HARD X-RAY AND HIGH-FREQUENCY DECIMETRIC RADIO OBSERVATIONS OF THE 4 APRIL 2002 SOLAR FLARE

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ABSTRACT

Hard X-ray and high frequency decimetric type III radio bursts have been observed in association with the soft X-ray solar flare (GOES class M 6.1) on 4 April 2002 (~1532 UT). The flare apparently occurred ~ 6 degrees behind the east limb of the Sun in the active region NOAA 9898. Hard X-ray spectra and images were obtained by the X-ray imager on RHESSI during the impulsive phase of the flare. The Brazilian Solar Spectroscope and Ondrejov Radio Telescopes recorded type III bursts in 800-1400 MHz range in association with the flare. The images of the 3-6, 6-12, 12-25, and 25-50 keV X-ray sources, obtained simultaneously by RHESSI during the early impulsive phase of the flare, show that all the four X-ray sources were essentially at the same location well above the limb of the Sun. During the early impulsive phase, the X-ray spectrum over 8-30 keV range was consistent with a power law with a negative exponent of ~ 6. The radio spectra show drifting radio structures with emission in a relatively narrow ($\Delta f \leq 200$ MHz) frequency range indicating injection of energetic electrons into a plasmoid which is slowly drifting upwards in the corona.

INTRODUCTION

In solar flares, both hard X-ray emission and decimetric type III bursts are excited by energetic electrons. A study of the relationship between these two emissions is therefore expected to lead to a better understanding of the acceleration and propagation of energetic electrons in solar flares. A number of studies conducted during previous solar cycles have helped to establish the basic characteristics of the relationship between hard X-ray and metric-decimetric type III radio bursts (cf. Kane 1972, Aschwanden et al. 1985, Benz and Kane 1986, Sawant et al. 1990). For example, correlation between these two emissions was found to increase with the increase in the hardness of the X-ray spectrum and the increase in the "starting frequency" of the type III bursts (Kane 1981). The type III radio emission is generally assumed to be plasma emission, the frequency f of the radio emission being related to the ambient electron density n_e in the region through which the exciter beam of energetic electrons propagates:

$$n_e \sim a f^2 \tag{1}$$

where a = 1.24 x 10^{-8} cm^{-3} Hz^{-2} for fundamental emission and 3.10 x 10^{-9} cm^{-3} Hz^{-2} for harmonic emission (cf. Benz et al. 1983). Therefore type III radio bursts starting at frequency $f \geq 1000$ MHz are of particular interest because they are excited in the solar atmosphere where $n_e \sim 10^{10}$ cm^{-3} (fundamental emission) and the radio emission source is, in general, expected to be much deeper in the solar atmosphere than that for the metric type III bursts.

A correlative analysis of the hard X-ray bursts observed by the X-ray imager on RHESSI and the high frequency decimetric radio bursts observed with the Brazilian Solar Spectroscope (BSS) and Ondrejov Radio

