The Role of Particles in Solar Magnetic Activity

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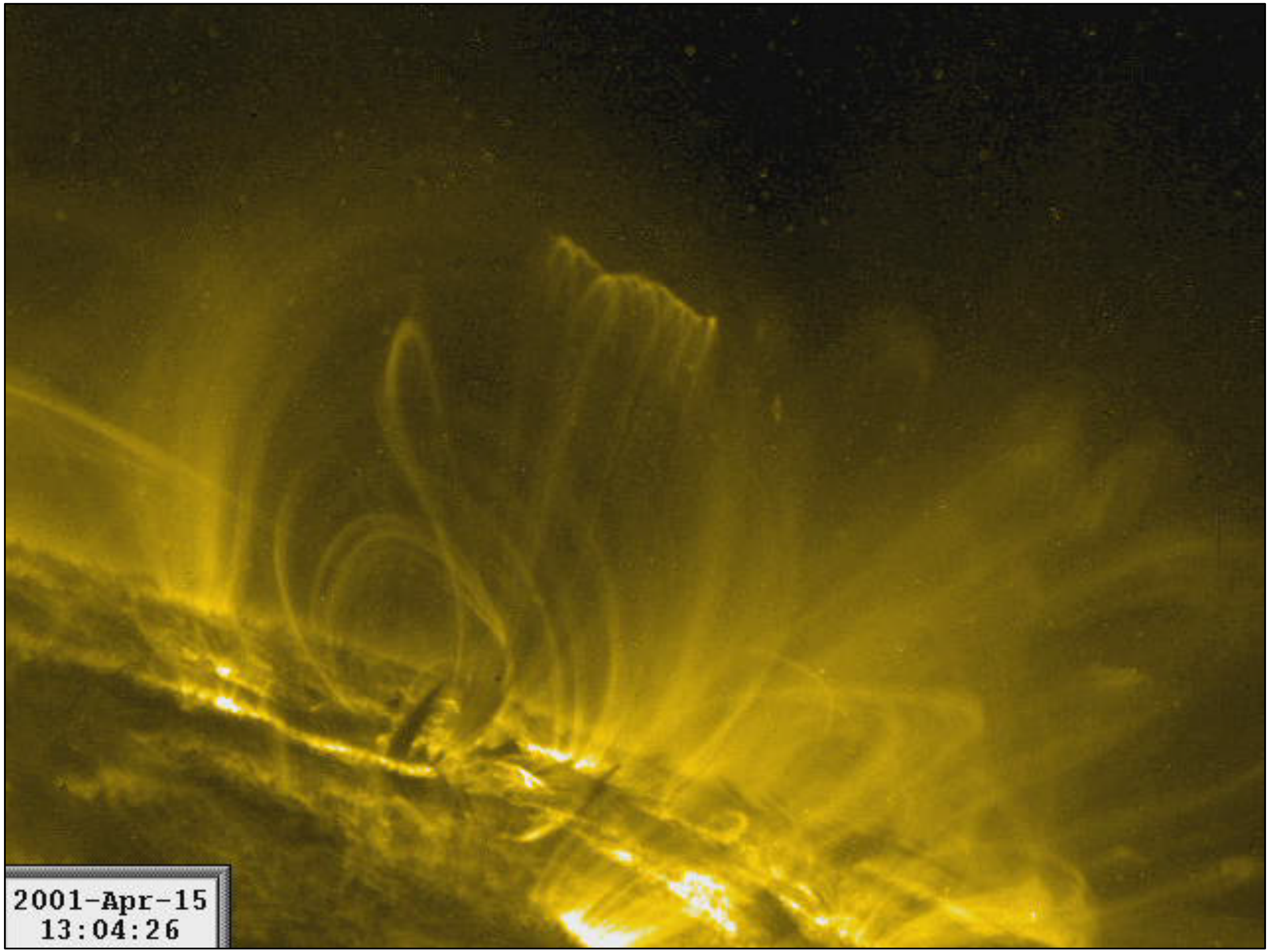
1.

The various aspects of solar magnetic activity include the topics of coronal heating, flares, CMEs, "space weather" and many other phenomena largely seen in the solar atmosphere. These often involve the acceleration of non-thermal particles, in large numbers and far outside the energies that particles would have in any fluid description of the process. I will describe our knowledge of these inherently non-thermal effects and ask how they relate to our theoretical descriptions, many of which simply ignore energy and momentum transport by the particles.

Favorite movie

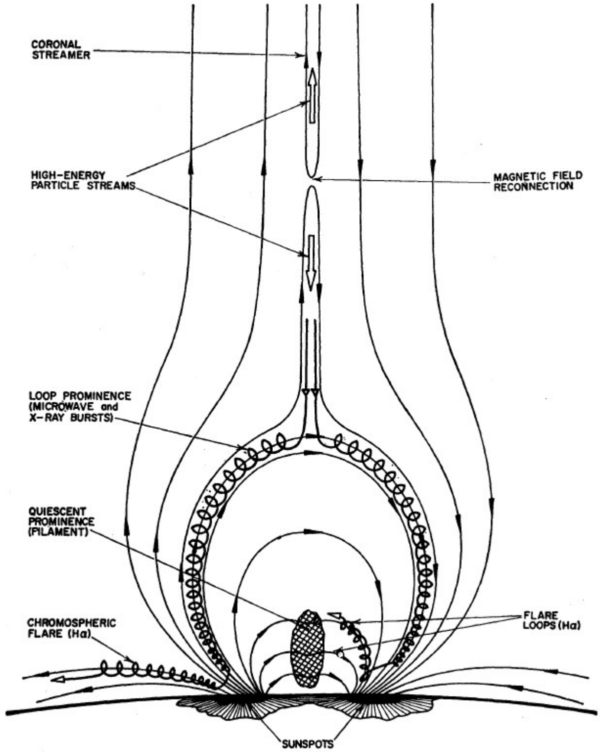


Favorite movie

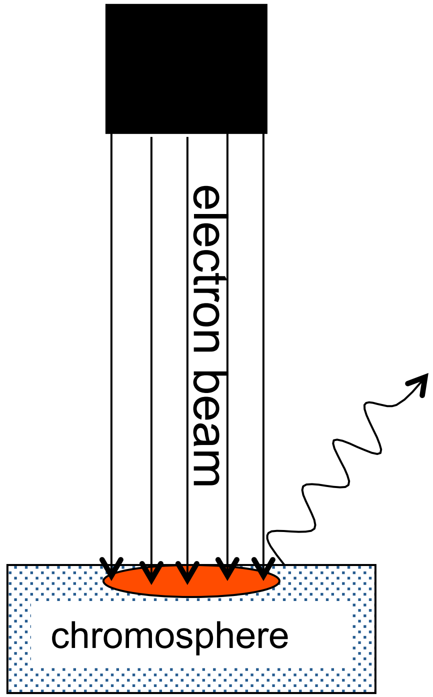
Things to note

- Implosion
- Compact energy release
- Dimming
- Coupled oscillations

Basic flare/CME concepts

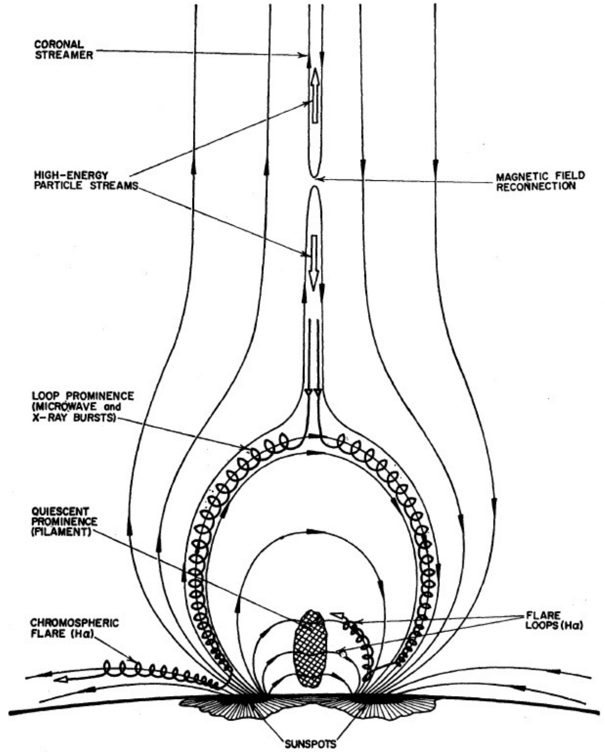


Strauss & Papagiannis, ApJ 164, 369 (1971) – basically, "CSHKP"



Kane & Donnelly, ApJ 164, 171 (1971) – basically, the "thick-target model"

Basic flare/CME concepts



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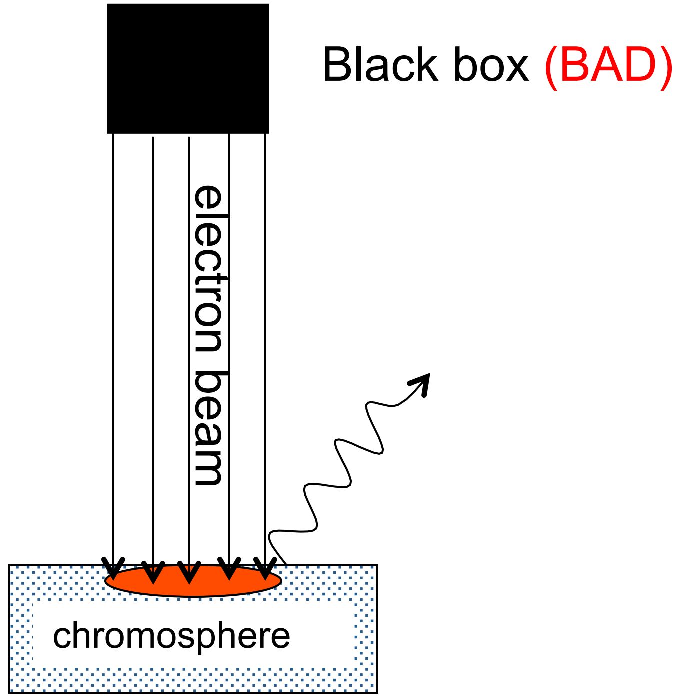

