Alternative Solar Paradigms for Stellar X-ray Activity

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Abstract: Solar flares generally have a well-defined spectral morphology as seen in soft X-rays (< 10 keV) hard X-rays (> 10 keV). This consists of the Neupert effect, relating coronal energization (soft X-rays) to non-thermal energy release (hard X-rays), plus the "soft-hard-soft" hard X-ray spectral variation. Such a pattern predicts a negligible "true" non-thermal hard X-ray flux from a stellar flare, which would scale such that a flare with an emission measure of 10^{55} cm^{-3}, at a distance of 100 pc, would produce a non-thermal hard X-ray flux of order 6 x 10^{-10} ph(cm^2 sec keV$)^{-1}$ at 35 keV. With this scaling a stellar hard X-ray flare would be difficult to observe. Other solar patterns of behavior do exist, though, and these might apply to other environments. We describe these different morphologies, which include the "extended flare" pattern, often marked by meter-wave Type IV radio bursts and a gradually flattening hard X-ray spectrum; the filament eruption/coronal mass ejection (CME) phenomenon; and the "impulse response" flare type originally described by White et al. (1992). RHESSI observations have recently revealed another candidate, a coronal hard X-ray source on the order of 0.3 R_sun in diameter and in height, which does not match the "extended flare" morphology. We discuss these patterns as they may extrapolate to a stellar application, illustrating the solar morphology with RHESSI hard X-ray and gamma-ray data.

About the poster. This poster is almost purely about flare morphology. Except for the standard morphology, none of the alternatives that we think we see are observed well enough to characterize quantitatively.

There is also a rich morphology, with different paradigms, of **solar energetic particle events** (SEPs). This is too big a subject for this poster but is important for Cool Stars, so maybe next time.

Because of all this morphology, there are many illustrations. We have tried to provide more detailed captions for these illustrations on second layers of the poster (such as this one). A question mark in the lower right corner identifies a slide as a one of these caption slides, which match the morphology of the corresponding main slide.

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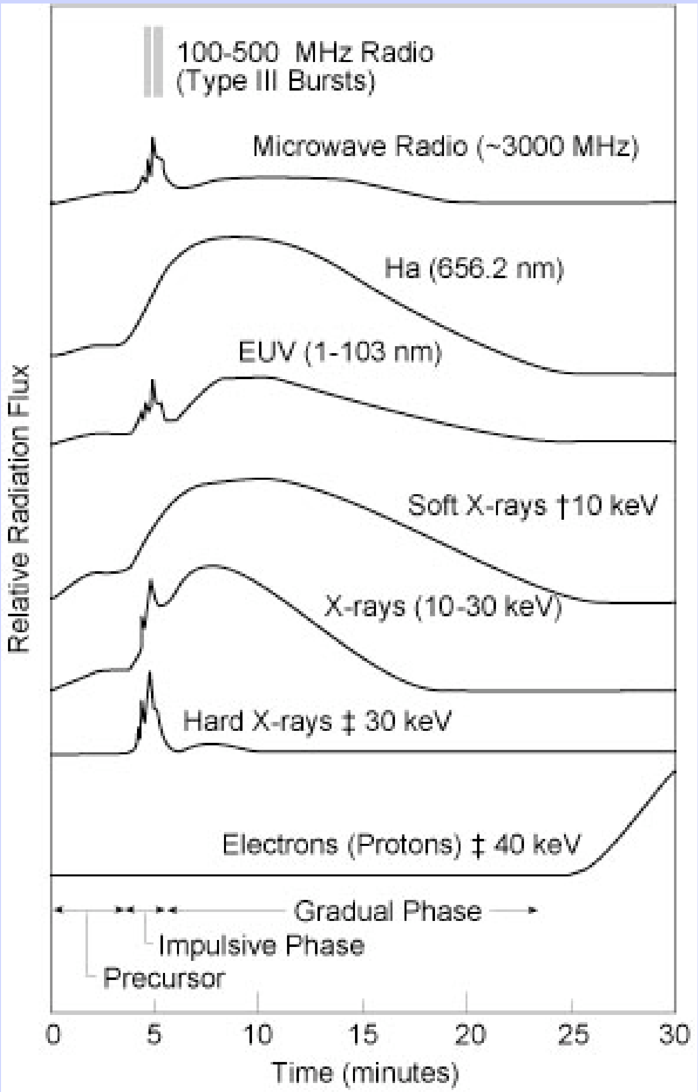
Normal Paradigm I: The Neupert Effect



Solar soft and hard X-rays

In the solar domain, "soft" means thermal (plasma) radiation, whereas "hard" means bremsstrahlung from non-thermal electron distributions. Often the boundary energy is about 20 keV but it depends upon conditions.

The Neupert Effect

Neupert (1968) noted that the time integral of the Solar microwave synchrotron emission tended to Match the time history of soft X-ray emission. The latter comes from hot gas trapped in coronal magnetic fields, hence we identify this "Neupert Effect" with the levitation of chromospheric material into the corona during the flare energy release.

Normal Paradigm I: The Neupert Effect

A schematic view of the time profiles of various solar flare radiations. The "impulsive phase" appears at many wavelengths, from radio to hard X-ray, whenever the medium is optically thin and the competing radiation is faint. The reference to "type III bursts" is to the escape from the Sun of weakly relativistic electrons, implying the existence of open magnetic field lines penetrating close to the flaring region in the low corona. These electrons later appear at 1 AU, as indicated.

Our interpretation of these two phases is simple. In the impulsive phase, a non-thermal explosive process happens; in the gradual phase the coronal field lines fill up with "evaporated" material that radiates in soft X-rays. The temperature of this coronal source is limited by the conductive flux to the chromosphere.

