Global properties of solar flares

Hugh Hudson
UC Berkeley and University of Glasgow

Early attempt at this kind of description published in Space Science Reviews (158, p. 5, 2011)

Outline

Queries:

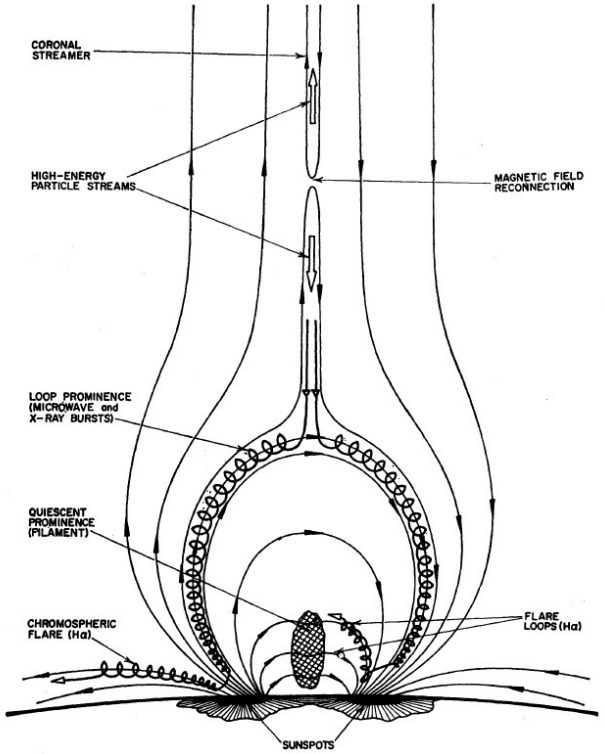
How do we understand the large-scale dynamics of a flare implosion and maybe explosion (CME), in the context of the fine structures of the observed emission products?

Where is the hammer that excites the seismic waves?

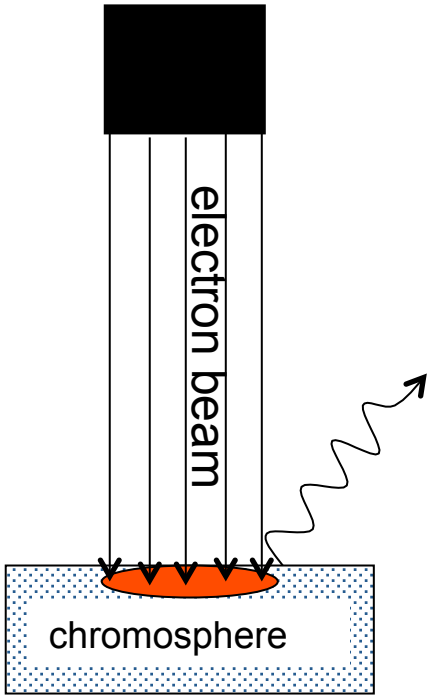
Presentation:

- *New observational results 2012-2013*
- *Framework for interpretation*
- *New information from HMI*

How does flare energy flow?



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

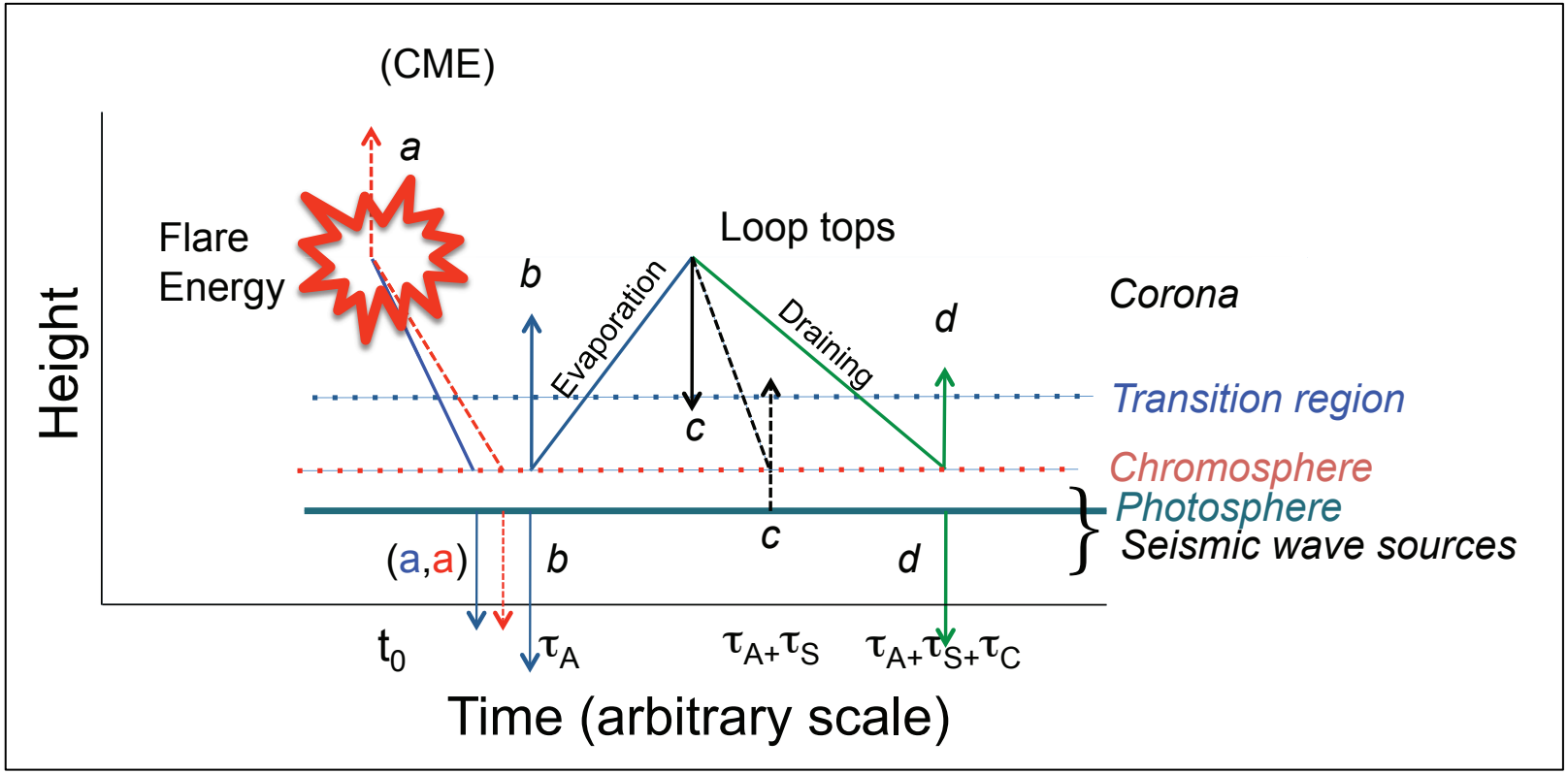


Kane & Donnelly, ApJ 164, 171 (1971) – basically, the “thick-target model”

Critique of the models

- There is no self-consistency between particle and fluid pictures
- The existing models have difficulty with energy conservation, and don’t address momentum
- In the interface region, ion-neutral coupling probably plays a major role, as in the Earth’s ionosphere

Where, when, and in what direction is flare momentum exerted?



Hudson et al., 2012

Recent observational results

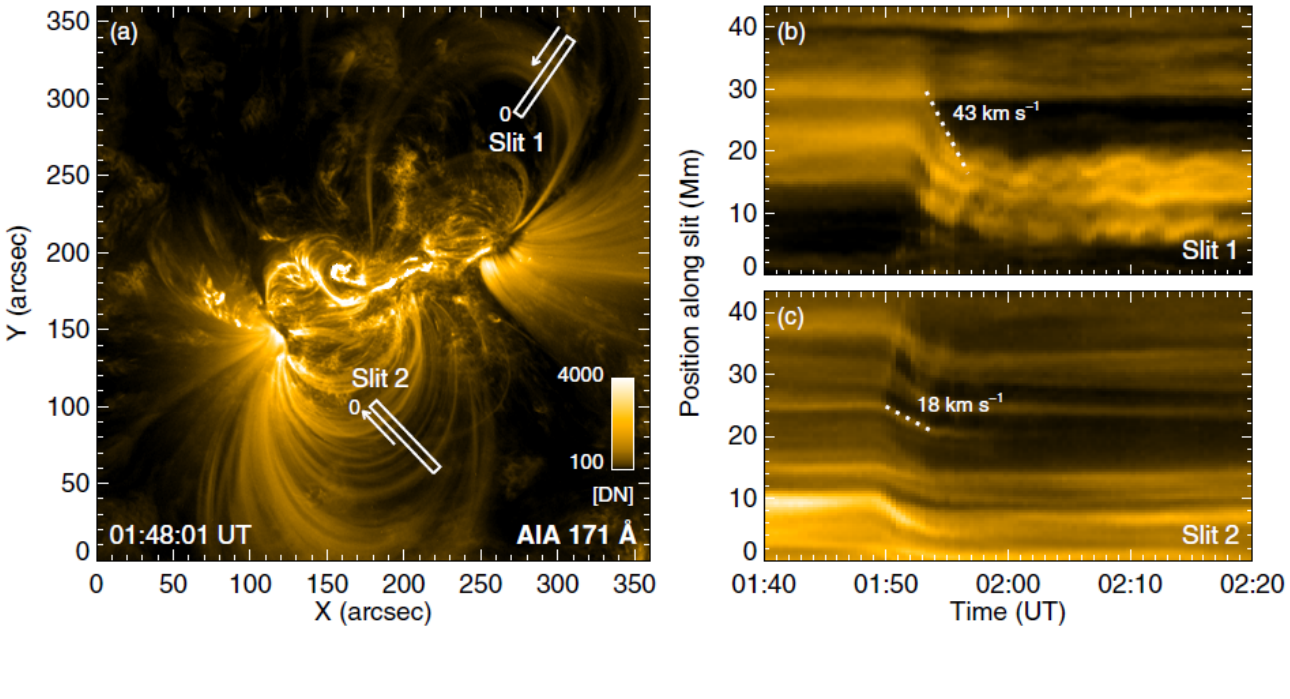
- *Implosion and oscillation (Simões et al., 2013)*

