# RHESSI OBSERVATION OF THE M4.0 FLARE ON 17 MARCH 2002

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## ABSTRACT

The M4.0/SF flare on 17 March 2002 is a good example of the early observations with RHESSI. We present hard X-ray images, light curves and energy spectra of individual hard X-ray sources, the spatial relationship between the hard X-ray sources and the H$\alpha$ emission regions, and comparisons of light curves observed by RHESSI and GOES. We found that the picture exhibited by RHESSI is consistent with the general cartoon of a solar flare. In particular, we showed that the hard X-ray image spectra could be explained by a power-law electron beam with a lower energy cutoff $E_c$. The derived $E_c$ could be as high as 40 keV, larger than the usually value of 20 keV.

## INTRODUCTION

The Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) (Lin et al., 2002), was launched on 5 February 2002. Detailed descriptions of the instrument and some preliminary studies can be found in a special issue of Solar Physics (November, 2002). In this paper, we make a comprehensive study of the flare on 17 March 2002 at 19:26 UT.

## LIGHT CURVES AND X-RAY IMAGES

The flare on 17 March 2002, classified as M4.0/SF and located at S22E16, began at 19:26 UT. Figure 1 shows its light curves at several energy channels from 10 keV to 300 keV in time resolution of 4 s. The data dropout after 19:36 UT is because RHESSI was in the South Atlantic Anomaly. We see from the figure that the impulsive character was blurred at energies between 10 and 20 keV, implying that thermal emission is dominant in this energy interval. In Figure 2, we present a series of hard X-ray images made using the CLEAN algorithm with collimators 3F to 7F and a field of view of $64'' \times 64''$. In order to increase the signal to noise, the integration time for each image was taken as 16.21 s (4 rotations). During the flare, the thin shutters of RHESSI were in the field of view of all the detectors, which results in considerable attenuation below 10 keV. Therefore, the images below 10 keV are not shown. The images in Figure

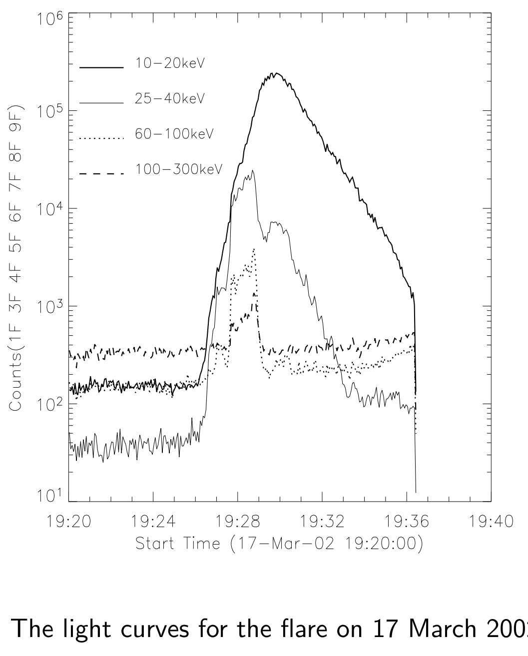


Fig. 1. The light curves for the flare on 17 March 2002.

2 suggest an assumption of a loop-like structure. In the early evolution, the hard X-ray emissions at footpoints are obvious, in particular at one footpoint. Later we see two footpoints formed in hard X-rays. From 19:28:12 UT, there gradually forms a looptop source in 10–15 keV. Thereafter, the source shows such a characteristic that the lower energy source (10–15 keV) seems to be at the top of the loop, while the higher energy source (20–25 keV except the later time, and above 30 keV) seems to be at the feet of the loop. This scenario of flare evolution is, in principle, consistent with the flare cartoon shown by Dennis (1988). If we think that the appearance of the soft X-ray source at the looptop results from evaporation from the footpoints bombarded by the energetic electrons, assuming a semi-circular loop, we derived from Figure 2 that the evaporation velocity is around 400 $\mathrm{km\,s^{-1}}$. This velocity is within the scope revealed by soft X-ray line observations with BCS/Yohkoh (e.g., Gan and Watanabe, 1997).

