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RHESSI and Microwave Imaging Observations of Two Solar Flares

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Abstract. We describe two flares of GOES class M5.7 and 1.5 which were observed simultaneously by RHESSI (Ramaty High Energy Solar Spectroscopic Imager) and NoRH (Nobeyama Radio Heliograph). Both of these flares exhibit slow motions suggestive of changing magnetic shear, loop expansion, or gradual reconnection.

1. Introduction

Energetic (> 10 keV) electrons accelerated during a flare produce a variety of emissions. Hard X-rays are produced by bremsstrahlung as the electrons interact with the ambient ions. Energetic electrons interacting with magnetic fields give rise to microwave emission via the gyro-synchrotron process. The microwave emission also requires that the electron spectrum extend to high energies (several hundred keV). Hard X-rays (HXRs) and microwaves provide unique tools for studying the electrons accelerated during solar flares to high energies, especially keV-MeV energies. Their observed spectral and spatial variations reflect physical processes that control the evolution of the electrons. Since the requirements for production of hard X-ray and microwave emissions are quite different, the populations of the radiating electrons and locations of the flaring sources in the two spectral domains can, in principle, be quite different. However, the observed similarity between the light curves of hard (> 10 keV) X-ray and microwave emissions during the early rise through maximum and early decay of a flare, has led to models in which a common electron population is assumed to be responsible for both emissions. In order to confirm such an assumption, it is necessary to know the spatial structure of the emission sources and the spectra of the radiating electrons. Such observations have become available only recently. Observations of coronal or near limb X-ray and microwave flares are particularly important in such studies because the coronal sources in both HXR and microwaves can be produced by a variety of processes. Hard X-rays are produced by thick-target absorption of large numbers of nonthermal electrons in the chromosphere. However, there exists evidence of coronal hard X-ray flaring sources in thin-target situation. (see e.g. Hudson 1978, Frost and Dennis 1971). These long-enduring bursts have extremely close time relationships with meter-wave and microwave continuum bursts. They therefore represent the thin-target bremsstrahlung of the coronal electron population whose high-energy tail produces the observed synchrotron emission. The simultaneous observations afford an excellent opportunity to describe these electrons, their accelerations and subsequent evolution, in a more complete manner. New observations by the Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI) (Veronig and Brown 2004) suggest that coronal hard X-rays may sometimes be produced in thick targets. The Veronig and Brown event was not above the limb, but other above-limb events may share the same characteristics.

In fact, Lee et al. (2002) and Qiu et al. (2004) analyzed two flares in which there were both impulsive and gradual radiation in microwave and HXR time profiles. They found that both are due to thick-target bremsstrahlung, the relative timing and spectral evolution of the HXR's and microwaves are largely controlled by the temporal variation of the injection spectrum. Lee et al. also proposed a flare geometry in which electrons are accelerated in the lower atmosphere and some of them are transported higher into the corona to be trapped in a larger loop in contrast to the traditional picture of electrons accelerated at some height in the corona and streaming down. This is somewhat different from the traditional trap-plus precipitation model and accounts for the larger number of electrons: $\sim 10^{33}$ for the impulsive precipitating component ($\geqslant 100$ keV) than for the gradual component electrons ($\sim 10^{32}$ for $\leqslant 100$ keV).

2. OBSERVATIONS

We present hard X-ray (RHESSI) and microwave (NoRH) imaging observations of two solar flares of M-class observed on March 14 and March 12 of 2002, one located near the disk center and the other near the E-limb. For the March 14 event (near disk center), both hard X-ray and microwave observations indicate that the flaring region consisted of a complex of multiple loops. In microwaves its spatial configuration has a double-loop structure; at the main flare site (primary flaring loop) we observe microwave, HXR, EUV emissions and at a remote site (connected to main site by a long loop) we observe microwaves only due to a strong magnetic field. Some HXR foot point sources (in 25-100 KeV bands) have co-located microwave foot point sources. The hard X-ray spectrum can be fitted with a thick target model with a thermal component and a broken power-law component. The March 12 E-limb event was fully observed by Nobeyama Radio Heliograph (NoRH), but in hard X-rays it was observed only from around the peak until the end of the flare, because of RHESSI night time. In hard X-rays (6-50 KeV) it was clearly a coronal source located above an EIT loop, and it seems to have significant motion in the post flare period. In microwaves it was also a coronal source in both 17 and 34 GHz. Due to the relatively poor resolution of NoRH, the overall source size in radio is large, encompassing the RHESSI source at the start and end of its motion. The spatial maximum of the 17 GHz source appears at a coronal height below the HXR source. The microwave source also shows motion, along with the expansion of the EIT flaring loop.

