Microwave and hard X-ray imaging observations of energetic electrons in solar flares: event of 2003 June 17

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Introduction

We discuss one large flare using simultaneous observations obtained with two instruments--Nobeyama Radio Heliograph (NoRH) at 17 and 34 GHz, and Reuven Ramaty High Energy Solar Spectroscopic imager (RHESSI). Energetic electrons accelerated to nonthermal energies are seen via microwave and hard X-ray emission from the solar corona. Imaging observations are necessary to study the energetic electrons in events such as these. NoRH is the most sophisticated and fully dedicated solar radio telescope operating at microwave frequencies (17 & 34 GHz) capable of imaging microwave emitting electrons in flaring loops. At 17 GHz it measures both Stokes I and V, and at 34 GHz Stokes I alone, with good sensitivity and spatial resolution of 10 and 5 arc seconds, respectively at the two frequencies. Hard X-ray emitting electrons are mapped by RHESSI.

Nonthermal microwave emission during large solar flares is produced by gyrosynchrotron mechanism which involves coronal magnetic fields of at least a few hundred gauss and electrons of energy of a few hundred keV. Hard X-ray emission, on the other hand, is produced by bremsstrahlung from beamed or trapped electrons of a few to hundreds of keV energy. The two different methods of mapping energetic flare electrons therefore complement each other, and provide good means of testing flare models which have been abundant in the recent literature. The RHESSI HXR and NoRH microwave imaging observations of the flare of 2003 June 17 are used here as an example. The flare in question was of class M6.8, and it was observed in AR 10386, a β–γ–δ region, two days after its east-limb passage.

In this event, during the pre-impulsive and early impulsive rise phases, we see brightening at low (3-25 keV) X-ray energies, with morphological changes in and around a "loop-top" source associated with a filament eruption observed in EUV and H-alpha. Early appearances and motions of HXR sources have been interpreted as signatures of the formation and development of current sheets (Sui, Holman & Dennis 2004, ApJ 612, 546). In some other events, the motions of footpoints have been correlated with the HXR flux, reflecting the variability of the reconnection rate and the acceleration of electrons (e.g. Krucker et al ApJ 595L 103, 2003). But not all flares show a temporal correlation of footpoint or loop motions with HXR flux (Grigis & Benz, ApJ 625L, 143 2005, Krucker et al 2003, Fletcher & Hudson, SoPH 210, 2002, Sakao et al 1998). It is important to use such observations to test and refine the reconnection model. This flare, because of its long rise phase and multitude of strong, isolated bursts seen in HXR and microwaves, provides additional information on the nature of magnetic reconnection and the association with the acceleration of electrons.

Left: RHESSI light curves (12-800 keV), NoRH Time Profiles
Right: NoRP Time Profiles

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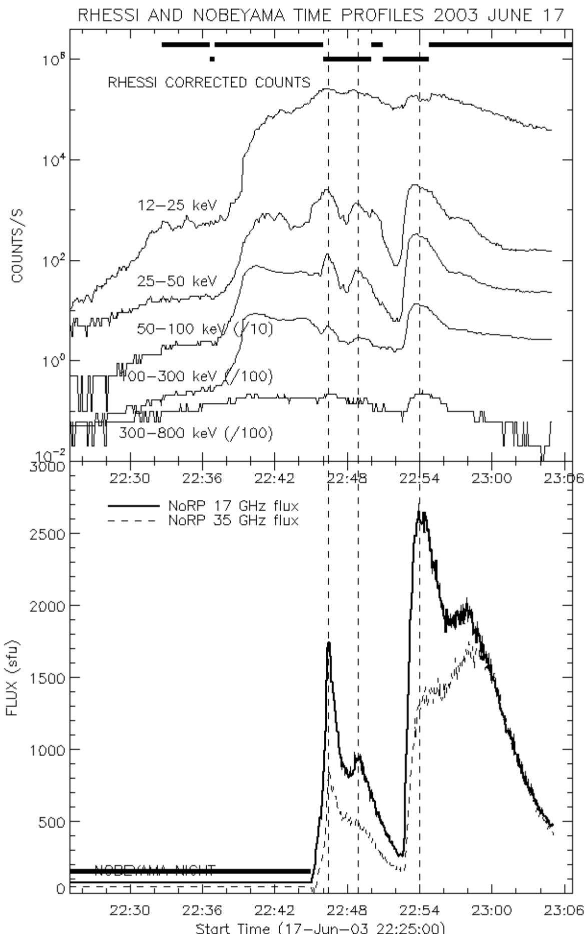


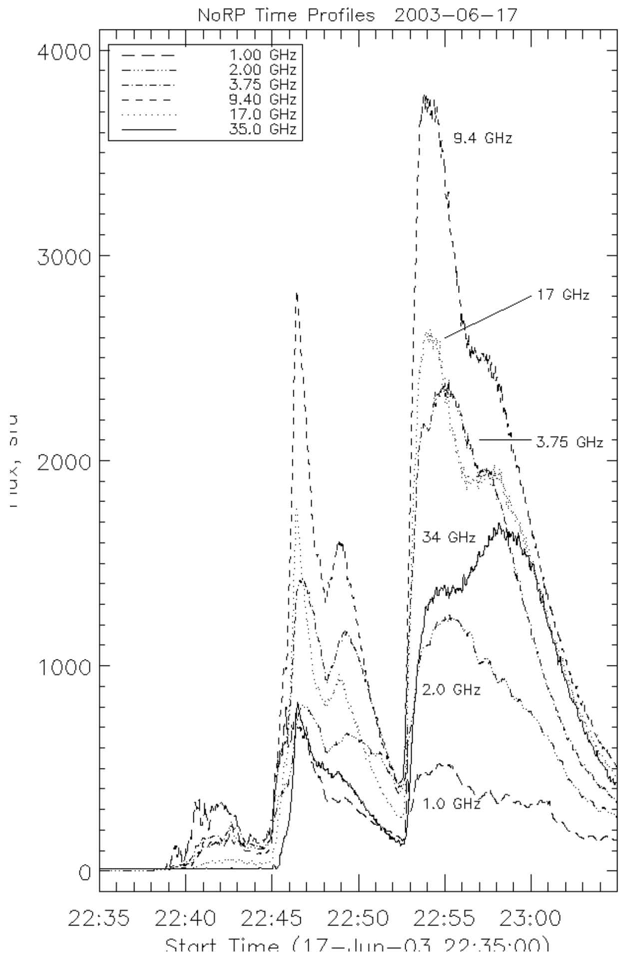


Fig 1ab

17, 34 GHz I and HXR 50-100, 100-180 keV overlays on MDI

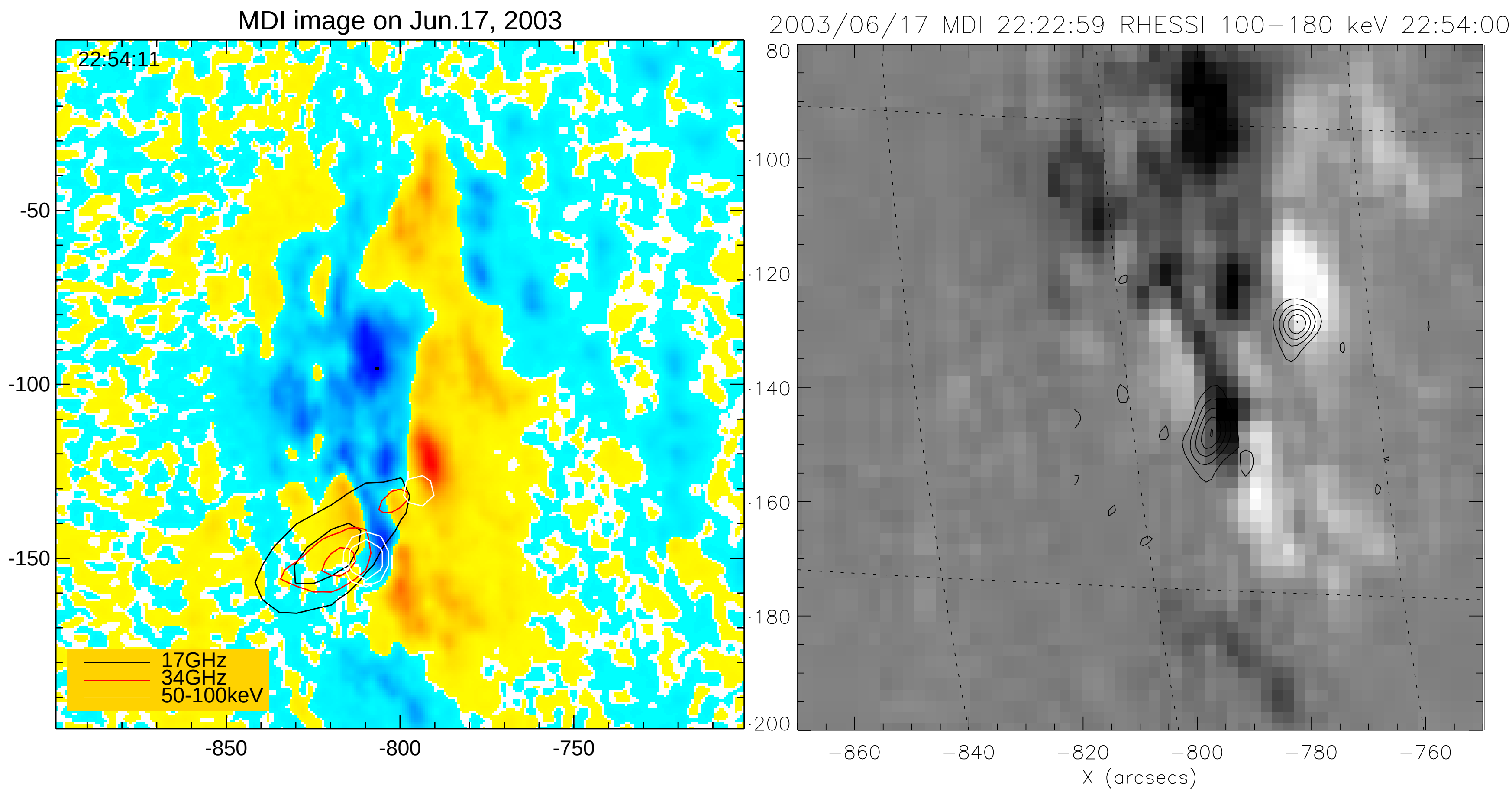
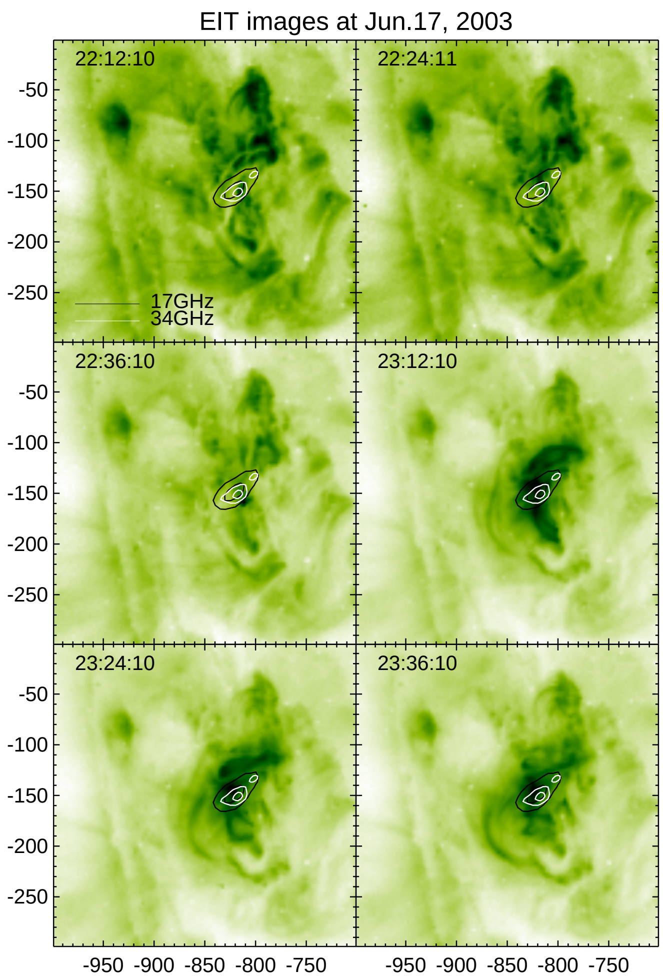