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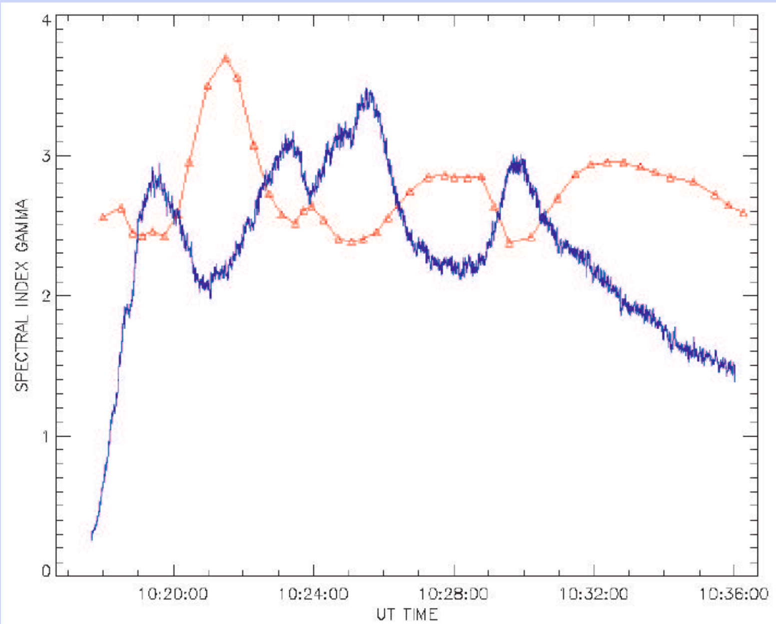
Normal Paradigm II: Soft-Hard-Soft pattern

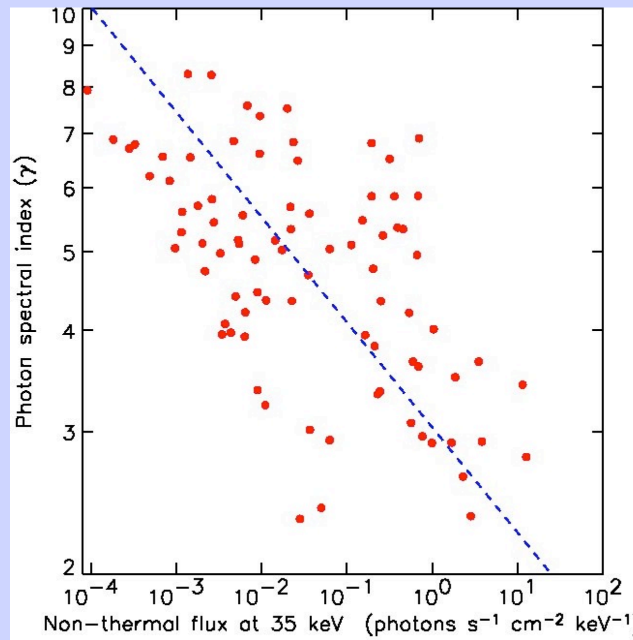


Soft-hard-soft (many events)

Marina Battaglia, in a RHESSI science nugget* has analyzed many RHESSI hard X-ray events and generated the correlation plot below. The soft-hard-soft pattern applies not only to a single event, but to most events when taken as an ensemble.

Soft-hard-soft (one event)

The hard X-ray spectral hardness correlates with the flux. That is, the spectrum appears to pivot around a low-energy fixed point.



*http://sprg.ssl.berkeley.edu/~tohban/nuggets/?page=article&article_id=9

Normal Paradigm II: Soft-Hard-Soft pattern

This figure shows the time variation of hard X-ray flux and spectral index (fitted power-law slope). The soft-hard-soft pattern is equivalent to noting that the spectrum pivots around some lower photon energy. Benz (1977) pointed out that this behavior was quite consistent with a stochastic acceleration model, in which some volume of turbulence contains and accelerates the electrons that we "see" via their bremsstrahlung in the thick target. See Hudson & Farnik (ESA SP-506, 261 (2002), on line) for a recent view of the observational situation.

The soft-hard-soft pattern seems to prevail not only in the individual peaks of a given flare's time series, as shown in the other figure, but also from flare to flare. This scatterplot for points from several events is from Zurich graduate student Marina Battaglia's work on RHESSI data, as described in a RHESSI science nugget*.

The significance of this soft-hard-soft pattern is a bit obscure, but it is certainly something that the acceleration process in impulsive solar flares must deal with.

