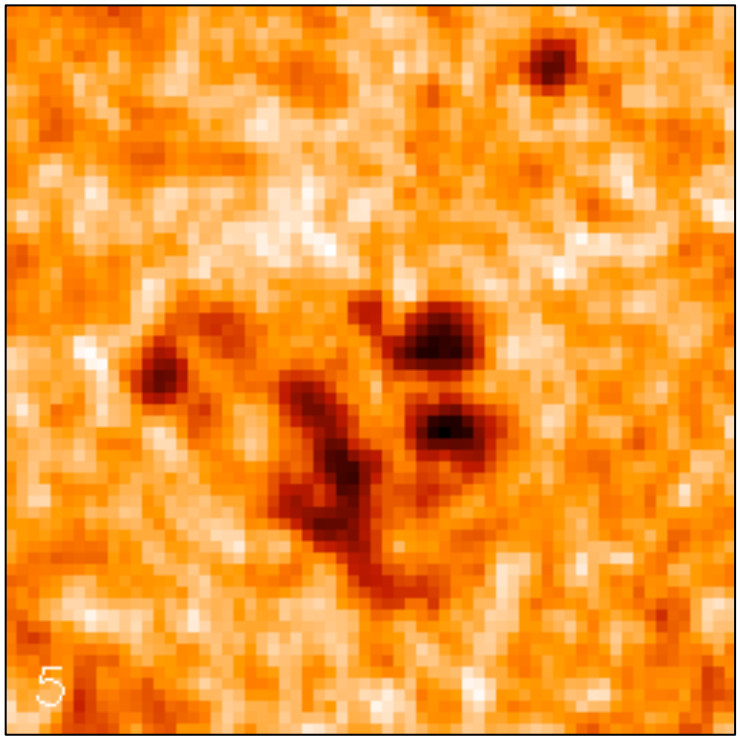


Stellar (YZ Cmi): Kowalski et al. 2012

“Impulsive footpoints”



The “Masuda flare”: a Yohkoh/SXT soft X-ray image



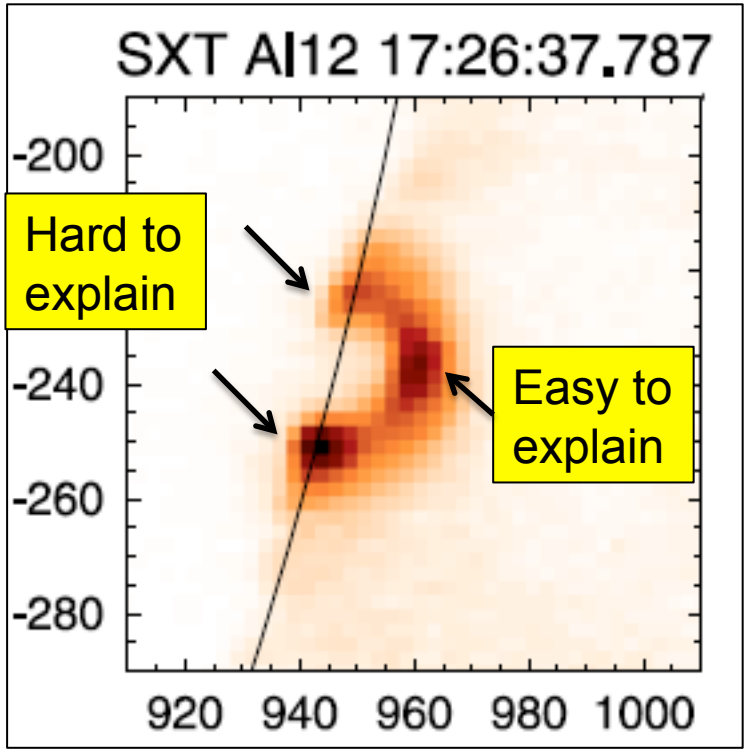
A white-light flare observed by TRACE, 5 s cadence, 0.5” pixels

The footpoint emission is broad-band, to high temperatures; it consists of multiple unresolved sources that vary rapidly with time

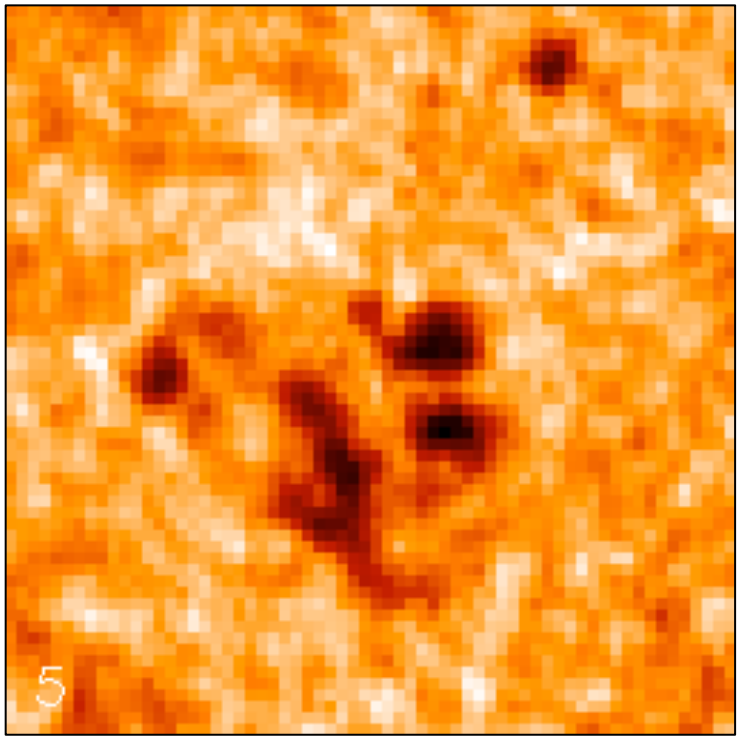
Cultural note

- Please note that the stellar spectra are a lot better than the solar ones, even though the Sun is a much, much brighter star
- This probably reflects the fact that the Sun requires *imaging spectroscopy*, whereas stars don't; and also because solar WL/UV spectroscopy has been slow to get into space
- The EVE instrument (subject of our Thursday practicum) is an interesting hybrid: the Sun as a star

