Hard X-ray Diagnostics of Solar Eruptions

H. Hudson

SSL, UC Berkeley and

U. Of Glasgow

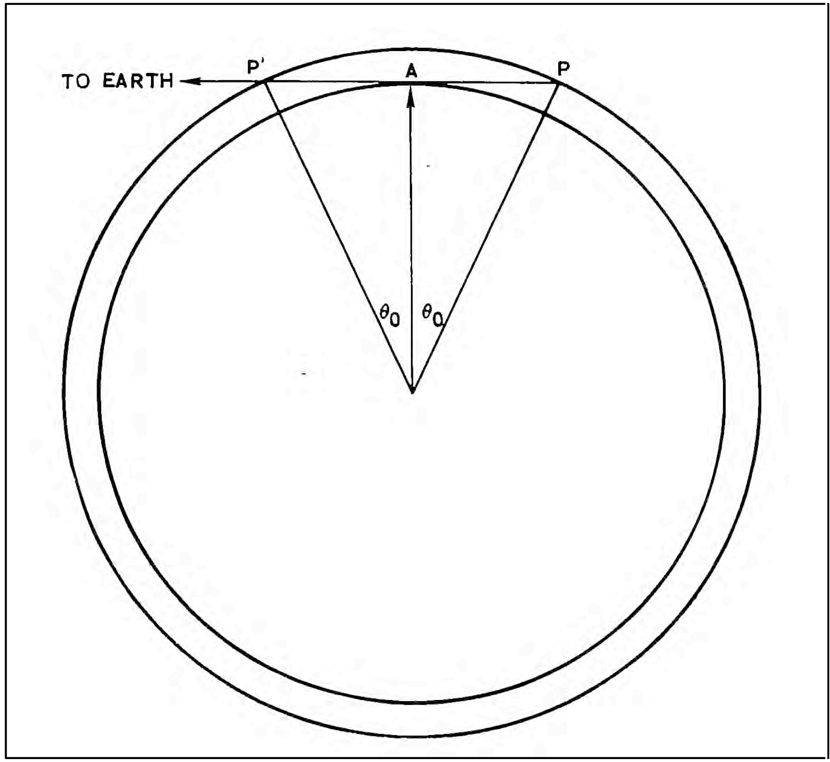
Background information

- Meter-wave radio phenomena require (types I-V etc.) require non-thermal electrons.
- These also emit X-ray bremsstrahlung, but not very efficiently ($\sim 10^{-5}$).
- With the X-rays, we can study energetics more directly.
- Limb occultation, plus imagers on *Yohkoh* and *RHESSI* have greatly expanded our knowledge.
- See Krucker et al., A&A Rev 16, 155 (2008) for full details.

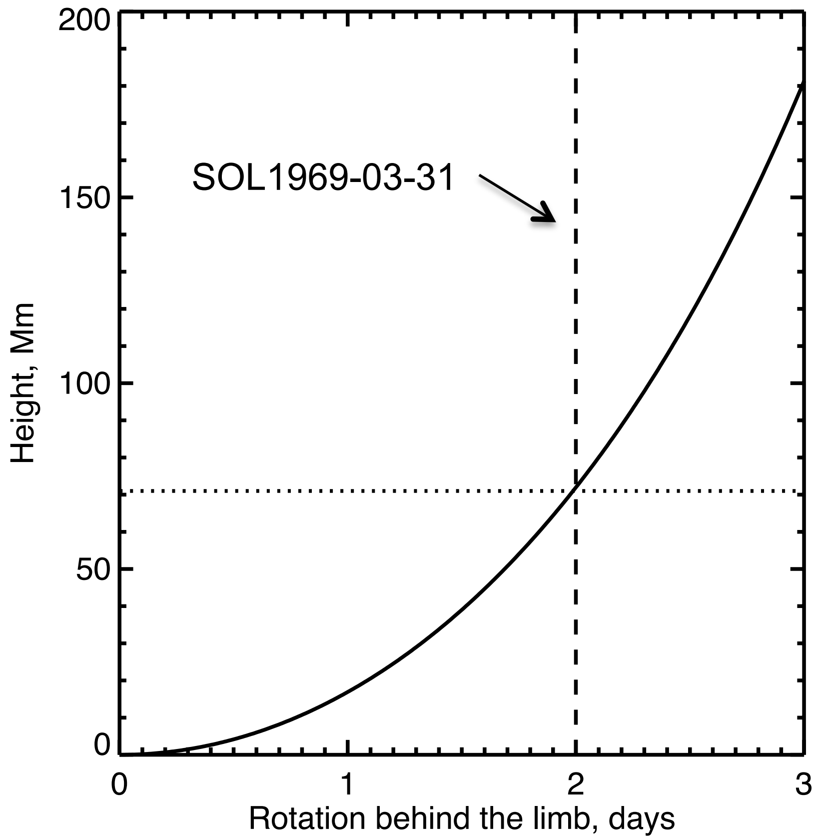
History I

- March 30, 1969 occultation event (OSO-5; Frost & Dennis 1971)
- Two occultation events observed by OSO-7 (Hudson 1978; Hudson et al. 1982)
- Direct imaging: Hinotori May 13, 1981
- Stereoscopic observations: Kane, 1983
- CME significance: Kiplinger 1995
- Moving coronal source: Hudson et al. 2001
- RHESSI: Krucker et al., A&A Rev 16, 155 (2008) for full details of many events