*http://sprg.ssl.berkeley.edu/~tohban/nuggets/?page=article&article_id=9

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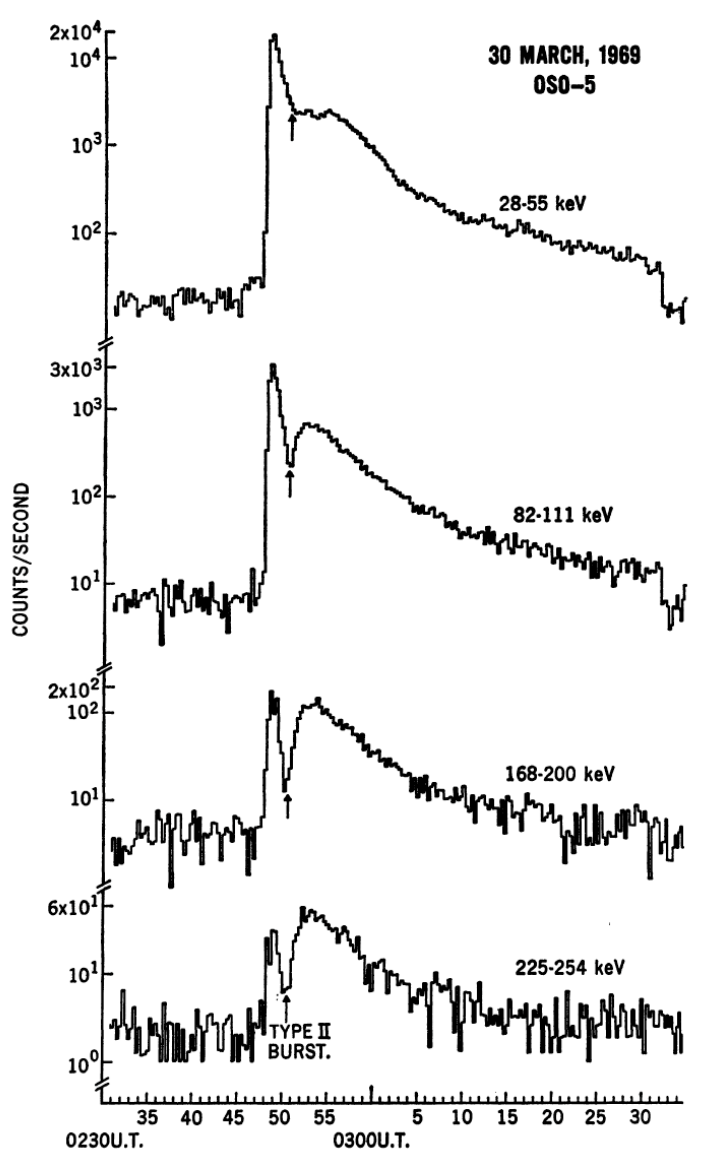
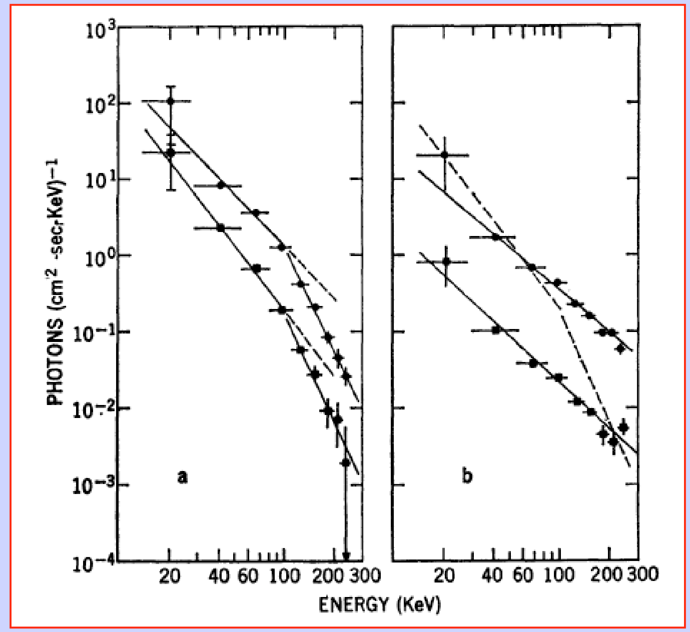
Non-standard paradigms

1. Extended events
   Frost & Dennis, 1971; Cliver et al., ApJ 305, 920 (1986)
2. Masuda events
   Masuda et al., PASJ 47, 677 (1995)
3. Non-thermal ejecta
   Hudson et al., ApJ 561, L211 (2001)
4. Coronal thick-target events
   Veronig & Brown, ApJ 603, L117 (2004)
5. Shock waves
   Hudson et al., Solar Phys. 212, 121 (2003)
6. Impulse response
   White et al., ApJ 384, 656 (1992)

New Paradigm # 1: “Gradual flares”



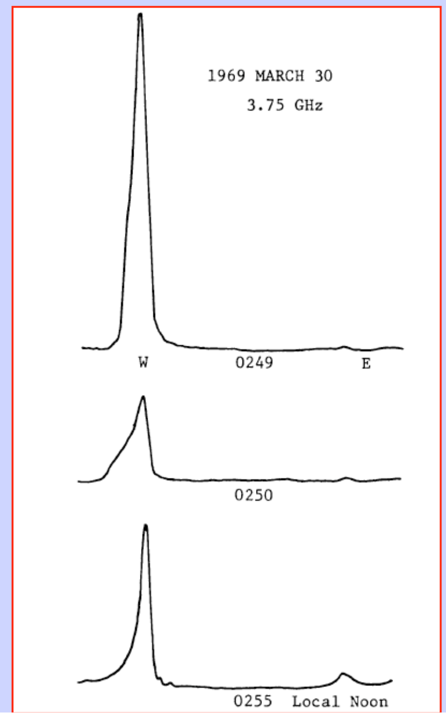
Frost & Dennis 1971



March 30, 1969:
X-rays and Microwaves

No Hα flare, ~W105

Enome & Tanaka 1971
(3.5 GHz)



New Paradigm # 1: "Gradual flares"

Spectra from the X-ray burst. These show broken power laws at early times, morphing into very flat spectra at later times. Such flat spectra, approaching $J \sim (h\nu)^{-2}$, have been observed in other similar over-the-limb events. Given the spectrum of bremsstrahlung, this means a relativsitc electron source. We still do not understand how these fast electrons find enough target density to radiate so strongly.

The light curves, from OSO-5, of the well-known event of March 30, 1969, reported by Frost & Dennis (1971). The fact that this exceptionally bright and hard-spectrum burst came from a flare 20-30 degrees behind the E limb was astonishing. The limb occultation then proved to be a good tool for helping to distinguish fainter coronal features from very bright sources at the footpoints. This particular event may have had enormous footpoint emission, but we should realize that this kind of coronal development may proceed fairly independently of the flare itself. certainly coronal mass ejections (CMEs) have physics that is unique to them, even though they are usually tightly associated with flares.

Microwave fan-beam scans Of the March 30 1969 event. The source was clearly expanding to the left (West) with time, as reported by Enome & Tanaka (1971) from an early Japanese microwave interferometer. Their interpretation was that it was a diffusing cloud, but it seems more likely now to have been expanding loops. Even if this event occurred today, though, we probably could not figure it out.