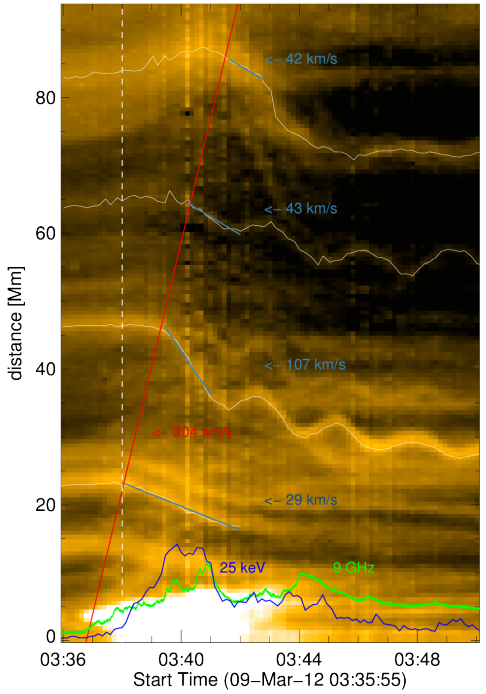
- *Hard X-ray flare height (Martinez-Oliveros et al., 2012)*

- *New HMI observations of coronal sources: the flare mass cycle (unpublished work)*

- *Mysteries of seismic-wave excitation (e.g., Zharkov et al., 2012)*

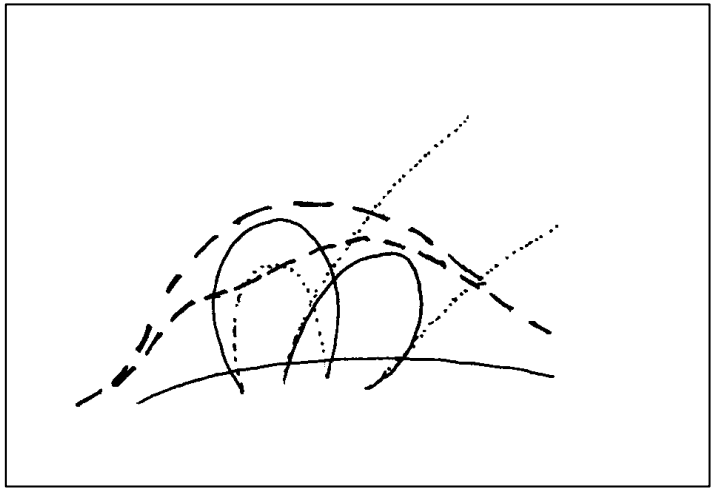
The flare implosion





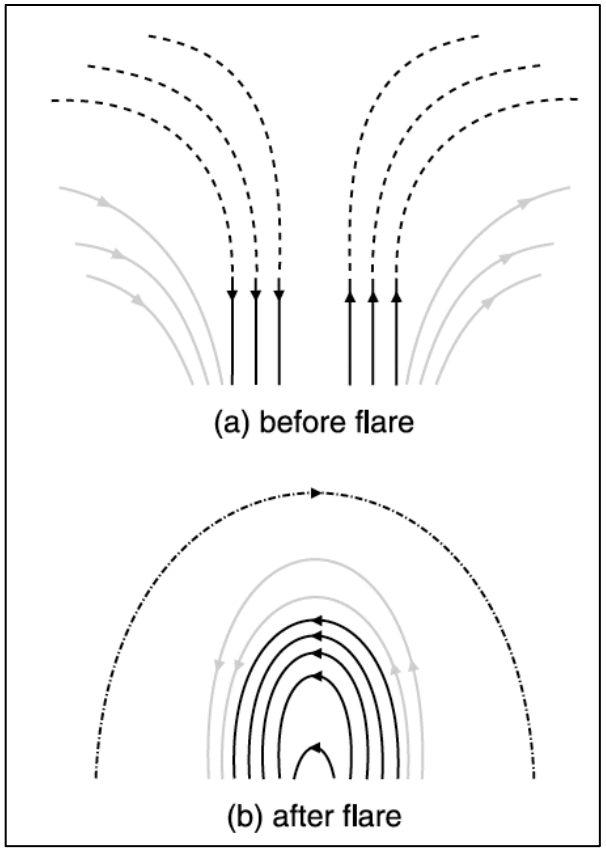
SOL2012-03-09 (Simões et al., 2013, submitted): the implosion commences in the AR core, and excites large-scale wave structures.

Implosion cartoons



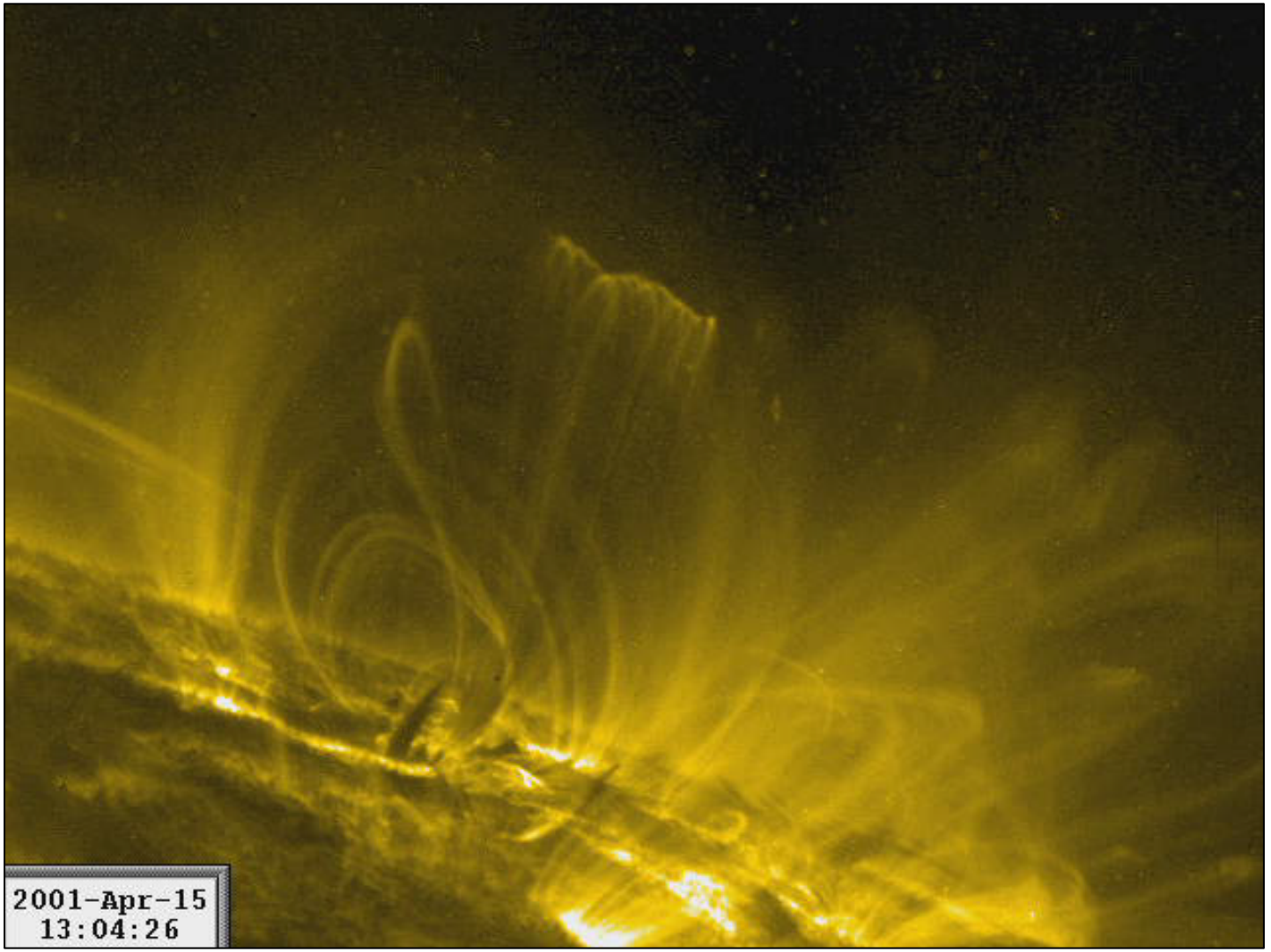
Hudson, 2000

- The level surfaces of B^2 must collapse as energy is extracted
- Existing MHD models typically don't show this