“Impulsive footpoints”



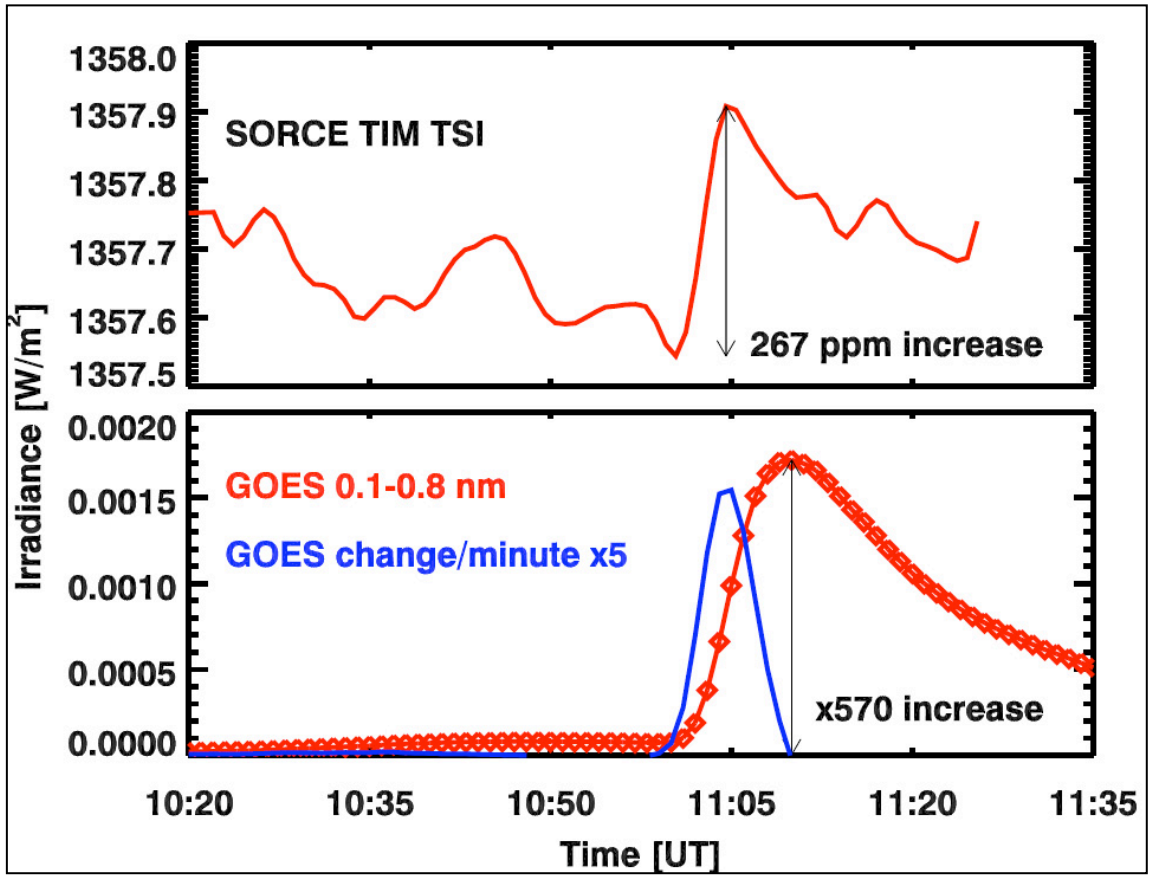
The “Masuda flare”: a Yohkoh/SXT soft X-ray image



A white-light flare observed by TRACE, 5 s cadence, 0.5” pixels

The footpoint emission is broad-band, to high temperatures; it consists of multiple unresolved sources that vary rapidly with time