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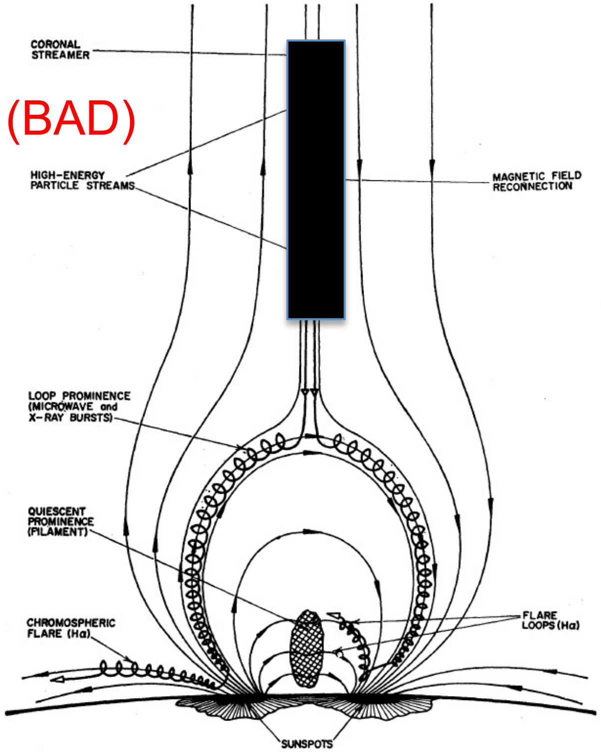
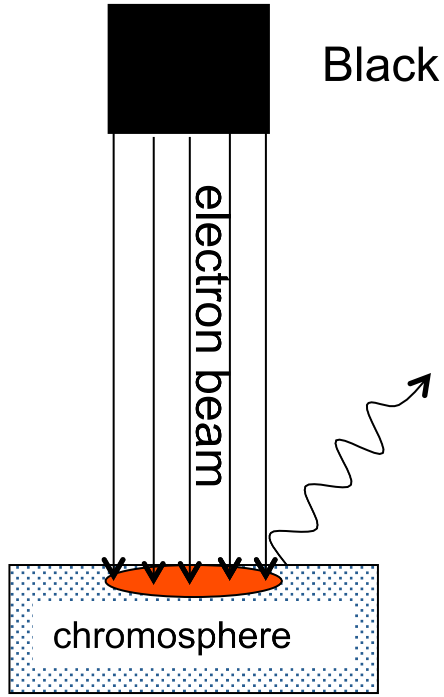
Basic flare/CME concepts

Another one (BAD)



Strauss & Papagiannis, ApJ 164, 369 (1971) – basically, "CSHKP"

Black box (BAD)



Kane & Donnelly, ApJ 164, 171 (1971) – basically, the "thick-target model"

Critique of standard models

- There is no self-consistency between the particle and fluid pictures. Basically the paradigms ignore one another.
- The existing models may have difficulty with energy conservation.
- The pre-existing current sheet and the black box are purely *ad hoc.* A pre-flare current sheet is not observed.

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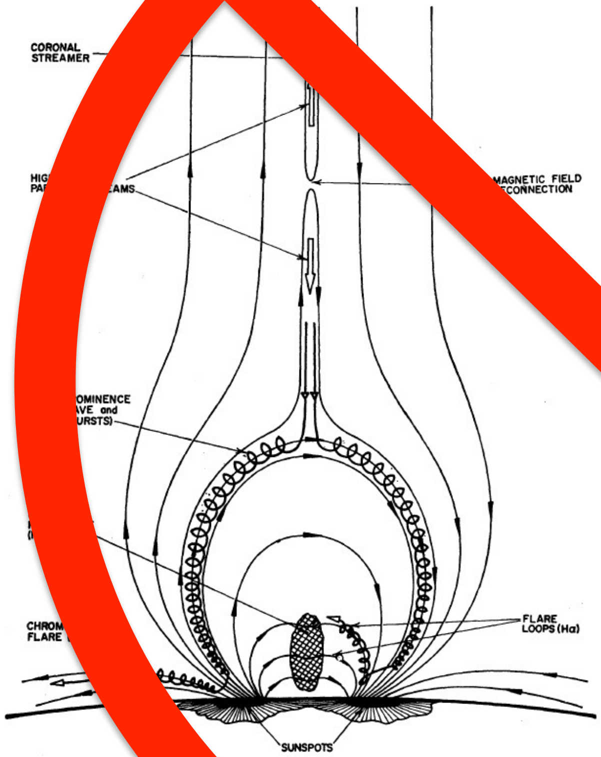
Particles are energetically important in both flares and CMEs, and the paradigms should not work at cross-purposes.

Purpose of this talk

- Describe flare/CME physics from a particle point of view
- Try to learn how to reconcile this with the current state-of-the art theories and models



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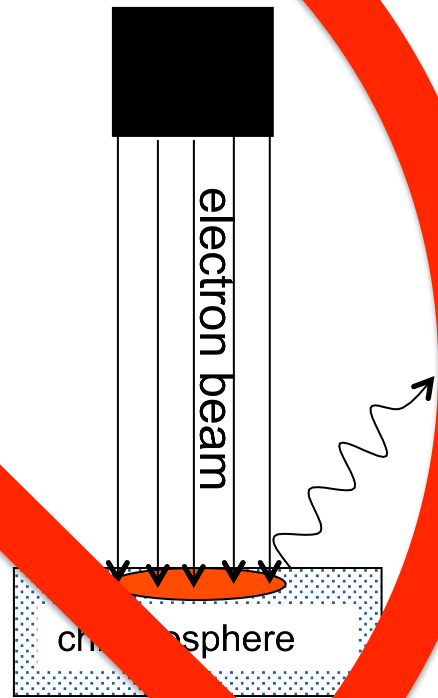
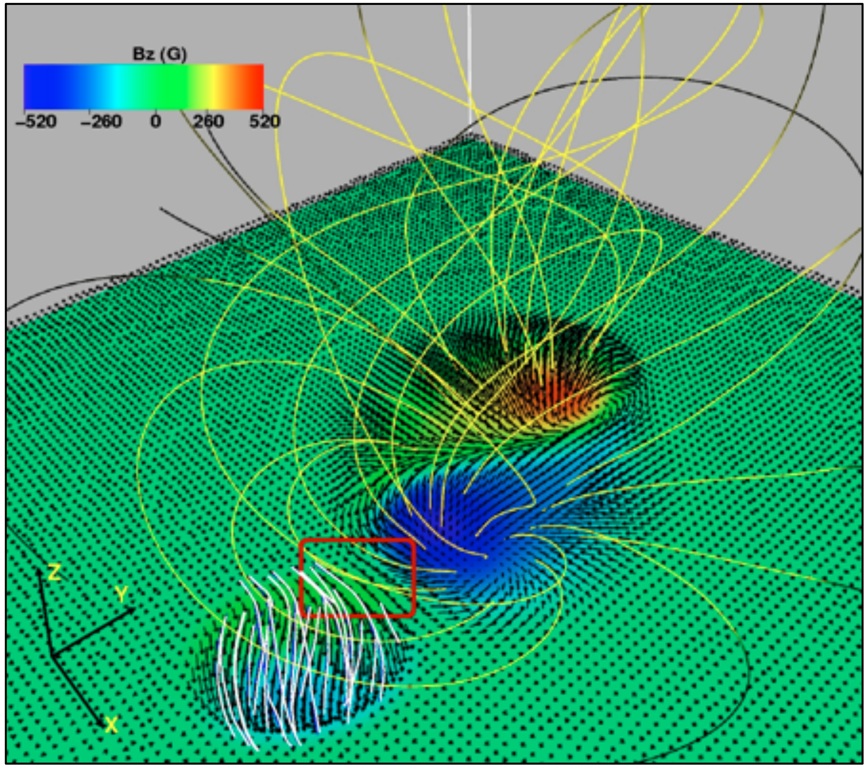
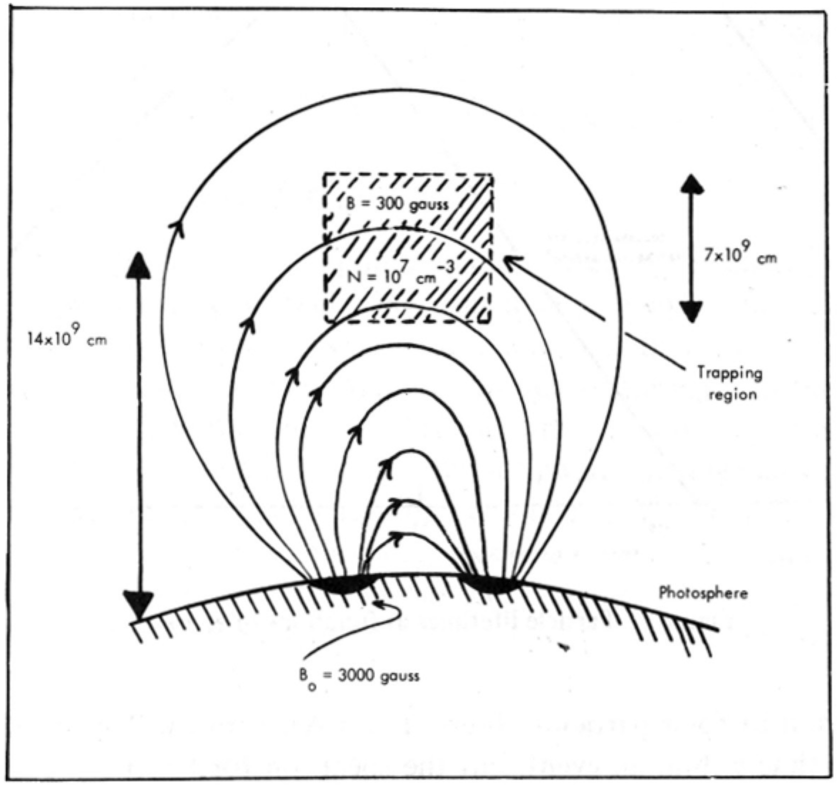


Kane & Donnell… 164, 171 (1971) – basic…, the “thick-target model”

By consensus, magnetic activity (flares etc.) requires coronal energy storage: *What stresses the magnetic field?*



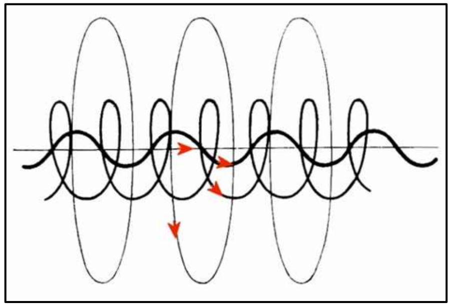
(a) Classical MHD view (footpoint motion; Gontikakis et al. 2009)



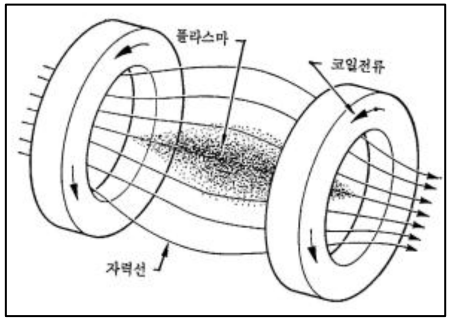
(b) Trapped-particle stress (Elliott, 1973)