Fig 2a,b

EIT and TRACE Observations with 17 & 34 GHz Images



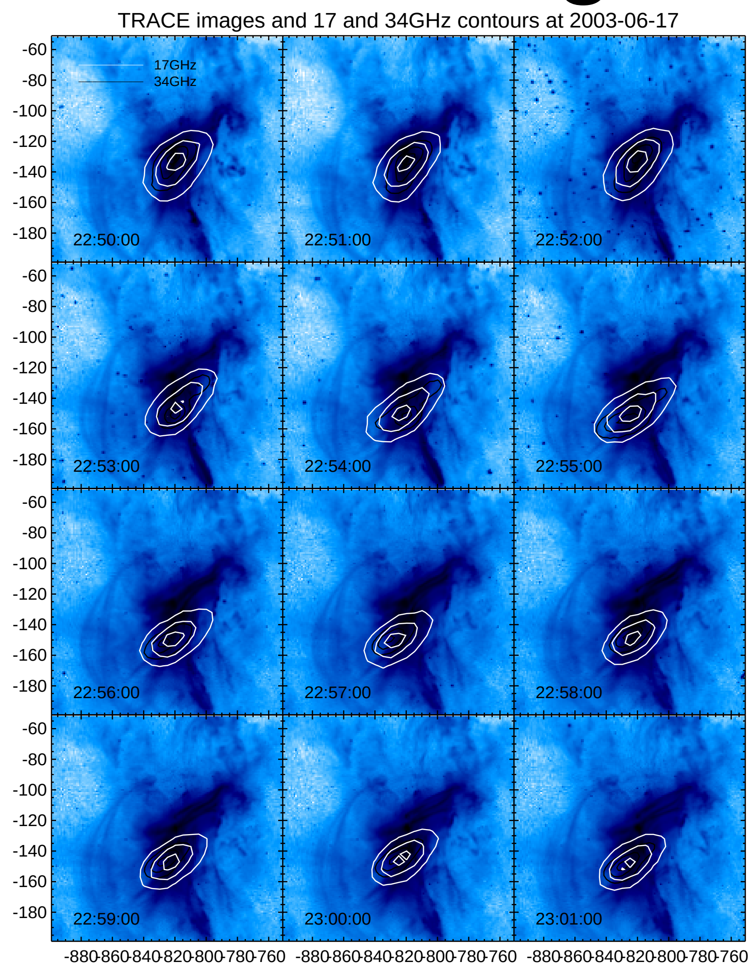


Fig 3a,b

Selected Pre-flare HXR Images

3-6, 6-12 & 12-25 keV

3-6 keV

6-12 keV

12-25 keV

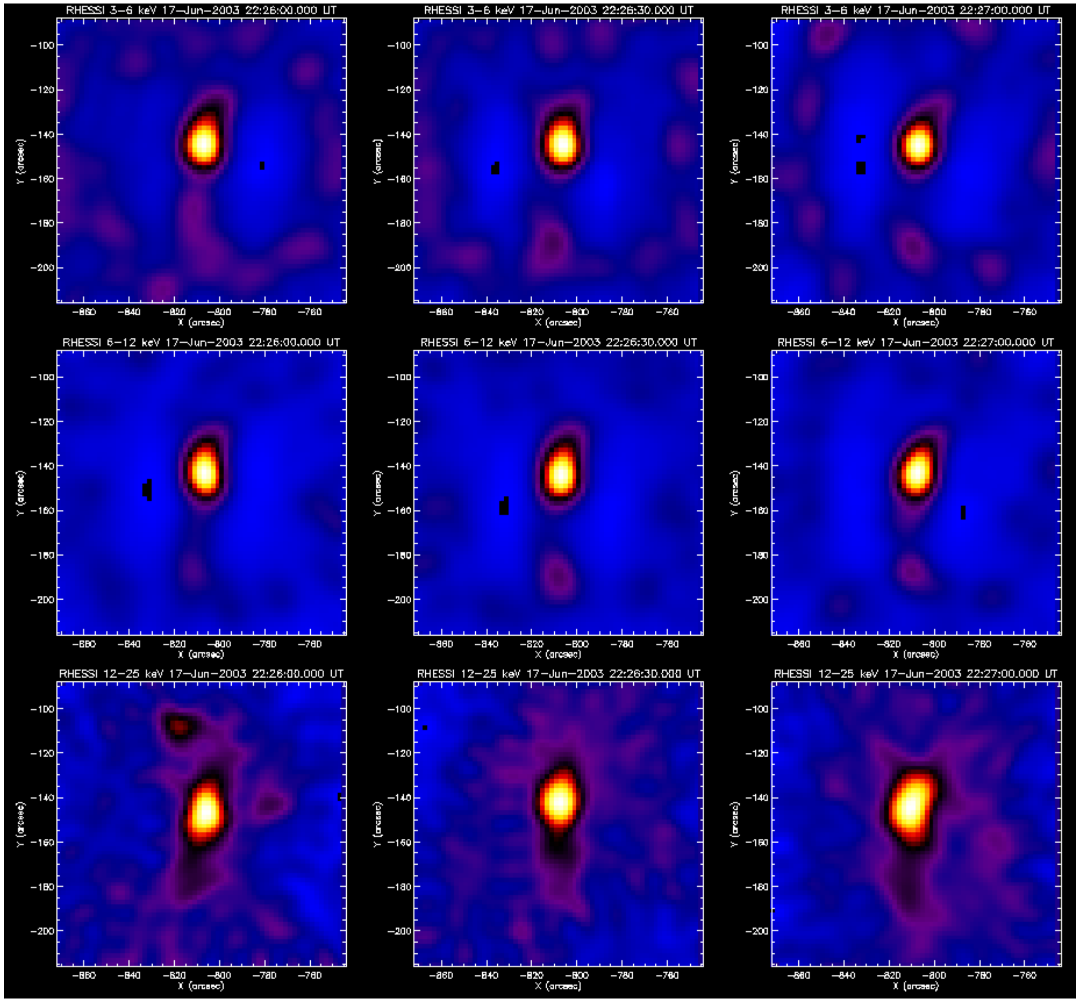
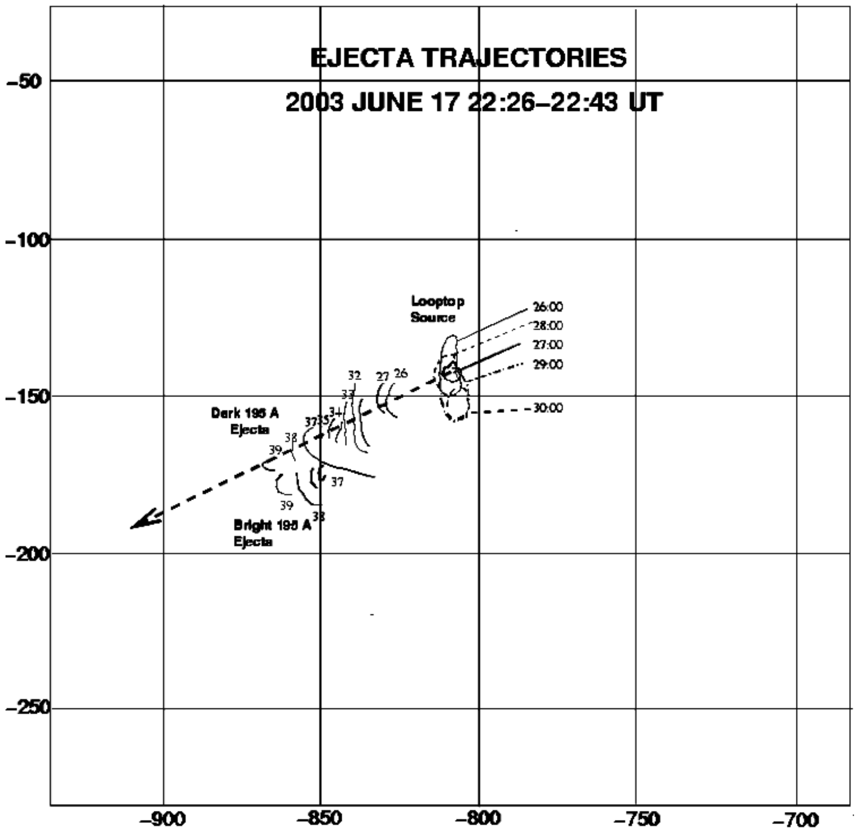
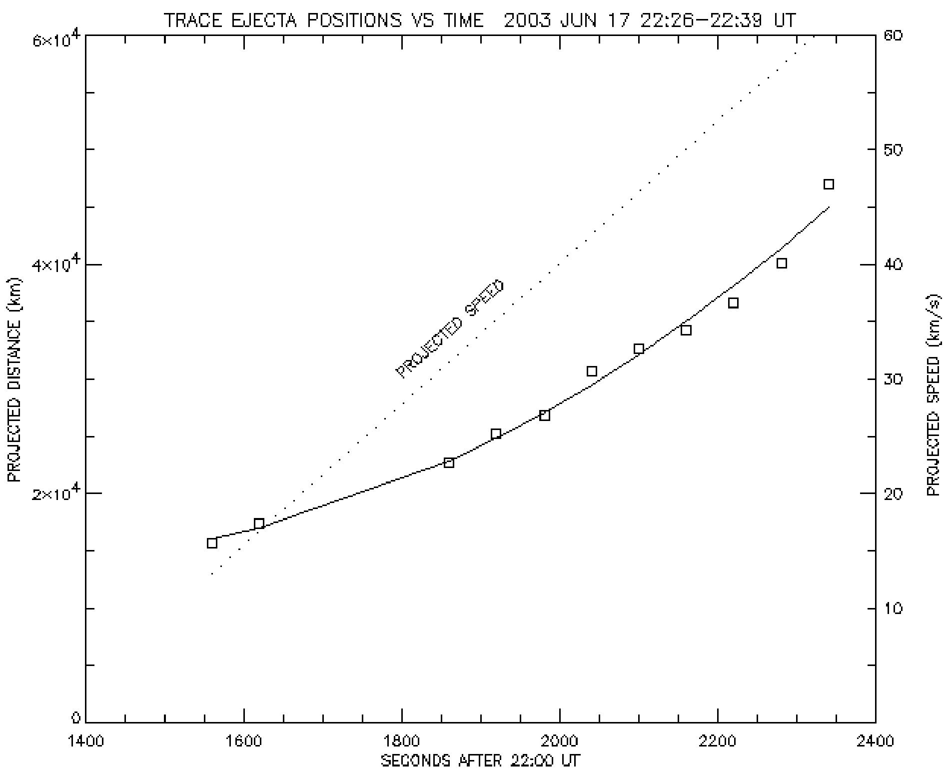