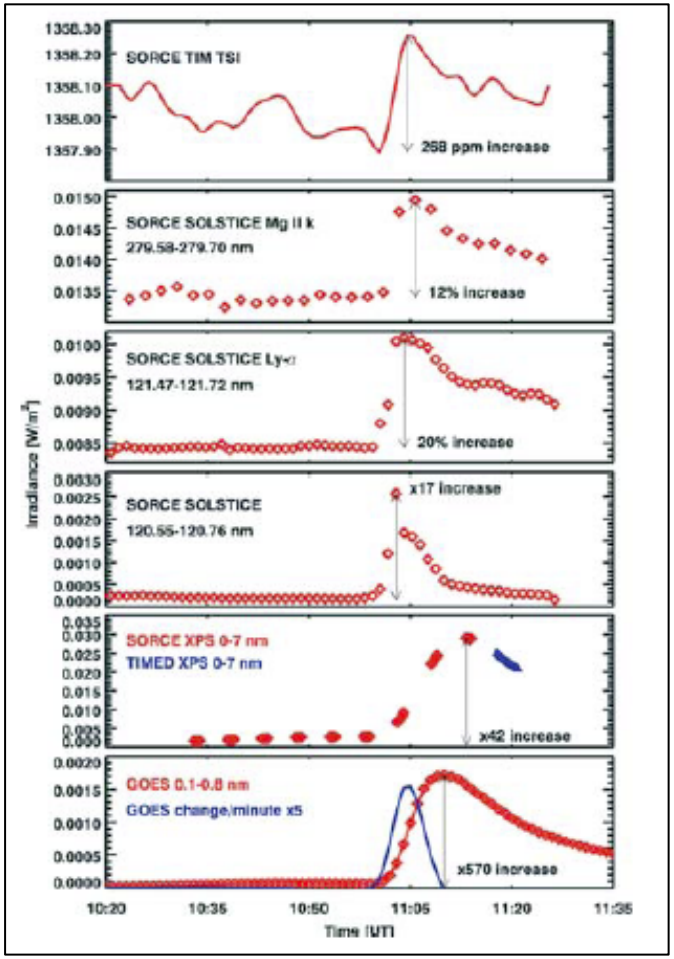


Liu et al., 2005

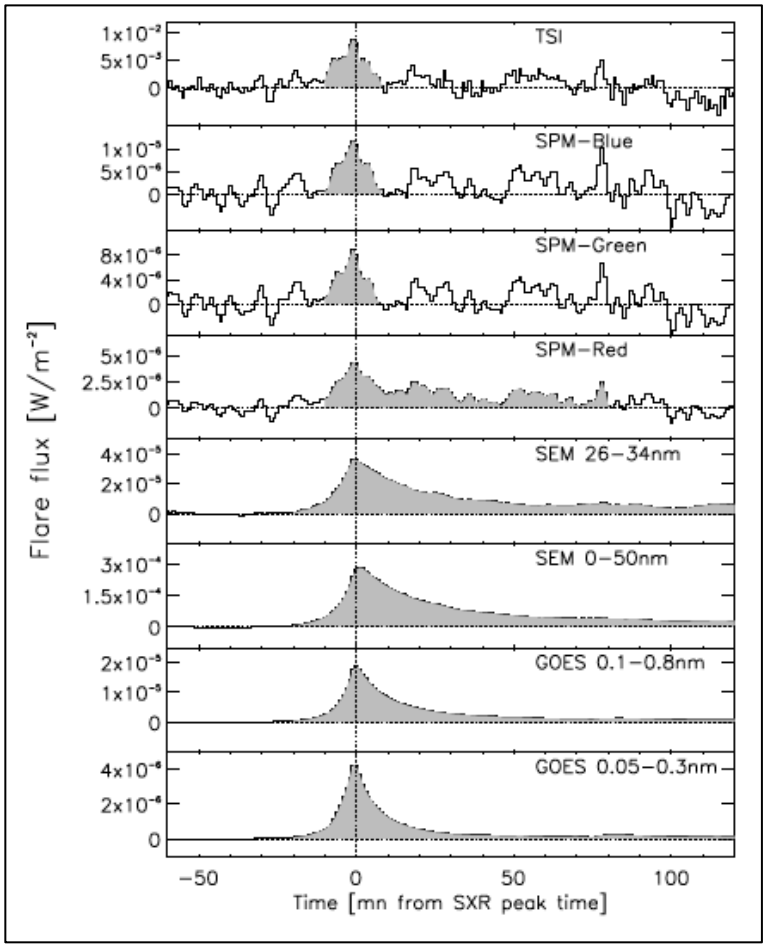
Favorite movie



Where does flare energy appear?



Woods et al. 2005

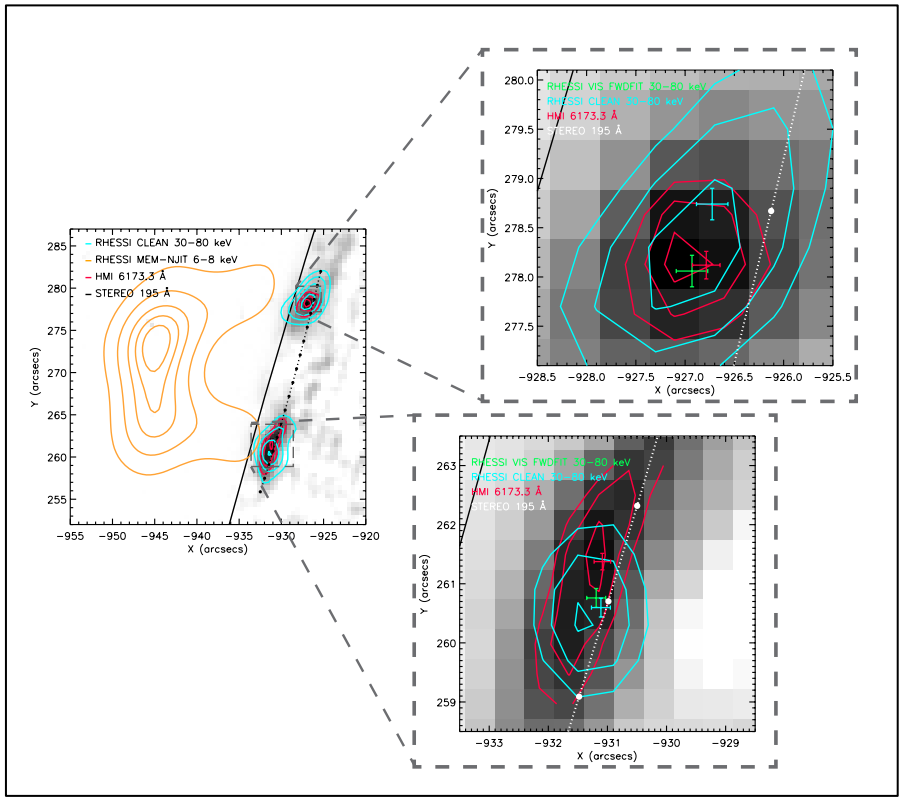


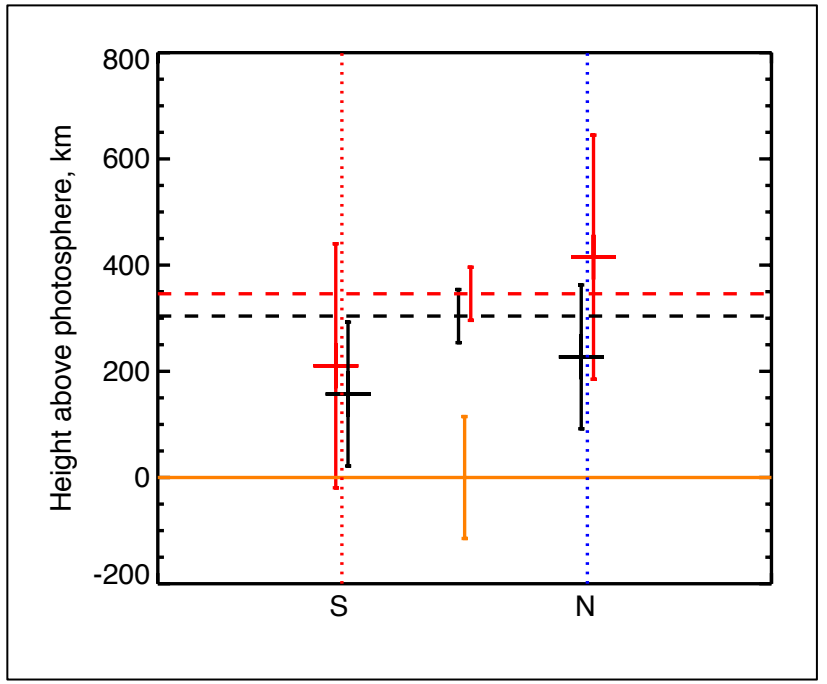
Kretzschmar 2011

Where does flare energy appear?