Particle stresses in a low-β plasma

- The mirror force can trap particles with energy densities that might be large compared with those related to weak parallel currents
- In the magnetosphere, one sees such particle distributions (mostly gyrotropic)
- Loss-cone or other instabilities may be present, and then one may need “agyrotropy”



1) Stress via externally driven current



2) Stress from trapped collisionless particles

Three questions about the MHD approach

1) Non-locality (cite Alfvén)
2) Absence of inductive field (see Melrose)
3) Modeling with no chromospheric physics (quote Hood)

Non-locality

- Solutions of differential equations depend on the assumed boundary conditions

- MHD generally ignores particles
  - at 20 keV, flare electrons are ~ 20 kT
  - at 1 MeV, SEP protons are ~ 1000 kT

- Waves as well as particles can effect “action at a distance”

The inductive electric field

THE ASTROPHYSICAL JOURNAL, 749:59 (8pp), 2012 April 10 doi:10.1088/0004-637X/749/1/59

MAGNETIC EXPLOSIONS: ROLE OF THE INDUCTIVE ELECTRIC FIELD

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Sydney Institute for Astronomy, School of Physics, The University of Sydney, NSW 2006, Australia
Received 2011 November 24; accepted 2012 January 6; published 2012 March 22

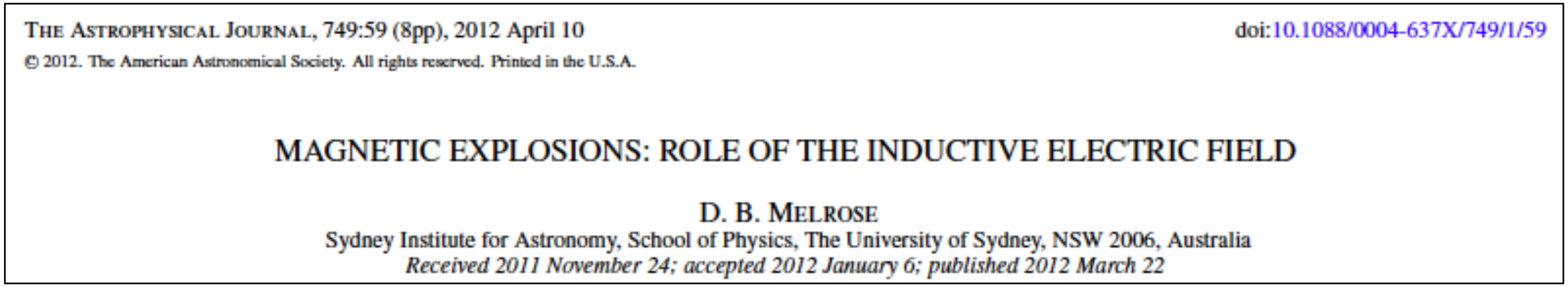
$$\mathrm{curl}\,\mathbf{E}_{\mathrm{ind}\,\perp} = -\frac{\partial \mathbf{B}}{\partial t}, \qquad \mathrm{div}\,\mathbf{E}_{\mathrm{ind}\,\perp} = \frac{\rho}{\varepsilon_0}.$$

$$\mathbf{E}_{\mathrm{ind}\,\perp} = -\mathbf{u}_{\mathrm{ind}} \times \mathbf{B}, \qquad \mathbf{u}_{\mathrm{ind}} = \frac{\mathbf{E}_{\mathrm{ind}\,\perp} \times \mathbf{B}}{|\mathbf{B}|^2}.$$

$$\frac{\partial \mathbf{B}}{\partial t} = \mathrm{curl}\,(\mathbf{u}_{\mathrm{ind}} \times \mathbf{B}),$$

"Inductive drift" motion can be identified with "field-line motion" and has a steeper gradient that magnetic pressure, otherwise implicated in driving reconnection. The inductive electric field is large.

The inductive electric field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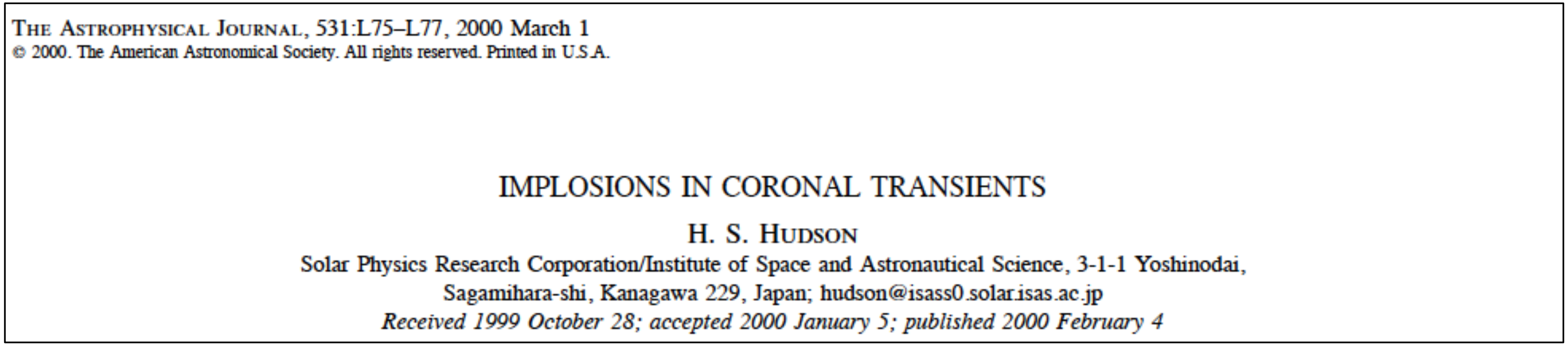
THE ASTROPHYSICAL JOURNAL, 531:L75–L77, 2000 March 1

IMPLOSIONS IN CORONAL TRANSIENTS

H. S. HUDSON
Solar Physics Research Corporation/Institute of Space and Astronautical Science, 3-1-1 Yoshinodai, Sagamihara-shi, Kanagawa 229, Japan; hudson@isass0.solar.isas.ac.jp
Received 1999 October 28; accepted 2000 January 5; published 2000 February 4

Implosion or explosion?

The Astrophysical Journal, 531:L75–L77, 2000 March 1

75 cites

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Received 1999 October 28; accepted 2000 January 5; published 2000 February 4

The Astrophysical Journal, 552:833–848, 2001 May 10

301 cites

ONSET OF THE MAGNETIC EXPLOSION IN SOLAR FLARES AND CORONAL MASS EJECTIONS

Ronald L. Moore and Alphonse C. Sterling[1]
Marshall Space Flight Center, SD50/Space Science Department, Huntsville, AL 35812; ron.moore@msfc.nasa.gov, asterling@solar.stanford.edu
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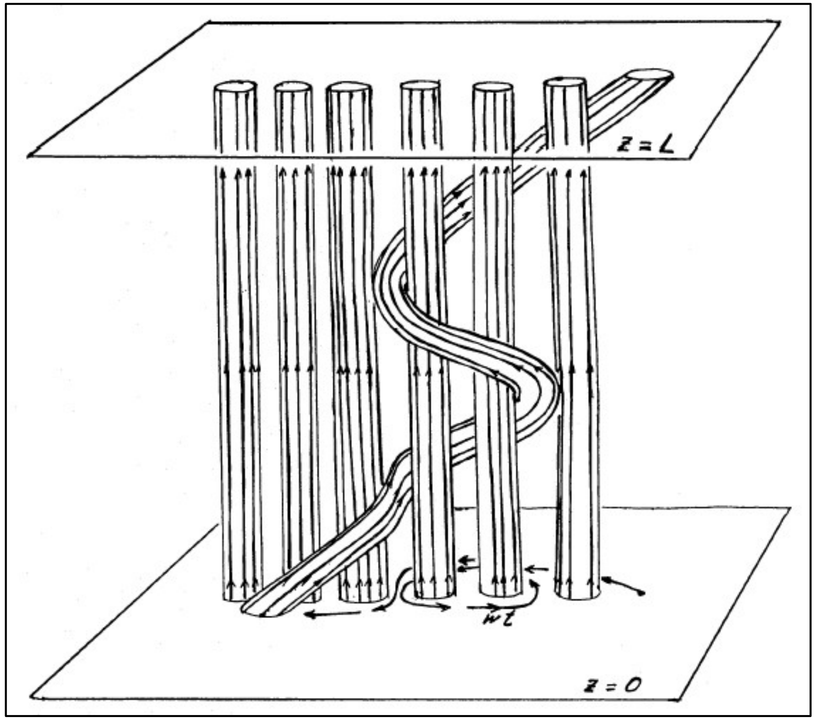
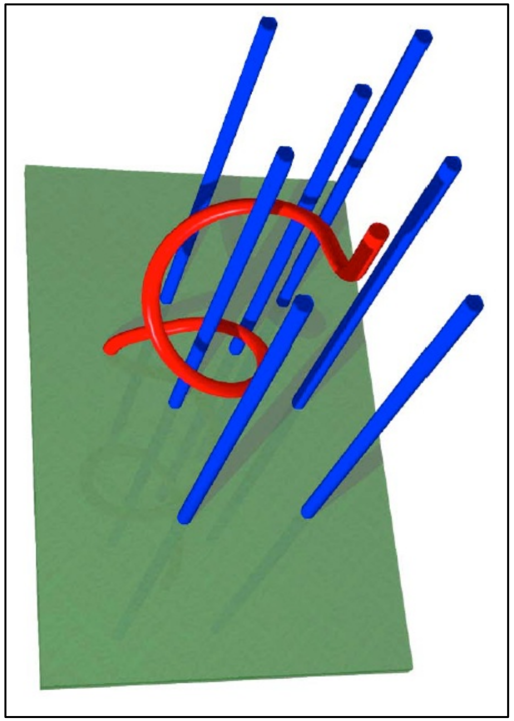
Received 2000 September 15; accepted 2001 January 19

Lack of chromosphere



Parker 1983



Sakurai 2007

The Parker problem: a “Coals to Newcastle” slide in Dundee!

Lack of chromosphere

- Ion-neutral physics
- Transition of beta
- Collisionality horizon
- Optical depth unity
- Big temperature jump
- Convective limit
- Flare radiant energy
- Alfvén speed brake

Inexplicably, this physics-laden domain (the chromosphere/TR) is often taken as a boundary for numerical simulations!

Are particles really important? Yes.

Are particles really important? Yes.

