First Gamma-Ray Images of a Solar Flare

G. J. Hurford,[1] R. A. Schwartz,[2] S. Krucker,[1] R. P. Lin,[1,3] D. M. Smith,[1] and N. Vilmer[3]
(1) Space Sciences Lab & (3) Physics Dept., Univ. of Calif., Berkeley,CA 94720
(2) NASA Goddard Space Flight Center / SSAI, Greenbelt, MD 20771
(4) LESIA, Observatoire de Paris, 92195 Meudon-Cedex, France

Abstract

We present the first gamma-ray images of a solar flare, obtained with the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) for the X4.8 flare of 2002 July 23. Two rotating modulation collimators (35″ & 180″ resolution) provided images of the narrow deuterium line at 2.223 MeV formed by thermalization and capture of neutrons produced in energetic ion collisions, the 3.25-6.5 MeV band that includes the prompt de-excitation lines of C and O, and the 0.3-0.5 and 0.7-1.4 MeV bands that are dominated by electron-bremsstrahlung. The centroid of the 2.223 MeV image was found to be displaced by $\sim 20(\pm 6)$ arcsec from that of the 0.3-0.5 MeV band, implying a difference in acceleration and/or propagation between the accelerated electron and ion populations near the Sun.

1. Introduction & Observations

The detection of nuclear gamma-ray line emission from large solar flares shows that they accelerate ions as well as electrons to high energies [1]. Collisions of energetic ions with the solar atmosphere produce excited nuclei which emit prompt nuclear de-excitation lines, as well as secondary neutrons and positrons that result in the delayed 2.223 MeV neutron-caption and 511 keV positron-annihilation line emission [9]. The RHESSI mission is designed for flare X-ray/gamma-ray imaging spectroscopy from 3 keV to 17 MeV [7]. The imaging system consists of 9 bi-grid rotating modulation collimators (RMC's), that provide FWHM angular resolution of 2.26″ to 183″ in logarithmically spaced steps. As the spacecraft rotates, the fraction of the incident flux that passes through the two grids in each RMC varies rapidly. RMCs #6 (35.3″) and 9 (183″) have 2 and 3 cm thick tungsten grids, respectively, to modulate effectively at gamma-ray energies. Behind each RMC is an electrically segmented germanium detector (GeD), cryogenically cooled to provide high spectral resolution (∼1-10 keV FWHM) [10]. Spatial information on the source is encoded in the timing of the detected counts[5].

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RHESSI observed the X4.8 flare of 2002 July 23, optically centered near the east limb at S13E72 [8]. Figure 1 shows rear segment count rates vs. time in the 0.3-0.5, 0.7-1.4, 2.218-2.228, and 3.25-6.5 MeV bands. All the images in this paper are made for the most intense impulsive peak (00:27:20 to 00:34:40 UT). The background-subtracted gamma-ray count spectrum from 0.3 to 8.5 MeV [8] was fit to a model which includes the prompt nuclear de-excitation lines, the 2.223 MeV neuron-capture line, the 0.511 MeV positron annihilation line, and a broken power-law electron bremsstrahlung continuum - all folded through the full instrument response, including non-diagonal terms from photons which deposit only part of their energy in the detector [10]. The best fit indicates that the 0.3-0.5 and 0.7-1.4 MeV bands are dominated by electron-bremsstrahlung continuum, while the C and O nuclear line complex dominates the 3.25-6.5 MeV band.

Fast neutrons from energetic ion collisions thermalize in the photosphere before being captured by hydrogen to form deuterium, which then emits a 2.223 MeV photon. This results in a very narrow (intrinsic width $<\sim$0.1 keV) line, delayed by $\sim$100 s. RHESSI detects it with high resolution ($\sim$4 keV FWHM), so a narrow energy band (2.218-2228 MeV) can be used for imaging, to effectively eliminate underlying continuum background and non-photo peak response.

Figure 2 shows low-resolution (183″) images made with the back-projection technique [5] using RMC 9 only. The main peaks show unambiguously that the gamma-ray sources are related to the optical flare at S13W72. Intermediate-resolution (35″) maps were made by summing back-projection images from RMC #6 and 9. Figure 3 shows the centroids for the 0.3-0.5, 0.7-1.4, and 2.218-2.228 MeV bands as circles with radii equal to the 1-σ statistical error.

2. Discussion

For the 0.3-0.5 and 0.7-1.4 MeV bands, the ratios of the imaged flux with RMC 6 (35″) to that with RMC 9 (183″) (the relative visibilities) - 0.54$\pm$0.06 and 0.57$\pm$0.16, respectively - are not unity, indicating that the sources were partially resolved on a size scale of 35″. A high-resolution (3″) 50-100 keV hard X-ray image (white contours in Figure 3) shows a string of compact hard X-ray sources extends $\sim$24″ along a NNE-SSW direction, with a second, $\sim$12 ″ long parallel string located $\sim$10″ closer to Sun-center [6,2,11]. A 7″ image at 0.3-0.5 MeV shows contours that overlap the east string, with the lowest intensity contour also covering the west string.

The relative visibility of the 2.223 MeV line source was 0.93$\pm$0.43, consistent with a value of unity, which would suggest a compact source. If we take 0.07 as a 2σ lower limit to the relative visibility and make an arbitrary (but simple) assumuption of a 'Gaussian model,' this would imply an 2σ upper limit to the 2.223 MeV source size of $\sim$1 arcmin FWHM.