Fig 4

The lower energy HXR appear first at 22:26, close to the time of a filament eruption seen in EUV and Halpha.

Preflare Filament Trajectories and Height vs Time from TRACE

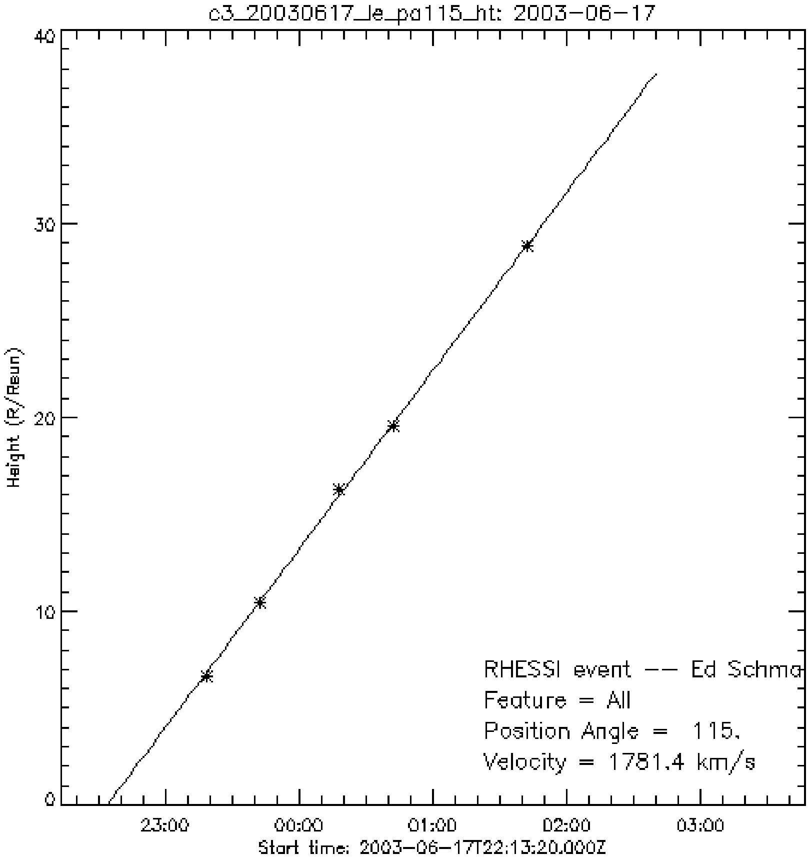


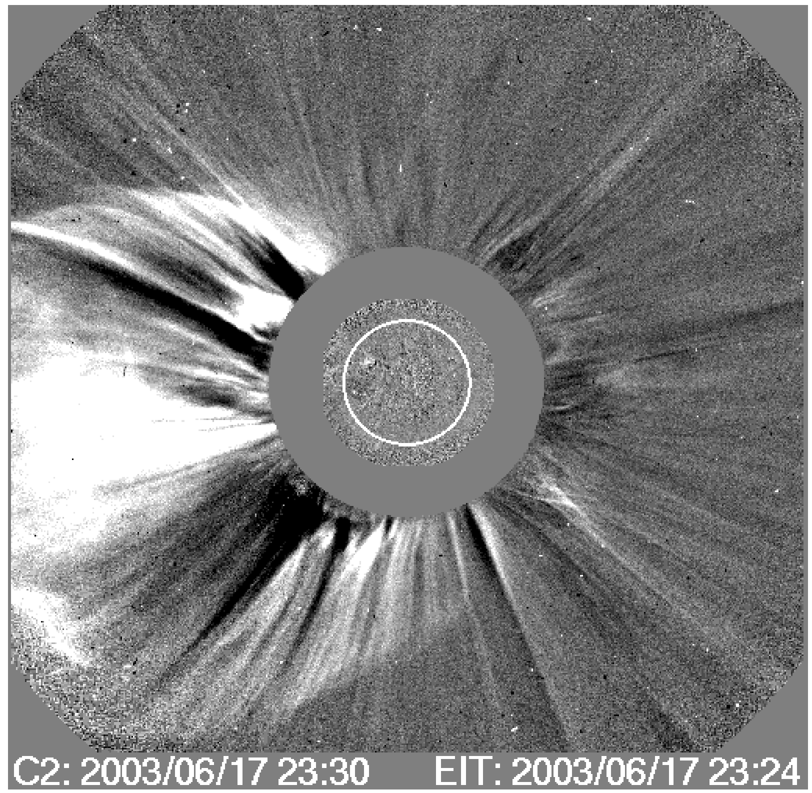


The filament ejection tracks directly from the 6-12 keV looptop source.

Fig 5

Left: Height-time plot
Right: Associated CME Image

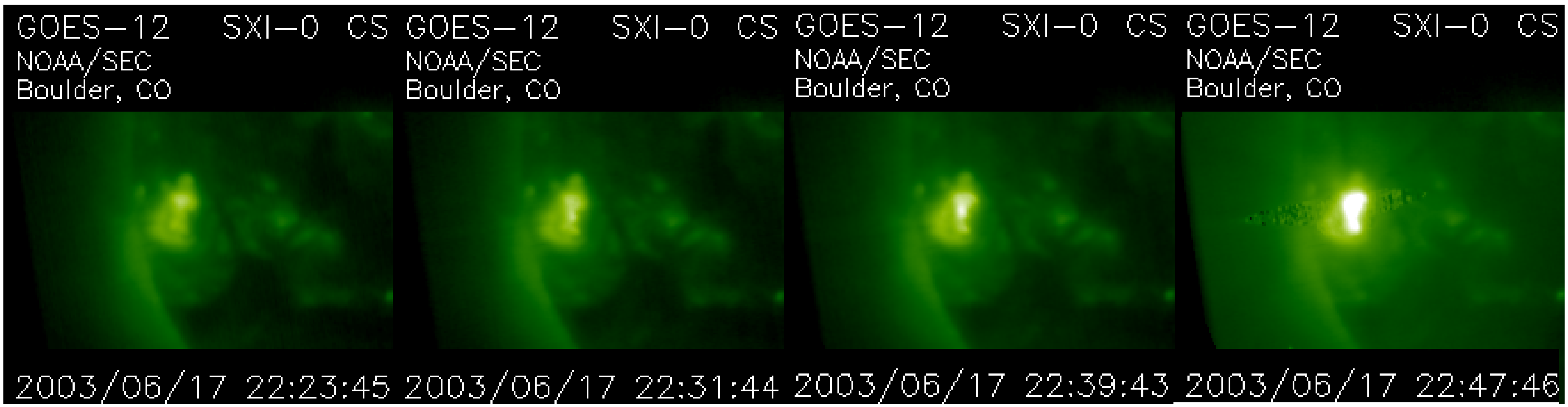




The CME tracks out of the filament ejection seen on the disk just before the flare.
Fig 6

SXI Preflare Images

There is a soft X-ray brightening at the same time and approximate location as the RHESSI pre-flare source.