- Flare impulsive phase (Lin & Hudson 1976; “…the 10-100 keV electrons… constitute the bulk of the total flare energy.”)
- Gamma-ray flares (Ramaty et al. 1995; “…a large fraction of the available flare energy is contained in accelerated ions.”)
- Coronal hard X-rays: non-thermal electron pressure may dominate (Krucker et al. 2011; “…density of electrons above 18 keV … at least 10^{10} cm^{-3}.”)
- SEPs (Mewaldt et al. 2005; “…The largest SEP events have an average SEP/CME kinetic-energy ratio > 10%.”)

Up to here and no further…

The Aly-Sturrock conjecture

- A “least upper bound” for the excess of the magnetic free energy of a stellar corona would be comparable to the energy of the fully open field (paraphrased from Aly, 1984).
- There may be ways around this (six lines of argument; see Forbes, 2000, or the Shibata & Magara LRAA article). But I don’t accept them.
- But it makes intuitive sense: field-aligned currents add magnetism and should inflate the field geometrically as they store energy (Low & Lou, 1991; Georgoulis et al., 2012).
- Opening the field, as in a CME, costs energy.

Implosion Conjecture

- Flare energy-release time scales are much shorter than the time scales for energy build-up

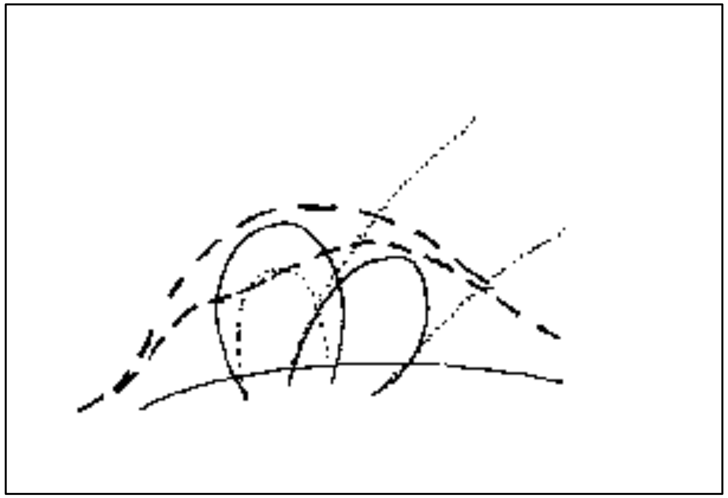
- The Alfven speed in the photosphere is low, so there can be little real-time energy transfer

- The total magnetic energy increases if the scale increases, as is seen in the Low & Lou exact solutions

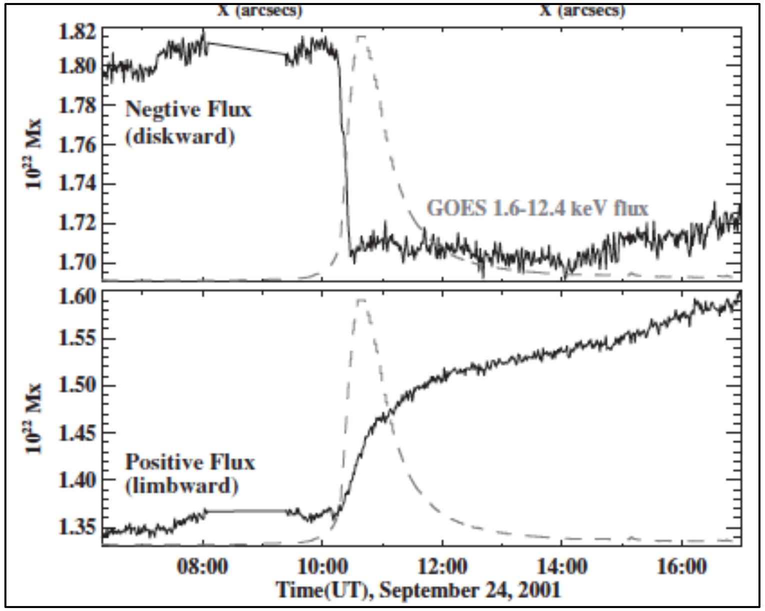
- Within the volume of energy storage, a shrinkage of the B^2 level surfaces must occur in some parts of the volume circumscribing the required energy E^*:

$$E^*(\Delta t) < \int_{V^*} \left(\frac{B^2}{8\pi}\right) dV \sim \frac{B^2}{8\pi}\frac{4\pi}{3}(\Delta t v_A)^3$$

The Magnetic Implosion



Hudson, ApJ 531, L75 (2000)



Wang & Liu, 2010

In this cartoon, the heavy dashed lines show "magnetoisobars," which must collapse into a smaller structure when the flare happens.

The observations show an inward tilt of the photospheric vector field, matching the time of energy release. (e.g. Liu & Wang, 2009)