First bolometric observation of a solar flare

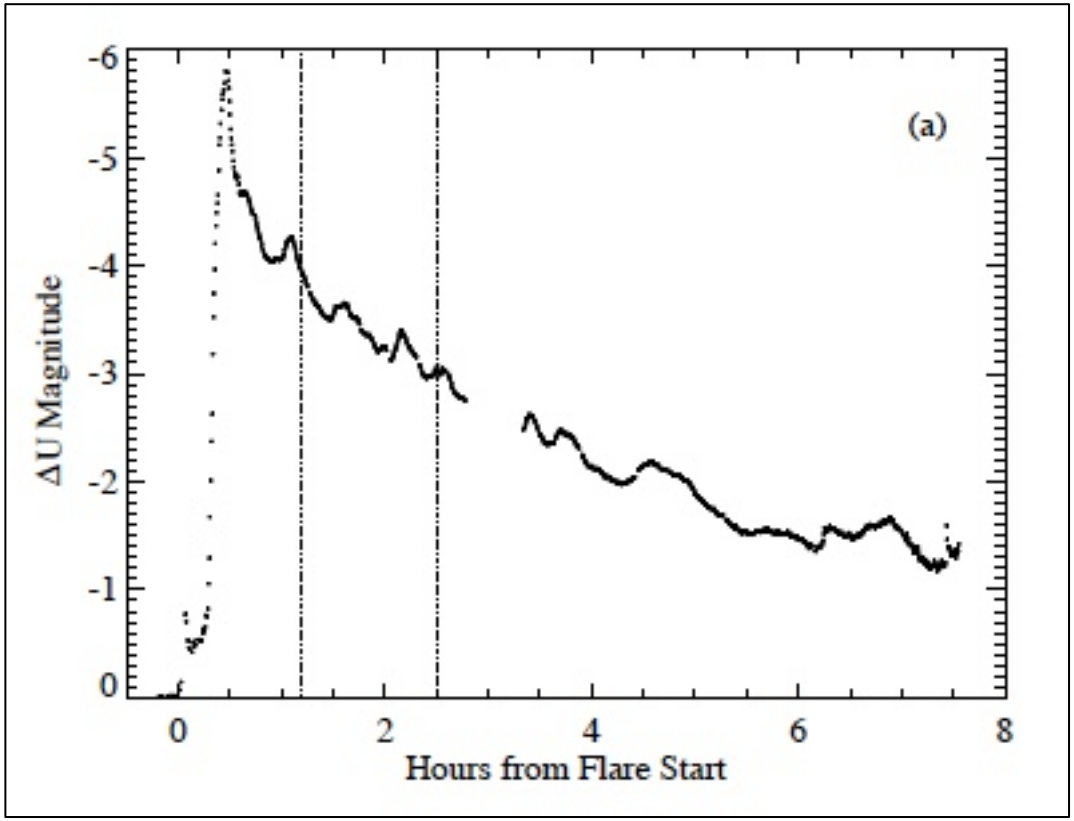


All of the flare radiant energy

About 1% of the radiant energy

Woods et al. 2004

Comparably bolometric observation of a stellar flare

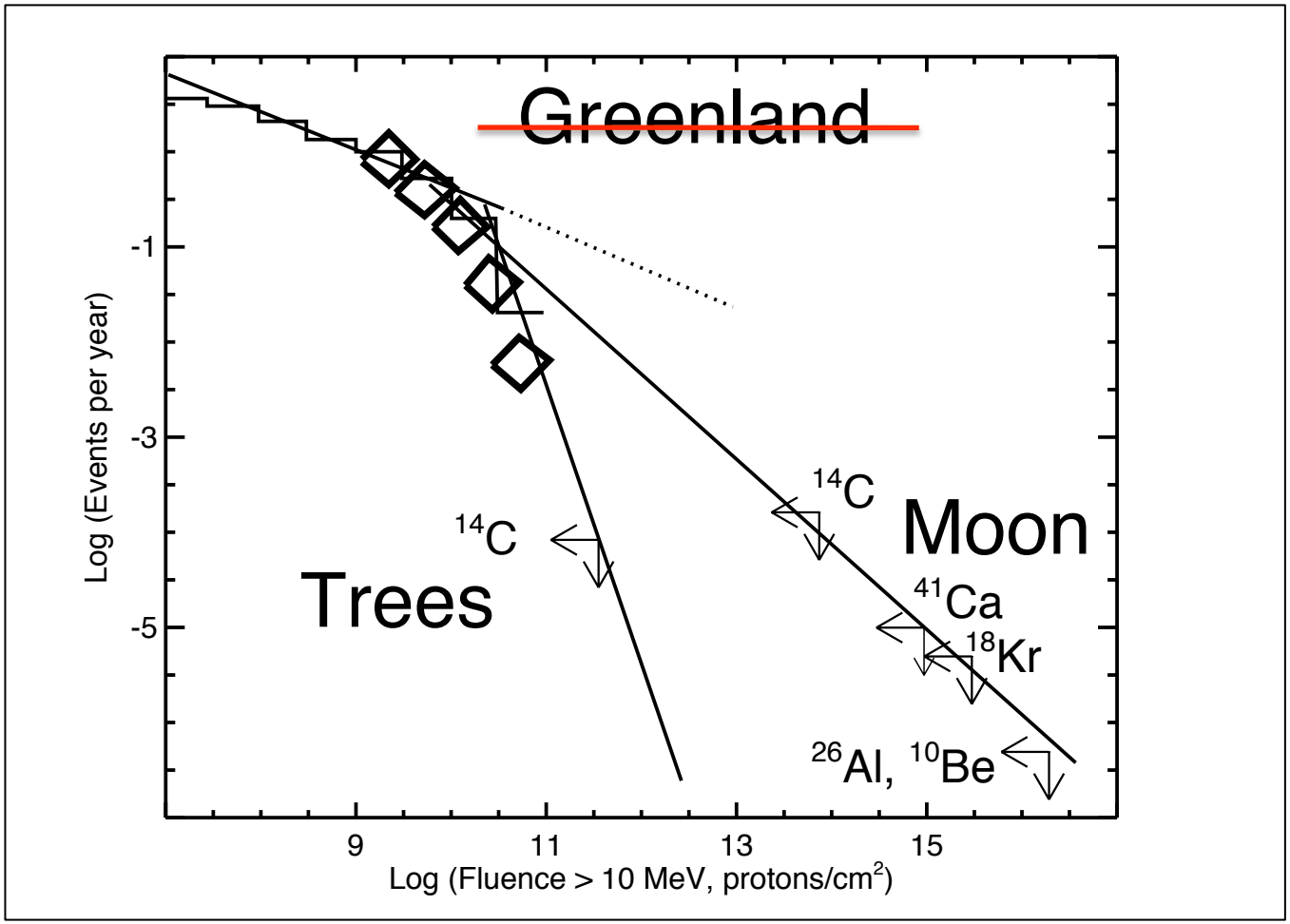


Kowalski et al. 2011

The stellar flare increase is expressed in magnitudes, not parts per million!