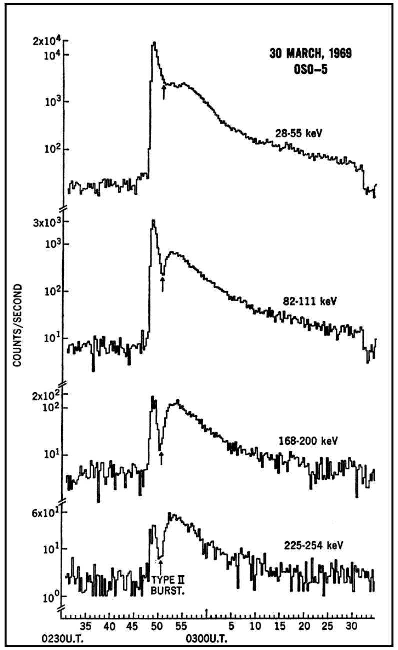
Limb occultation



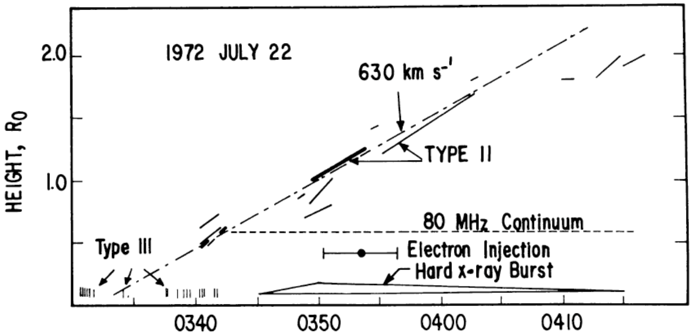
McKenzie, 1975



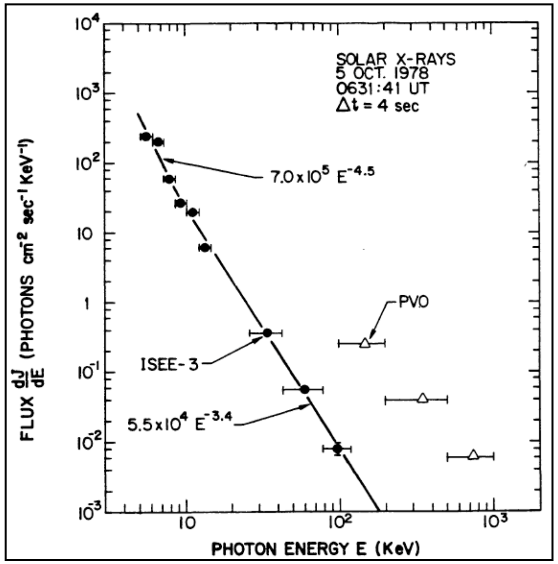
History II



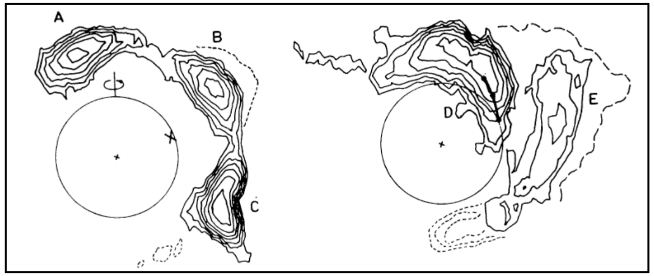
Frost & Dennis 1971



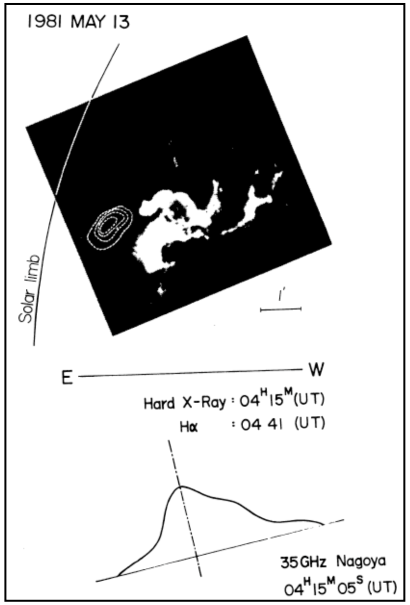
Hudson et al. 1978



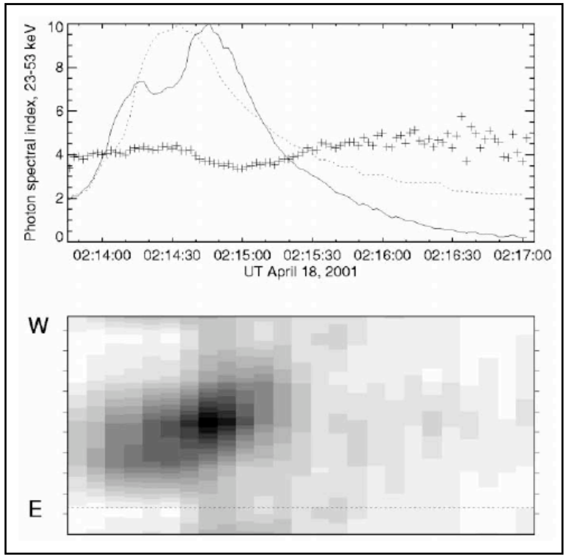
Kane 1983



Palmer & Smerd 1972

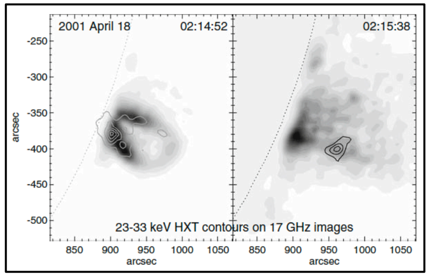


Kawabata et al. 1983

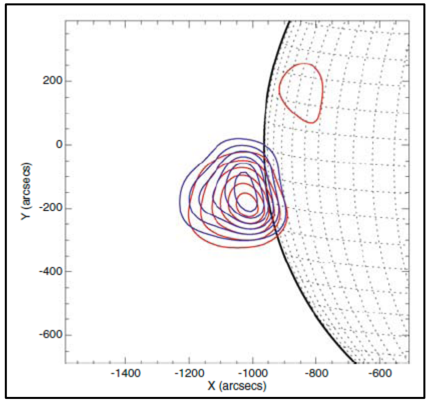


Hudson et al. 2001