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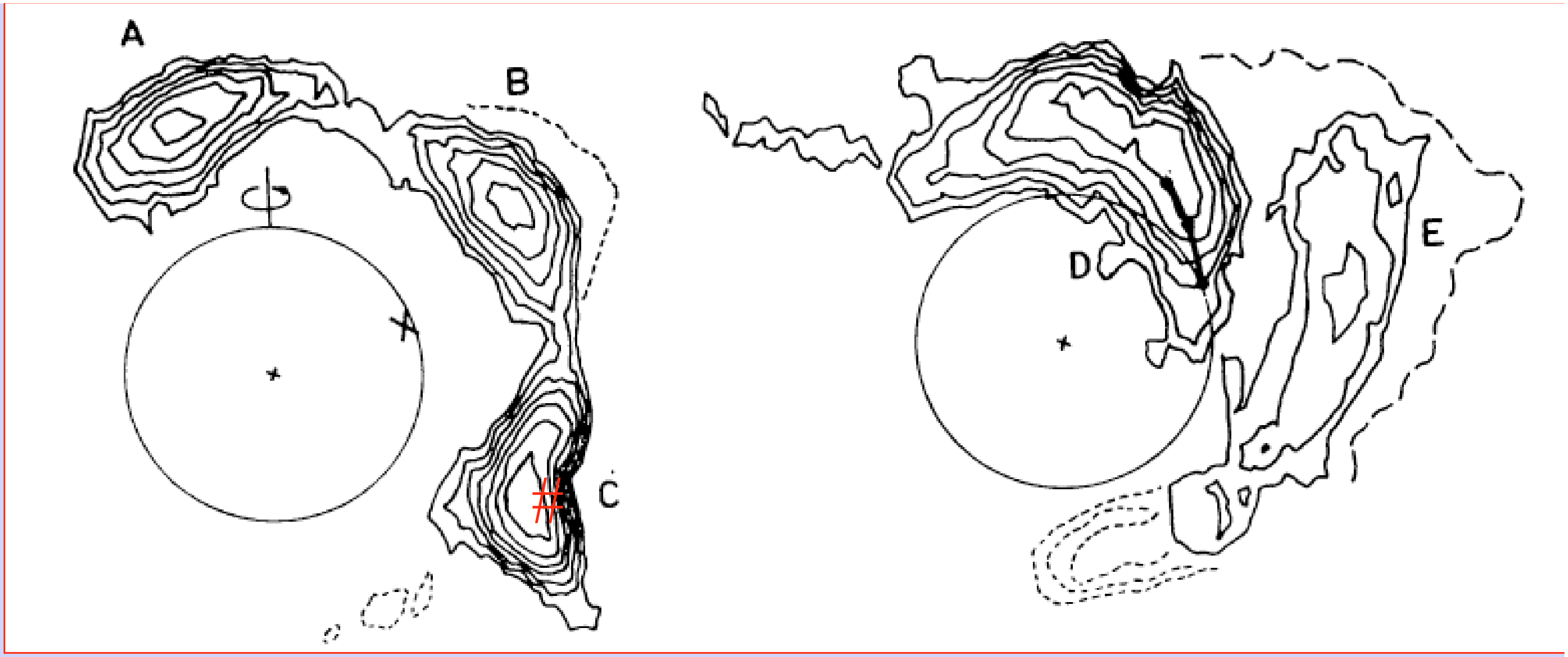
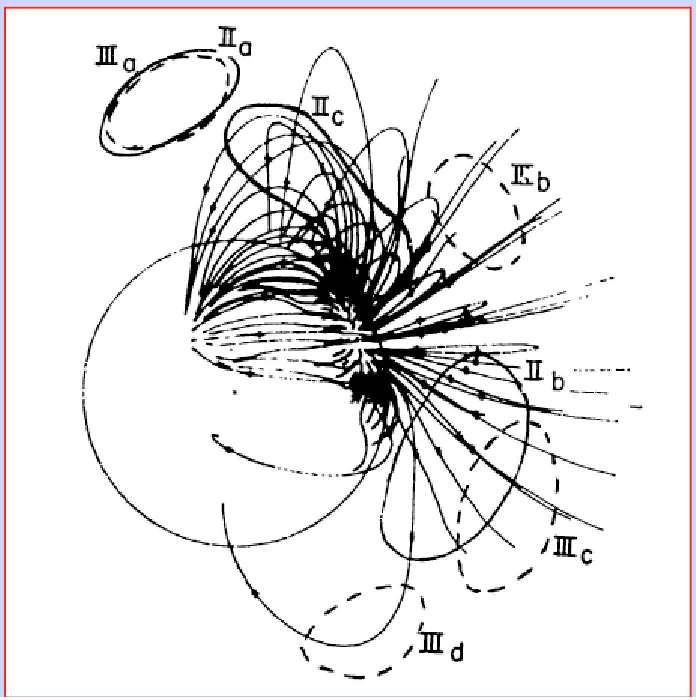
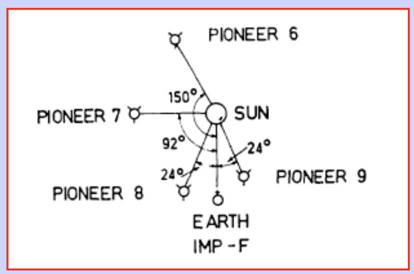
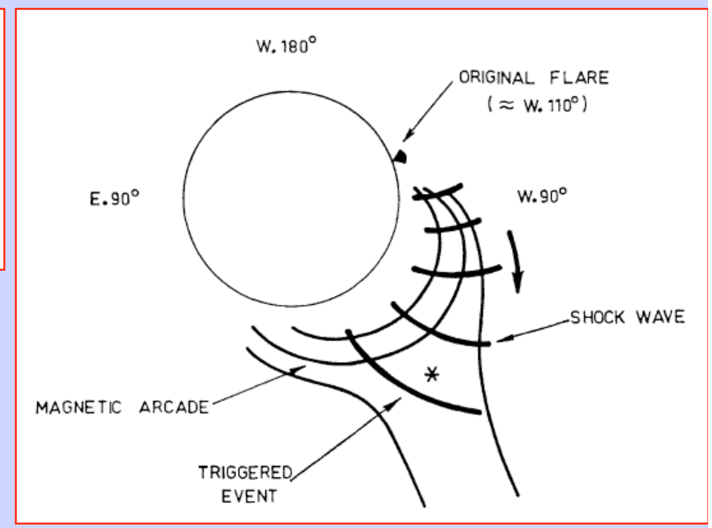




March 30, 1969: meter waves (Culgoora)



Palmer & Smerd, 1972



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The figures on this page show observations from the meter-wave radioheliograph at Culgoora (Australia). This wonderful telescope operated for many years, but then was given up and in fact has been overbuilt by the Australia Telescope Compact Array. Editorially speaking, I don't think this was a wise move, because the observational capability represented by the Culgoora solar array has never been duplicated.

