RHESSI Discovery of a Coronal Non-thermal Hard X-ray Source in the 23 July 2002 Gamma-ray Line Flare

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Abstract

The Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) observations of the gamma-ray line flare of 2002 July 23, show that in the ∼8 minute rise prior to the impulsive phase, the hard X-ray emission comes from a coronal source which has no counterpart in the simultaneous TRACE EUV images or in the Hα images. The spectrum above ∼10 keV fits to a double-power-law shape with break energies at ∼20-40 keV and exponents of ∼5 below and ∼7 above, with no obvious thermal emission above ∼10 keV. This coronal non-thermal source implies that substantial energy release and electron acceleration occurs before the impulsive phase.

1. Introduction

Large solar flares are the most powerful explosions in the solar system, releasing up to $10^{32} - 10^{33}$ ergs in $10^2 - 10^3$s. The flare-accelerated 10-100 keV electrons (and sometimes >∼1 MeV/nucleon ions) appear to contain the bulk of this energy, indicating that the particle acceleration and energy release processes are intimately linked. The Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) mission is designed to investigate particle acceleration and energy release in solar flares, through high resolution imaging and spectroscopy from soft thermal X-rays (∼3 keV) to gamma-rays 17 MeV [4].

The RHESSI imager is made up of nine bi-grid rotating modulation collimators (RMCs), each consisting of a pair of widely separated grids mounted on a rotating spacecraft, to provide spatial resolution of 2.3arcsec to 3 arcmin over the full Sun (∼1 deg.) field of view. Behind each RMC is a segmented coaxial germanium detector (GeD), cooled to <∼75 K by a mechanical cryocooler to achieve spectral resolution of ∼1 keV FWHM in the hard X-ray range. As the spacecraft rotates, the RMCs convert the spatial information from the source into temporal modulation of the photon counting rates of the GeDs.

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2. Observations

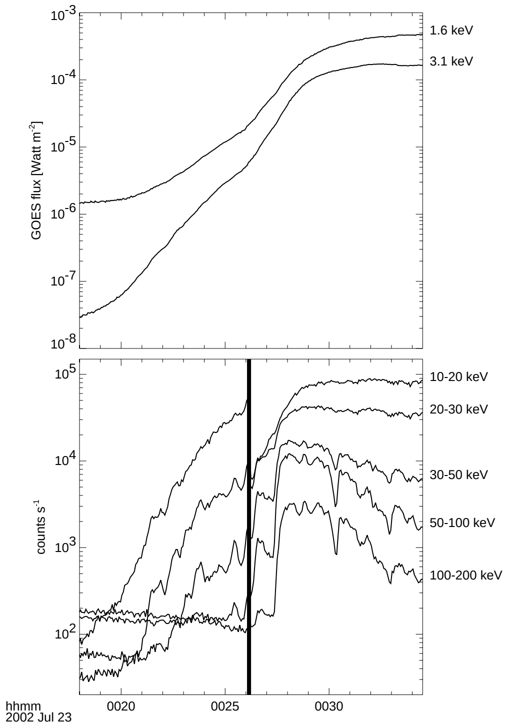
The intense 23 July 2002 gamma-ray line flare (GOES class X4.8, optical importance 2B) began ∼0018 UT in NOAA active region #0039 at S13E72 (NOAA Solar Geophysical Data). The Halpha, microwave radio, and hard X-ray emissions all peaked at ∼0028-31 UT, with GOES soft X-rays peaking later, at 0035UT. Type II, III, and IV emission were reported at meter wavelengths.

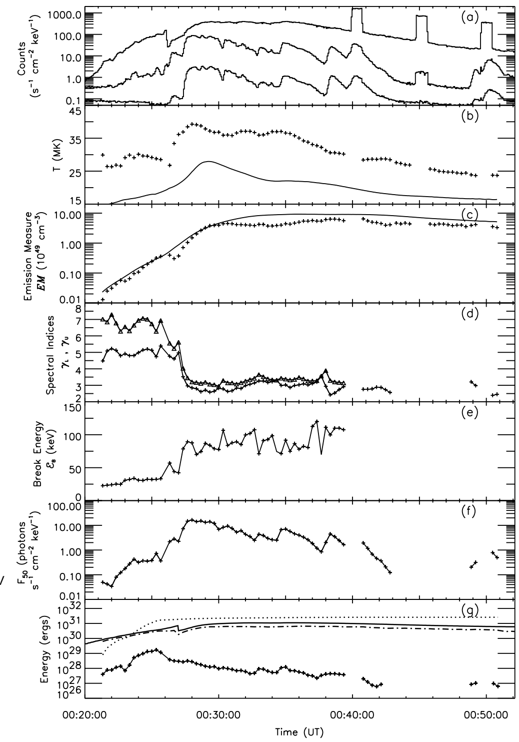
The RHESSI observations of the flare (Figure 1) show a "normal" impulsive phase (∼0027 to ∼0043 UT) dominated by footpoints with intense hard X-ray/gamma-ray continuum emission [2], and by a superhot (∼40 million degrees) thermal source in the corona (similar to the above loop-top source observed by Yohkoh HXT [5]). Gamma-ray line emission is detected in this phase. In the preceding rise starting at ∼0018 UT, however, the hard X-ray emission above 10 keV is concentrated in a source about 22″ size located approximately 20 arcsec east of the optical flare (Figure 2a). There were no counterpart observed in TRACE 195 A, SOHO MDI visible or Hα images [2], indicating that this source is actually high in the corona and seen in projection.