2.1. *First Flare: Microwave and RHESSI Hard X-ray Observations of the M5.7 Flare of 2002 March 14*

We studied a flare of GOES class M5.7 which was observed simultaneously by RHESSI and NoRH (Nobeyama Radio Heliograph). The flare occurred in active region AR 9866 located near disk center. The time profiles of the flare in HXR and microwaves are shown in Fig. 1, left panel. Both hard X-ray and microwave imaging observations indicate that the flaring region consisted of a complex of multiple loops. In the microwave domain it clearly is of a class characterized by a double loop configuration: a small loop or flux interacting with an old loop or flux, which is the main flare site, meaning that this is the site where we observe microwave, HXR, EUV emissions, and a remote flare site which is observed only in radio (Fig. 2, right panel).

In HXR there are clearly three loops, two of which have distinct foot points with co-located microwave source in one foot point; the third loop is large and filled with energetic electrons primarily emitting lower energy (12-25 keV) HXR. The successive

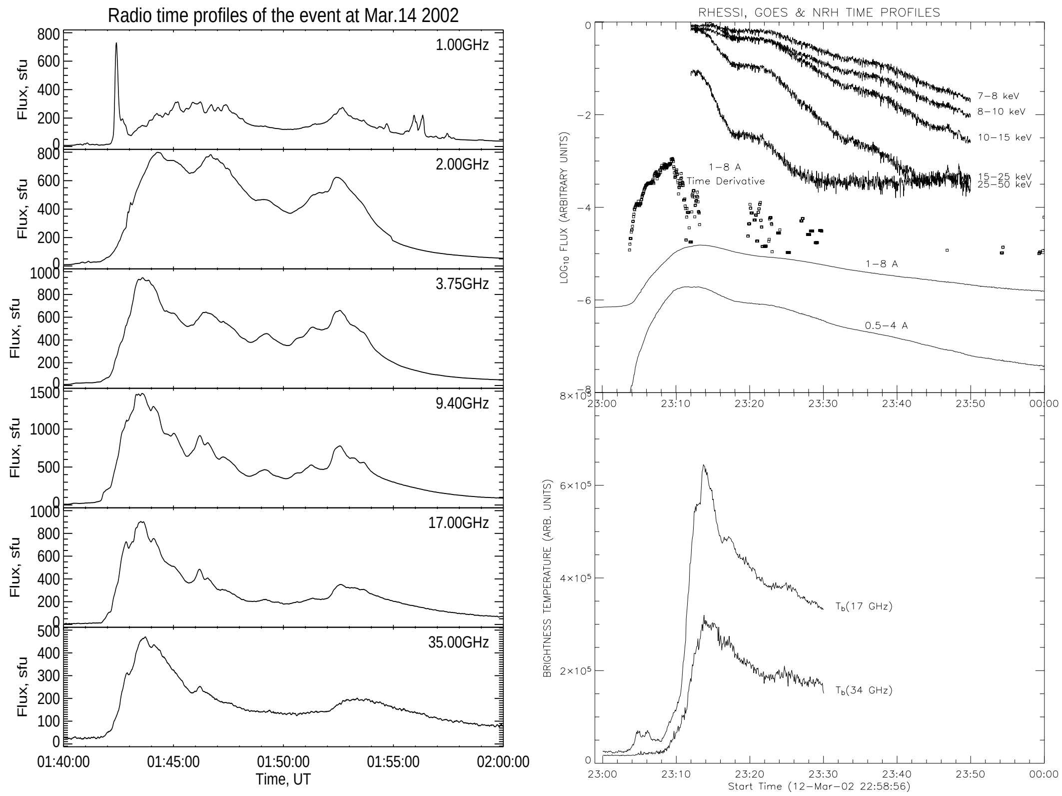

Figure 1. Left panel: The time profiles of the 2002 Mar 14 flare in HXR and microwaves. Right panel: The time profiles of the HXR, soft X-ray and microwave flare of 2002 Mar 12.