L_{flare}/L_{star} is about 10^6 larger for this YZ CMi “megaflare” than for the greatest observed solar flare

Are there Solar Megaflares? No



Hudson, 2010

Summary of spectral information

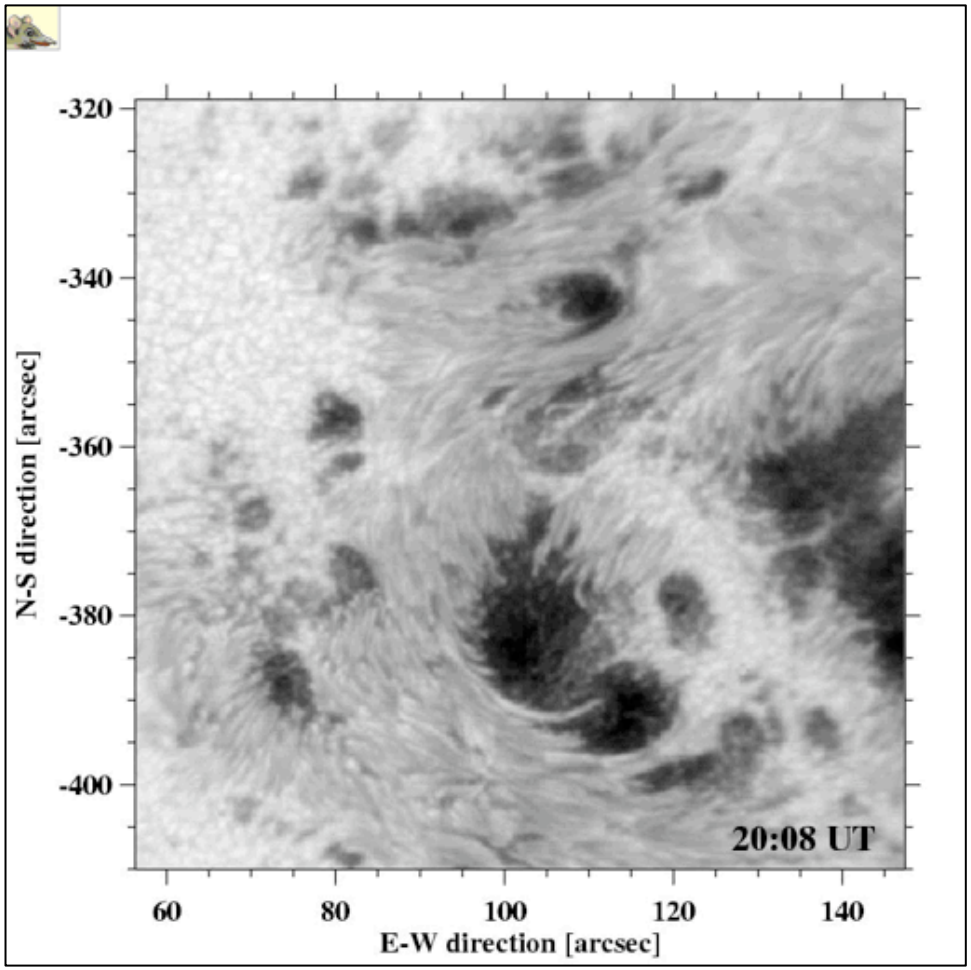
- The solar spectra suggest, and the stellar data establish, the presence of the Balmer jump – hence, optically-thin recombination radiation
- The total energy in the spectrum is not well known because of the lack of UV observations
- The TSI observations constrain the total radiated energy to be about 100x the GOES level

Where is the continuum formed?

- In principle, at the “photosphere” of the flaring region
- But the signatures of recombination suggest a “cloud” layer substantially above the true photosphere
- Are the exotic alternatives, such as synchrotron emission or plasma radiation?

