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RHESSI: First Results

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Abstract. The RHESSI observations consist of imaging spectroscopy in the γ-ray, hard X-ray, and “firm X-ray” (3-20 keV) bands. These data are now the most extensive and capable solar high-energy observations at high spectral and spatial resolution. The low-energy hard X-ray spectrum bridges the thermal and non-thermal ranges of solar electron distributions in flares systematically for the first time. In this presentation I survey some results from the first 18 months of observation, including findings on image and spectral morphology (both hard X-ray and γ-ray), and the behavior of microflares in the 3-20 keV band.

1. Introduction

RHESSI (the Reuven Ramaty High-Energy Spectroscopic Imager), which began observation February 12, 2002, carries out X-ray and γ-ray observations of flares and other forms of solar magnetic activity (Lin et al., 2002). It thus continues the work of *Yohkoh* and earlier high-energy satellites, but with much-improved capabilities. The RHESSI mission may continue so that it overlaps Solar-B, although this of course cannot be guaranteed, and if we are very lucky both missions will extend into the next solar maximum period. With overlap we can expect meaningful intercomparisons related to flares; Solar-B lacks imaging capability in the non-thermal emissions essential to the physics of energy release and particle acceleration. The RHESSI spatial resolution cannot match that of the SOT observations, but is comparable with XRT and EIS.

The “firm” X-ray band, 3-20 keV, has seldom been observed with RHESSI’s spectral resolution and imaging capability, with earlier imaging observations from SMM/HXIS (e.g., Hoyng et al., 1981) and spectral observations from *Hinotori*/FLM instrument (Tanaka et al., 1984). There are several reasons why this spectral band is important. It bridges the thermal and non-thermal domains of bremsstrahlung, thus giving us information about the energy deposition of the energy-rich particles accelerated in the impulsive phase. These low energies also reflect the presence of low-energy non-thermal electrons, which are especially observable in the smaller events such as microflares and X-ray jets. This great improvement is possible because of RHESSI’s pioneering system of absorbing shutters (Lin et al., 2002).

For the γ-rays, RHESSI provides the very first imaging observations, plus a much higher spectral resolution that is sufficient to resolve the widths of all of the γ-ray lines except for the 2.223 MeV neutron-capture line. At the time of writing five 2.223-MeV flares have been detected by RHESSI.

The purpose of this paper is to sketch out some recent RHESSI high-energy observations for the Solar-B community. Owing to a lack of space the range of topics is not comprehensive, so an interested reader should really study the original materials. There is already much published work – in *Solar Physics* see Volume 210, 2002, and in *ApJL* see Volume 595, 2003, devoted to the γ-ray flare of 2002 July 23. Some of the items in this paper come from presentations at the Fall 2003 meeting of the AGU and are not yet in final form.

2. First results from RHESSI

2.1. Imaging

The imaging from RHESSI bridges a large range of photon energies, and the illustrations in Figure 1 show two X-ray studies.

A sequence of flares studied by Sui et al. (2004) show a novel pattern of source height versus time (Figure 1, left). In contrast to most *Yohkoh* experience, these flares show initially downward-moving loop-top sources, plus an initially stationary above-the-looptop source. This downward motion should be distinguished from "shrinkage" (Švestka et al., 1982) but is consistent with the inward motions suggested by Hudson (2000). The upward motions following the initial phase would be consistent with "plasmoid" eruption as envisioned in the classical flare models, but the stationary phase is puzzling. Three events from the same active region showed this morphology.

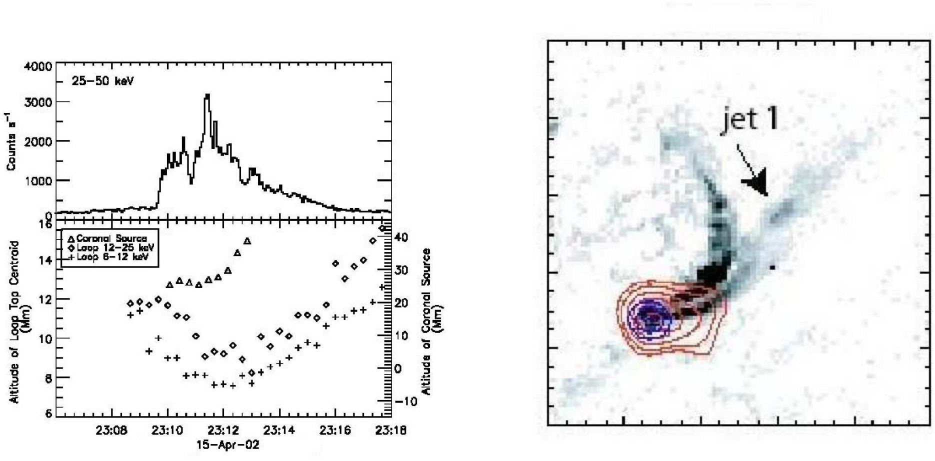

Figure 1. **Left**, observations of a flare showing downward motions in the early impulsive phase and an initially stationary above-the-loop-top source (Sui et al., 2004), both novelties. **Right**, Observation of an X-ray jet, with TRACE 195Å shown as the gray scale and RHESSI as contours (two sets: 3-12 keV, 12-25 keV). The hard X-ray contours match the loop footpoint, but the softer band shows an extension into the corona consistent with direct bremsstrahlung from electrons flowing through the jet and out into the upper corona.