- “...the brilliancy was fully equivalent to that of direct sun-light…” (Carrington, 1859); “...brilliant star of light, much brighter than the Sun’s surface…” (Hodgson, 1859)
- These observations suffice to demonstrate that the impulsive phase of the flare dominates the process of energy conversion
- We can now determine the absolute height of these white-light (and near UV) emissions

Where does flare energy appear?

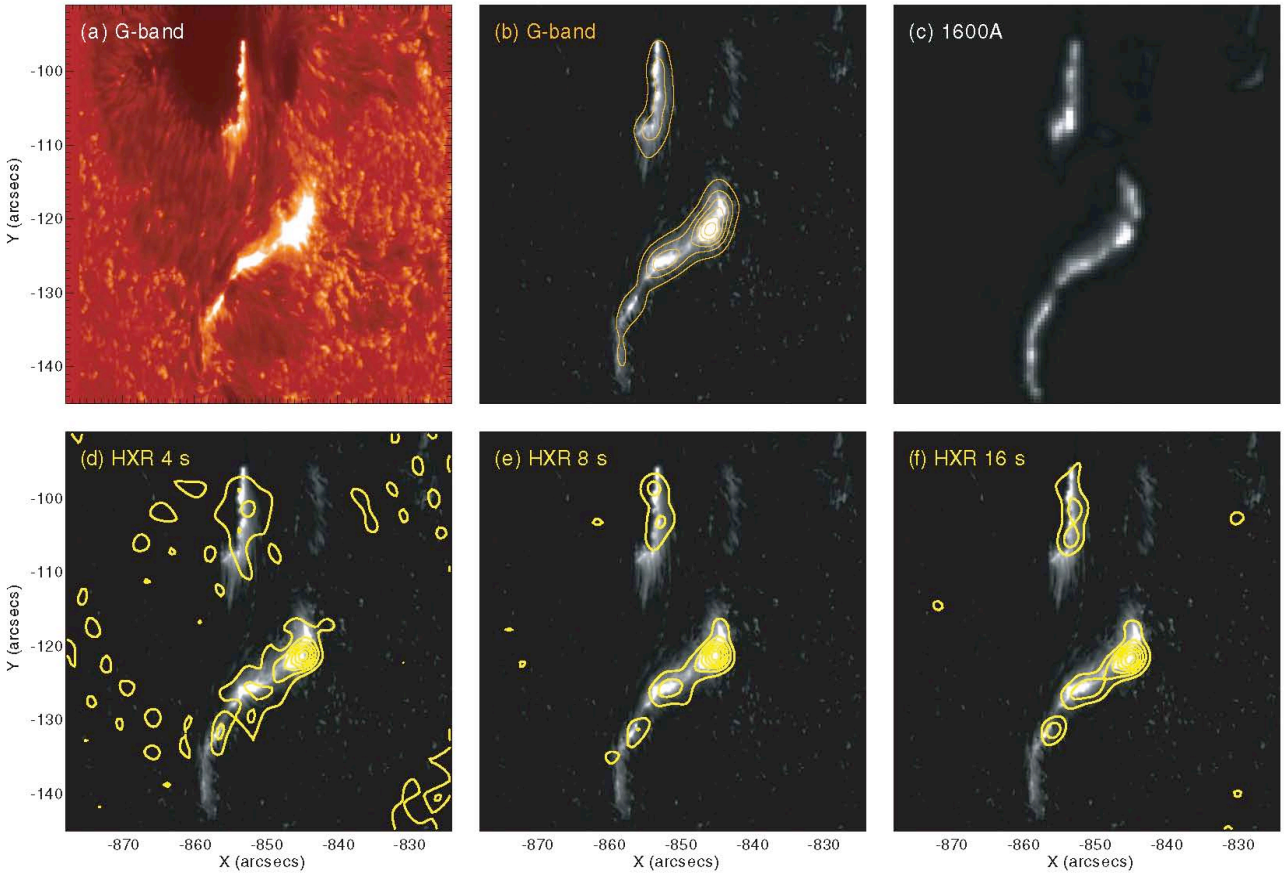




Martínez Oliveros et al., ApJ 753, 26, 2012

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.

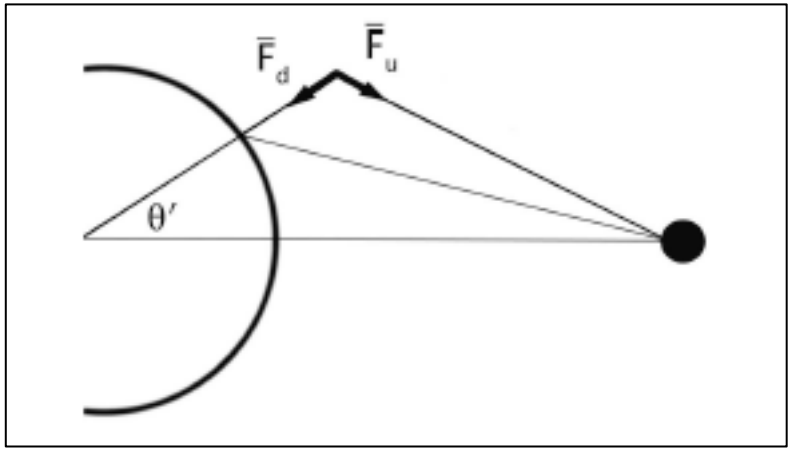
Where does flare energy appear?

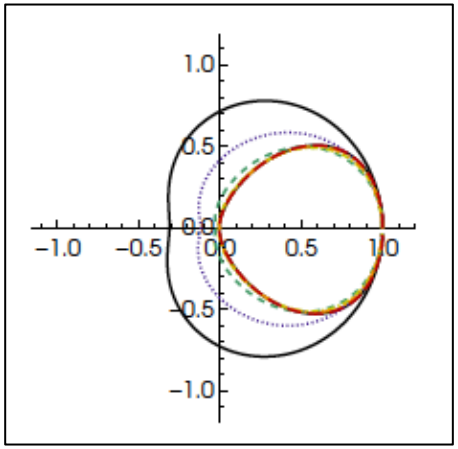


Krucker et al., ApJ 739, 96, 2011

The powerful emissions of a solar flare are unresolved in space and in time, but are systematically organized. The bulk of the flare energy appears in WL/EUV emission from the footpoint sources.