Preflare   Preflare Rise   Impulsive Rise   Flare

Fig 7

Selected RHESSI 12-25 & 25-50 keV maps in different epochs of the main phase

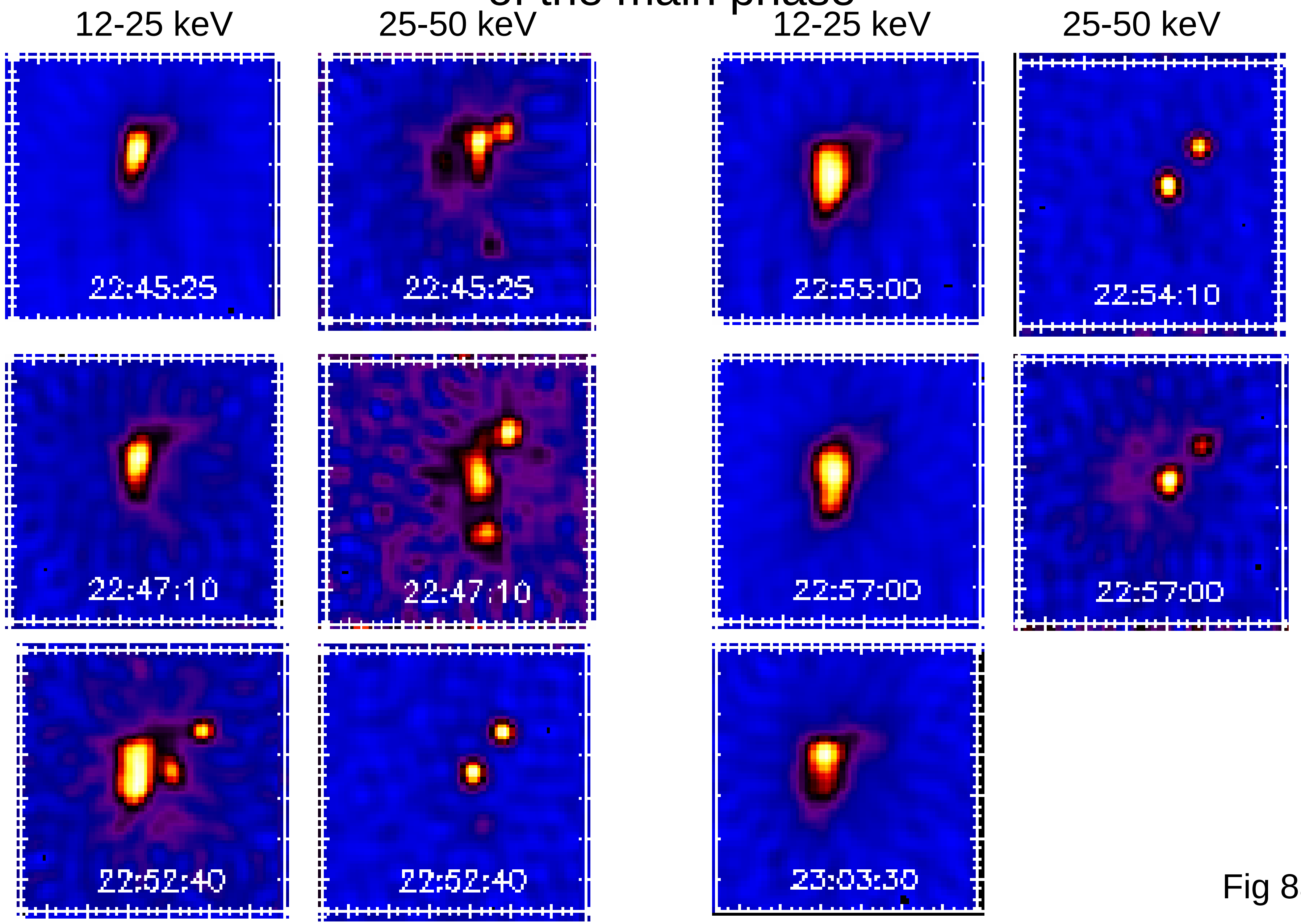
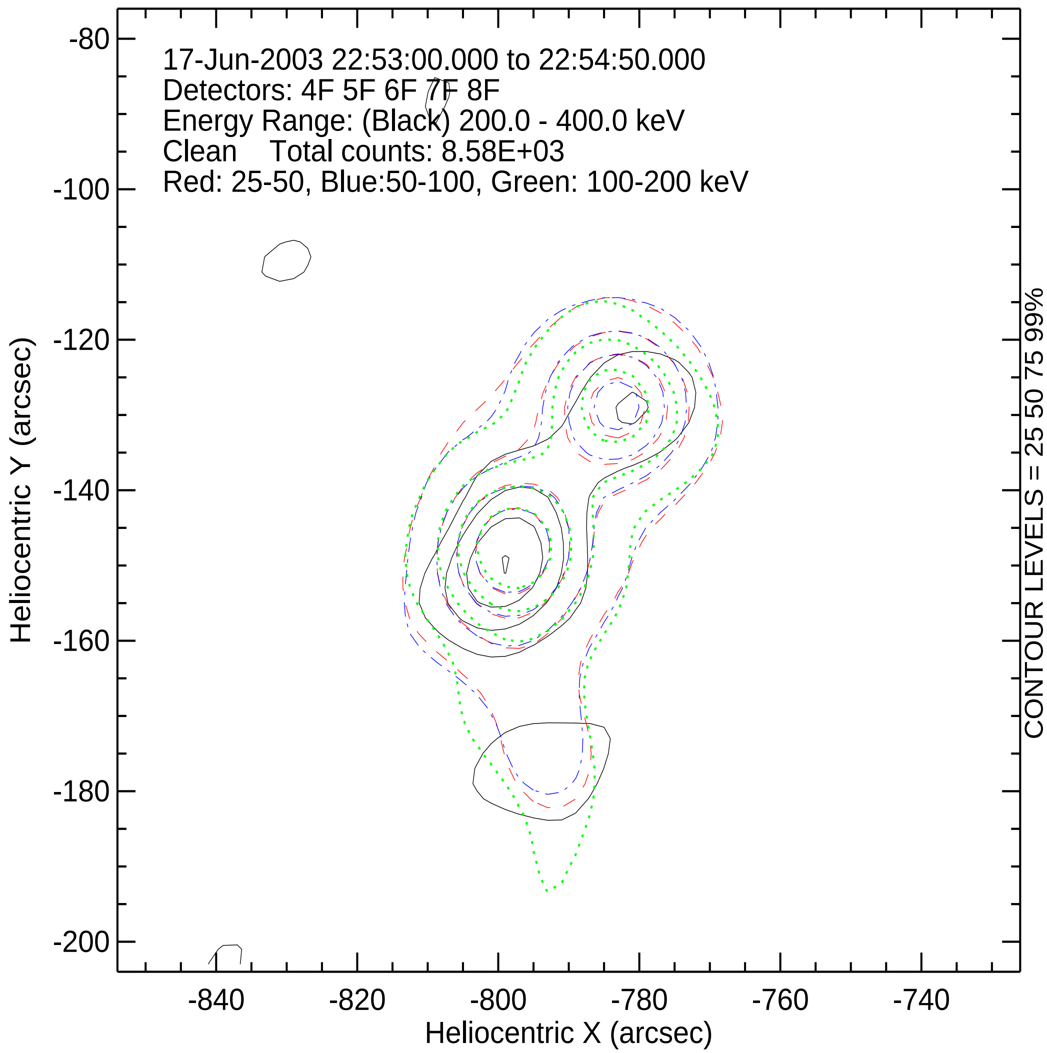