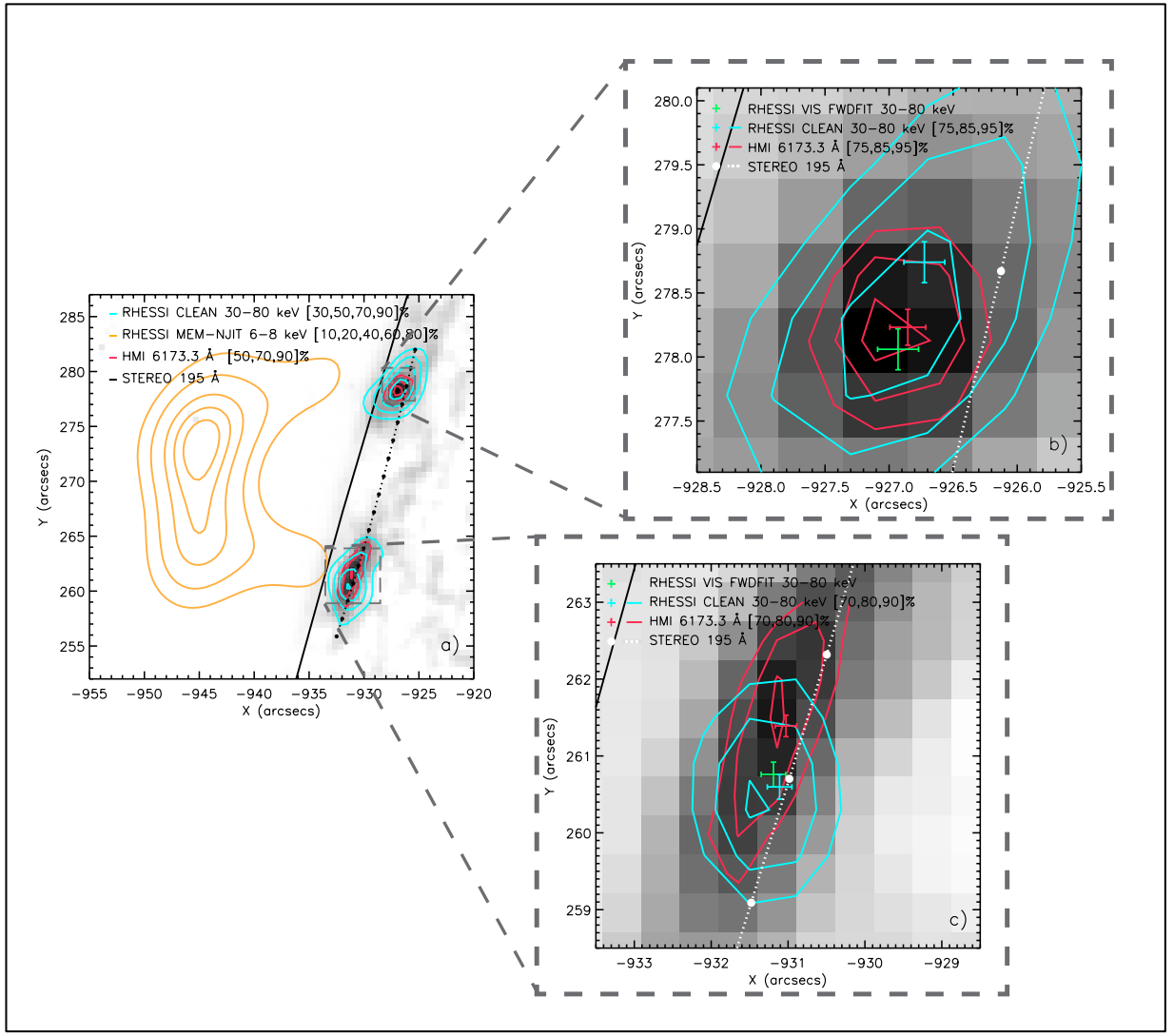
- Spectral and spatial clues now exist…

Flare observation at 1.56μ
“opacity minimum region”



Xu et al. 2004

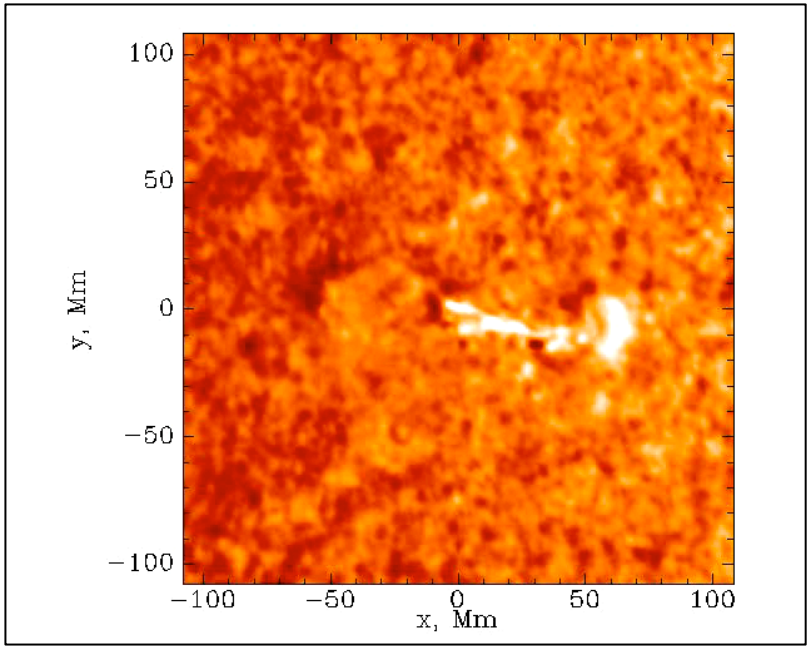
Limb flare SOL2012-02-24



Martínez-Oliveros et al. 2012

Seismic waves

- Flares produce photospheric disturbances at the time of the impulsive phase
- Flare quakes first detected by Kosovichev & Zharkova (1996)



n.b. enhanced!

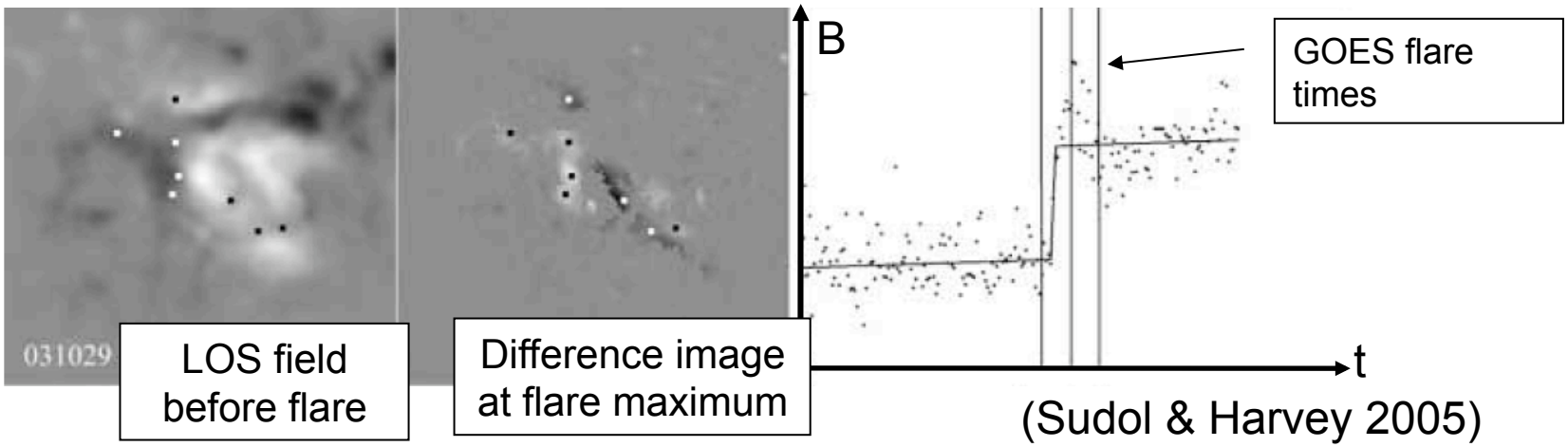
Quake origin is approximately co-spatial with hard X-ray sources, and consumes about 0.01-0.1% of flare energy.