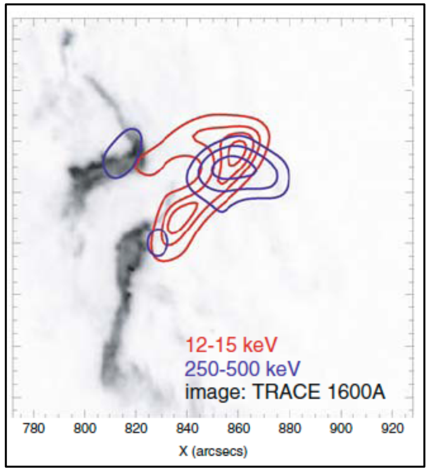
Coronal Hard X-ray Sources



SOL2000-04-18: Yohkoh/SXT observation, 23-33 keV, occultation height ~88 Mm. For this event one could infer that the non-thermal pressure dominated the core plasma pressure (Hudson et al. 2001).

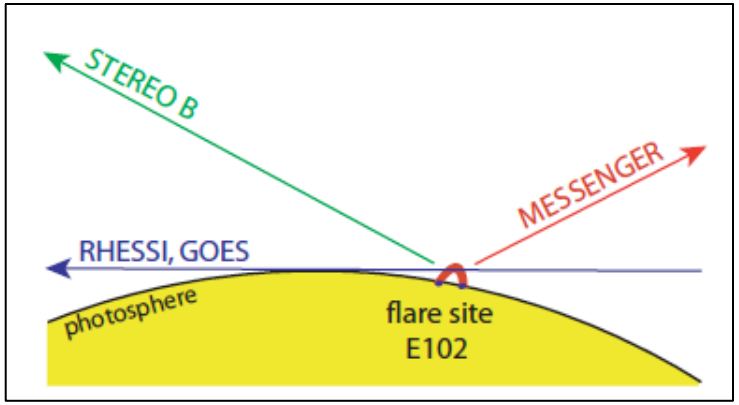


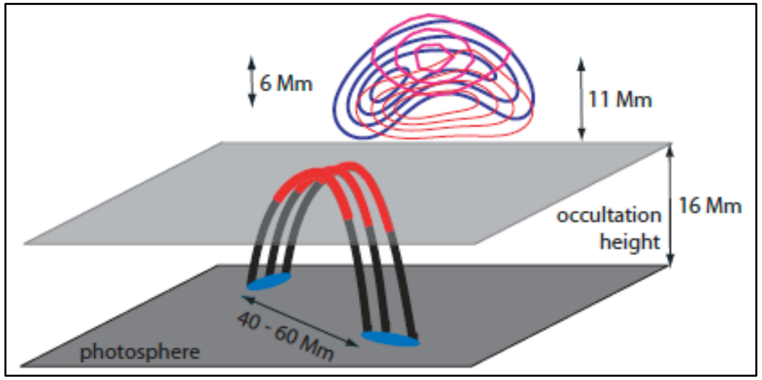
SOL2002-10-27: RHESSI observation, 10-30 keV, occultation height ~100 Mm (Krucker et al. 2007). This event was also see on-disk from a Mars perspective.