In this event one sees a complicated array of sources strung out around the solar limb. Mostly this is plasma-frequency radiation, including type II "slow drift" sources associated with CME-driven shock waves. The radius of the photosphere of the Sun at these wavelengths, or the $\tau = 1$ surface, is far above the optical photosphere, and one gets a good feeling about its location from images of this sort. Some of the emission is also type III ("fast drift", due to weakly relativistic electrons escaping from the Sun on open field lines); some of it probably is also type IV (normally associated with relativistic electrons trapped in large-scale coronal loops.

The X marks the flare location, but on the *invisible* hemisphere. See Smerd (1970) or Palmer & Smerd (1972), or the Annual Reviews article in 1972 by Wild & Smerd.

Another view of the Culgoora observations of the March 30, 1969 event. Here Palmer & Smerd have attempted to represent the coronal magnetic field via an expansion based on magnetograph data. We can do a lot better with this sort of thing nowadays and it would really be nice to have a meter-wave imaging capability that showed type II bursts - shock fronts - that we could compare with reasonable magnetic field models.

This event occurred when there was an interplanetary fleet making multi-point particle observations.

The Parker-Smerd (1972) cartoon view of the March 30, 1969 event. This shows the flare location and some pretty speculative ideas about arcades, shock structures and the like.

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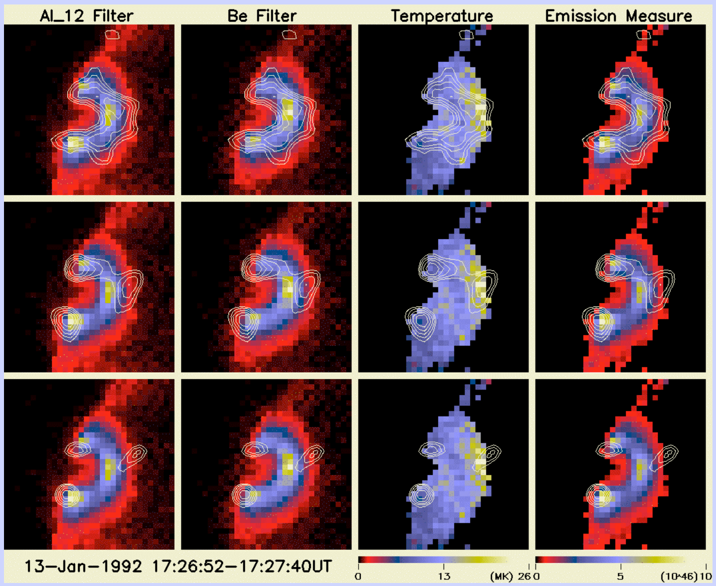
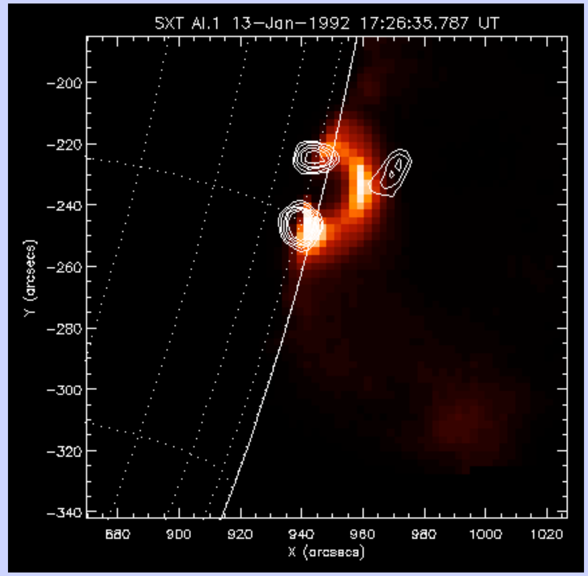
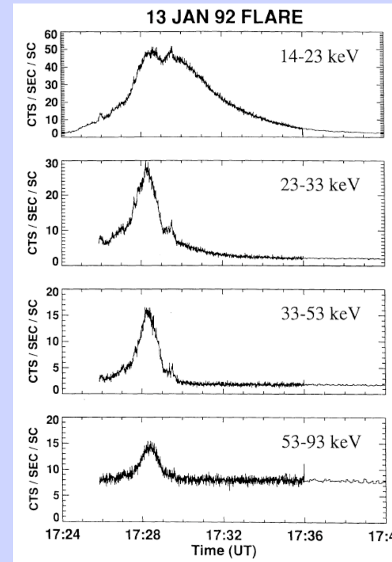
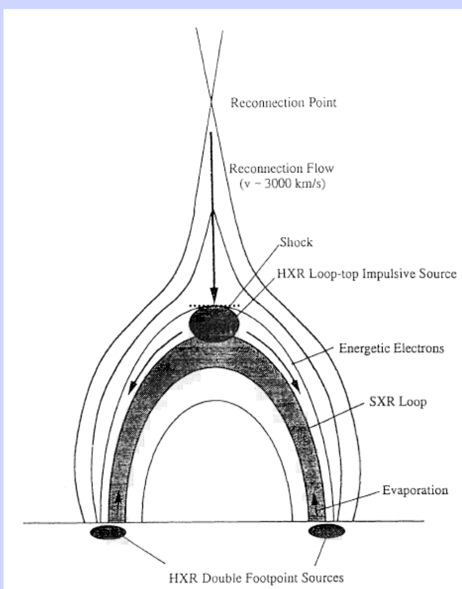
New Paradigm # 2: "Masuda flares"









One of a kind?

This flare of Jan. 13, 1992, has come to be iconic in solar flare theory. In fact, however, it represents an unusual and still-unexplained phenomenon. Neither further *Yohkoh* searches nor observations with RHESSI have turned up comparable examples of this "above-the-loop-top" source. However other examples of coronal hard X-ray emission are now fairly numerous.

New Paradigm # 2: "Masuda flares"

An original view of the "Masuda flare" of Jan. 13 1992, as observed by the soft X-ray and hard X-ray telescopes on Yohkoh (SXT for the background image and physical parameters; HXT for contours trom the three lowest energy channels: 14-22 keV, 22-32 keV, and 32-52 keV. Note that the "above-the-loop-top" source has a hard spectrum. The limb runs from top to bottom (as seen in the image on the right.