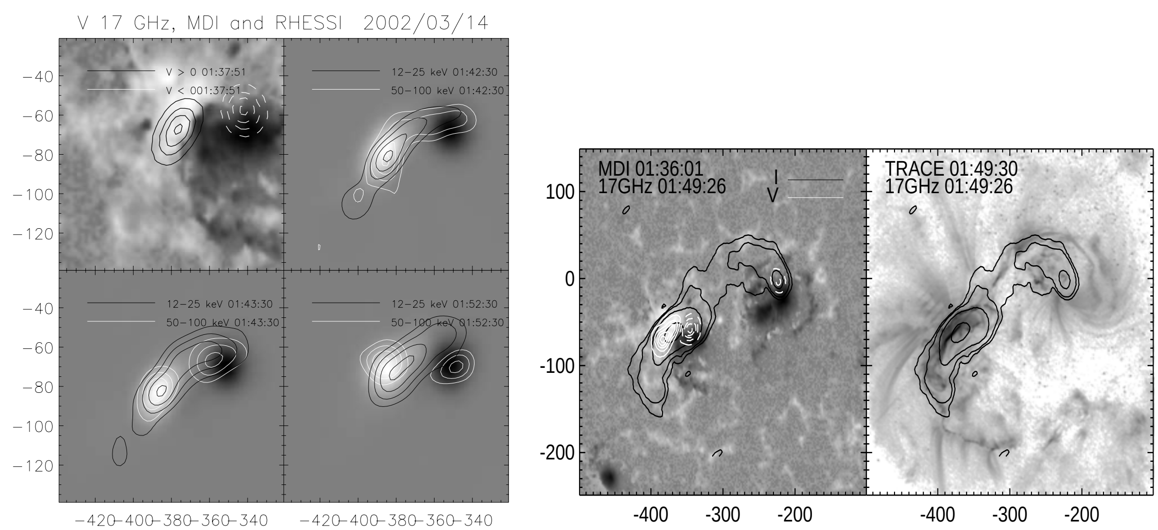

Figure 2. RHESSI and Nobeyama maps showing the multi-loop configuration of the 2002 March 14 flare. Left panel: A sequence of 12-25 keV RHESSI maps overlain on MDI (top left) and 17 GHz V images. Right panel: The remote source (upper right) seen at 17 GHz but not in HXR, and its connection to the main source (lower left) in 17 GHz maps. These are overlain on MDI (left) and TRACE (right) images.

energization of the loops gives the appearance of re-orientation with time of RHESSI flaring loops. There is a second peak in flaring emission in both microwaves and HXR at $\sim$ 01:53 UT, which also shows up as a short duration weak continuum in dynamic spectra (in the frequency range 30-500 MHz, 01:50-01:57 UT). Spectroscopic analysis of the RHESSI data shows that the spectrum can be fitted with a thick-target model with a thermal component and a broken power-law component. Viewed overall, the successive loops inferred from microwaves and HXR appear to show a decrease of magnetic shear as the flare proceeds.

2.2. *Second Flare: The Event of 2002 March 12*

The flare in question was a GOES M1.5 class, located at S19 E83, close to the E-limb. The flare was not observed fully by RHESSI because the rise phase was in night time. The RHESSI observations started from about 23:12 UT, close to the peak of the RHESSI time profile. After this time HXR emission had a steady decline (Fig. 1, right panel).