We notice from Figure 2 that the two footpoints do not seem to evolve simultaneously. We therefore isolate the squares S0, S1, and S2 (using code IMSPEC in SSW) to represent the two footpoint sources and the looptop source, respectively. Figure 3 shows the light curves corresponding to these sources. For 25–50

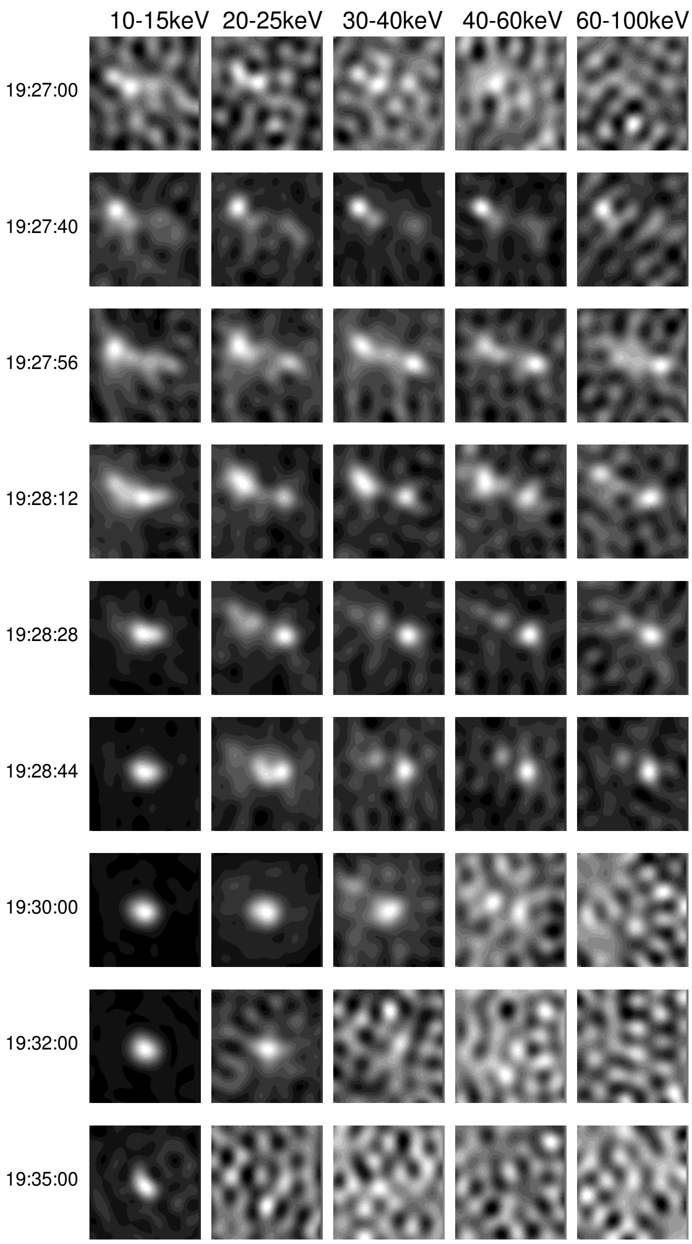


Fig. 2. The X-ray images for the M4.0 flare on 17 March 2002, reconstructed with the CLEAN algorithm using detectors 3F, 4F, 5F, 6F, and 7F. Each image is $64'' \times 64''$ in size.