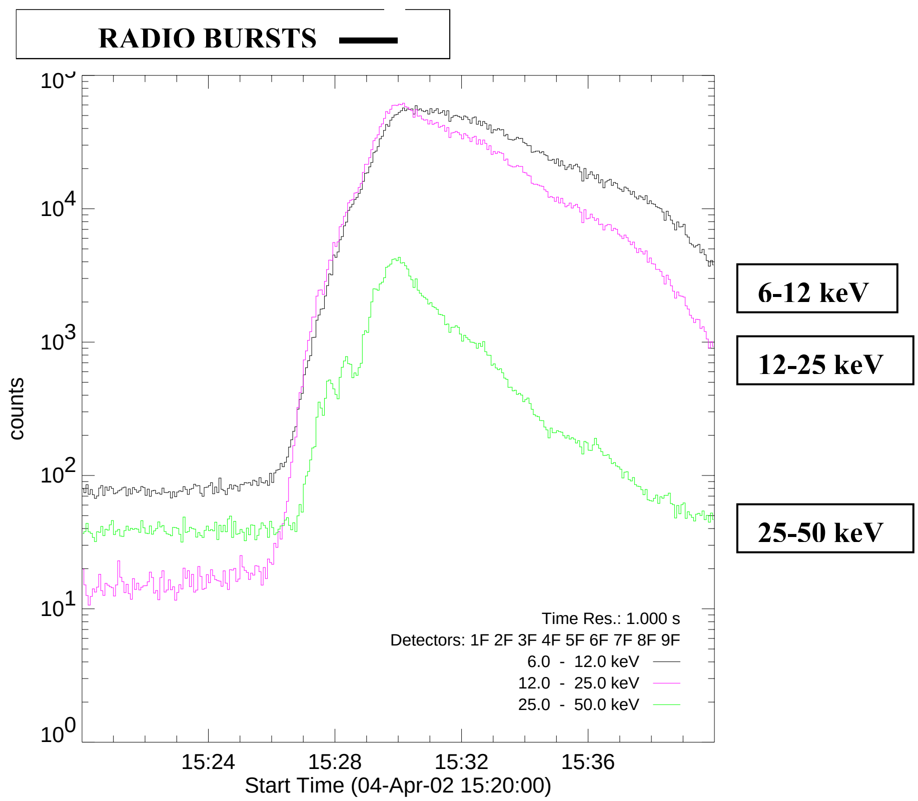

Fig. 1. Light-curves for the 6-12, 12-25, and 25-50 keV X-ray emission observed by RHESSI during the 1520-1540 UT period on 4 April 2002. The time interval in which type III radio bursts were observed is shown at the top.

Telescopes (ORT) has been recently initiated. An important aspect of that analysis is to study the characteristics of the radio-X-ray relationship when the relevant flare is located behind the solar limb. The purpose of this short paper is to present an example of the new hard X-ray and radio observations relevant to such a study of the behind-the-limb solar flares.

INSTRUMENTATION

The hard X-ray-gamma-ray imager on the RHESSI satellite has been described extensively by Lin et al. (2002) and references there in. In this paper the X-ray images and spectra of interest are those observed in 3-50 keV range. The spatial resolution of the images and the energy resolution of the spectra analysed here was ~ 4 arc-second and ~ 2 keV respectively. The X-ray images and spectra presented here are averaged over time intervals of ~ 30 seconds. The X-ray flux incident on the instrument depends on the "shutter" (attenuator) interposed between the incident radiation and the detectors. At the time of the 4 April 2002 flare discussed here no shutter was present. The sensitivity of the instrument was, therefore, relatively high for 3-10 keV X-rays. However, if the incident X-ray flux is large, absence of a shutter makes the instrument susceptible to pulse pile-up and consequent spectral distortion.

Type III bursts and other fine structures in the decimetric solar radio emission have been observed with BSS and ORT. BSS has been described by Sawant et al. (2001). Since April 1998 it has been operating in the 1000-2500 MHz frequency range with a frequency resolution of 3 MHz and a time resolution of 0.01-1.0 seconds. The sensitivity to solar radio bursts is ~ 3 solar flux units. The ORT cover 800-4500 MHz frequency range in 512 frequency channels. The time resolution is 0.1 seconds.