The energy range observed by RHESSI was 6-50 KeV which permitted us to produce good maps in several bands. The most striking feature of these maps (Fig. 3) is that the HXR source is located well into the corona - apparently above an EIT loop and close to the flaring EUV bright source at the top of the loop. The HXR source shows motion in a direction approximately orthogonal to the loop.The microwave time profiles are rather gradual, starting at 23:08, peaking at $\sim$ 23:14 UT and then steadily declining. The peak of the 17 GHz source seems to lie below the HXR source. This gradual time profile is

one of the characteristics of coronal flares. The NoRH maps (Fig. 4) show that both 17 and 34 GHz flaring sources are also in the corona, but because of insufficient resolution the overall source size is large, and part of the source seems to be on the disk. The microwave sources encompass the RHESSI sources both at the beginning and at the end of its motion. The HXR source motion is mainly from 23:12 to 23:20 UT. There are 4 EIT loop images available at 23:12, 23:24, 23:36, and 23:48 UT. In the declining phase an additional EIT loop appears to the south of the loop we are concerned with. This southern loop also seems to be a source of microwave radiation at both 17 and 34 GHz. The 17 GHz emission is polarized, and the polarized source is co-located with the total intensity source.

As mentioned earlier, one of the interesting aspects of this coronal hard X-ray source is its motion, mostly taking place from 23:12 to 23:48 UT. The motion of the HXR source is not along the EIT loop, but at an angle across the loop [e.g.. Sui and Holman 2003).

From the HXR spectral point of view, it is a thermal source. The microwave time profile has a gradual rise and even more gradual decline continuing beyond 23:30 UT. However, the microwave emission must be nonthermal, being produced by gyro-synchrotron radiation of energetic electrons. It appears that the microwave source also has motion. In microwaves the main flaring source is also in the north like the RHESSI source. In future work we will study the footpoint motion (where it is visible) of the HXR and microwave sources, their connectivity to the microwave sources observed on the disk, and thus investigate if the acceleration of electrons takes place in the corona by reconnection of magnetic field lines or in the lower atmosphere due to interaction of multiple loops.

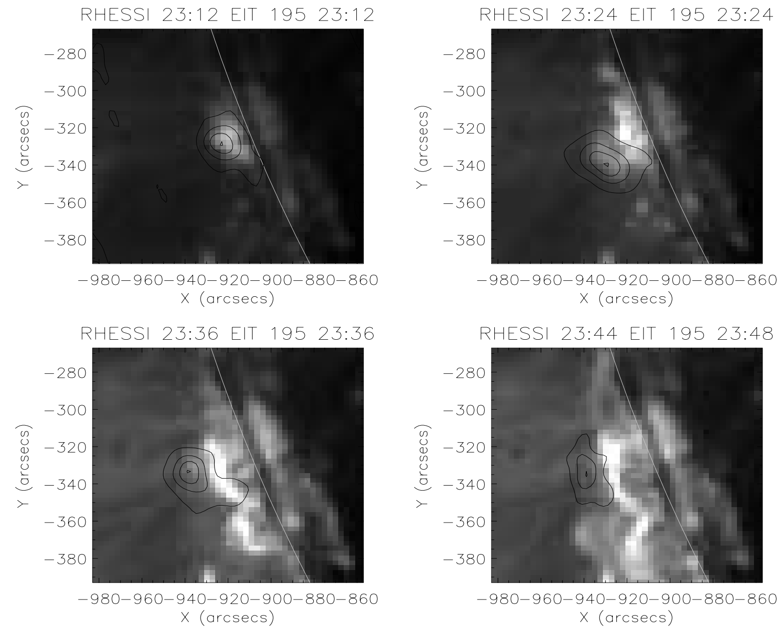

Figure 3. RHESSI 10-15 keV contour maps overlain on EIT images of the 2002 Mar 12 flare.

3. SUMMARY

We discuss the properies of two solar flares- one near the disk center and the other at the E-limb. The limb flare is associated with coronal hard X-rays as observed by RHESSI and coronal microwave radiation as observed by the Nobeyama Radio Heliograph (NoRH).