Fig 8a

RHESSI 200-400 keV Image along with lower energy maps



Note that the low energy and high energy sources are co-located

Fig 8b

RHESSI Burst Profiles

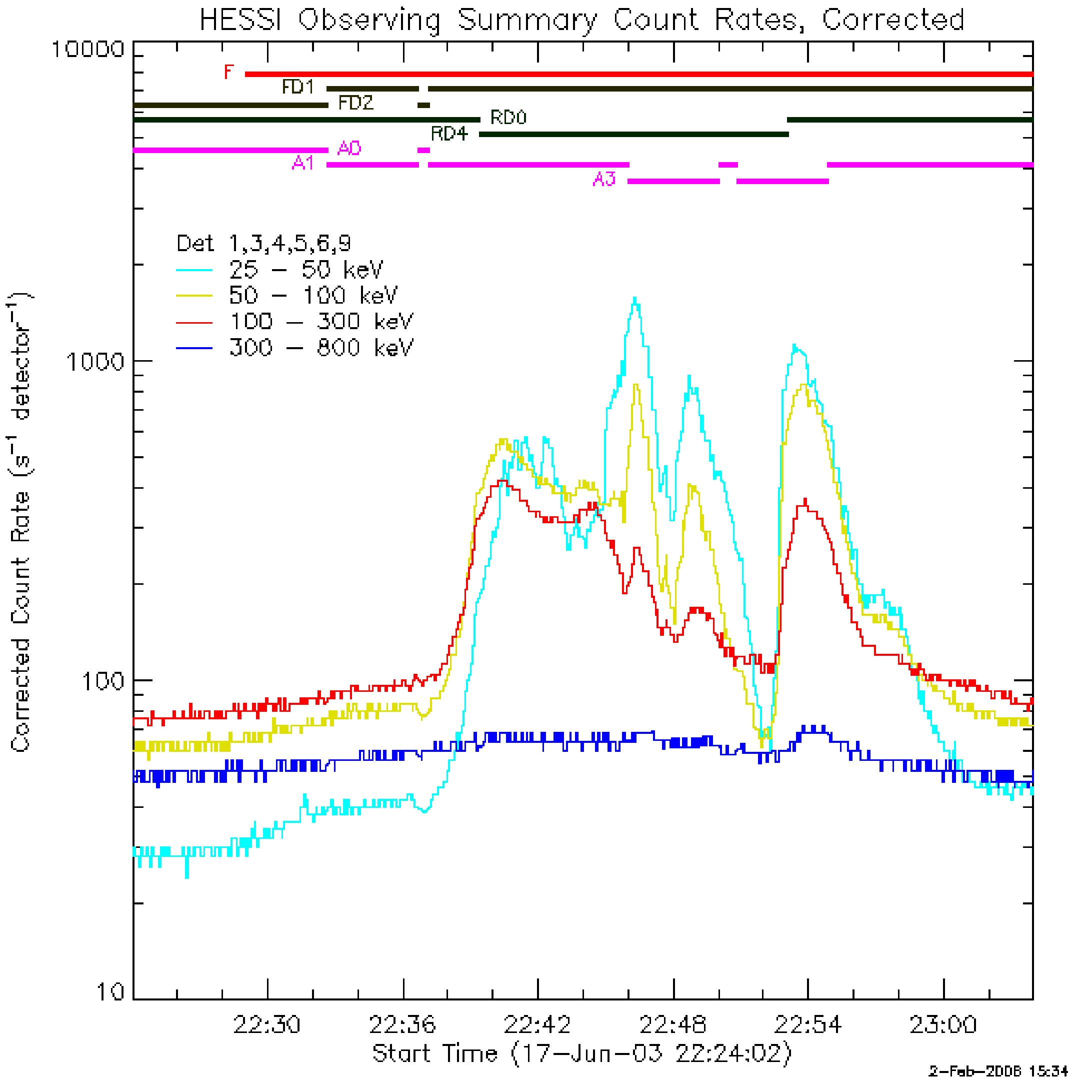


Fig 9

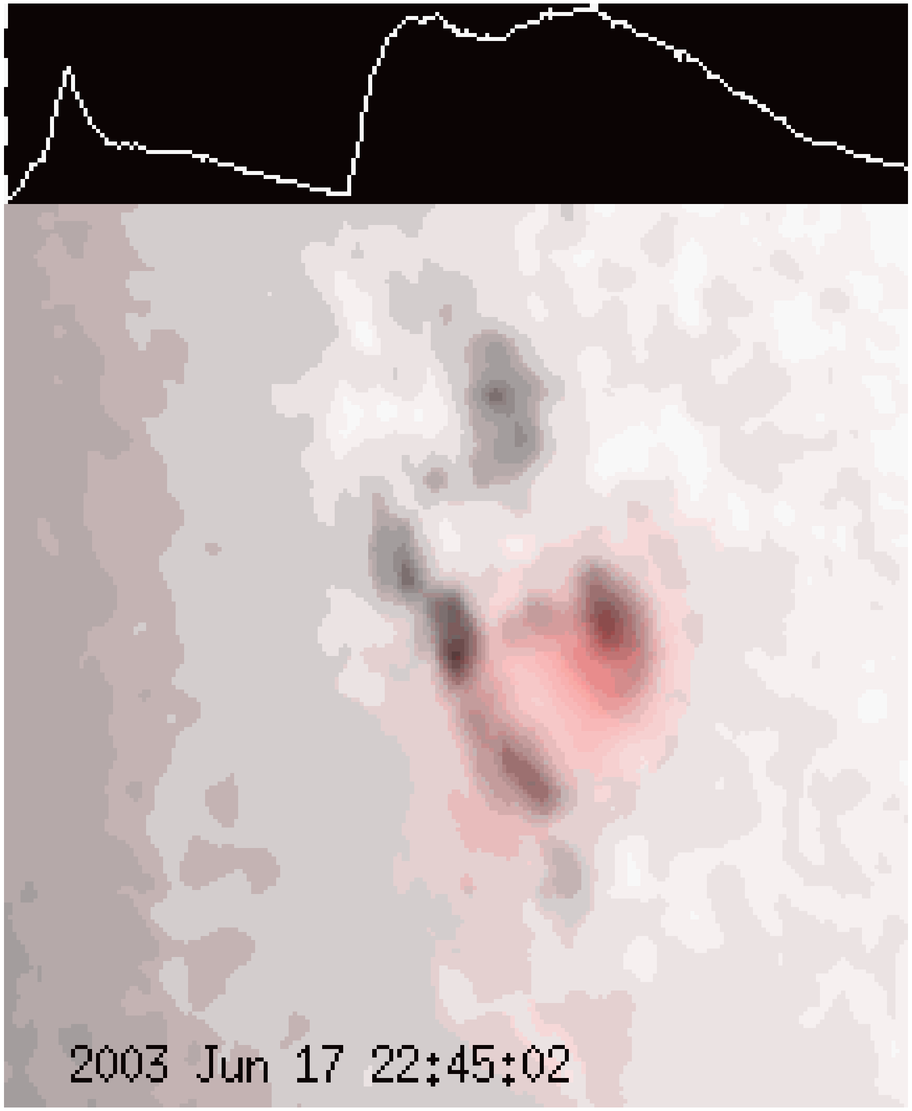
There are five major HXR spikes/acceleration events:

#	start	end	duration (s)
1.	22:39:20	- 22:41:35	105
2.	22:43:30	- 22:45:38	128
3.	22:45:43	- 22:47:22	99
4.	22:48:01	- 22:50:21	140
5.	22:52:30	- 22:56:30	240

- The first four events show significant emission in the 100-300 keV band, but event 5 is the only one to show evidence for 300-800 keV X-rays.
- The first event shows sub-pulses at lower energies.

Five major acceleration events

- The first four events show significant emission in the 100-300 keV band, but event 5 is the only one to show evidence for 300-800 keV X-rays.
- Spikes 1 and 2 are most complex morphologically, with more than two components, some spatially extended.
- Spikes 3 and 4 have 3 compact components at 25-50 keV (all at similar positions).
- Spike 5 has 2 components in that band, with these 2 components nearly cospatial with 2 of the 3 components in spikes 3 and 4.
- Maps above 300 keV are very "noisy" (no significant information below the 50% contour), but the brightest feature appears at the same position as at lower energies (see Fig.8b)

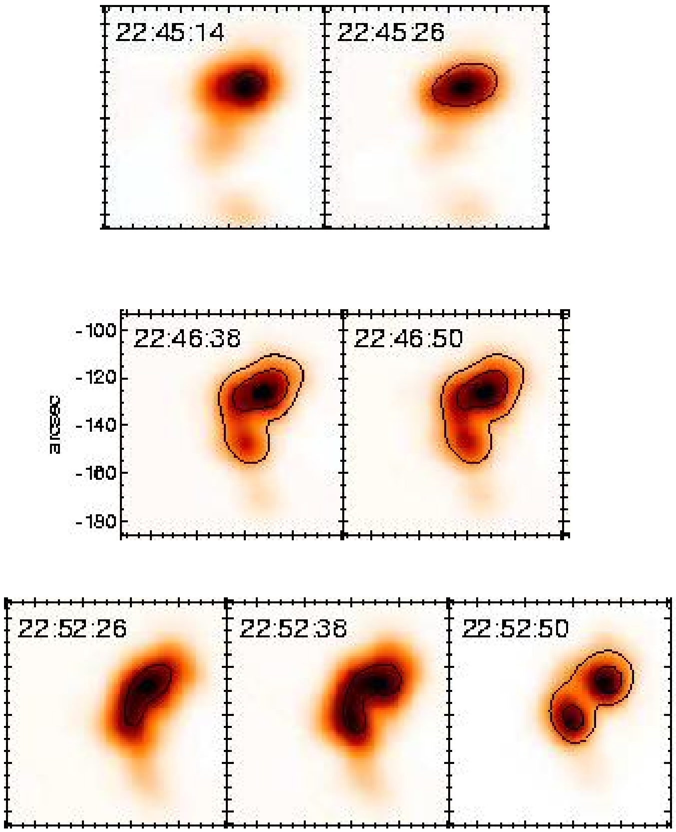


Movie at 17 GHz

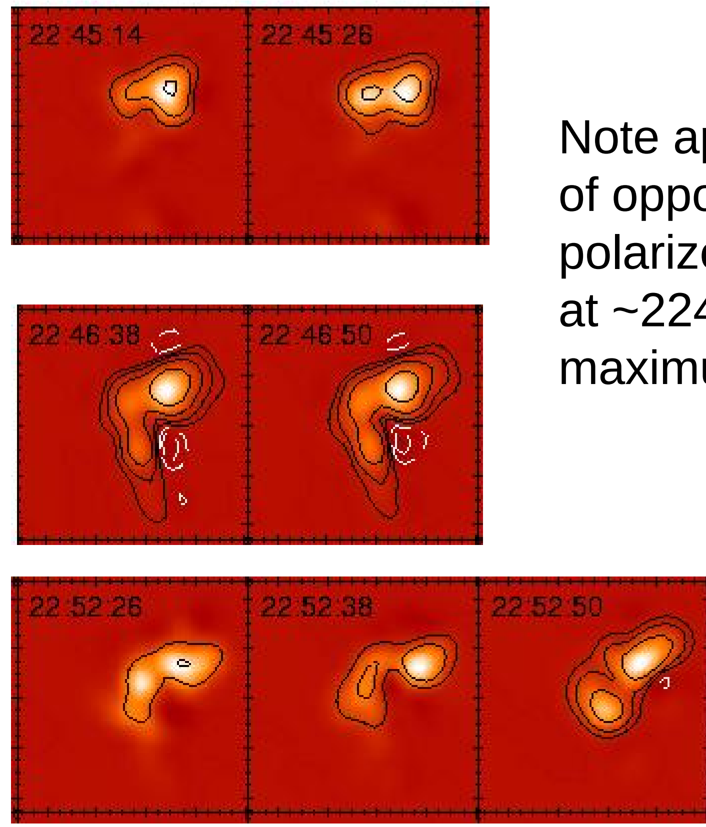
One frame every 4 seconds from the start of observing at 22:45 UT, just after flare start.

Spatial resolution 12 arcseconds, peak brightness temperature over 10^8 K.