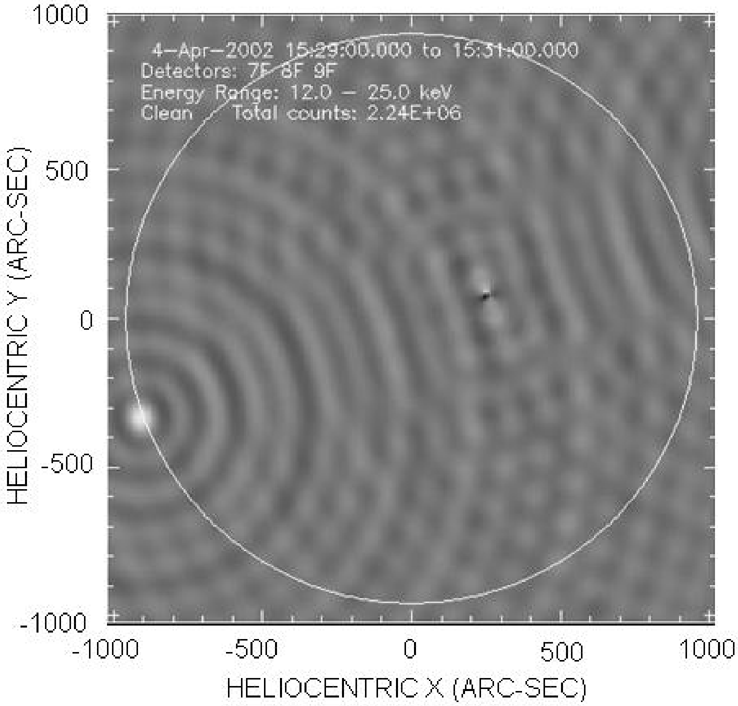

Fig. 2. Location of the 12-25 keV X-ray source associated with the flare on 4 April 2002 (1530 UT). This image of the X-ray source relative to the solar disk was obtained by the imager on the RHESSI satellite.

OBSERVATIONS

Since the launch of RHESSI the first significant group of decimetric radio bursts recorded by BSS during the observing time of the RHESSI X-ray imager occurred on 4 April 2002 at ~ 1528:55 UT. These radio bursts were also observed by ORT. The associated soft X-ray burst observed by GOES satellite has been classified as M 6.1. It lasted from 1524 UT to 1538 UT and had a maximum at ~1532 UT. No optical flare has been reported at the time of this burst.

Hard X-ray Observations

Light-curves for the 6-12, 12-25, and 25-50 keV X-ray emission observed by RHESSI during the 1520-1540 UT period on 4 April 2002 are shown in Figure 1. The time interval in which type III radio bursts were observed is also indicated. The hard X-ray flare started at ~1524 UT and reached its maximum at ~1530 UT. Since there was no shutter (attenuator) between the incident X-rays and the detectors, the sensitivity of the instrument was relatively high for 3-10 keV X-rays. Because of possible pulse pile-up and consequent spectral distortion, the analysis presented here is confined primarily to the time interval 1524-1529 UT which covers most of the rise of the X-ray emission but excludes times close to the X-ray maximum.

Position of the 12-25 keV X-ray source relative to the solar disk is shown in Figure 2. It can be seen that the source is located near the south-east limb of the Sun. High resolution images of the 3-6 keV, 6-12 keV, 12-25 keV, and 25-50 keV X-ray sources relative to the solar limb were obtained simultaneously by RHESSI. These images, averaged over the time interval 1527-1528 UT during the rise of the X-ray flux, are shown in Figure 3. It can be seen that all the four X-ray sources are essentially at the same location well above the solar limb.

In all the four images shown in Figure 3 the X-ray source is located well above the solar limb indicating that the relevant flare probably occurred behind the south-east limb of the Sun. On 4 April 2002 no active region was visible on the solar disk near the south-west limb of the Sun (Solar Geophysical Data). Active region NOAA 9896 (Magnetic type Alpha) appeared for the first time on 6 April 2002 at the location S11E74. It was followed by the region NOAA 9898 (Magnetic type Beta) which appeared on 7 April 2002 at the location S19E66. Whereas the region NOAA 9896 did not produce any flares, region NOAA 9898 produced three GOES class C flares, one on 7 April 2002 and two on 8 April 2002. It is therefore very likely that the flare on 4 April 2002 discussed here was