Q. How do we get energy down to such deep layers of the atmosphere, and conserve momentum?

Photospheric field changes

In all large flares the line-of-sight B field at the photosphere changes suddenly by ~10% (0.01 – 0.02T, 100-200 G)

These changes occur are simultaneous with flare, roughly co-spatial with the flare ribbons, and irreversible

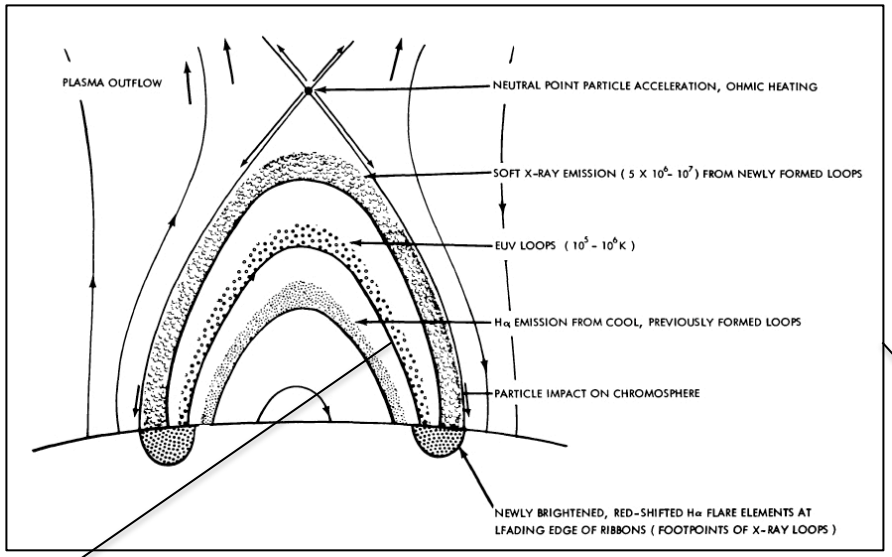


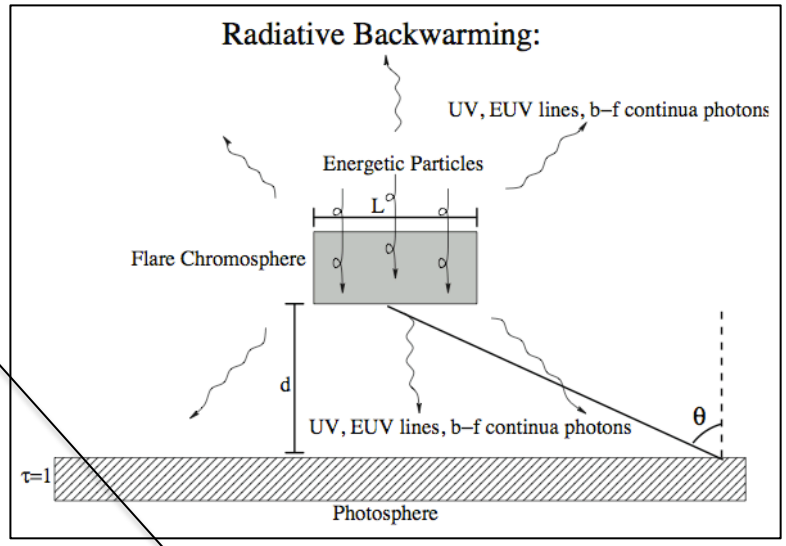
(Sudol & Harvey 2005)

• Does this reflect a “jerk” as the coronal magnetic field reconfigures?

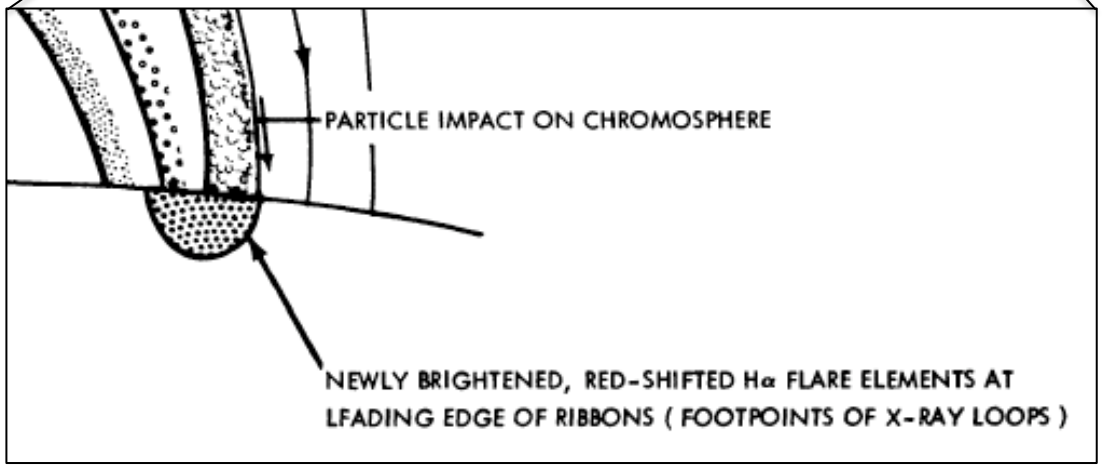
• Note that the timing matches the impulsive phase, consistent with magnetic energy release