The ingenious dentist's mirror

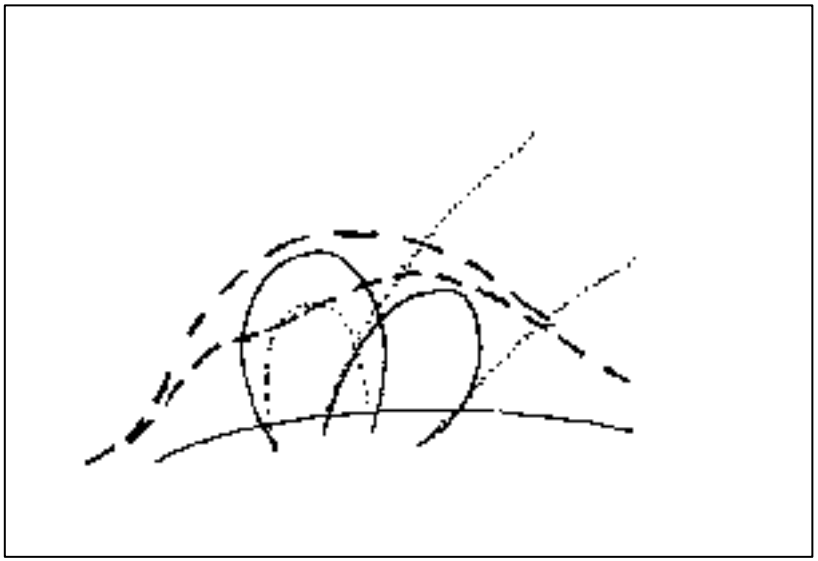




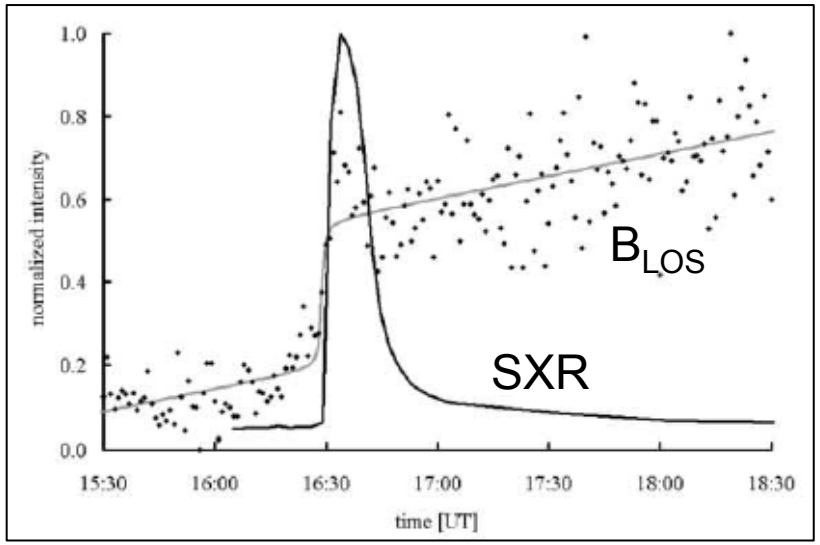
- RHESSI hard X-ray spectra can be deconvolved into a direct and an albedo component, which sample the bremsstrahlung polar diagram
- "The results show little evidence for strong anisotropy and the mean electron flux spectra are consistent with the isotropic electron distribution." (Dickson & Kontar, 2013)
- This result is fully consistent with many statistical studies of flare hard X-ray emission, which do not show the expected limb brightening
- Hence… no strong beaming

These observational results, and the lack of hard X-ray directivity, strongly reject electron-beam transport of energy

The flare implosion



Hudson, ApJ 531, L75 (2000)

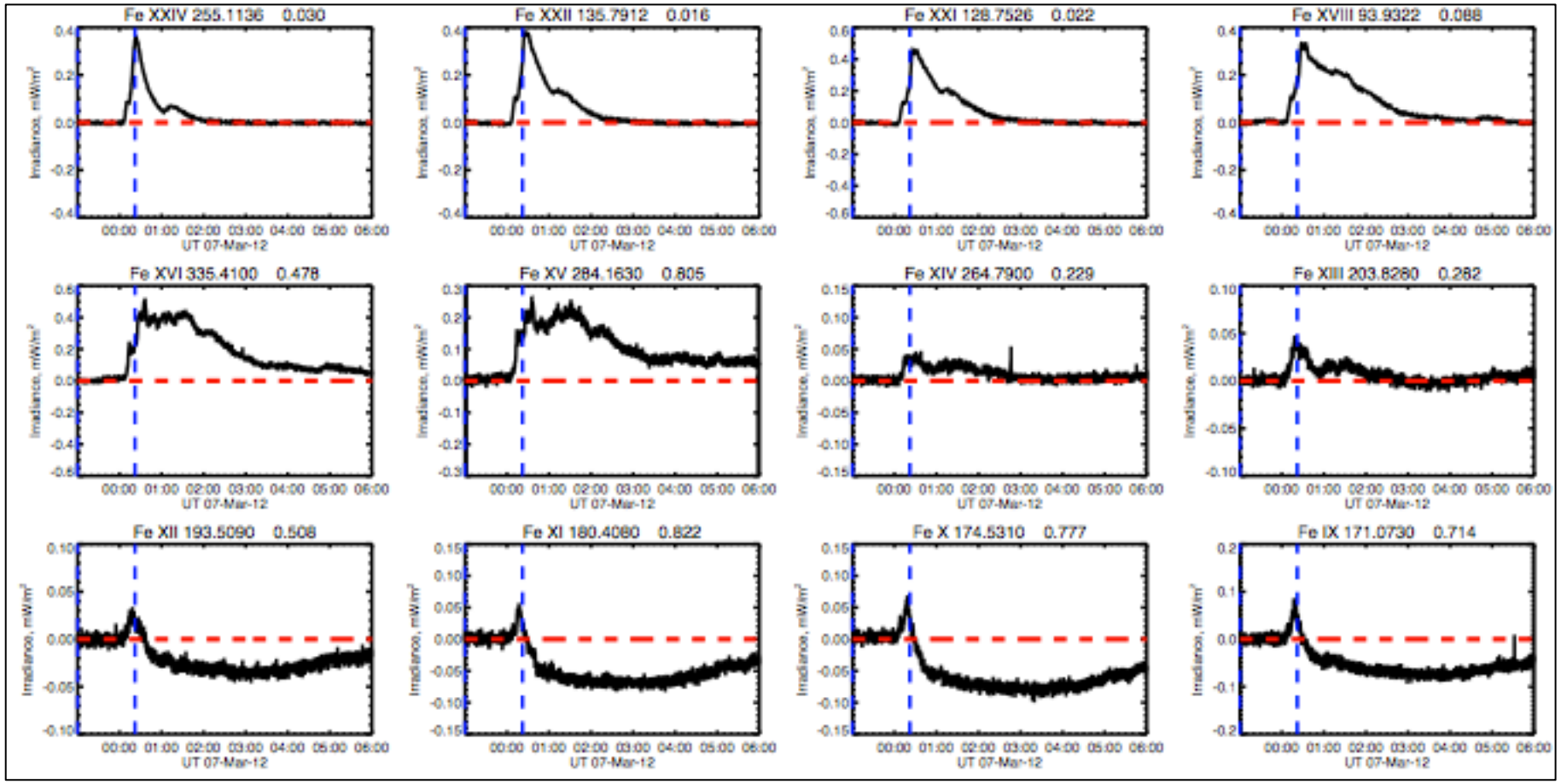


Sudol & Harvey, ApJ 635, 647 (2005)

In this cartoon, the heavy dashed lines show “magnetoisobars,” which slump into a smaller structure when the flare happens.

The observations (BBSO) show an inward tilt of the photospheric field, matching the time of energy release.

Sun-as-a-star EVE



SOL2012-03-07 (Hinode event)

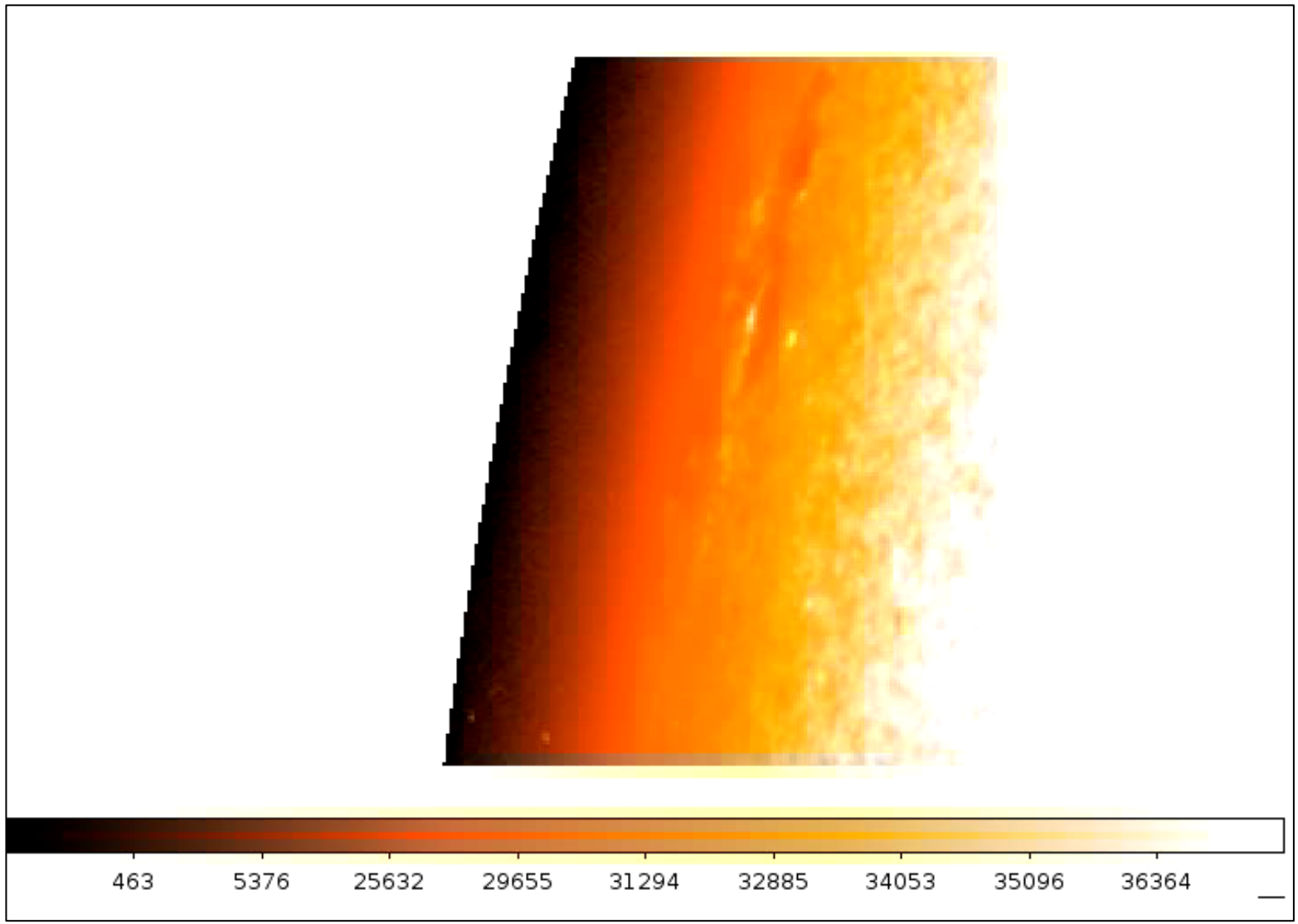
Particle distribution functions and ion-neutral coupling