The right panel of Figure 1 shows an X-ray jet associated with a radio type III burst and an interplanetary electron event (Christe et al., 2003). Associations of type III bursts and X-rays are well known (Aurass et al. 1994). The morphology of such events often suggests the geometry proposed by Heyvaerts et al. (1977), in which one footpoint of a loop flare also seems to be the point of origin of the jet. What is new about the RHESSI observations is their potential for actually showing the direct bremsstrahlung from the particle event itself. The interplanetary particles are on open field lines, but they should be visible either in the corona as they escape, or else as a closely-related population of downward-beamed electrons undergoing thin-target interactions near the footpoints of the open field lines.

2.2. Spectra

The RHESSI detectors (high-purity Ge) work as non-dispersive spectrometers, with a spectral resolution (FWHM) ranging from less than one keV at low energies, to several keV at γ-ray energies. The illustration in the left panel of Figure 2 shows some of the potential of these low-energy measurements. The spectrum clearly shows both the Fe feature from K-shell transitions (6.7 keV for the Fe XXV lines) but also an Fe-Ni feature at ∼8 keV. These spectral features give different perspectives on the electron distribution function in the source region, and complement the information obtained from the bremsstrahlung continuum. Note that this spectrum was obtained through the thinner RHESSI attenuator on a flare of GOES magnitude M4.3 (Caspi et al., 2003).

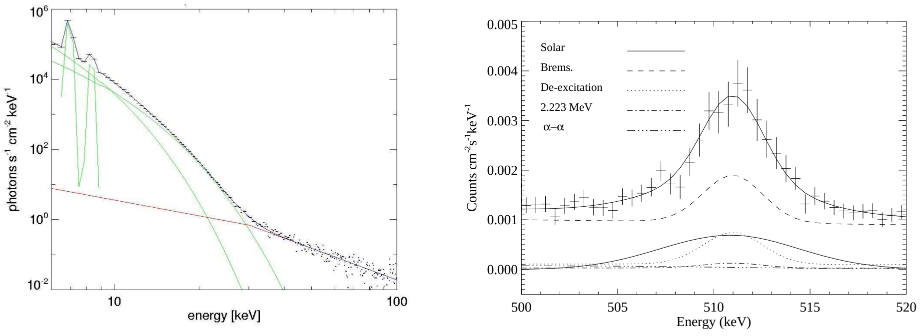

Figure 2. **Left**, X-ray spectral observations of a flare from 20 February 2002. The data for this 12-s exposure clearly show the presence of not only the Fe K-shell feature at about 7 keV, but also a line feature at slightly higher energies due to both Fe and Ni (Caspi et al., 2003; Phillips, 2004); there were also limited observations of this latter feature by *Hinotori* (Tanaka et al., 1984). **Right**, the γ-ray line at 511 keV due to positron annihilation in the flare of 2002 July 23 (Share et al., 2003). This line is resolved spectroscopically by RHESSI, as are all other γ-ray lines except for the 2.223 MeV line. The different lines, as labeled, show the contributions *to the line region* of secondary counts from the model components indicated.

The right panel of Figure 2 illustrates the RHESSI capability for γ-ray spectroscopy, showing the observation of the 511-keV line of positron annihilation as observed in RHESSI's first γ-ray event, 2002 July 23 (Share et al., 2003). The finite width of the line suggests a formation process deep in the photosphere, as described by Crannell et al. (1974) and as expected from particle transport considerations. From the Solar-B point of view, this suggests that flare effects in the deep atmosphere might be studied with high resolution using SOT.

2.3. Gamma-rays

Although RHESSI is a latecomer to solar high-energy observations, following many successful satellite observations at hard X-ray and γ-ray energies, it adds two crucial "firsts": imaging and high-resolution spectroscopy. We describe here two of the initial results from these capabilities, both derived from the flare of 2002 July 23.

The 2.223 MeV data in Figure 3 (left) show the first meaningful solar γ-ray imaging. We interpret the centroid location (the diameter of the circle shows the uncertainty) as the locus of interaction of accelerated nuclei. At these high energies there are very few photons, and in addition only two of RHESSI's nine modulation collimators can be used for imaging; thus a full image cannot be constructed as easily as in the hard X-ray range. The hard X-ray and γ-ray centroids differ in position by about 5σ in this case, indicating a real displacement between electron and ion acceleration.