Selected 17 GHz maps in I and V at different epochs of the main phase



Intensity

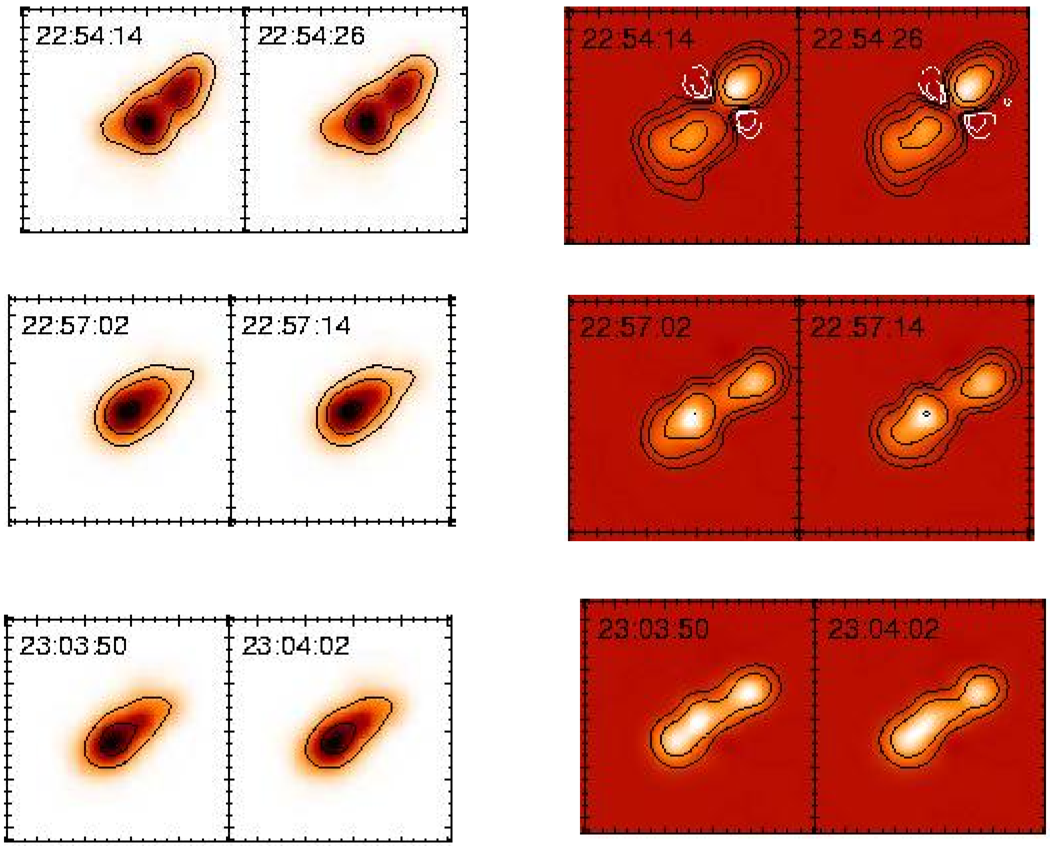


Polarization

Note appearance of oppositely polarized source at ~2246 –- first maximum.

Fig 10a

(continued)



Intensity

Polarization

Note oppositely polarized sources at ~ 225430 -- second maximum

Fig 10b

HIRAISO DYNAMIC SPECTRUM

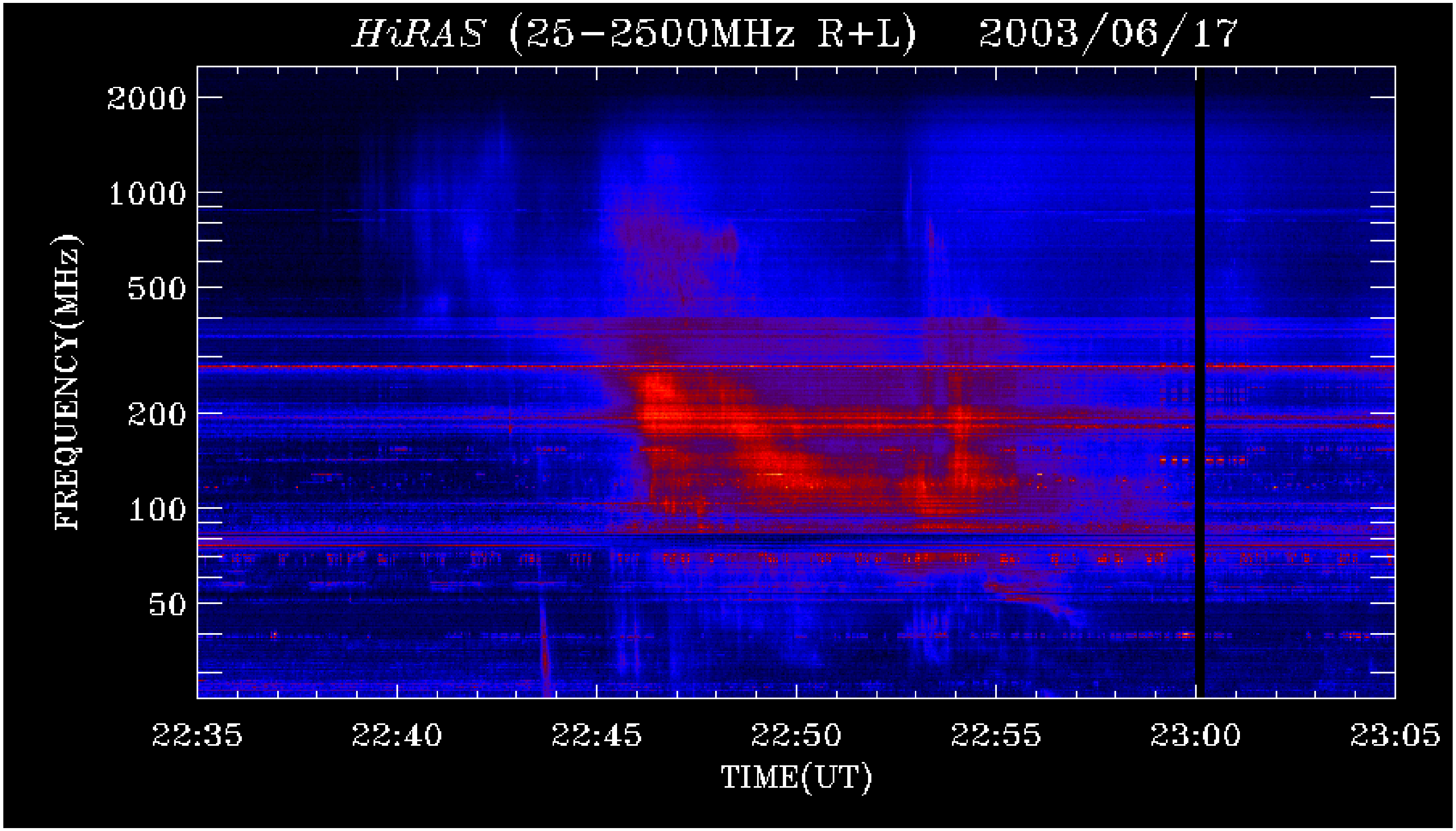


Fig 11

Note type IV starting at ~ 22:40 UT from ~400 to ~2000 MHz and type II starting at 22:45 UT--the onset of the first big burst at 17 GHz.