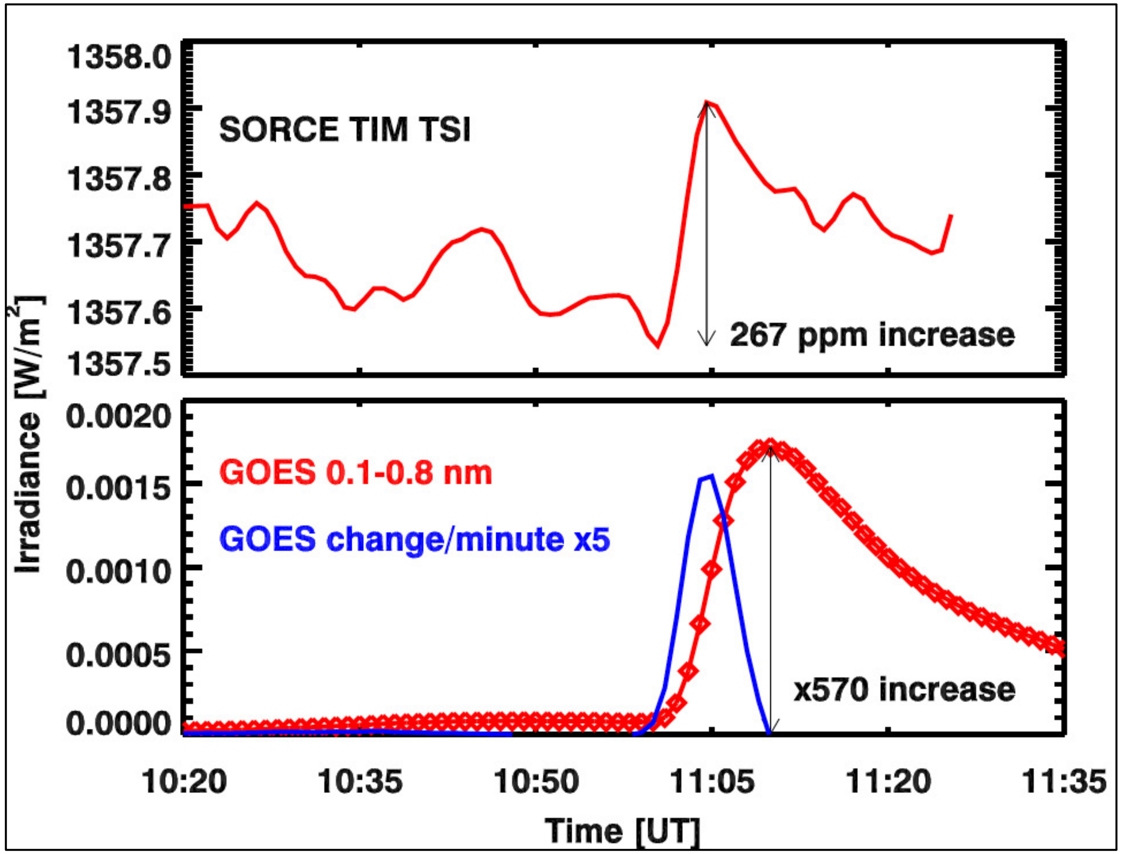
Recent observational results

(1) Flares observed in total irradiance and the impulsive phase

(2) White-light flare heights

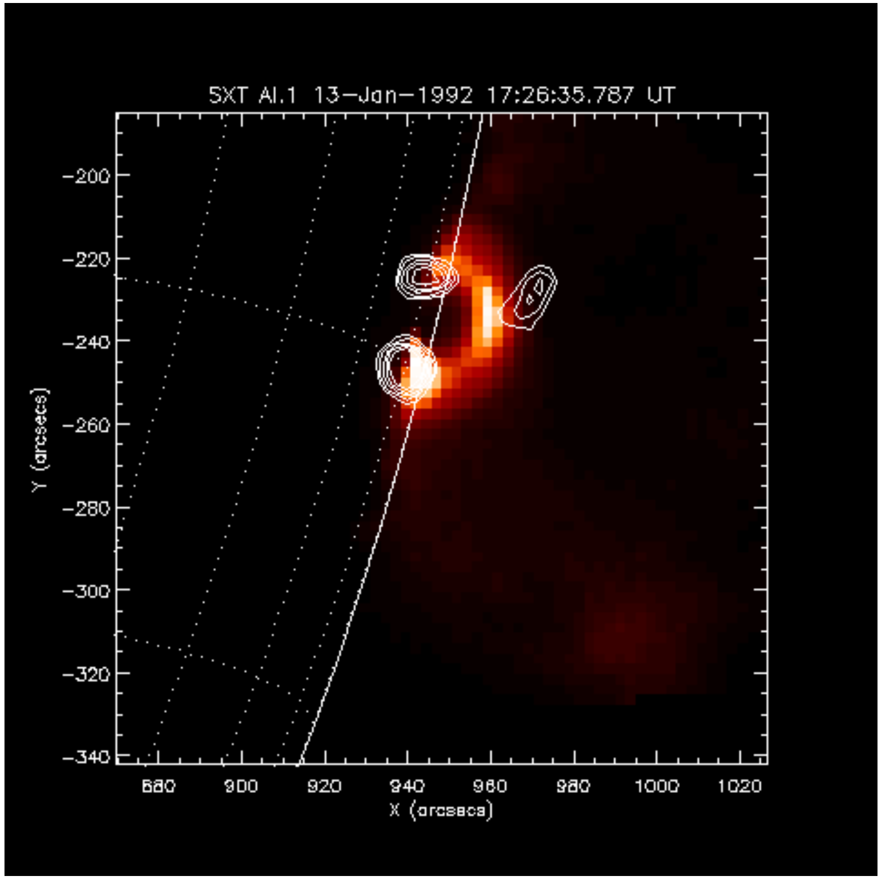
(3) The implosion itself

Bolometric detection

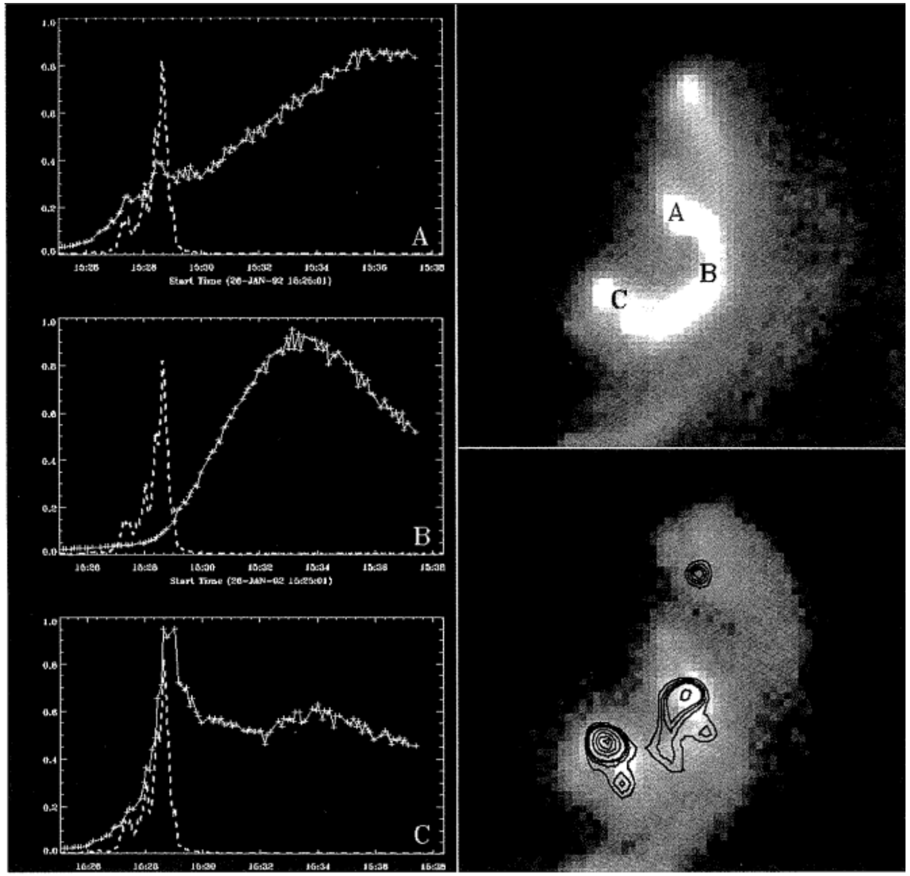


- Woods et al. (2003); Kretzschmar (2011)
- The impulsive phase is energetically dominant

Impulsive soft X-ray footpoints

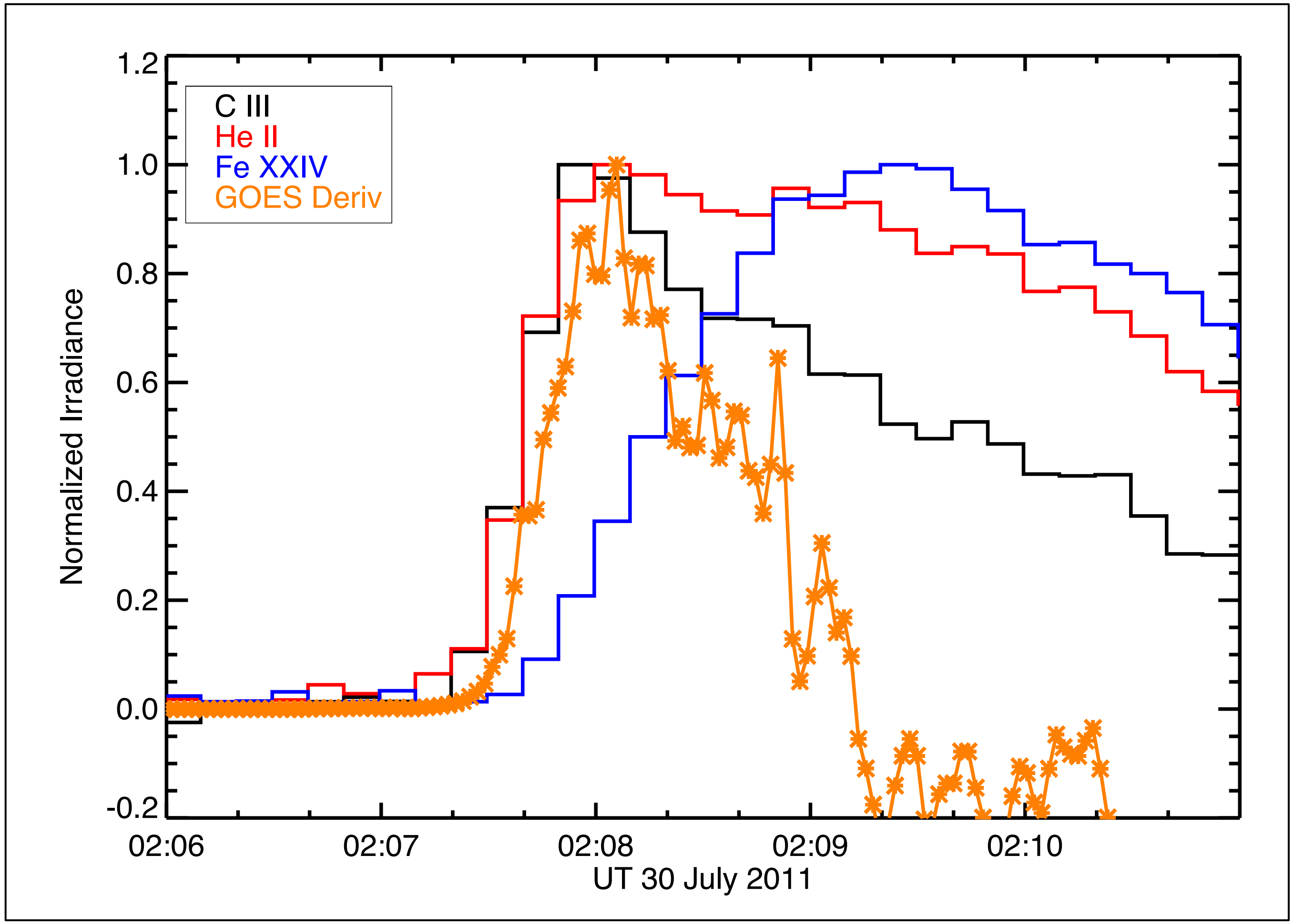


Above-the-loop-top
(Masuda et al. 1994)



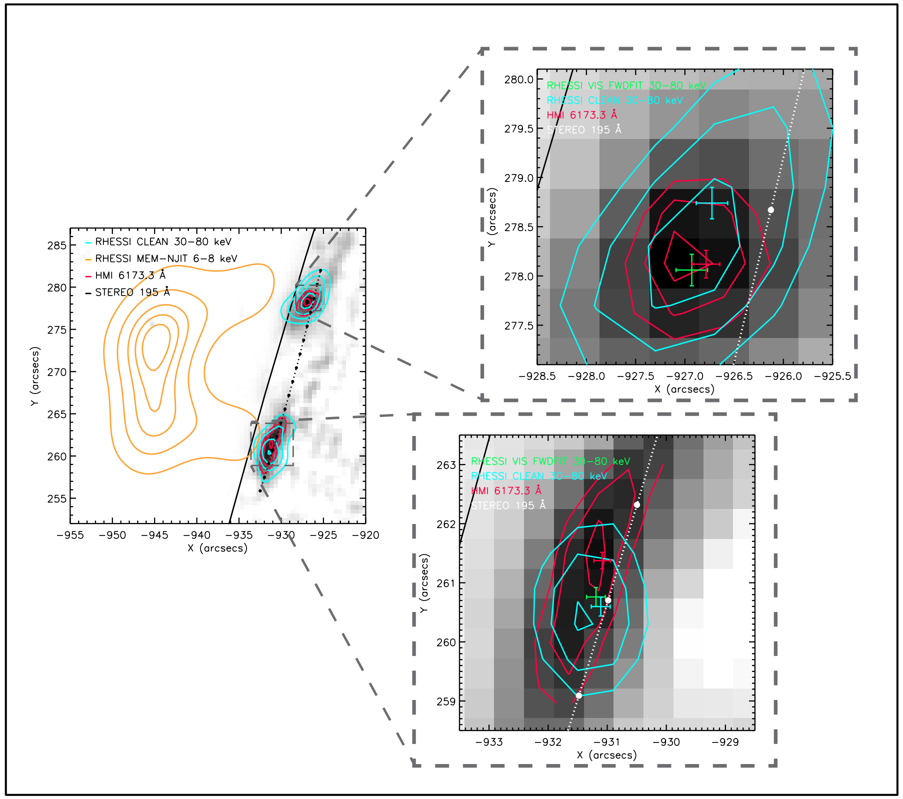
Impulsive footpoints
(Hudson et al. 1994)

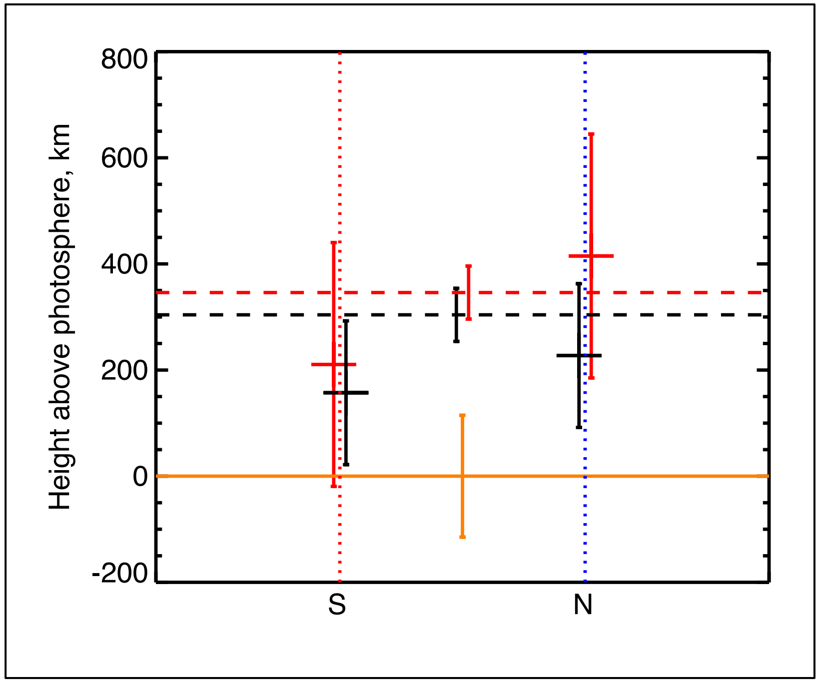
Impulsive soft X-ray footpoints



SOL2011-07-30 (EVE and GOES)

Where does flare energy appear?