- In the flaring corona, the physical conditions are not what is normally assumed:
  - We may have v_A approaching c
  - We may have $T_e >> T_i$
  - Plasma beta can drastically increase

  See Krucker et al., ApJ 739, 96, 2011

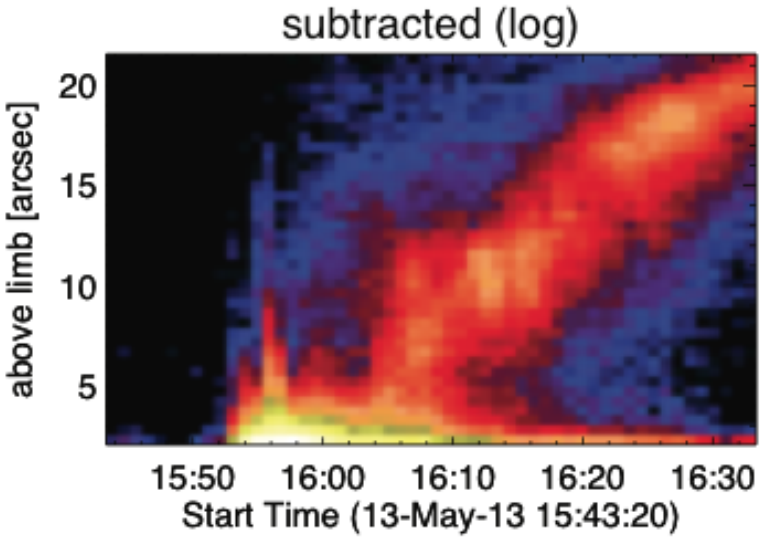
- In the lower “boundary” of the coronal plasma, ion-neutral effects may dominate

HMI coronal observations
flares of May 2013

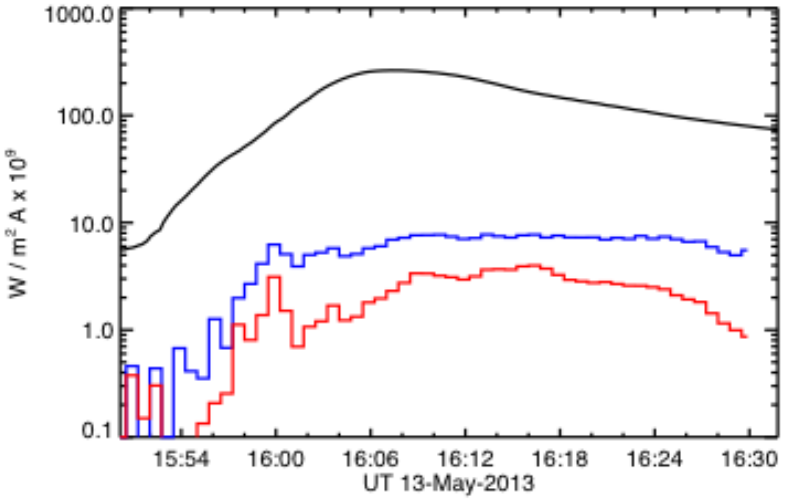


HMI SOL2013-05-13T16 (courtesy Martinez-Oliveros)

SOL2011-05-13T16

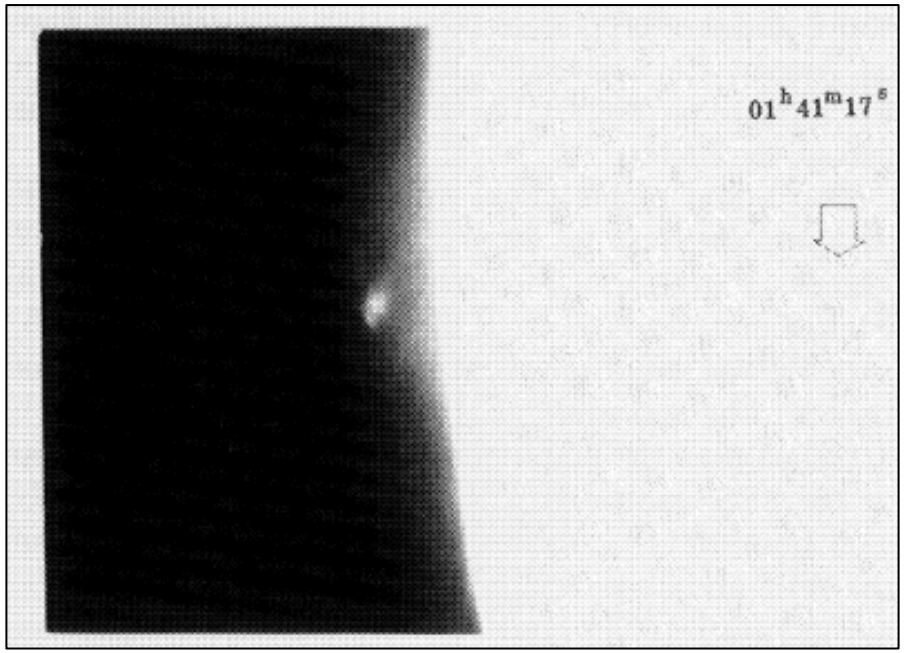


Sa”m Krucker

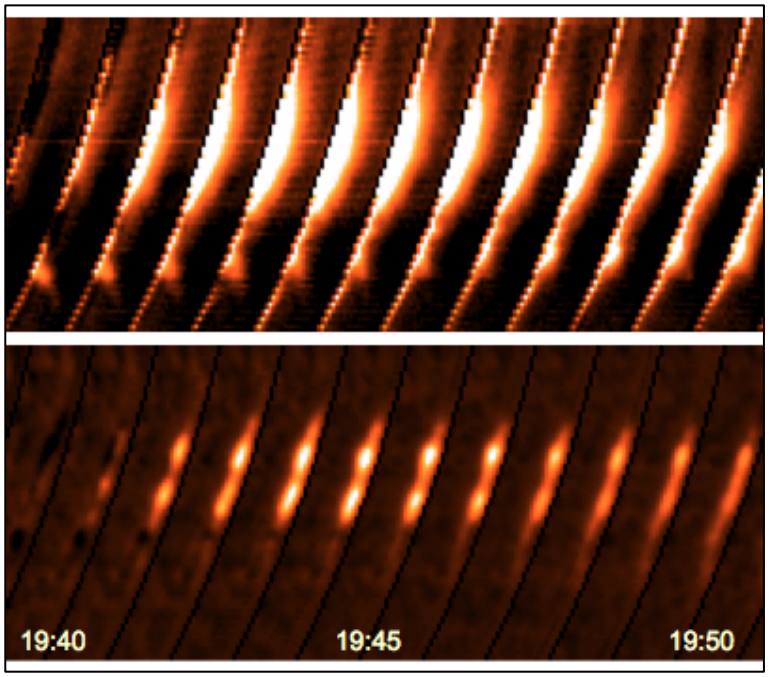


- GOES (black) + CHIANTI
- HMI total (blue)
- HMI impulsive thing (red)