HXR 50-100 keV & 17 GHz (I) overlays at selected epochs

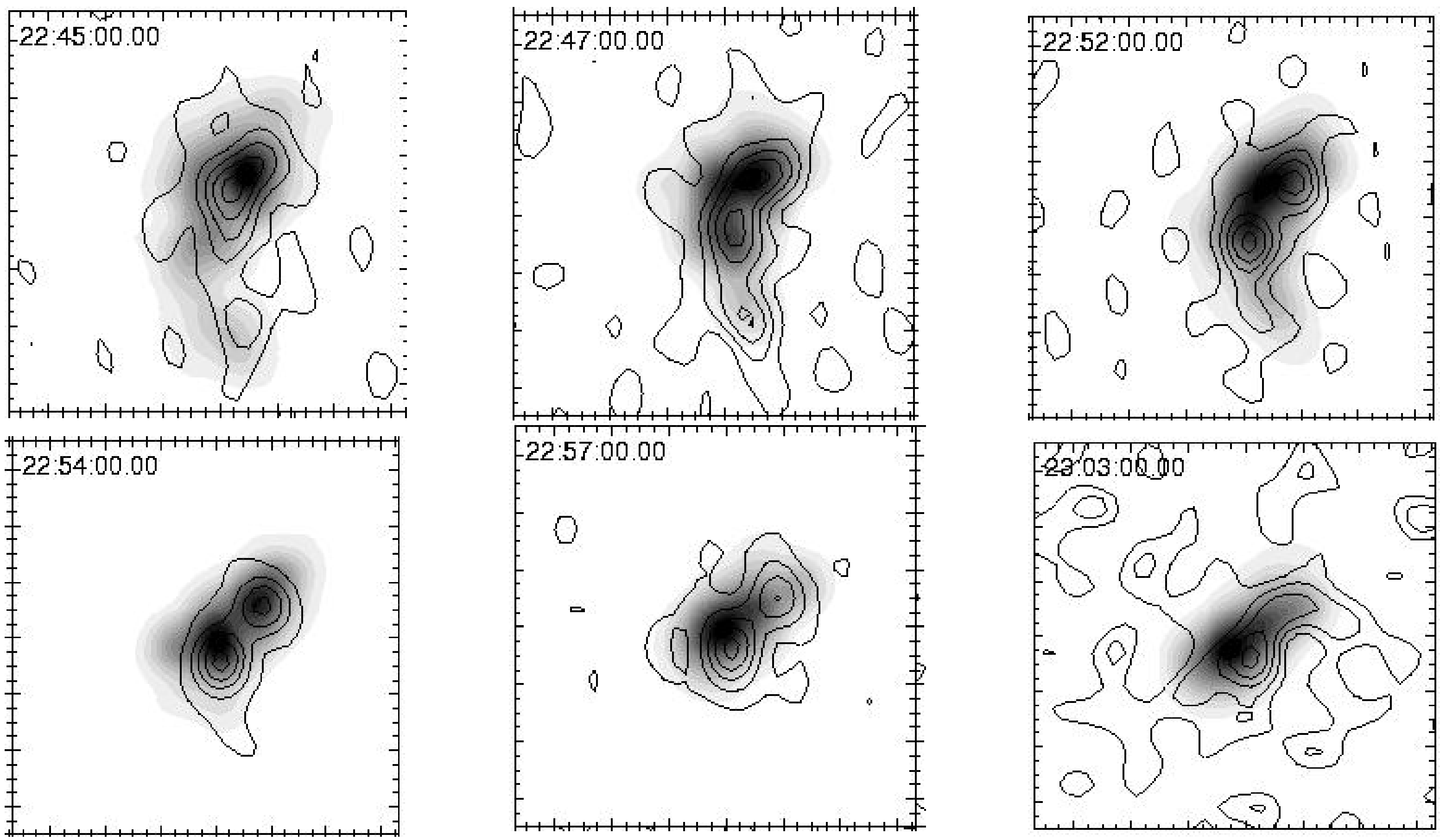
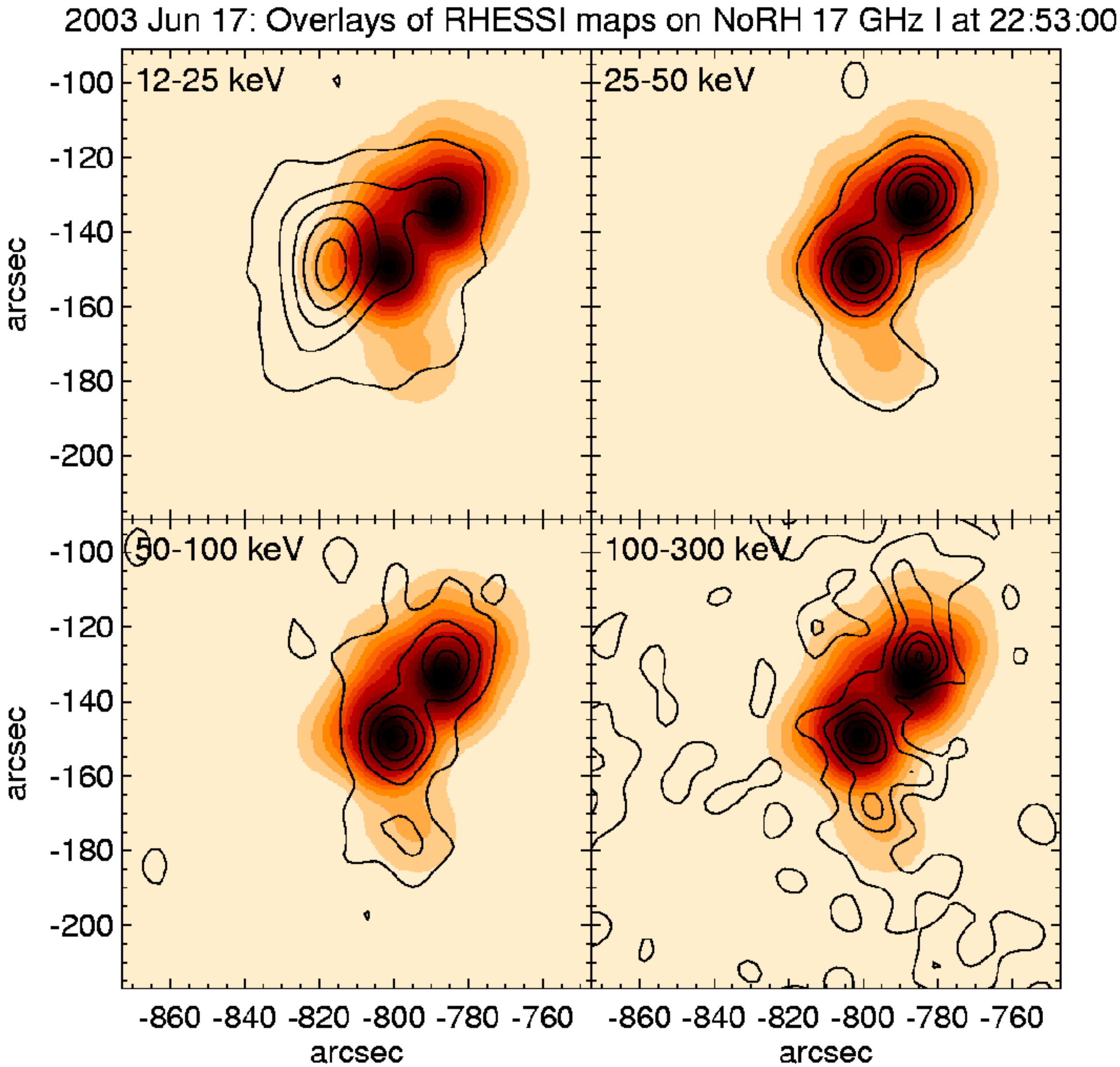


Fig 12a

Both HXR & 17GHz flaring sources have strong components coincident, and 17 GHz source looks more like a loop.

HXR & 17 GHz I



HXR (contours at 10,30,..,90%)
& 17 GHz I (color)

Note coincidence of HXR & 17 GHz flaring sources

SUMMARY AND CONCLUDING REMARKS

- We discuss a flare of GOES class M6.8 using simultaneous imaging observations by RHESSI in HXR and by NoRH in microwaves.
- The preflare phase was observed well by RHESSI, but not by NoRH due to Nobeyama night time. The important feature of the RHESSI preflare phase is that we observed a TRACE ejecta whose height-time positions were well determined. The trajectory of the absorbing material tracks directly from a 6-25 keV "looptop" source, consistent with the scenario that open field lines extend above a reconnection region near the top of the flare loop, and that material--possibly a plasmoid--is ejected upward from that region.
- Shortly after the ejection, accelerated electrons are beamed downwards from that reconnection region to the footpoints where they appear in hard X-rays with energies > 25 keV.

SUMMARY AND CONCLUDING REMARKS (continued)

- At 2245-224530 UT the 6-12 and 12-25 keV sources are shifted toward the limb by about 20", relative to 17 GHz source, most likely due to a height difference. The offset diminishes at higher energies 25-50 keV and above, we see at least three component sources of which the northern HXR component coincides well with the 17 GHz source. Around the first large peak 224630 UT the flaring source is delineated like a loop -- better in microwaves than in HXR.
- Near the main broad minimum at 225230 we see the flaring loop quite well in microwaves, but less so in HXR. In general,we see both HXR and 17 GHz sources as loops - one below the other, with several components in each loop. The strongest component in both seem to coincide well in location.
- The interacting multiple loops that develop before 2254 seem to coincide with the steep intensity rise to the 2253-2256 burst maximum. We speculate that the second burst steep rise is related to the appearance of two interacting loops. The first burst may be related to the start of the Type II in Hiraiso spectrum - and therefore a shock which accelerates electrons.
- The burst maximum at 225430 seems to consist of two distinct components -- N & S, eventually with the southern component dominating. In HXR there is a northern extension of the emitting region below 25 keV.

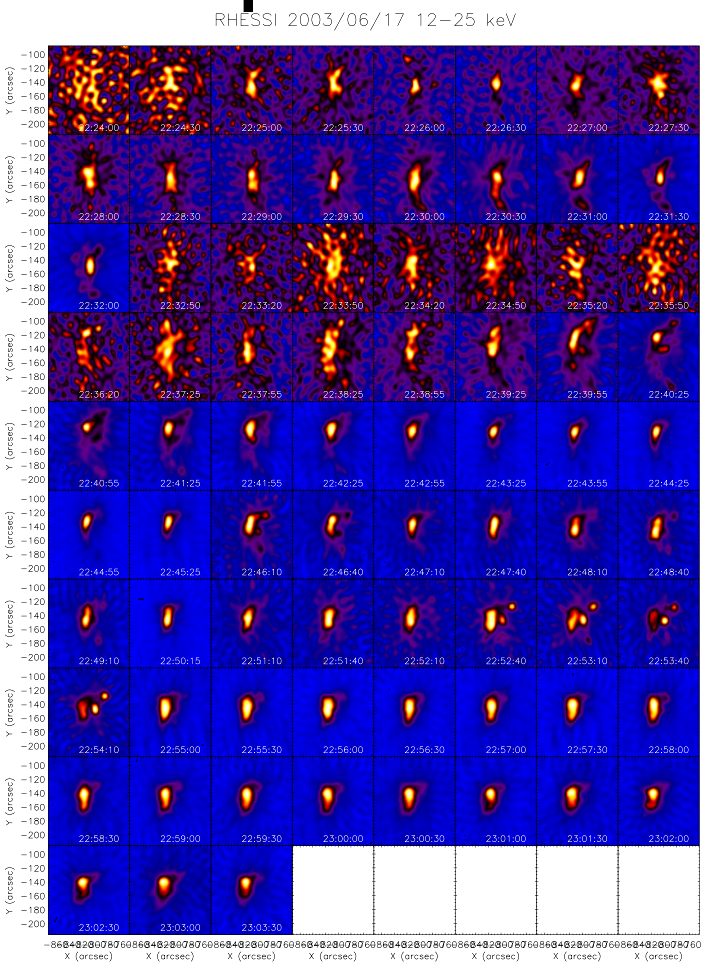
SUMMARY AND CONCLUDING REMARKS (continued)

- In polarization (Stokes V) the entire microwave source is polarized in one sense only - with the exception of a few images around the first maximum and the second maximum. Here it appears that there are at least two loops which are located close together and seemingly interacting and probably producing something significant (magnetic reconnection?) responsible for the production and subsequent acceleration of electrons producing HXR & microwave radiation. It is also worth noting that a type II burst was observed by the Hiraiso spectrometer at metric wavelengths at about 2245 UT, the start time of one of the bursts. This signifies that a shock may be responsible for the acceleration of electrons which produced the HXR & microwave flare.

- RHESSI maps produced with high resolution in energy bands 25-180 keV show two dominant sources almost co-spatial with the 17 GHz sources. The southern HXR source is the most dominant like the microwave source (Fig. 12). Note further that we produced a RHESSI HXR map at 200- 400 keV energy band.