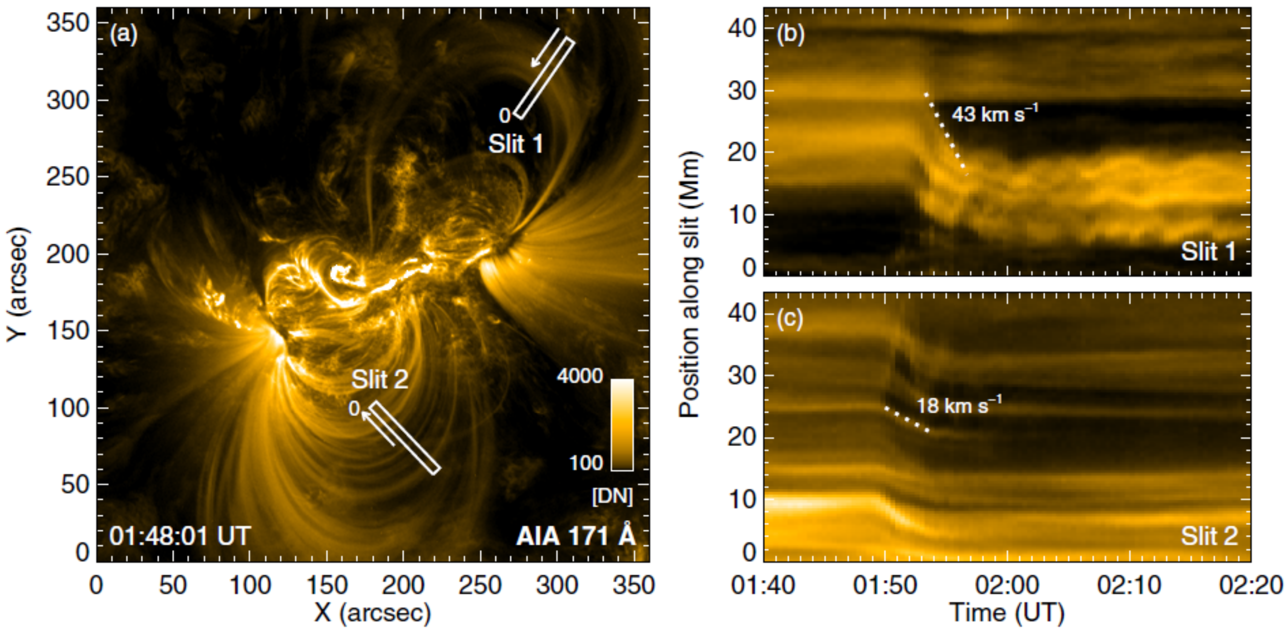
Martínez Oliveros et al., ApJ 753, 26, 2012

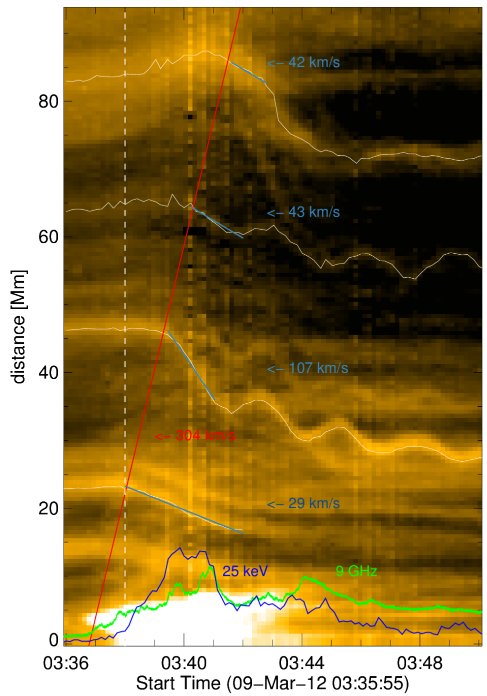
A surprising result: the first absolute height determination of hard X-ray and white-light emission shows them *both* to be near or at their respective $\tau = 1$ heights. This is inconsistent with the thick-target model! Flare SOL2011-02-24.

Failures of the thick-target model

- No obvious directivity in hard X-rays as detected stereoscopically *(nb good opportunity with Orbiter)*
- No beaming detected by Kontar’s “dentist’s mirror” analysis
- Hard X-ray source height
- Number problem
- Various theoretical arguments

The flare implosion

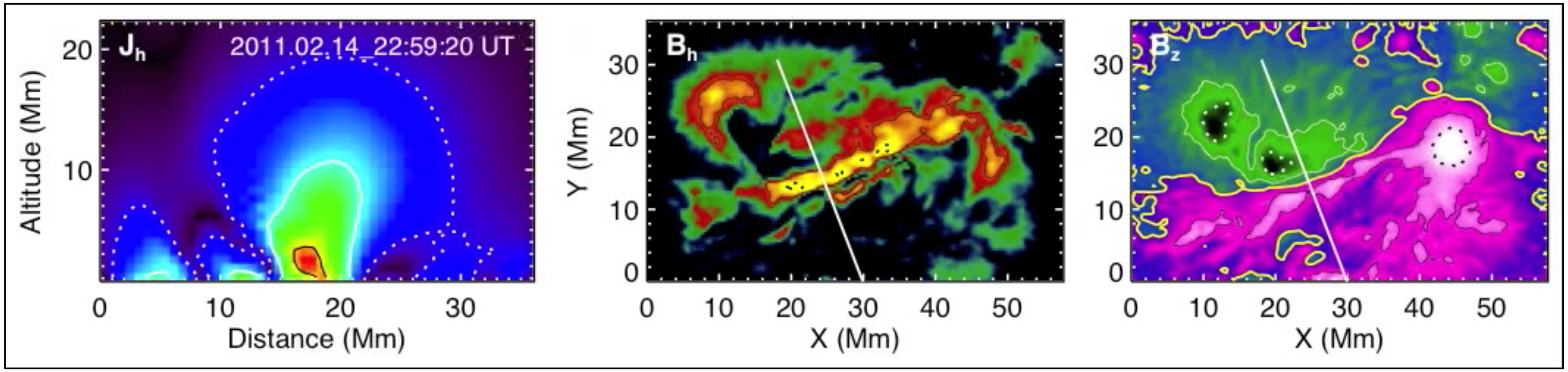


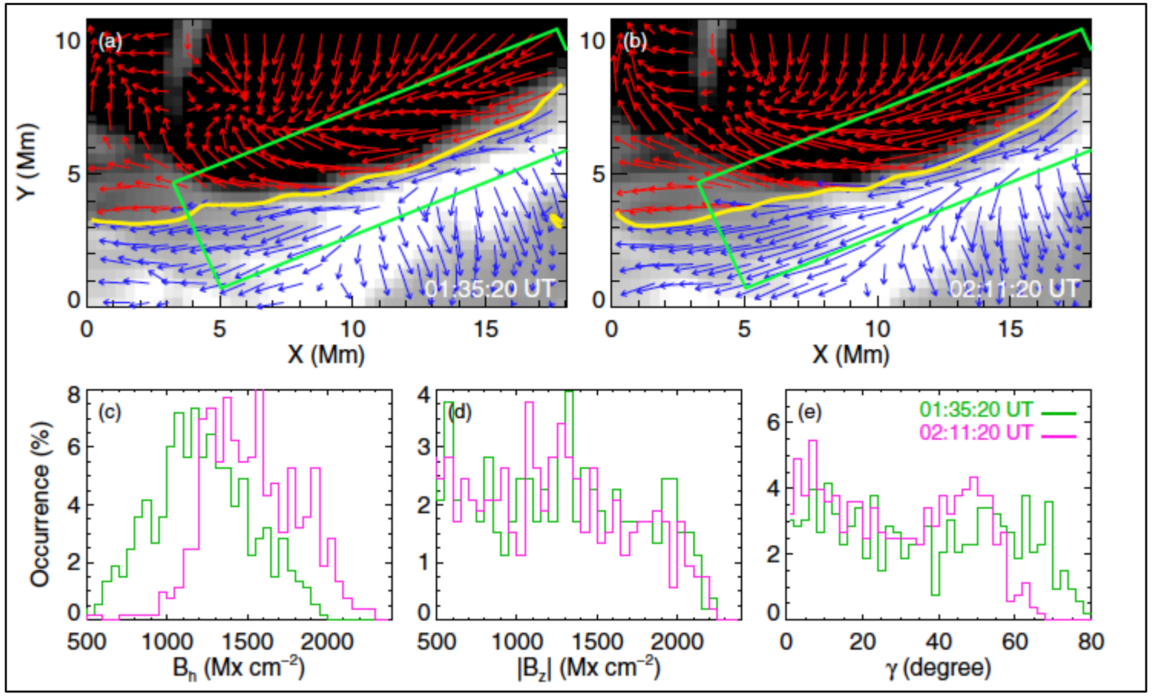


SOL2012-03-09 (Simões et al., 2013, ApJ 777, 152)

- The implosion commences in the AR core
- The excitation of large-scale wave structures proceeds outwards

Sun et al. 2012





Within the green box the horizontal field increases suddenly, while the vertical field doesn't change

Implosion or reconnection?

- We have good evidence for implosions coinciding with primary flare energy release.

- In my view, i**mplosion is the basic flare process**. Reconnection happens as needed, and may or may not be important.

- Current cartoons* and numerical simulations do not provide sound guidance for observers.