Cartoon descriptions of the footpoint sources



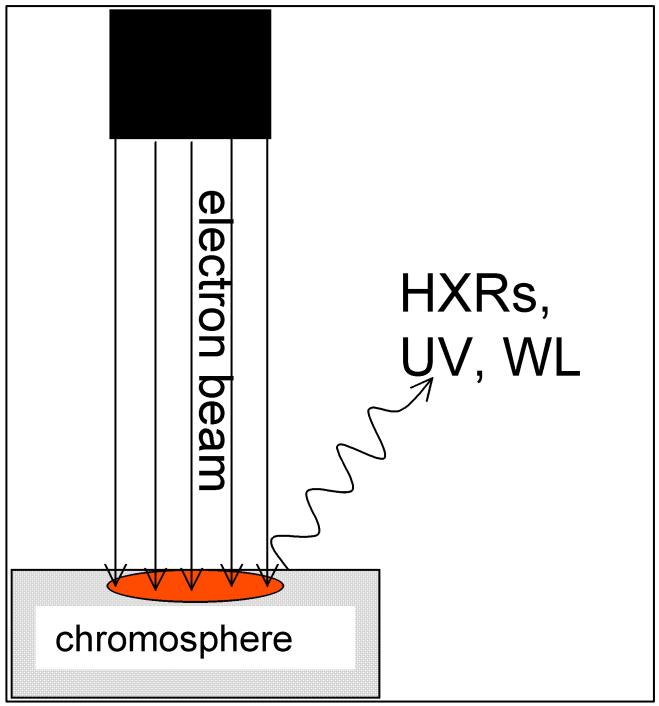


Fisher et al., 2012

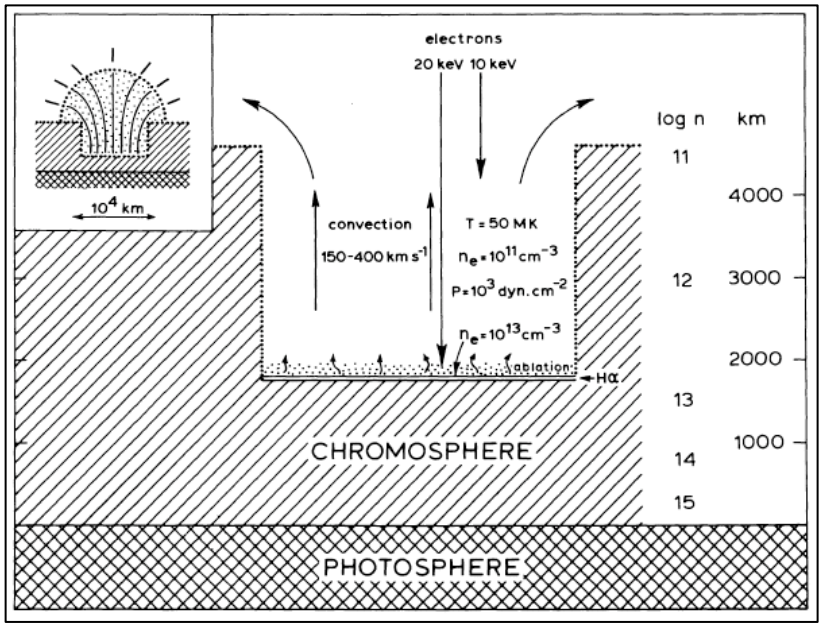


Švestka, 1980

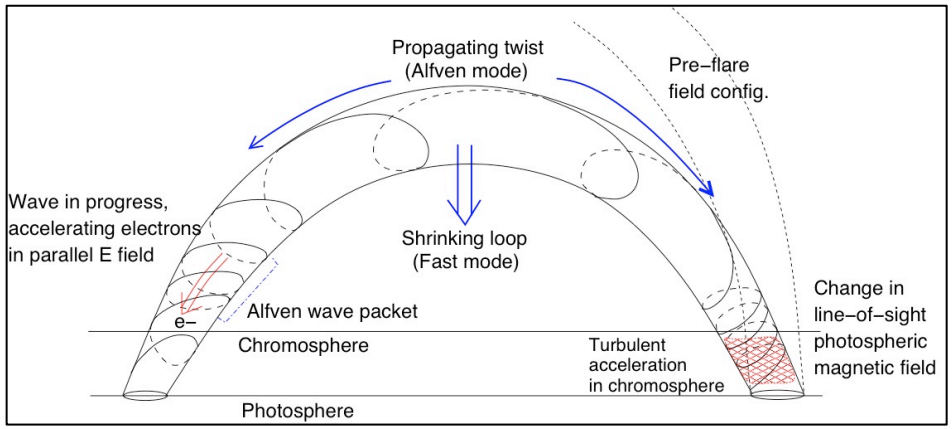
Cartoon descriptions of the footpoint sources



Brown, 1971; Hudson, 1972



De Jager, 1985



Fletcher & Hudson, 2008

Physical descriptions of footpoint sources

- We don’t have any, really, except for the 1D radiation hydrodynamic simulations
- Are these adequate? They omit lots of key physics
- The presence of 10 MK features in the “impulsive footpoint” sources is a mystery
- Probably the true plasma physics is far from our horizon at present, and we must be guided by auroral physics

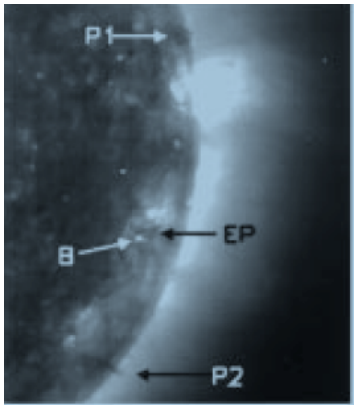
Note on nomenclature: Hudson et al (1994) used this term, but De Jager et al. (1986) and Hoyng (1981) had called them “flare kernels.” This latter is probably a better name.