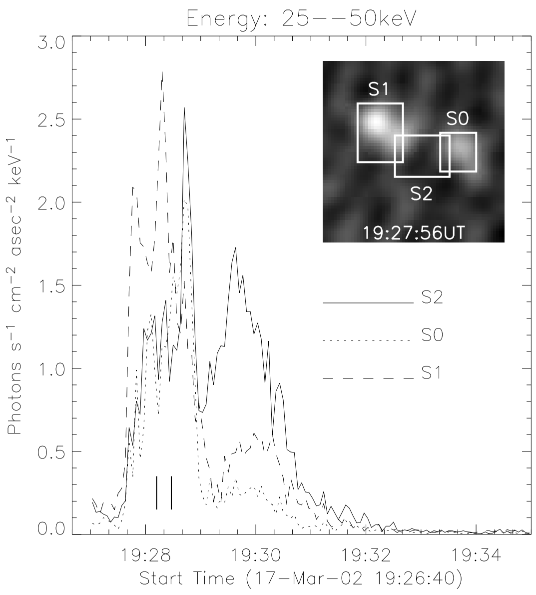


Fig. 3. The light curves for individual source regions.

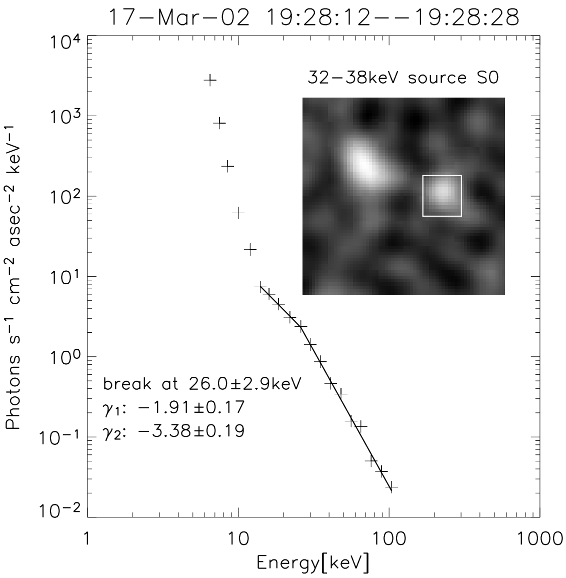


Fig. 4. The image spectrum for source S0 at 19:28:12 UT.

keV, the maximum time of S1 is about 20 s ahead of S0. This phenomenon has been explained as a consequence of asymmetric trapping of electrons (Alexander and Metcalf, 2002).

## IMAGE SPECTRA AND THEIR EXPLANATIONS

Although much image spectra work has been done with data from HXT/Yohkoh (e.g., Kosugi at al., 1994), due to the poor energy resolution, it was impossible to make a detailed fit to the energy spectra. The higher spectral resolution of RHESSI provides us a new chance to study the image Referring to Gallagher et al. (2002), however, we do not fit the spectrum below about 15 keV, since the steep spectrum below 10 or 15 keV (like S0 in Figure 4) seems to be the result of contamination from the other brighter source or sources in the same images. Besides, the instrument response function is not sufficiently well known at present to accurately correct for the attenuation below about 10 keV when thin shutters were in the detector fields of view. We here use a broken power-law to fit the spectrum above 15 keV. As an example, Figures 4 shows the image spectrum for source S0 at 19:28:12 UT. Figure 5 shows how the power-law indices and break energies change with time for the three sources, where $\gamma_1$ is the power-law index in the lower energy end. We see from Figure 5 that for three sources the spectrum evolves from initially broken-down ($\gamma_1 < \gamma_2$) to later broken-up ($\gamma_1 > \gamma_2$) or to a single power-law ($\gamma_1 = \gamma_2$ for S1). The similar variation was also shown by Krucker and Lin (2002). In fact, this kind of spectral evolution has been found by Dulk et al. (1992) by using the data from HXRBS/SMM. But HXRBS/SMM has no imaging ability. Therefore, this seems to be the first demonstration that the hard X-ray spectrum from an individual hard X-ray source changes from the broken-down to broken-up during the flare. However, this broken-up result might have been influenced by the background, especially at high energies where the background spectrum is flat (Gallagher et al., 2002). Detailed modelling of the