Another view of the Masuda source, showing the location of the solar limb. The loop top (seen in soft X-rays) and the "above-the-loop-top" source (seen in hard X-rays) clearly are projected against the corona, not the disk, and therefore must actually *be* in the corona. **Unfortunately this is the only clear example of this kind of morphology, which RHESSI essentially does not confirm.**

Time histories from HXT's four energy channels during the Masuda flare. The longer tail in the softest channel shows the usual thermal source, according to the normal paradigm, but the impulsive-phase source did not turn out to be just at the footpoints. The images (see left) showed the mysterious "above-the-loop-top" source as well.

The cartoon drawn by S. Masuda to describe his "above-the-loop-top" source in terms of a standing fast-mode MHD shock wave resulting from reconnection outflow. This shock would then be implicated in the acceleration of the impulsive-phase electrons and the footpoint hard X-ray emissions. This picture is very influential and is often used to represent the normal paradigm.

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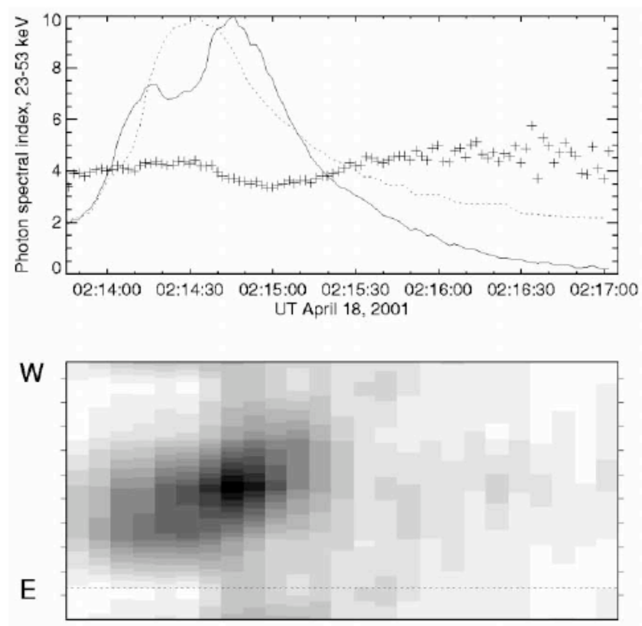
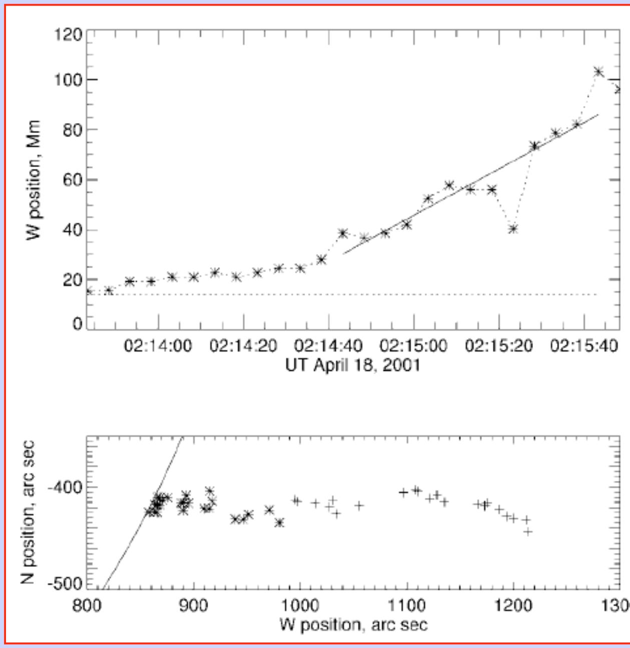
New Paradigm # 3: Moving HXR source



Left: Time series: HXR solid, SXR dotted, HXR spectral index. This event is highly non-paradigmatic

Bottom Left, both right: Source motions as seen in hard X-rays and at the Nobeyama Radio Observatory



A moving coronal hard X-ray source

An over-the-limb flare of April 18, 2000 produced a rapidly-moving (order 10^3 km/s) hard X-ray source that could be tracked both by Yohkoh/HXT in hard X-rays, and by the Nobeyama Radio Observatory in microwaves. Because of limb occultation this source could be tracked to a great altitude, of order 10^5 km. This event so far is unique in hard X-rays but suggestive of various radio phenomena.

New Paradigm # 3: Moving HXR source

The remarkable moving hard X-ray source - also unique in the *Yohkoh* data - of April 18, 2001. The upper panel shows the standard GOES soft X-rays (dashed line) and the HXT 14-22 keV hard X-rays (solid line). The points show the HXT spectral index. This is not a soft-hard-soft pattern.

The lower panels shows source motions as a stack of 1D images (see the plots on the other figure for more detail).

(Upper) Height vs. time for the hard X-ray source, showing a final outward motion at roughly 10^3 km/s. The source was being "de-occulted" by the limb as it emerged from a behind-the-limb flare; the limb altitude was of order 0.03 R_0.

The lower panels shows the motion of the corresponding Nobeyama 17 GHz source. The overall morphology suggests the eruption of a filament in which non-thermal particles are being accelerated. The interpretation of Hudson et al. (2001) suggests that non-thermal pressure could play an important dynamical role.