THE END

Selected RHESSI maps in main phase in 12-25 & 25-50 keV



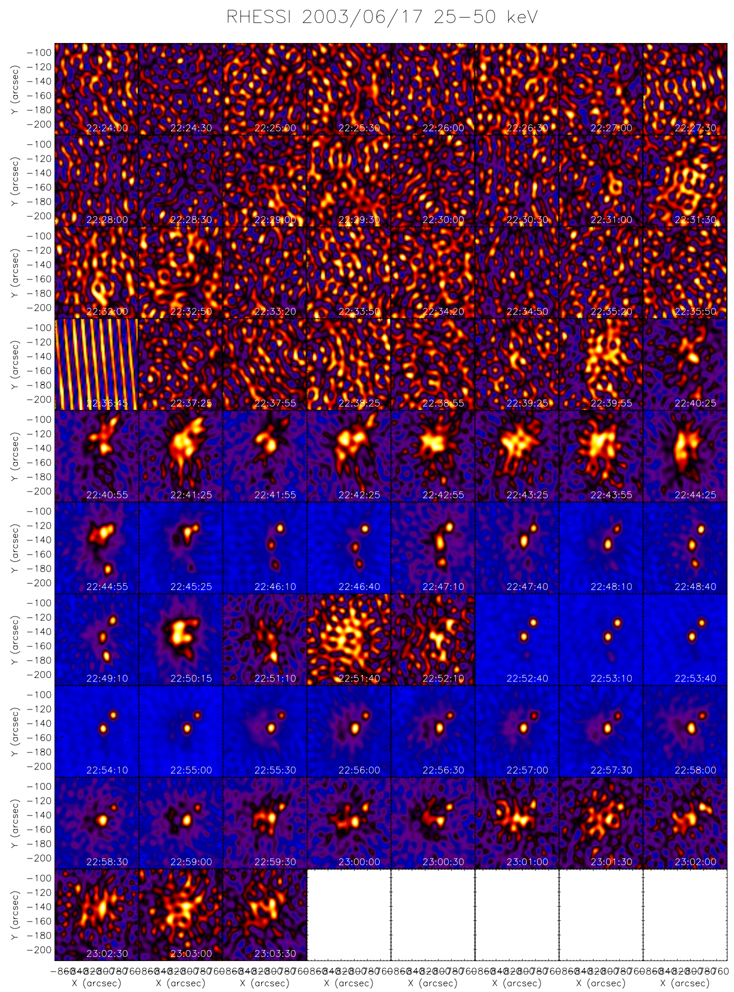


fig 9a

Observations

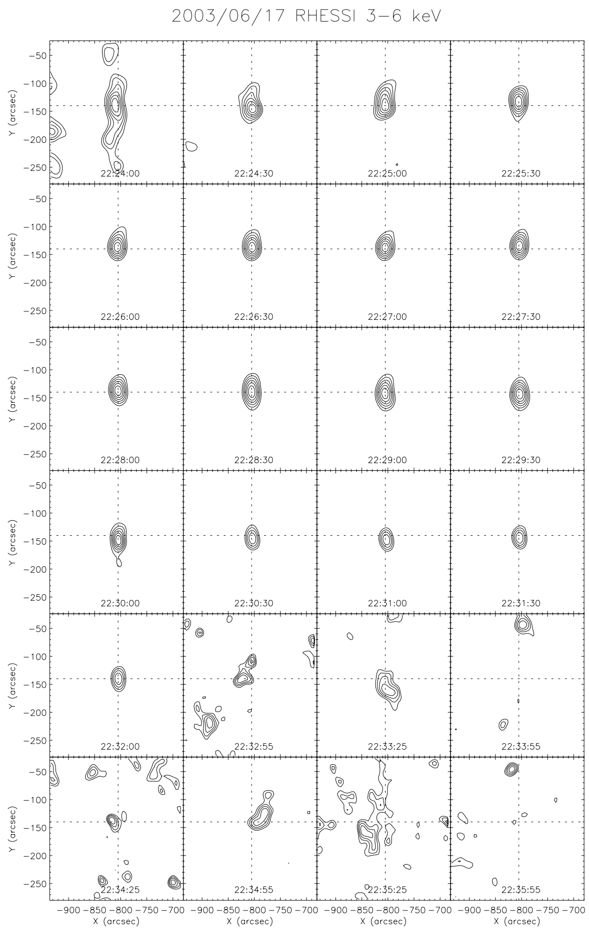
- Because of Nobeyama night time preflare phase was not observed in radio.
- However,it was well observed by RHESSI. The main flare was fully observed at 17 and 34 GHz, starting at 2245 UT.
- Microwave onset at 2245 UT for both 17 & 34 GHz
- reaches a maximum for first burst at ~ 224630 UT;
- A minimum at about 2252-2253 UT.
- A sharp rise to a maximum in second burst at about 2254-2255 UT.
- The decline at both 17 & 34 GHz is similar, implying that the emission may be thermal at this time. But over the period 2252-2254 UT (which includes second burst maximum), emission at the two frequencies is quite dissimilar, meaning nonthermal emission here.
- At 17 GHz the flare has a flux of ~ 1125 sfu.

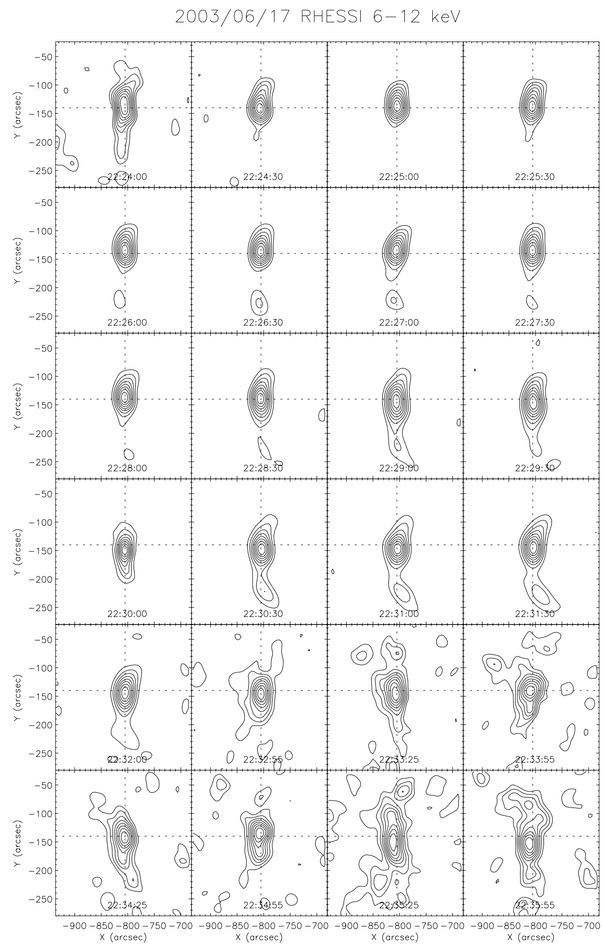
Overlay of I & V with RHESSI

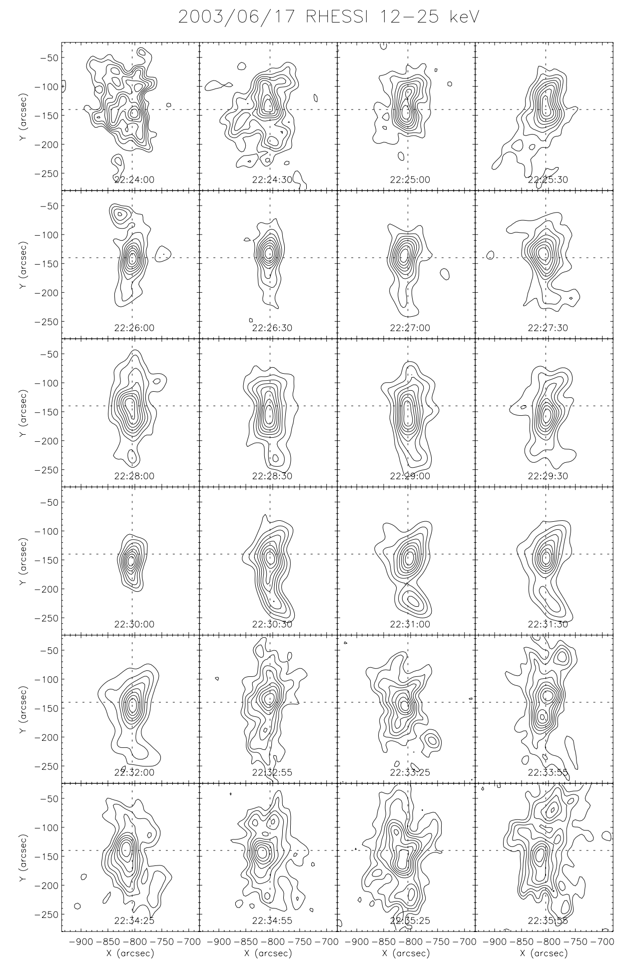
fig 12

Selected Pre-flare HXR Images

3-6, 6-12 & 12-25 keV







The lower enegy HXR appear first at 22:26, close to the time of a filament eruption seen in EUV and Halpha.

- Fig.1a: (Top) RHESSI light curves at 12-25,25-50,50-100,100-300,300-800 keVand (bottom) NoRH light curves at 17 and 35 GHz
- Fig. 1b: NoRP time profiles - starting at 22:38 UT at 1,2,3.75,9.4,17,34 GHz.
- Fig. 2: MDI magnetogram at 22:54 UT showing 17 & 34 GHz source locations along with RHESSI 50-100 keV sources- lying on either side of the neutral line. A new region appears at 22:22 UT on the magnetogram. Also shown, MDI magnetogram with RHESSI 100-180 keV.
- Fig.3a: EIT images at different times with superposed 17 and 34 GHz sources at one time .
- Fig.3b: TRACE images at different times with 17 & 34 GHz contours.The TRACE image is at one time only.
- Fig.4: Sample RHESSI images in three energy bands 3-6, 6-12, 12-25 keV bands.
- Fig.5 : Ejecta trajectories from TRACE data. Also shown is the projected speed as a function of time.
- Fig.6. Height-time plot and a difference image of the associated CME.

- Fig. 7: SXI images at 4 different times-- 2223, 2231, 2239, 2247 UT. Only the limb source is shown.
- Fig. 8a: Shows selected RHESSI maps in different -- both low and high -- energy bands.
- Fig. 8b: Shows a map in the 200-400 keV band.
- Fig. 9: RHESSI time profiles in energy bands 25-50,50-100,100-300, & 300-800 keV.
- Fig.10: Selected 17 GHz I and V images.Times-- 2245-224530, 224630-224638, 2252-225230,2253, 2254-2255,2257,2304
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