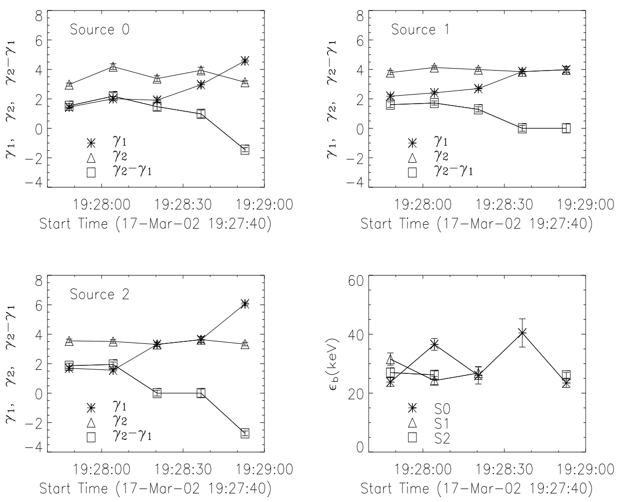


Fig. 5. The fitted power-law spectral indices and break energy vs. time for the three source boxes.

background is probably the only way that this influence can be fully removed. Another feature in Figure 5 is that the $\gamma_1$ increases monotonically with time for all three sources.

Gan et al. (2001, 2002) developed a method to derive the lower energy cutoff based on an observed broken-down hard X-ray spectrum. They found that about 44% broken-down hard X-ray spectra observed with BATSE/CGRO could be directly explained by a power-law electron beam with a lower energy cutoff. We use the same method to check our image spectra here. In order to let the fitted energy range be consistent, we recalculated the theoretical relationships between $\gamma_1$ and $\gamma_2$ as well as $\gamma_1$ and $\varepsilon_b$, taken the lower energy limit as 15 keV. It is found that for S1, $E_c$ is 43±3 keV and 40±2 keV at 19:27:40 UT and 19:28:12 UT, respectively. The values of $E_c$ obtained here are still obviously greater than 20 keV, implying that the energy carried by non-thermal electrons could be much less than previously estimated. For the other broken-down spectra presented in Figure 5, we cannot directly explain them by using a power-law electron beam with a lower energy cutoff. Maybe the mixed populations between trapped electrons and newly accelerated electrons complicate the problem. Considering that the data analysis procedures are in progress, we here would not like to make a further detailed study.

## COMPARISON WITH OTHER OBSERVATIONS

### Overlapping on BBSO H$\alpha$ images

It is generally thought that the H$\alpha$ flare is a result of bombardment of non-thermal electrons emitting hard X-rays. The position of hard X-ray footpoints should therefore coincide with that of the H$\alpha$ emission region. However, the situation is not always as expected. Figure 6 presents the H$\alpha$ images taken by Big Bear Solar Observatory (BBSO), overlapping with hard X-ray sources (in contour, reconstructed with the CLEAN algorithm using detectors 3F, 4F, 5F, and 6F) at 10-15 keV and 25-50 keV. We see from the