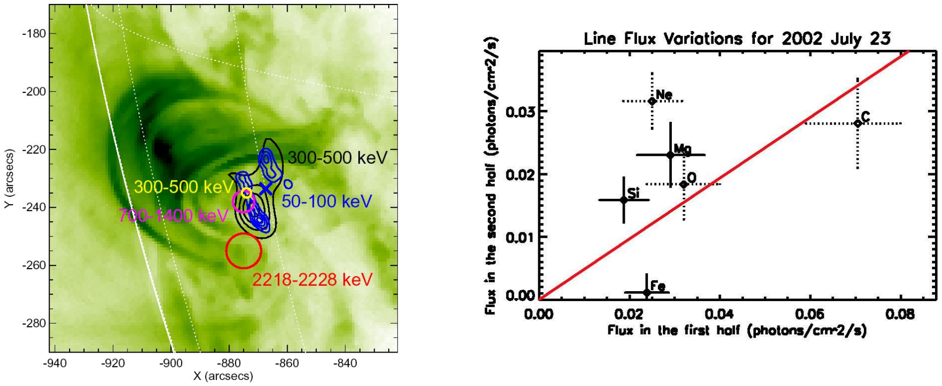

Figure 3. **Left**, centroid of emission at 2.223 MeV in the γ-ray event of July 23, 2002. Its displacement from the hard X-ray centroid location (and the flare ribbons) indicates that the energetic ions and electrons differ spatially (Hurford et al., 2003). Note that the TRACE image is from a late phase of the flare and does not show the corona at the time of the observations. **Right**, ratios of γ-ray line fluxes comparing early and late epochs of the flare of 2002 July 23, separated by element (Shih et al., 2003) with high FIP shown dotted.

The right panel of Figure 3 shows a result on elemental abundance variations as inferred from the γ-ray line intensities at two epochs in the flare of 2002 July 23 (Shih et al., 2003). The two epochs during the flare have strikingly different intensity ratios (Fe, for example, becomes relatively weak in the second half of

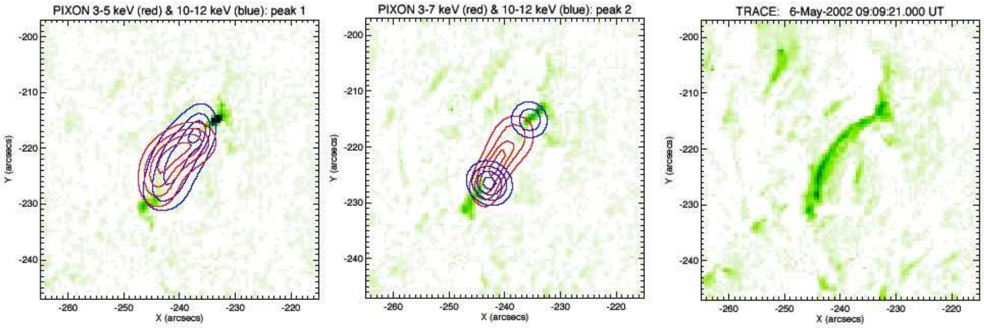

Figure 4. RHESSI and TRACE observations of a microflare. The RHESSI contours at low energies (3-7 keV) are elongated, matching the TRACE loop that appears late in the event, and at higher energies (10-12 keV) are compact, as one would expect for non-thermal bremsstrahlung at the loop footpoints (Rauscher et al., 2003).

the event). The variations furthermore are not organized by FIP (first ionization potential), suggesting that other mechanisms for differentiation may exist. These intensities refer to the narrow-line components of the γ-ray lines and hence show the abundances in the target population.

2.4. Microflares

Microflares (and nanoflares, if any) are being observed by RHESSI in a novel manner because of sensitive access to the 3-20 keV band. The RHESSI data show many microflares, so many that it is difficult to find time intervals *without* them during the first years of the mission. We find (Benz and Grigis, 2002; Krucker et al., 2002) that these events mostly occur in active regions, and so even at this level of sensitivity one would not be able to associate them with the heating of the general corona.

Figure 4 shows an example from 2002 May 6, an event so faint as to be imperceptible on the GOES low-energy (1-8Å) channel (Rauscher et al., 2003). The 10-12 keV images show the behavior typically seen at higher energies in “true” flares, namely footpoint brightening. This illustrates the ability of RHESSI to follow the non-thermal spectrum to much lower energies than previously possible, and to make images. The softer X-ray images show excellent consistency with TRACE, which shows plasma at much lower temperatures.

3. Conclusions: anticipating Solar-B comparisons

RHESSI and Solar-B perform almost perfectly complementary observations, since Solar-B has no high-energy component while RHESSI could not afford to incorporate “context” instruments. We therefore hope to have simultaneous observations of flares and flare-like manifestations. The Solar-B definition of the lower boundary of the corona, at high resolution, should help in the interpretation of the RHESSI results. This lower boundary of the corona is physically rich, in the sense that it contains transitions between strikingly different physical states of matter, radiation, and fields. It is in this region that the RHESSI and Solar-B observations may overlap most significantly. The 511-keV line observation described above (Figure 2) for example, requires that flare effects appear in the deepest layers of the solar atmosphere. This also is the site of electron-induced effects, specifically the white-light and UV impulsive-phase emissions (e.g., Metcalf et al., 2003). The accelerated particles, viewed more directly by RHESSI, show where energy release takes place. The Solar-B magnetograms will provide the best possible framework for identifying the trajectories and origins of these particles, as well as their magnetic sources of energy.

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