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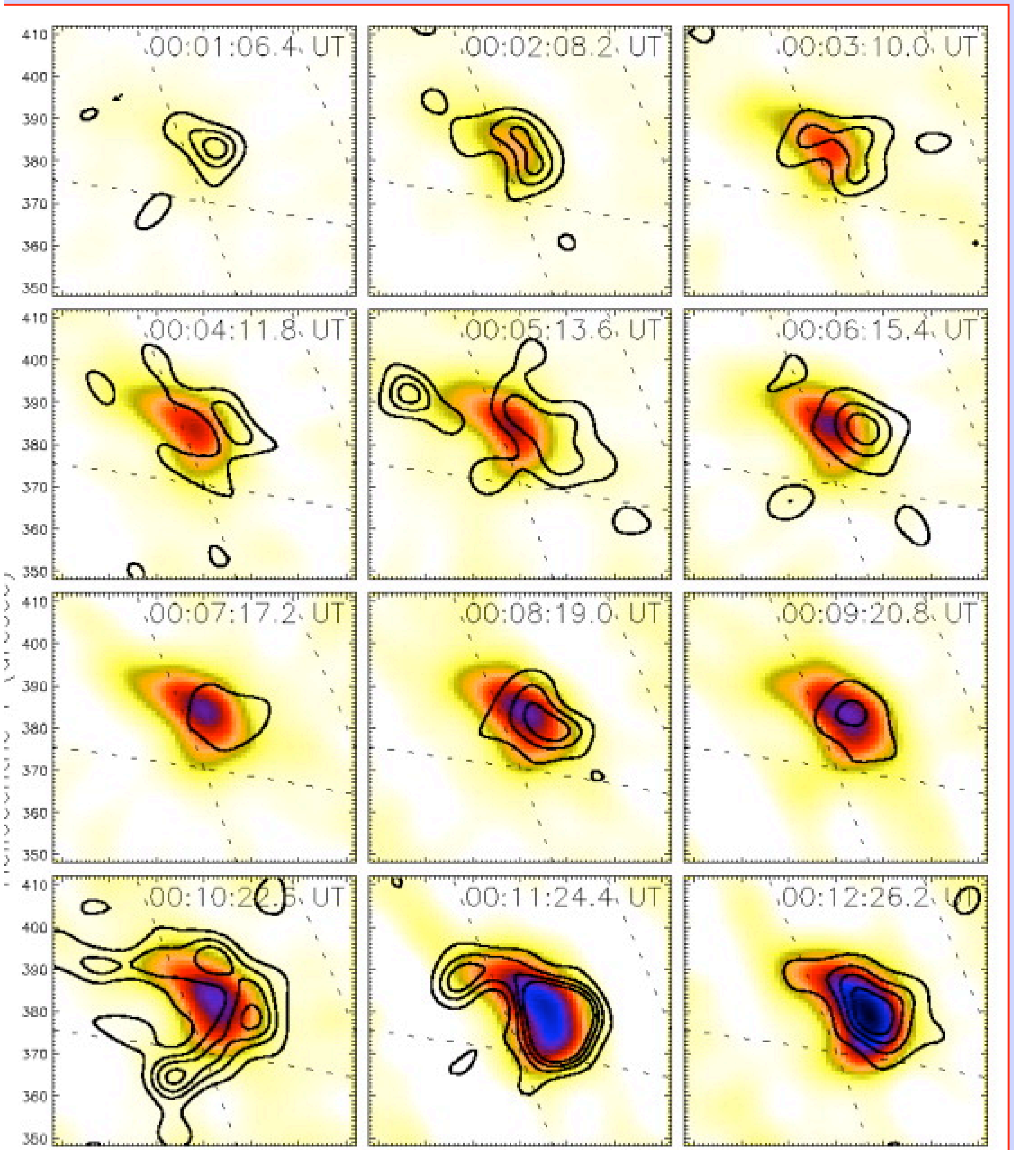
New Paradigm # 4: Coronal thick target



Collisionally trapped electrons

In two sources observed by RHESSI a "coronal thick target" appears to be the preferred explanations. Such events do not have strong HXR footpoint emission, as expected from the normal paradigm, but are consistent with the existence of dense coronal loops capable of the collisional stopping of ~50 keV electrons.

New Paradigm # 4: Coronal thick target

A series of panels showing RHESSI hard X-ray images from a new class of solar hard X-ray sources discovered by Veronig & Brown (2004). The absence of obvious footpoint emission, even at reasonably high X-ray energies (25 keV) indicates that the coronal structure of the loop is collisionally thick to the motion of the ~50 keV electrons producing the bremsstrahlung. This means that a previous flare or some other unknown mechanism has loaded the coronal magnetic loop with enough mass to make a "coronal thick target." In the normal paradigm, the mass loading ("evaporation") probably happens in a sequence of filamentary flux tubes, each one of which has a low coronal density at the time of energy release.

Flares of this type are few in number, but several other examples were found in later RHESSI observations.

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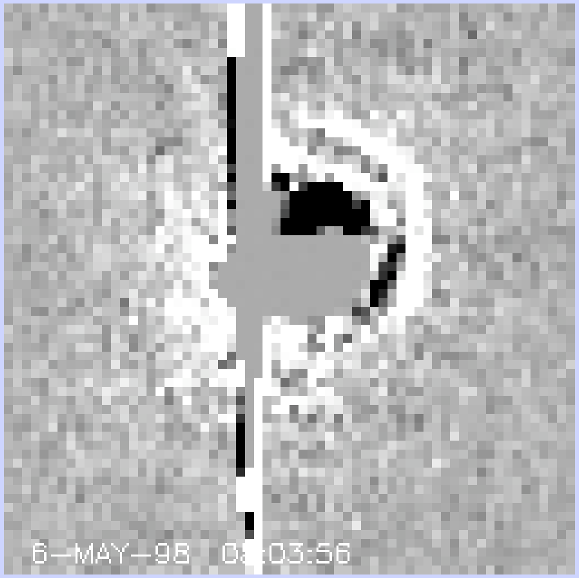
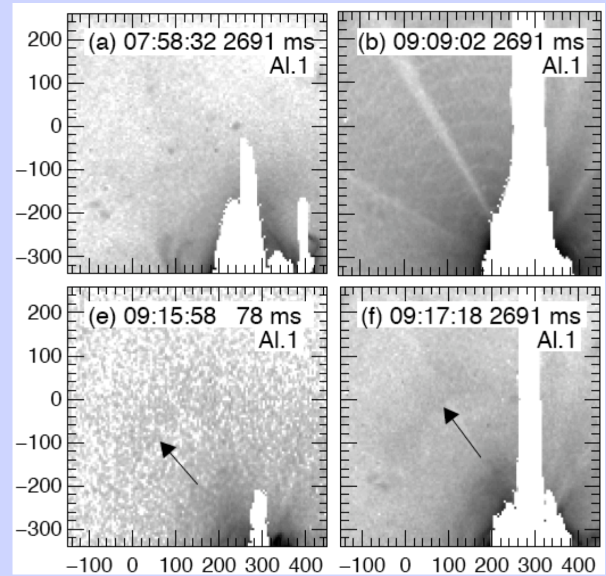
New Paradigm # 5: Coronal shock waves



Left: soft X-ray observations
Of a limb flare (May 8 1998)

Right: soft X-ray observations
of a disk flare (Nov. 3 1997)



The flare blast wave

Hardly a new suggestion for astrophysicists, a shock wave can form and heat the ambient corona. A flare can do this in two ways: the initial magnetic restructuring can launch a blast wave (metric type II burst and Moreton wave in Hα), and the resulting CME can drive a bow shock ahead of its motion all the way to 1 AU (or beyond).