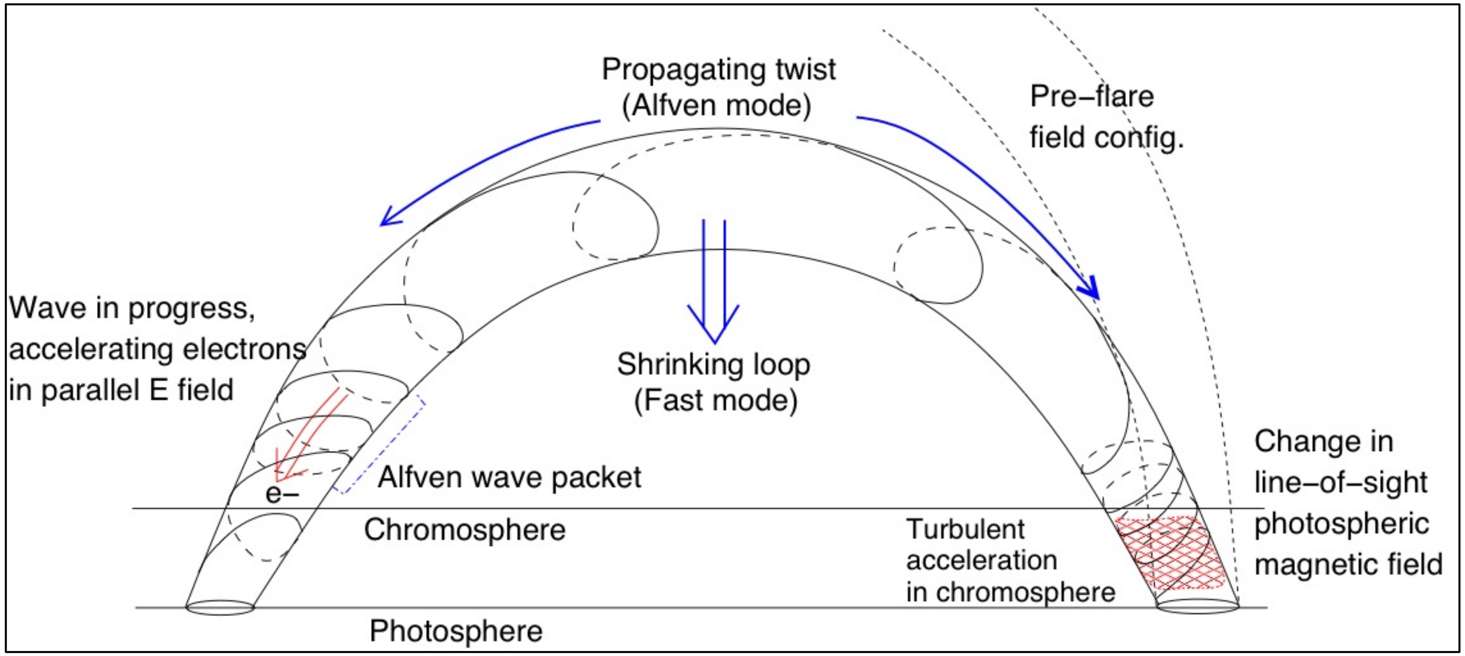
*http://solarmuri.ssl.berkeley.edu/~hhudson/cartoons/

Conclusions

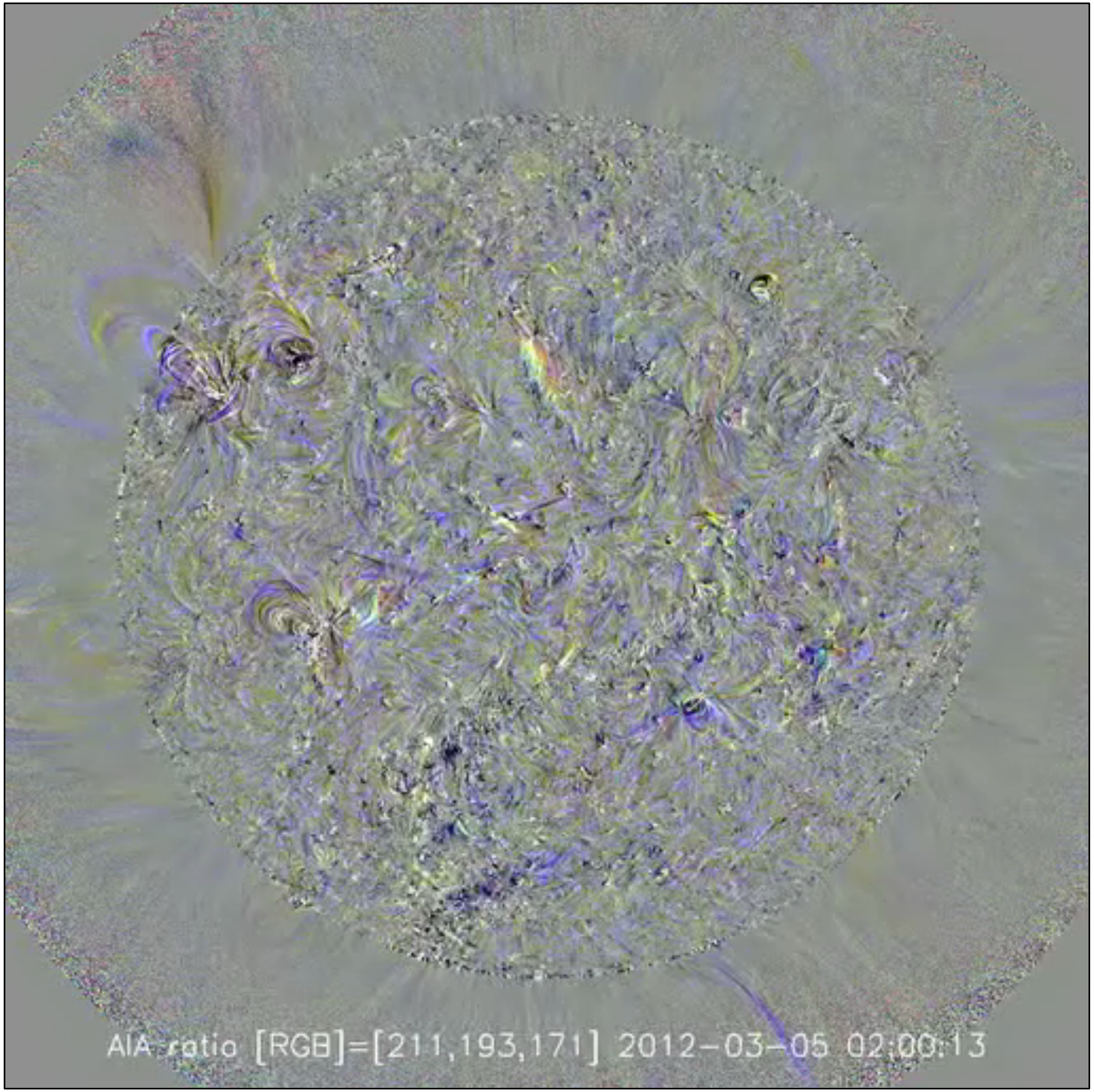
- The observational frontier of understanding is the "interface region".
- New tools for understanding the magnetic structure in the low corona may soon expand our knowledge:
  - Incorporating 3D geometry (Malanushenko)
  - Imaging spectroscopy of gyroresonance (FASR)
- Wave energy transport in the flaring volume needs improved understanding.

Thanks!

Trying to fit large-scale waves into the global picture



Fletcher & Hudson, 2008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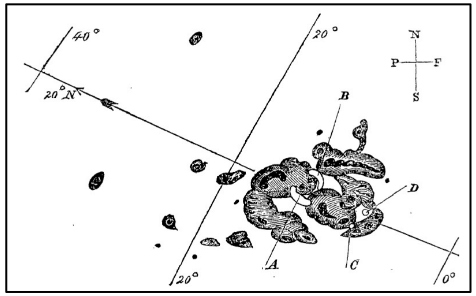
Carrington Flare energetics

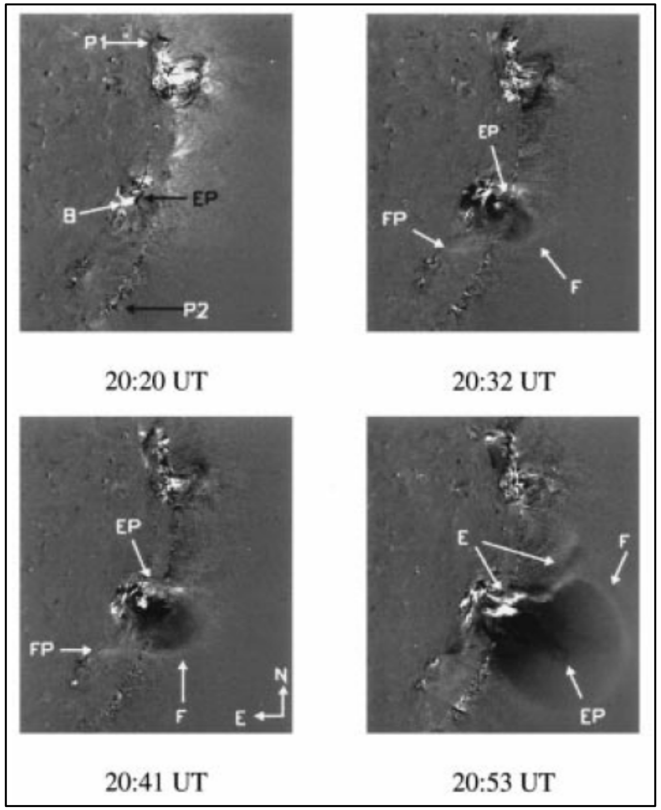


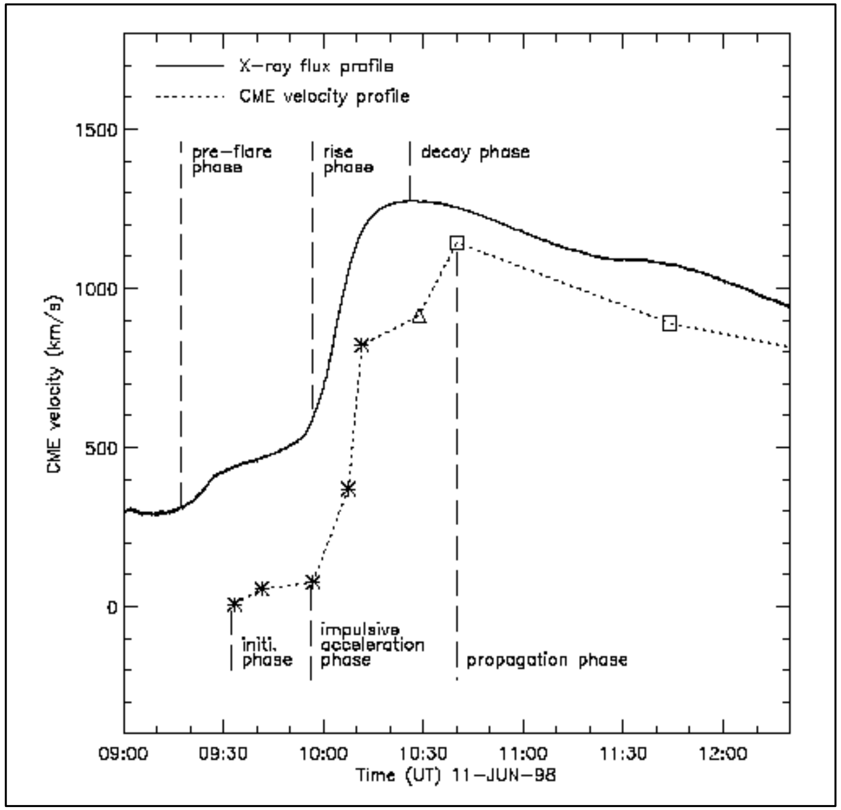
- WL area ~ 200 MSH*
- Flare duration ~ 300 s
- Flare intensity 2x solar

Energy ~ 2 x 10^{32} erg

A reasonable modern interpretation of this simple result is that the radiant energy in the flare's impulsive phase dominates the flare energy – do modern data confirm this?