The hard x-ray spectra show a double power-law shape (Figure 2b), so a model [1] double power-law with exponents (γ_L and γ_H), break energy (E_B) and normalization (the flux at 50 keV, F_{50}); plus an isothermal bremstrahlung spectrum with temperature (T) and emission measure (EM), was fit to the data. Figure 3 shows the fit parameters every 20 s. During the rise phase, the spectrum above 10 keV could be fit by a double power-law alone, but also by an isothermal component plus a double power-law with a low energy cutoff as high as ∼18 keV. Assuming thick target emission in a cold ambient medium ($E_e >> kT$), the energy deposited by energetic electrons, integrating over time from the rise to ∼0026UT, is $\sim 4\times10^{32}$ ergs (for a 10 keV cutoff) down to a minimum of $\sim 2\times10^{31}$ ergs (for a cutoff of ∼18 keV).

The GOES soft X-ray time profile is similar to the time integral of the RHESSI hard X-ray (12-25 keV) flux [i.e., the "Neupert" effect], suggesting that the non-thermal electrons are depositing their energy into the soft X-ray plasma. The GOES measurements at 0026 UT give T∼19 MK and EM$\sim 1.6\times10^{49}$ cm^3. Assuming that the GOES source is co-spatial with the RHESSI source (volume$\sim(22'')^3 = \sim 4\times10^{27}$cm^3) we obtain a density of $\sim 6\times10^{10}$ cm^{-3} and an energy content in the soft X-ray plasma of only $\sim 10^{30}$ ergs, much less than the energy deposited by non-thermal electrons. Even assuming that the GOES thermal source is ten times larger only increases the thermal energy to $\sim 5\times10^{30}$ ergs. For a density of $\sim 6\times10^{10}$ cm^{-3}, the e-folding energy loss time for 20-100 keV electrons is ∼0.05-0.5 s [3], implying that the primary flare energy release is going into accelerating electrons to continuously replenish the coronal source.

TRACE detects brightenings in 195A emission along three approximately N-S aligned flare ribbons, located ∼40″, ∼10″, and ∼20″ west of the coronal hard





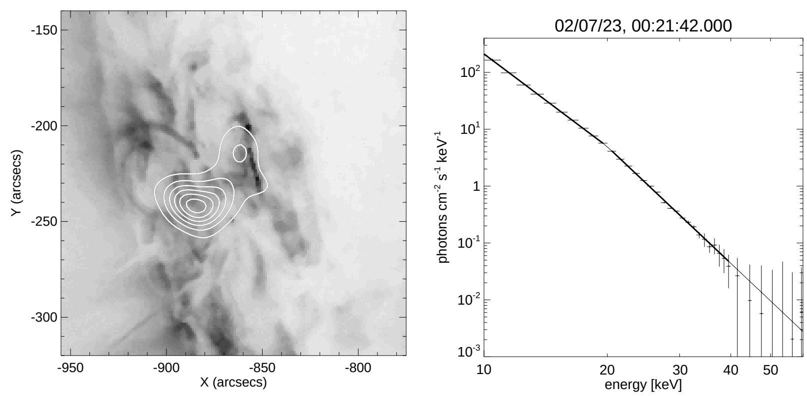


Fig. 1. (upper left) Time profiles for GOES soft X-rays (top) and RHESSI hard X-rays. The vertical line indicates where the second shutter was inserted.

Fig. 2. (a) (lower left) RHESSI 12-20 keV contours showing the coronal source (east) superimposed on a TRACE image, with weak emission (west) along a TRACE ribbon. (b) (lower right) X-ray spectrum for this coronal source.

Fig. 3. (a) RHESSI X-ray light curves: 12-40 keV (top, $\times 0.6$), 40-100 keV (middle, $\times 3$), and 100-300 keV (bottom). (b) The temperature of the isothermal component (plus signs), solid curve is derived from GOES data. (c) The isothermal emission measure (plus signs); solid curve is from GOES, scaled by a factor of 0.25. (d) Double power-law spectal indices (below break, plus signs; above break, triangles). (e) Break energy. (f) Photon flux at 50 keV. (g) Energy in GOES (solid line) and RHESSI (dot-dash line) isothermal fits (see text), compared with accumulated energy in non-thermal electrons (dotted curve) above 18 keV. Lower curve (pluses) gives energy injection rate (ergs·s^{-1}).

X-ray source, beginning at ∼0021, 0023, 0024 UT, respectively. Some >10 keV hard X-ray emission, always much weaker than the coronal source, is detected sporadically from these ribbons. Thus, most of the energetic electron energy must be deposited into the coronal source. Some energy might be transported by conduction from the soft X-ray plasma to the TRACE chromospheric ribbons.

At ∼0026:15 UT the impulsive phase begins with strong footpoint emission, accompanied by co-spatial TRACE, MDI, and H-α emission brightenings [2]. A "superhot" (∼40 MK) thermal spectrum begins to dominate below ∼30 keV. At that time the centroid of the 12-30 keV source abruptly shifts by ∼6-7 arcsec, suggesting that this superhot source is not co-spatial with the rise phase coronal non-thermal source.

The electron energy deposition rate is largest during the rise phase of the flare (Fig. 3g), substantially greater than during the impulsive phase. Although, in principle, a distribution of thermal sources with a range of temperatures might be able to reproduce the observed double power-law spectral shape, this would be highly contrived, since the spatial source appears not to change substantially with energy. Thus, we conclude that very substantial energy release in this flare goes into electron acceleration high in the corona, prior to the impulsive phase. Similar rise phase emission appears to have been detected in other flares, but in general this emission may be too weak to detect in much smaller flares.

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References

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