SOL2005-02-20: RHESSI observation, 250-500 keV, height ~40 Mm (Krucker et al. 2008). With RHESSI imaging one does not absolutely need the accident of occultation since we can just use projection to get a crude altitude. These high photon energies are remarkable and imply a highly non-thermal plasma inclusion in the corona.

RHESSI Occultation Event





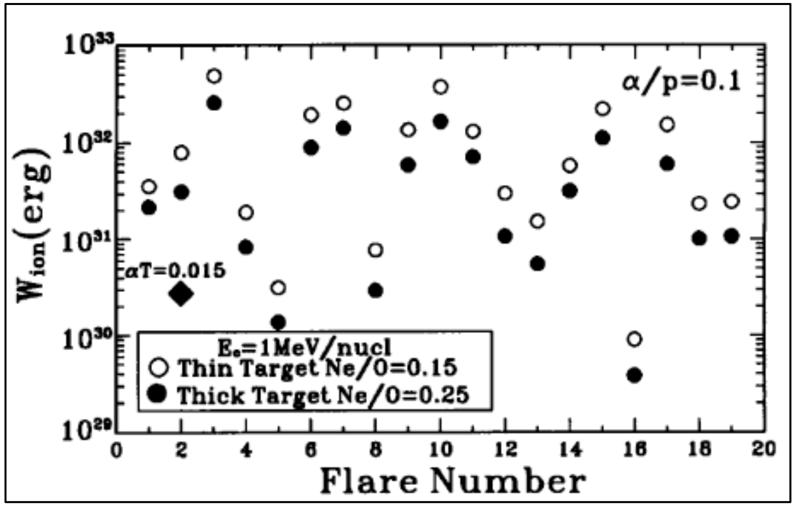
- Observations of SOL2007-12-31 reported by Krucker et al. (2010).
- Thin-target bremsstrahlung observations require rapid heating:

$$dT/dt = 4.5\ n_9^{-1}\ \text{keV s}^{-1}\ .$$

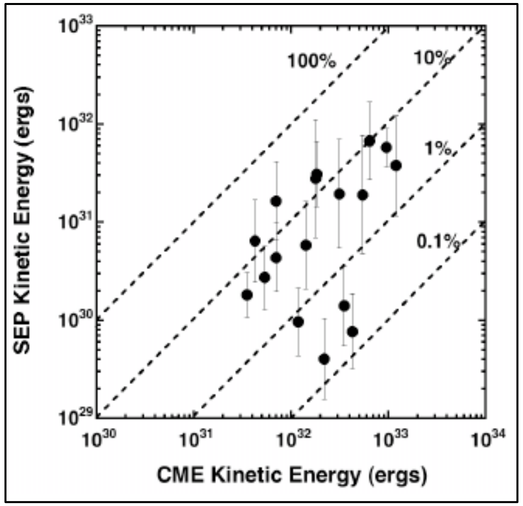
- For the observed limit on ambient density, this source requires dT/dt ~ 5 MK/s. This is faster than the Coulomb (e,p) relaxation can permit, and so there is no core thermal distribution for electrons in this plasma.

Particles and Energetics

- Electron acceleration to >10 keV (to ~100 kT) dominates the impulsive-phase energy release (Kane & Donnelly, 1971; Brown, 1971; Hudson, 1972; Lin & Hudson, 1976).
- SEP protons may contain 10% of the total flare energy (Mewaldt et al., 2008).
- Ion energy in the impulsive phase may compare with electron energy (Ramaty et al. 1995).



Ramaty et al. 1995



Mewaldt et al. 2008

Action at a Distance

- In resistive MHD models, Ohm's Law imposes the requirement of local heating.
- This is not what we observe! Particles can have enormous ranges, approaching the physical scale of the corona.
- Models this superficial may be forced to resemble the data, but can never self-consistently describe the physical processes involved with any precision.
- The several strong lines of evidence that particles contain important parts of the flare/CME energy – *most* of the impulsive-phase energy – means that we cannot ignore their property of "action at a distance".

Conclusions

- Highly accelerated non-thermal particles dominate the energetics of all phases of a solar flare.
- The particles have long stopping ranges, and the energy they transport does not dissipate locally.
- Flare theories and models need to account for this “action at a distance.”

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