A detailed physical model of the 2.223 MeV line emission that includes energy losses, magnetic mirroring, and pitch angle scattering in a loop with an active region atmosphere [3,4] shows that the accelerated ions interact in the lower chromosphere/upper photosphere to produce the fast neutrons and prompt de-excitation lines, while the neutron thermalization and capture on hydrogen occurs close by in the photosphere within $\sim$500 km or $\sim 1''$.

The 2.223 MeV source centroid was found to be displaced in the southward direction from the weighted average of the 0.3-0.5 and 0.7-1.4 MeV sources by $20\pm6''$, which is nonzero with statistical confidence of >99.7%. Since the 0.3-0.5 and 0.7-1.4 MeV bands are partially contaminated by nuclear line emission, this is an underestimate of the actual displacement. In the vicinity of the 2.223 MeV centroid, no significant hard X-ray emission is detected; all the hard X-ray sources are north and toward Sun-center. Thus, the ions must accelerate and/or propagate differently from the electrons. One possibility is acceleration by DC electric fields, which would send electrons and ions in opposite directions. Although their flux-time profiles are similar (Fig. 1), the prompt gamma-ray line emission appears delayed by $\sim$10s relative to the electron bremsstrahlung emission, perhaps enough time for electron heating of the solar atmosphere, producing a shock wave that then accelerate the ions.

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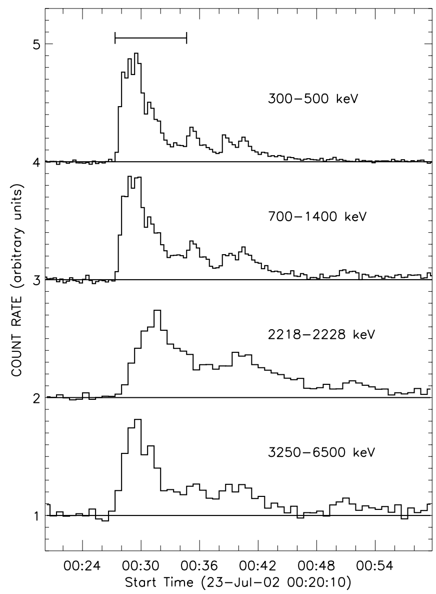

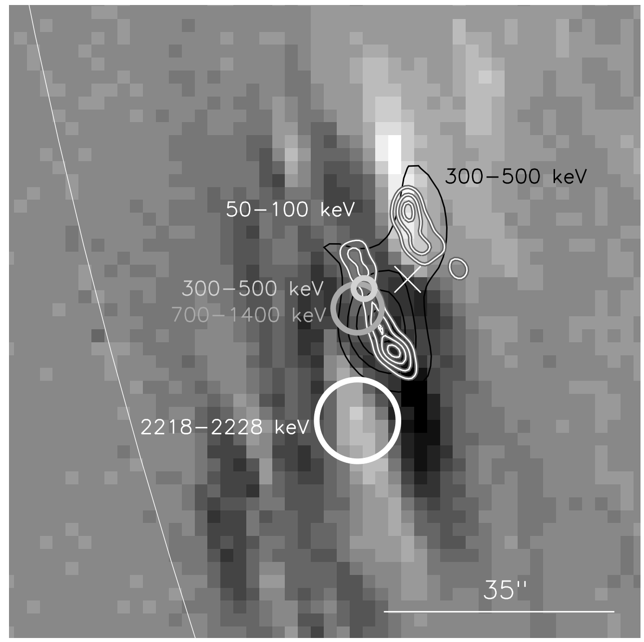

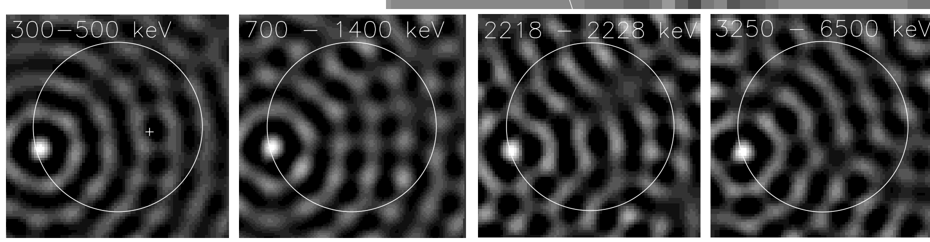

Fig. 1. (top left) Background-subtracted light curves at the 4 imaged gamma-ray energy bands. Time resolutions are 20,20, 40 and 40 s respectively. The time interval used for imaging (00:27:20 to 00:34:40) is shown at the top.

Fig. 2. (bottom) Low-resolution (183″ FWHM) 'dirty' maps at 4 gamma-ray energies. The 2218-2228 keV map was made with a total of only 130 counts. The grey scale is linear with negative sidelobes suppressed. The circle represents the solar disk with heliocentric north and west at the top and right, respectively. RHESSI was rotating about a spin axis indicated by + with a period of 4.084 s.

Fig. 3. (top right) Locations of the gamma-ray sources. The thick circles represent the 1σ errors for the centroids of the 300-500 keV (light grey), 700-1400 keV (dark grey) and 2218-2228 keV (white) sources. White contours show the high-resolution 50-100 keV map with 3″ resolution (the cross shows the centroid), the black contours show the 300-500 keV map with 7″ resolution.