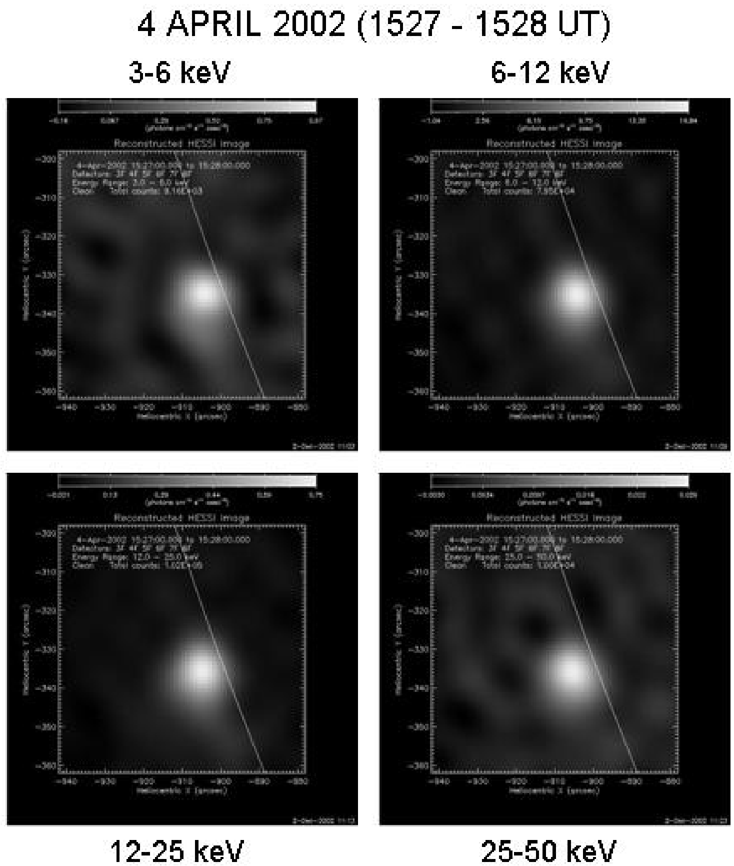

Fig. 3. High resolution images of the 3-6, 6-12, 12-25, and 25-50 keV X-ray sources obtained with RHESSI during the flare on 4 April 2002. Relative location of the solar limb is also shown. Each image is an average over the time interval 1527-1528 UT.Note that the X-ray sources at all four energy intervals are essentially coincident and well above the limb of the Sun.

produced by region NOAA 9898. Location of the X-ray source relative to the solar disk (Figure 2) is consistent with this inference. The estimated location of the 4 April 2002 flare is therefore S19E96 and hence the flare was most probably located ~ 6 degrees behind the east limb of the Sun. The implied occultation height is estimated to be ~ 4000 km.

Analysis of the X-ray spectra is in progress. Here we only mention that a preliminary analysis has shown that, during the rise of the X-ray flux, the 8-30 keV X-ray spectrum is consistent with a power law with negative exponent of ~ 6. Contribution from a thermal component is found to be negligible. A detailed analysis of the spectral characteristics will be presented in a future report.

Decimetric Radio Observations

Radio bursts were recorded by BSS and ORT during the period 1527:30-1530:00 UT. As an example, radio spectra observed by ORT during the period 1528:30-1529:30 UT are shown in Figure 4. Radio “structures” with a slow negative drift in frequency are quite evident. The emission from these radio structures is confined to a relatively narrow range of frequencies ($\Delta f \leq 200$ MHz). Four radio burst groups have been identified: A (1527:52 UT), B (1528:19 UT), C (1528:56 UT), and D (1529:43 UT). Their characteristics are presented in Table 1. While group A was confined to frequencies below 1000 MHz, groups B, C, and D extended to frequencies ≥ 1000 MHz. All the burst groups occurred during the rise of the X-ray flux and had characteristics of type III bursts. Groups A, B, and C lasted for less than 0.5 second and had normal frequency drift (high to low frequency). Group D had a reverse drift and lasted for 1.6 seconds. The starting frequency of groups B and C was higher than that for group A.

SUMMARY AND DISCUSSION

The hard X-ray and high frequency decimetric radio observations of the 4 April 2002 solar flare presented above may be summarized as follows:

1. The images of the 3-6, 6-12, 12-25, and 25-50 keV X-ray sources, obtained simultaneously by RHESSI during the early impulsive phase of the flare, show that all the four X-ray sources were essentially at the same location well above the limb of the Sun. A thermal + power law fit to the observed X-ray flux has shown that, during the early impulsive phase, X-ray spectrum over 8-30 keV range was consistent with a power law with a negative exponent of ~ 6. The contribution of the thermal component was found to be small.
2. RHESSI observations indicate that the flare occurred behind the south-east limb of the Sun. An analysis of the X-ray images obtained by RHESSI and the optical observations reported in the Solar Geophysical Data indicate that the flare probably occurred in the active region NOAA 9898. It is estimated that the flare was located ~ 6 degrees behind the east limb of the Sun and the occultation height was ~ 4000 km.
3. Four distinct high-frequency decimetric bursts A, B, C, and D were identified in the BBS and ORT observations. Whereas bursts A, B, and C had normal frequency drift, burst D had reverse drift. Bursts B, C, and D extended to frequencies ≥ 1000 MHz. The implied electron density in the radio emission source is ~ 3×10^9 cm^{-3} or ~ 1×10^{10} cm^{-3} depending on whether the emission is assumed to be harmonic or fundamental. The radio spectra show drifting radio structures with emission in a relatively narrow ($\Delta f \leq 200$ MHz) frequency range. These structures are similar to those reported earlier by Karlicky et al (2002). Presence of these radio structures suggests injection of energetic electrons into a plasmoid which is slowly drifting upwards in the corona.

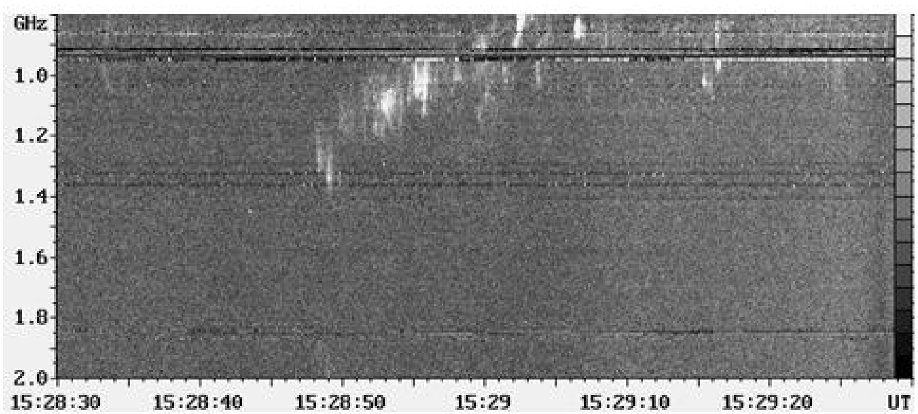

Fig. 4. Spectra of radio "structures" associated with the flare on 4 April 2002. Type III radio bursts were observed by BSS and ORT during the period 1527:30-1529:00 UT. Only the bursts observed by ORT during 1528:30-1529:30 are shown here.

Table 1. 4 April 2002 flare - radio burst characteristics

Burst No.	Time (UT)	Frequency (MHz)	Drift Rate (MHz/s)	Duration (sec)	Electron Density (10^9 cm^{-3})
A	15:27:51.5 - 15:27:51.5	866-997	-437	0.3	2.3-3.1
B	15:28:19.2 - 15:28:19.6	1044-1231	-468	0.4	3.4-4.7
C	15:28:55.6 - 15:28:55.8	969-1138	-845	0.2	2.9-4.0
D	15:29:42.5 - 15:29:44.1	955-1030	47	1.6	2.8-3.3

During the last solar activity cycle, multi-spacecraft observations of behind-the-limb solar flares revealed the existence of flare associated hard X-ray sources in the corona extending to heights ≥ 50000 km (cf. Kane et al. 1982, 1992). However images of these sources were not available. RHESSI observations have shown that, even in relatively small (GOES class C) solar flares, "gradual" hard X-ray sources exist in the corona (Kane and Hurford

2003). The heights of these sources are much larger than those observed earlier in relatively large flares by hard X-ray imaging instruments aboard Hinotori (Takakura et al. 1986) and Yohkoh (Masuda et al. 1995) satellites.

In this paper we have presented images of a flare-associated "impulsive" hard X-ray source located at a height of ~4000 km above the photosphere. The source is found to be non-thermal. The narrow range of emission frequencies ($\Delta f \leq 200$ MHz) and slow negative drift in frequency for the associated radio structures suggests injection of energetic electrons into a plasmoid which is slowly drifting upwards in the corona. Only the early results related to the hard X-ray and high frequency decimetric radio observations of the 4 April 2002 flare have been presented here. More detailed results including analysis of X-ray spectra and other correlated emissions (such as microwave radio) will be presented in a future report.

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