Compact sources of CMEs



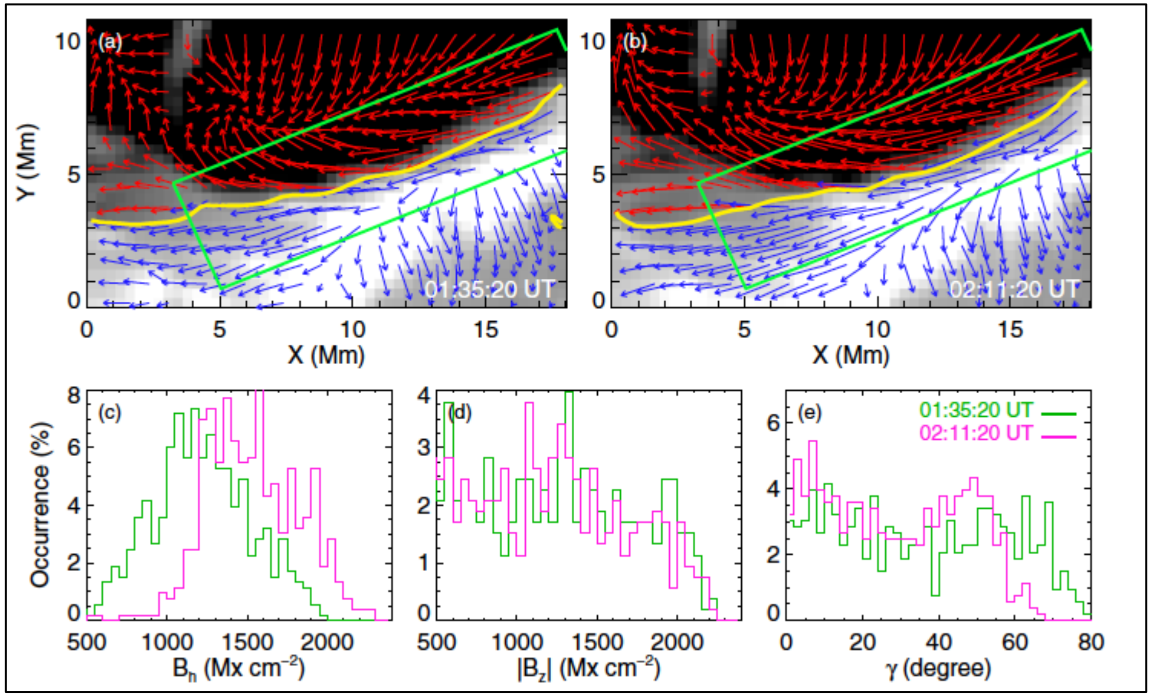


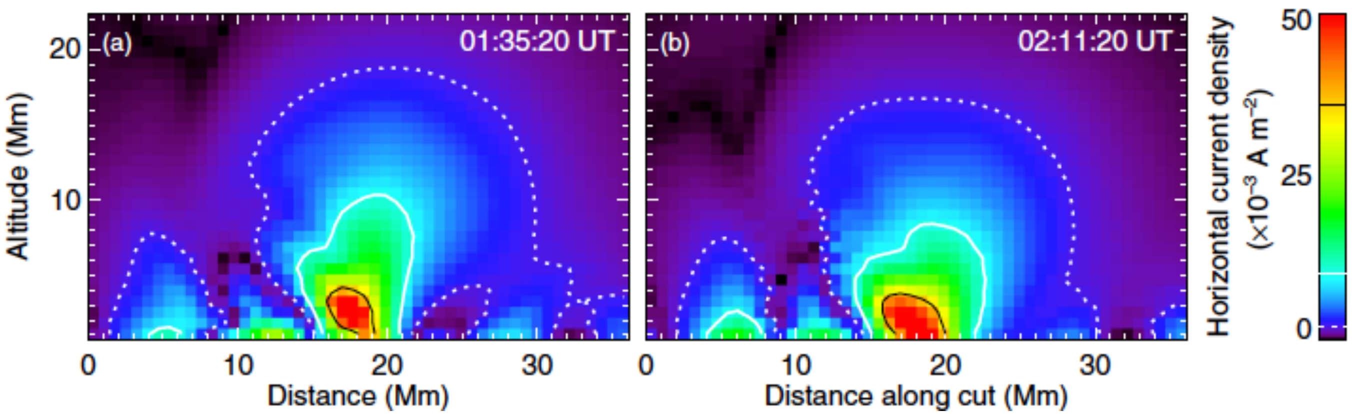
Dere et al., 1997

Zhang et al., 2001

* See also "dimming": Hudson & Webb, 1997; Harra & Sterling 2001

Sun et al. 2012





Recent observational results

- *The impulsive phase dominates the energy release*

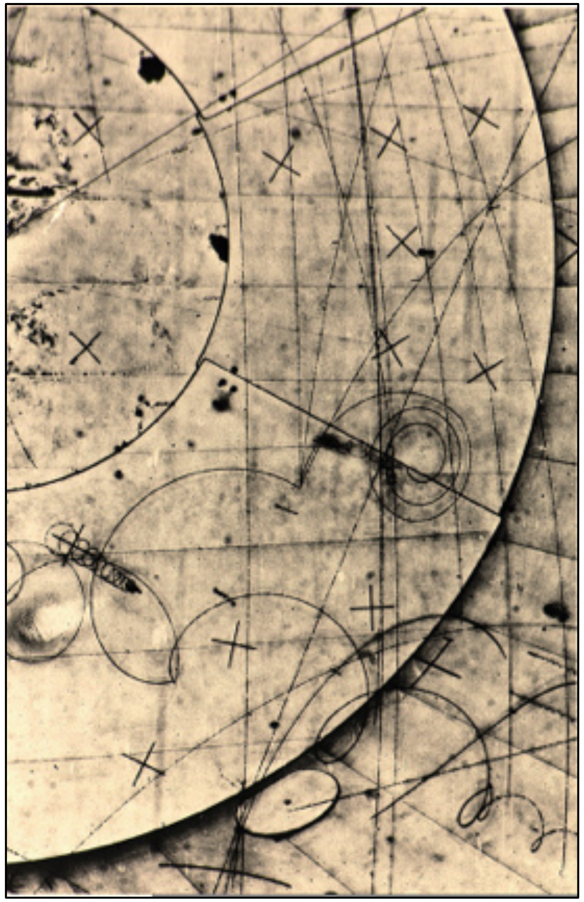
- *Implosion and oscillation (Simões et al., 2013)*

- *Hard X-ray flare height (Martinez-Oliveros et al., 2012)*

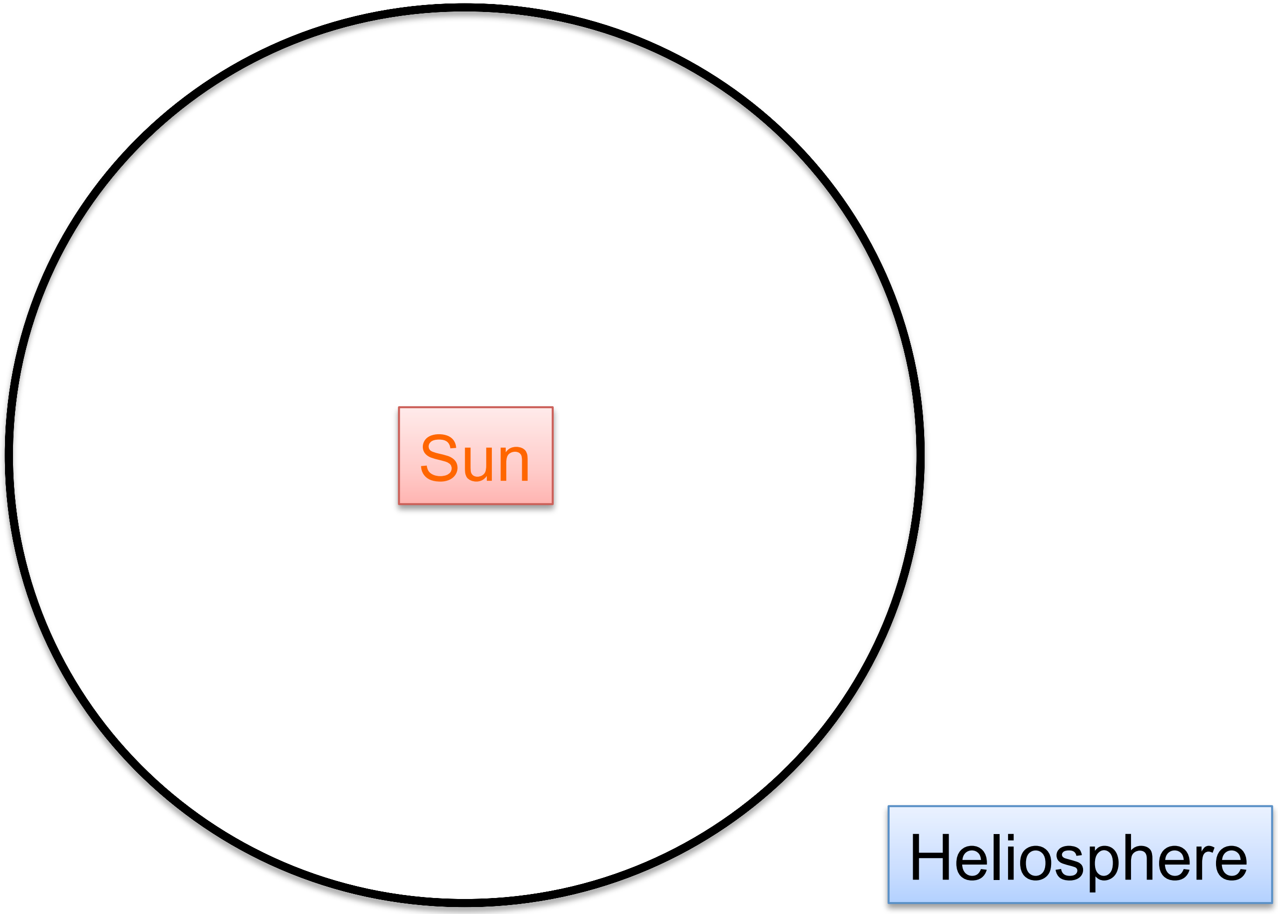
- *HMI observations of coronal sources*

- *Interior acoustic waves*

MHD



Not MHD


Sun
Heliosphere