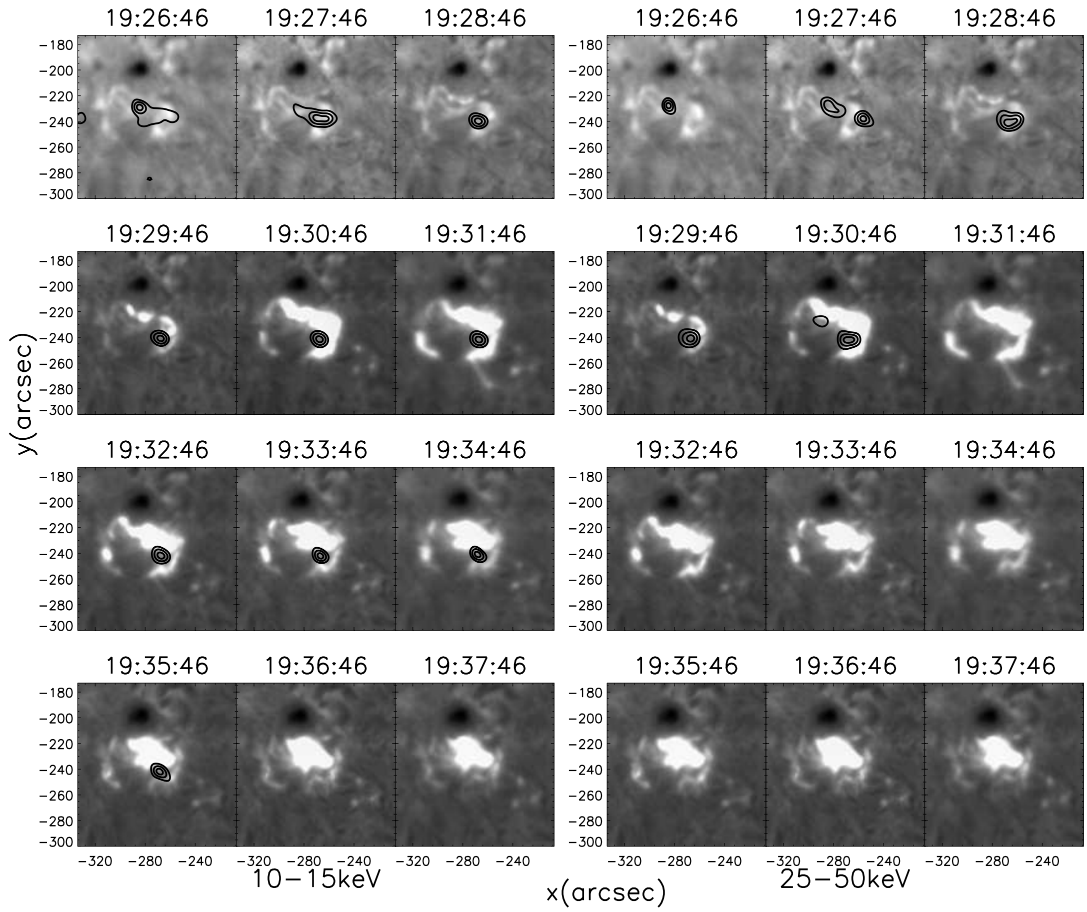


Fig. 6. The comparisons between BBSO H$\alpha$ images and RHESSI X-ray images (contours in 50%, 70%, and 90%).

figure that the spatial coincidence between hard X-rays and H$\alpha$ emission is limited to the early impulsive phase, i.e., before 19:28:46 UT, when the H$\alpha$ brightness is still at a low level. Afterwards, the spatial coincidence does not exist. In particular, at the later impulsive phase, the hard X-ray source at 25-50 keV disappeared while the H$\alpha$ is still in its increasing phase. The spatial separation between hard X-ray sources and the main ribbon of H$\alpha$ is visually about $10^4$ km. This is a rather strange result. How to explain this non-correspondence between the hard X-ray source and the H$\alpha$ source in the later impulsive phase seems to be a challenge to the standard scenario of solar flares.

**Light Curves Compared with GOES**

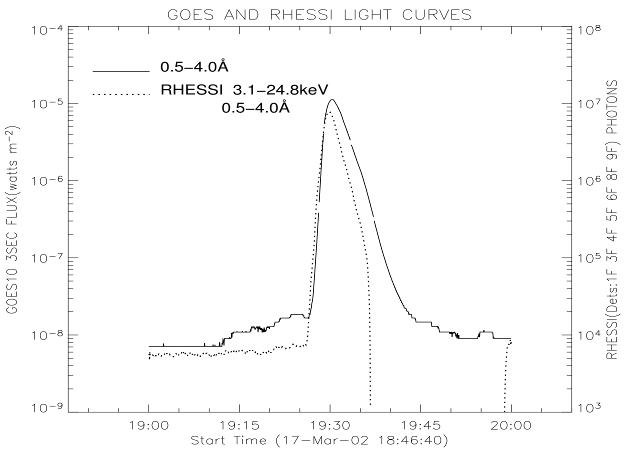


Fig. 7. GOES light curve compared with RHESSI.