Prior related observations



SOL1989-08-16 (~X20): Hiei et al., 1992



SOL2003-11-04 (~X20): Leibacher et al., 2004

The coronal mass cycle of a flare

- Flare energy release produces coronal overpressure, which drives mass up to fill closed-field regions (key observation by Neupert, 1967)
- These regions relax towards hydrostatic equilibrium, cool, and lose pressure according to “Serio scaling”: $n^2 \sim T$ (Serio et al., 1991)
- Thermal instability follows cooling, and the final mass excess falls gravitationally as “coronal rain” in H-alpha

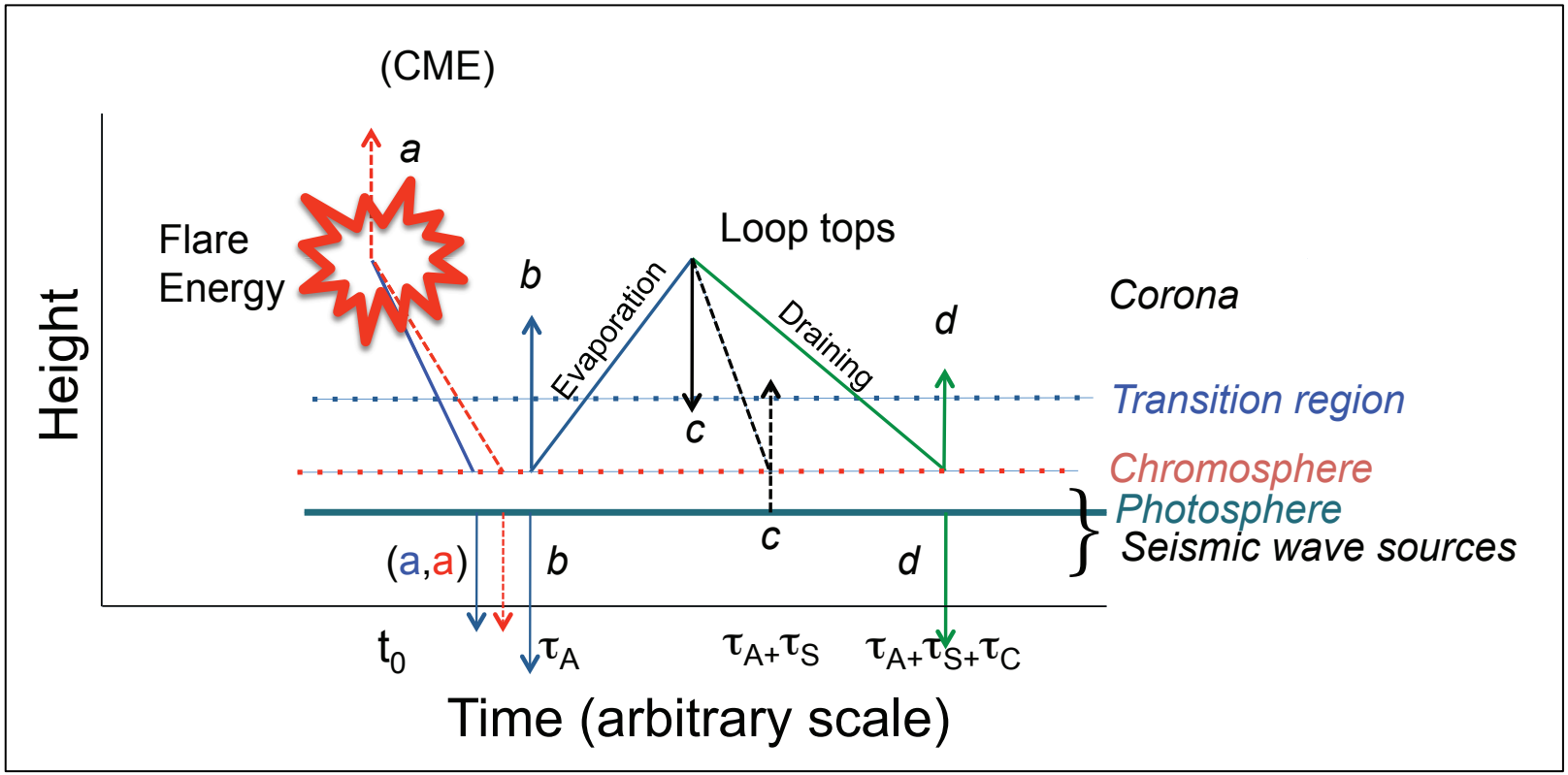
This scenario has been well-observed via H-alpha “loop prominence systems”, “sporadic coronal condensations,” “post-eruption arcades,” radio “post-burst increases” etc.; see Cargill et al (1995) for a theoretical overview

Do the new HMI observations match this view of the mass cycle?

- Do we see ejecta that do not not attain X-ray temperatures, but have appreciable mass and energy?
- Are there features that could be related to the “hammer” need for exciting interior seismic waves?

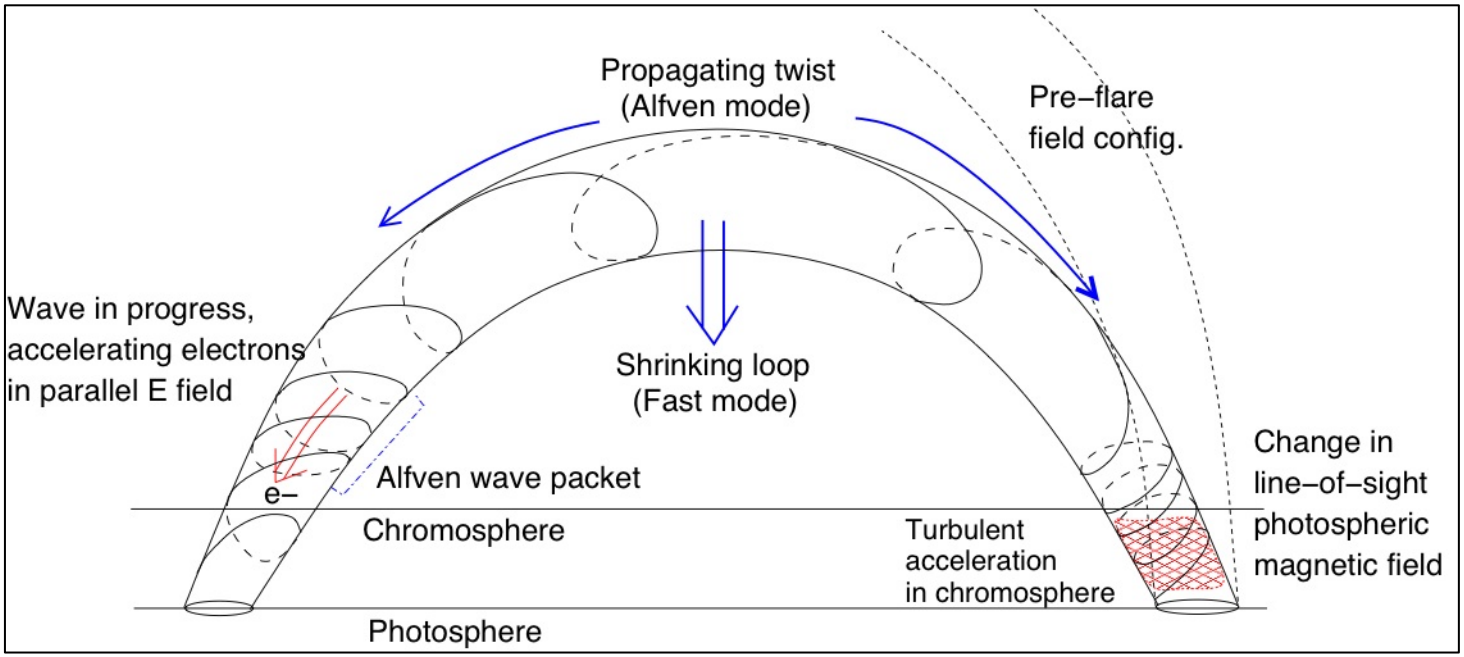
As always, the caveat is that at low plasma beta, the observed mass may not be related to the important EM dynamics

Momentum conservation



Hudson et al., Solar Phys. 277, 77 (2012)