New Paradigm # 5: Coronal shock waves

One frame from a soft X-ray movie showing the direct action of a flare blast wave (Hudson et al. 2003), as seen by Yohkoh. The flare was just at the W limb, so the curved shock front is projected against dark sky. This image is a difference image and is dominated by a saturation spike, the result of the deep overexposure required to catch the wave emission. According to the analysis, the Mach number of this wave was about 1.4; this would not be enough to create strong particle acceleration and support hard X-ray emission (not observed).

A second example of a soft X-ray blast wave as observed by *Yohkoh* SXT (Khan & Aurass, 2002). The arrows point to the faint wavefront, difficult to seen in the presence of many image artifacts (cf the shadows of the spider in the upper right) due to deep overexposure.

This particular observation was quite important because the timing allowed the authors to make a definitive identification of the X-ray wave with its metric type II burst and Moreton wave counterparts, thus neatly completing the picture put forward by Y. Uchida decades ago.

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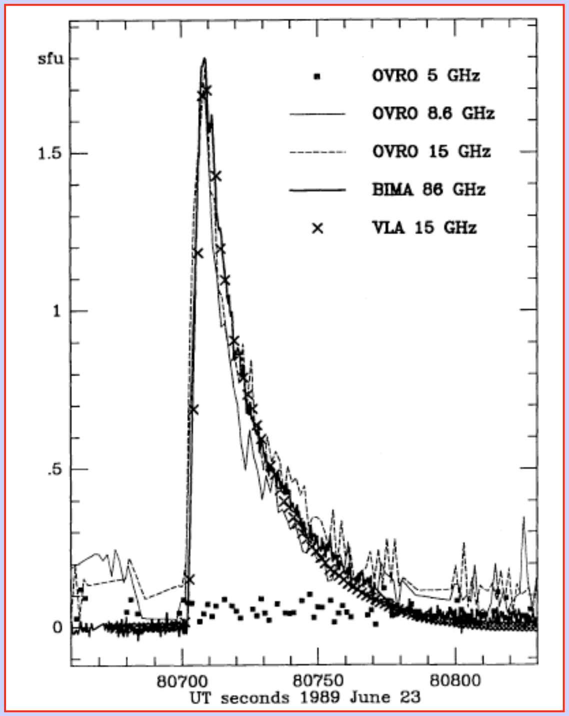
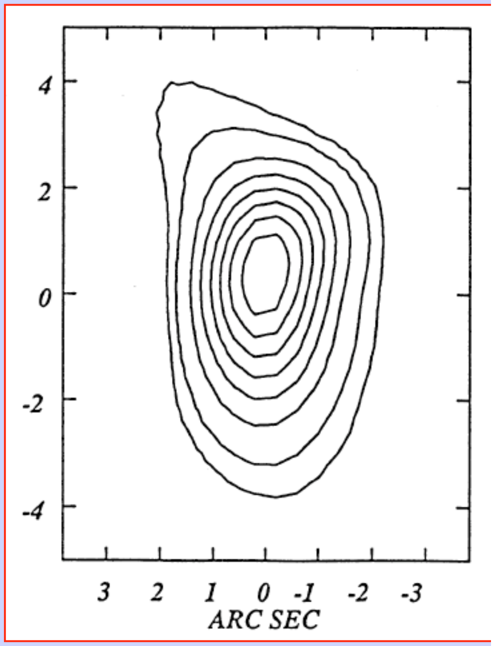
New Paradigm # 6: Impulse response



Left: Time profile and broadband spectrum as derived from several observatories. Note the spectral pecularity of a flat f_ν following an extremely sharp microwave cut-on.

Right: Somewhat boring VLA image at 15 GHz. To a solar eye, this looks like an unresolved loop of a scale hardly large enough to reach into the corona. The source, thought not understood at all, presumably involves relativistic electrons in the chromosphere.



Impulse response flares

Really only a small literature (White et al. 1993 is about it) but equally as important as the Masuda phenomenon. These are events with a simple "impulse response" time profile and a narrow range of parameters, as illustrated. The significance to high-energy astrophysics is the extension of the radio spectrum into the millimeter waves, where relativistic particles are required.

New Paradigm # 6: Impulse response

Broad-band spectral data from several solar radio observatories: OVRO = Owens Valley Radio Observatory; BIMA = Berkeley Illinois Maryland Millimeter Association (Hat Creek); VLA = Very Large Array.

Note the absence of a signal at 5 GHz. This very sharp cut-on presumably means a thick overlying layer, consistent with a chromospheric site.

Several other impulse-response flares have been reported by the same group, but none with such good coverage (including VLA imaging, see the other graphic).

VLA imaging of the prototype impulse-response flare. At about 750 km per arc sec at the solar surface, this object appears to be a loop so short that on a crude semicircular geometrical assumption, it would hardly extend into the solar corona. Other observations (e.g., Big Bear Ha and magnetogram) were available. The original paper (White et al. ApJ 384, 656, 1992) is certainly worth a read, even if it comes to the conclusion that we don't understand the phenomenon. Probably what we need are high-energy and/or stellar observations of related phenomena.

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Conclusions

- New solar observations are beginning to show X-ray sources with atypical properties
- Some of these new paradigms depend on coronal observations at large spatial scales
- We speculate that some of the same physics might also be at work in various forms of stellar activity