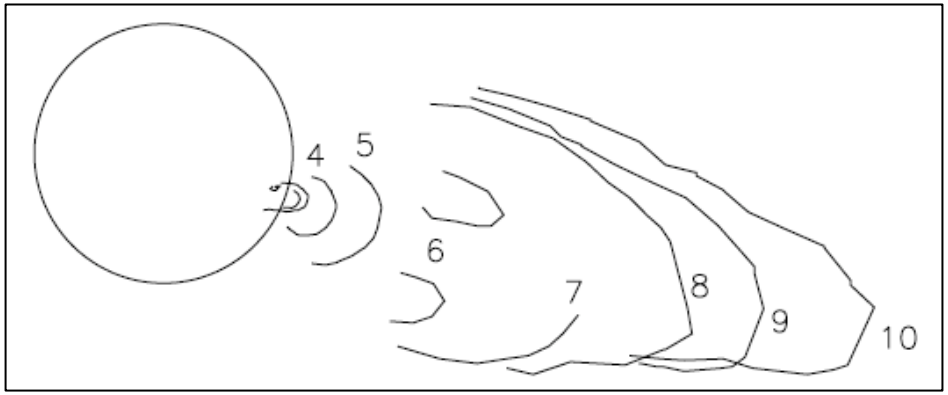
A Quandary

- The IR emission and the direct imaging tell us that the source is at the level of the pre-flare photosphere
- The spectrum tells us that the radiation is from a cloud formed in an optically thin layer
- We need detailed observations of the lower atmosphere, and they are arriving: IBIS now, IRIS and ALMA soon, ATST under construction

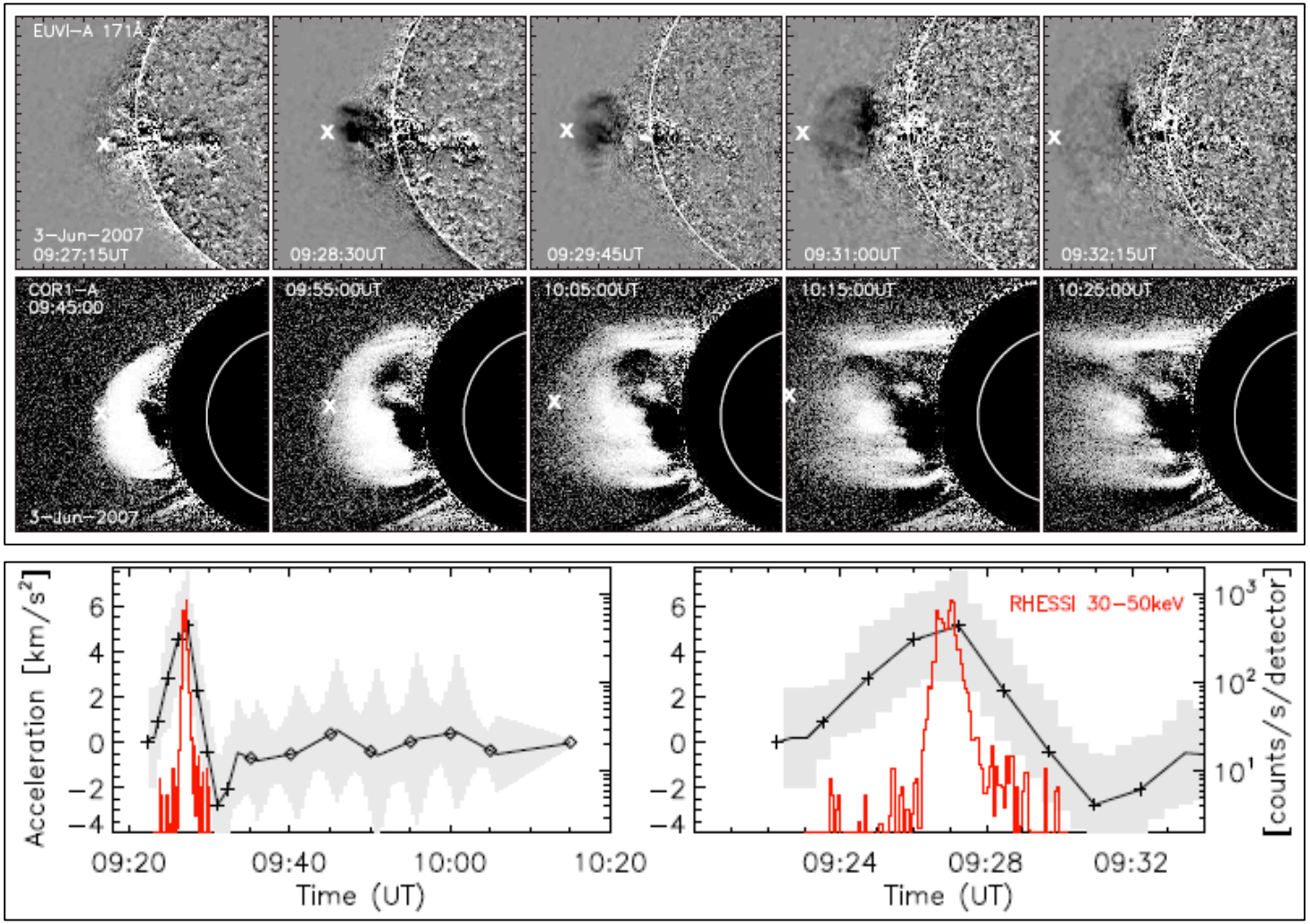
CME initiation and the impulsive phase

- There has been a widespread belief that CMEs (next lecture) are somehow independent of, and more energetic than, solar flares
- This belief is incorrect, even though it features in modern 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

Features of the impulsive phase

- Intense release of main flare energy
- Stepwise changes in the magnetic field
- CME acceleration
- Seismic waves in the interior
- Energetically significant particle acceleration

What to remember

- Solar flares have clearly defined simple paradigms
- The impulsive phase dominates the energetics of a flare/ CME
- The physics of the interface region has many interesting and almost wholly un-studied problems
- There are now, and will soon be, lots of highly relevant new data

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)
- H. Hudson, 2011, “Global Properties of Solar Flares,” SSR 158, 5
- 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