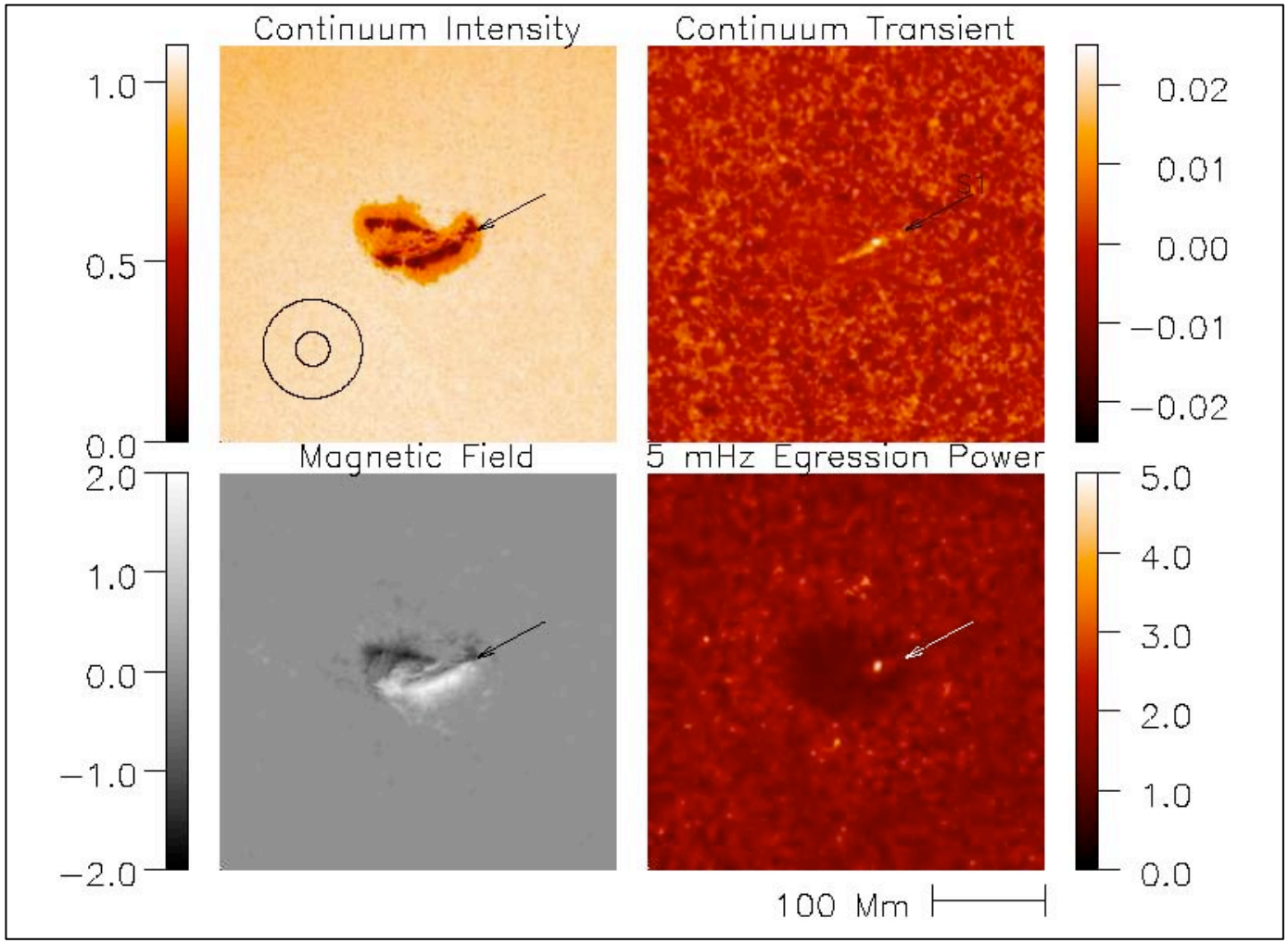
Trying to fit large-scale waves into the global picture



Conclusions

- The classic models of flares are becoming less and less adequate
- We have great new data (RHESSI, Hinode, SDO, Fermi) and more coming (IRIS)
- The interface region (chromosphere) and its ion-neutral physics must be understood
- So… how do seismic waves fit in?

Interior acoustic waves



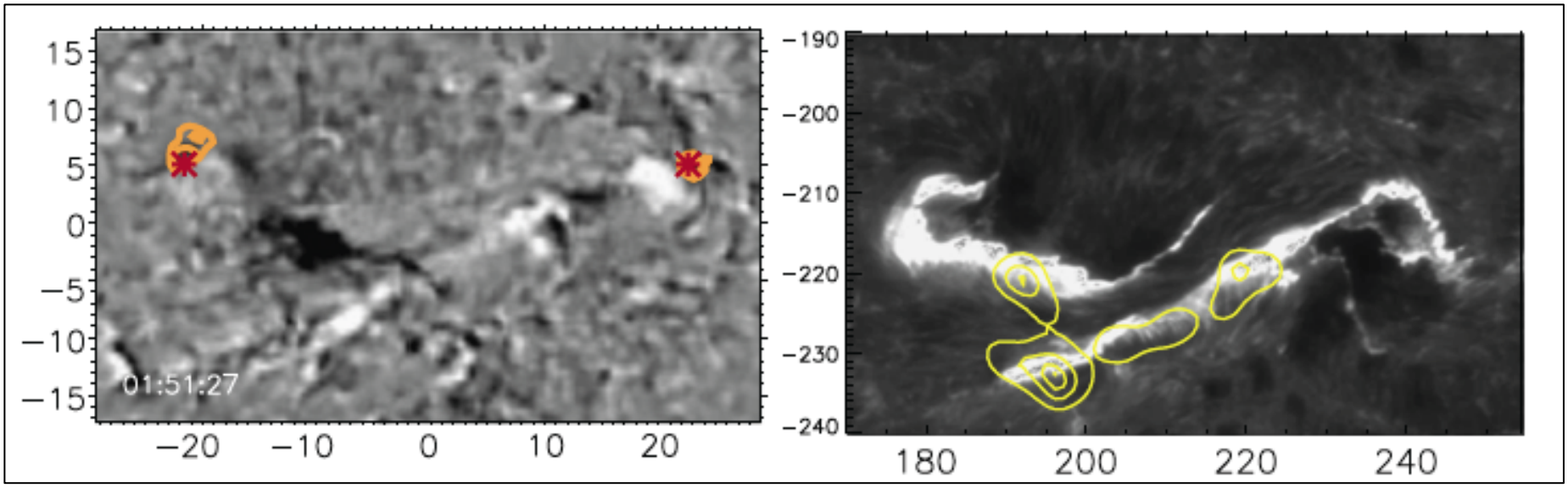
SOL2005-01-15 (Lindsay et al. 2013, in press)

What is the source of the impulse?

1) Particle beam (thick-target model)
2) Shock wave resulting from flare heating
3) Magnetic impulse
4) Penetrating high-energy particles (> 300 MeV)
5) Other

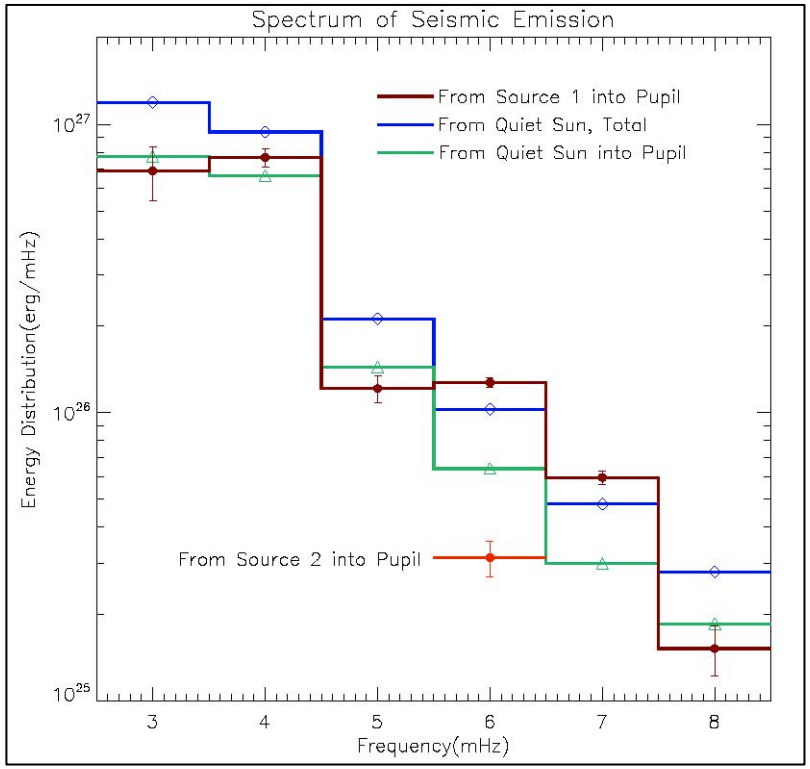
SOL2011-02-15

Our favorite flare dashes all preconceptions?



Zharkov et al. (2013)

Interior acoustic waves



Alvarado et al., 2011

- Seismic energy can amount to a fraction 10^{-3}-10^{-4} of the flare/CME energy
- Substantial vertical momentum transfer is required

Questions

- What connects the corona and the interior?
- Why are the seismic sources so compact?
- How deep are the sources?
- How do we interpret the seismic energy spectrum?
- How (e.g., SOL2011-02-15) can the seismic sources be so distinct spatially from the manifest flare energy?