For the first flare (2002 March 14) which occurred near disk center, both HXR and microwave images show multiple loops. The 17 and 34 GHz images show a double loop configuration (see e.g. Kundu et al 2001), consisting of a main flare site where one observes only microwave and HXR, and a remote site which is observed only in radio. We emphasize that even with the high sensitivity and high resolution of RHESSI, no HXR emission is observed at the remote site. The HXR images show two loops with distinct footpoints, one with a co-located microwave source. There is a third HXR loop filled with energetic electrons emitting 12-25 keV radiation. The HXR spectrum can be fitted with a thick target model with thermal plus power-law components. The successive HXR loops show gradual re-organization of their alignment, and thus exhibiting evidence of decreasing magnetic shear.

For the second flare (2002 March 12) which occurred at the E limb, one finds that both microwave and HXR time profiles are gradual which is typical of coronal sources. The RHESSI observations started near the peak and continued until the end of the flare ($>$ 23:30 UT). The HXR and 34- and 17-GHz sources are clearly in the corona, but because of the relatively poor resolution in radio, part of the 17-GHz source appears to lie on the disk. The HXR source is on and above the brightest part of the EIT loop and also above the 17-GHz source. 17-GHz V souirce also coincides with the brightest part of the EIT loop. The HXR and microwave sources show systematic motion at an angle to the EIT loop.

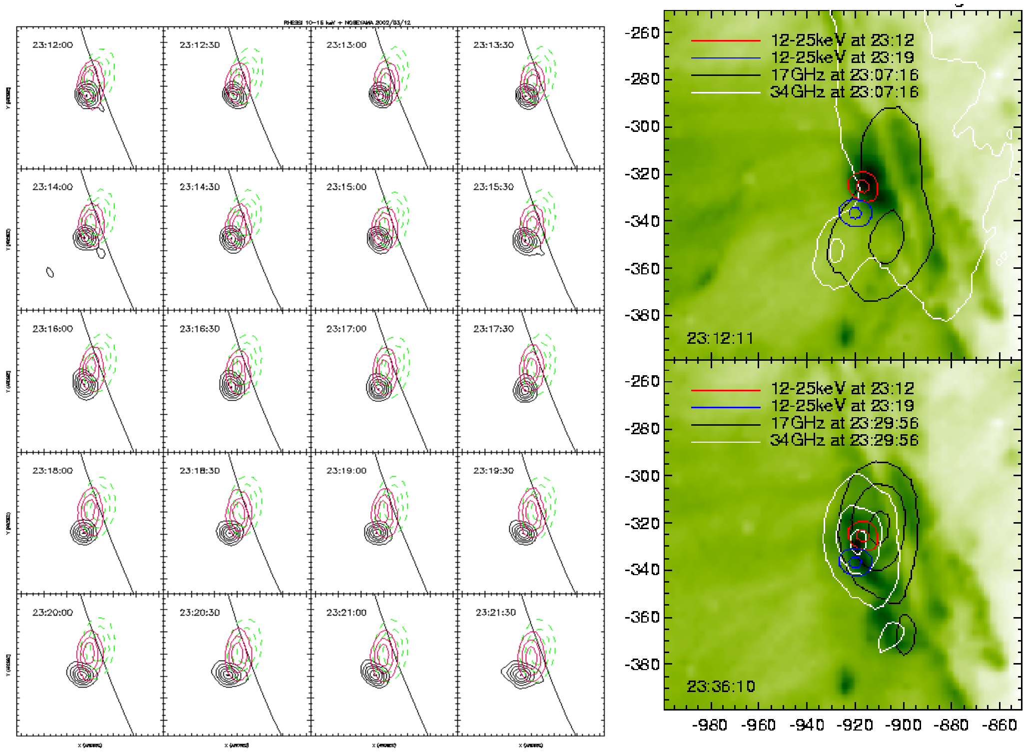

Figure 4. Left panel: The relative locations of the 10-15 keV HXR sources (thick contours), 34-GHz (light contours), and 17-GHz (dashed contours). THe limb is shown on the right side of the maps. Right panel: HXR, 17- and 34-GHz contours overlain on EIT images. The motion is genarally to the southeast in all the sources, but the HXR source moves relative to the microwave sources.

Acknowledgements

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