In principle, the light curves observed by separate detectors should be the same if they have the same energy coverage. Figure 7 shows the time profiles obtained with the GOES (solid line) and RHESSI (dashed line) at the same energy interval. The rising phase looked to be consistent with each other, but the decay phase for RHESSI is obviously different from that for GOES. The reason resulting in this discrepancy is that for this flare the thin attenuators were in the field of view for the entire event. Thus, the count rate for the 3.1 to 24.8 keV range was dominated by emission in the high energy part of the energy range. For GOES, the emission is dominated by the low energy part of the energy range. Since high energy emission tends to drop off faster than low energy emission, the discrepancy between the two light curves is therefore explained.

**SUMMARY**

Being a good example in the early observations with RHESSI, the M4.0 flare on 17 March 2002 brought us some new results, which are summarized as follows:

(1) The flare presents a typical scenario: two footpoint sources plus one looptop source.

(2) The light curves at the two footpoints have a different evolution.

(3) The broken-down hard X-ray spectra are a typical form in the early impulsive phase, which could be explained by a power-law electron beam with a lower energy cutoff. The derived lower energy cutoff could be as high as 40 keV.

(4) The $\gamma_1$, the power-law index in the lower energy end, presents hard-soft-softer temporal behavior.

(5) The spatial coincidence between the H$\alpha$ emission region and hard X-ray footpoint sources does not seem to exist, except in the early impulsive phase, when H$\alpha$ emission is very weak.

## ACKNOWLEDGMENTS

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## REFERENCES

Alexander, D., and T. Metcalf, Asymmetric trapping in solar flares, *Solar Phys.*, **210**, 323-340, 2002.

Dennis, B. R., Solar flare hard X-ray observations, *Solar Phys.*, **118**, 49-94, 1988.

Dulk, G. A., A. L. Kiplinger, and R. M. Winglee, Characteristics of hard X-ray spectra of impulsive solar flares, *ApJ*, **389**, 756-763, 1992.

Gallagher, P. T., B. R. Dennis, S. Krucker et al., RHESSI and TRACE observations of the 21 April 2002 X1.5 flare, *Solar Phys.*, **210**, 341-356, 2002.

Gan, W. Q., and T. Watanabe, A statistical study of the resonance line of CA XIX observed with YOHKOH bragg crystal spectrometer, *Solar Phys.*, **174**, 403-412, 1997

Gan, W. Q., Y. P. Li, and J. Chang, Energy shortage of non-thermal electrons in powering a solar flare, *ApJ*, **552**, 858-864, 2001.

Gan, W. Q., Y. P. Li, J. Chang, and J. M. McTiernan, An improved method to derive the lower energy cutoff of non-thermal electrons from hard X-rays of solar flares, *Solar Phys.*, **207**, 137-147, 2002.

Kosugi, T., High energy solar flare observations by Yohkoh: a review, in *Proceedings of Kofu Symposium*, edited by S. Enome and T. Hirayama, NRO Report No. 360, pp. 11-18, 1994.

Krucker, S., and R. P. Lin, Relative timing and spectra of solar flare hard X-ray sources, *Solar Phys.*, **210**, 229-243, 2002.

Lin, R. P., B. R. Dennis, G. J. Hurford et al., The Reuven Ramaty high energy solar spectroscopic imager (RHESSI), *Solar Phys.*, **210**, 3-32, 2002.

Vestrand, W. T., G. H. Share, R. J. Murphy et al., The solar maximum mission atlas of gamma-ray flares, *ApJSS*, **120**, 409-467, 1999.

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