Gamma-ray Flare Occurrence Patterns

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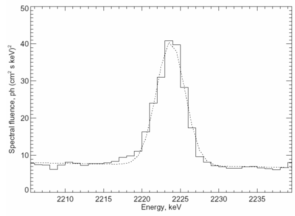
ABSTRACT

As of 2003 July 15, RHESSI (the Reuven Ramaty High-Energy Spectroscopic Imager) had obtained coverage for the entire GOES duration for 60 M- and 4 X-class flares, and for each of these we estimate the ratio of the 2.223 MeV line fluence to the GOES soft X-ray fluence. All are upper limits except for one M-class event and one X-class event. The GOES fluence is known to scale well with total flare energy. The statistics of these observations, considering as well the solar gamma-ray line observations from other spacecraft plus the statistics of proton events in the heliosphere, are not consistent with the hypothesis that ion acceleration scales proportionally with total flare energy.

Figure 1: **The deuterium γ-ray**. Observation of the γ-ray line at 2.223 MeV (deuterium formation) by RHESSI on July 23, 2002 (Lin et al., 2003). The dotted line shows a Gaussian fit to the (unresolved) line shape. The imaging observations (Hurford et al., 2003) show the γ-ray source (and hence the ion acceleration) to be physically remote from the flare arcade and footpoints in this event.



THEORY OF THE 2.223 MeV γ-RAY LINE

This line, the brightest γ-ray line useful for astronomers, forms when protons of the ambient solar material fuse with neutrons to form the stable isotope deuterium. The neutrons come as secondary products of nuclear reactions caused by high-energy primary particles, typically in the 10-100 MeV range. The neutrons must thermalize via scattering prior to the fusion reaction, which takes place at low temperatures. This means the photosphere, and the resulting thermal width of the line is too narrow even for RHESSI to resolve (Smith et al., 2002). Figure 1 shows the first example from the RHESSI observations.

RELEVANCE TO MHD AND TO MAGNETIC RECONNECTION

The solar γ-rays show us the presence of a strongly non-Maxwellian particle distribution. It has been shown by Ramaty et al. (1994) that a substantial fraction of the flare energy can reside in this inherently non-thermal distribution function of ions; Lin and Hudson (1976) had already give a similar result for the non-thermal electron distribution function. Because MHD treats the medium as a fluid, it cannot deal theoretically with these facts in a self-consistent manner.

On the other hand, the magnetic reconnection required by MHD theories of flares and CMEs certainly involves non-Maxwellian distribution functions at a microscopic level. Some theories of particle acceleration in solar flares (e.g. Litvinenko, 2003) attempt to use the reconnection process directly to explain the non-thermal particles; other classes of theory involve more indirect relationships, e.g. particle acceleration via shock waves or turbulent media.

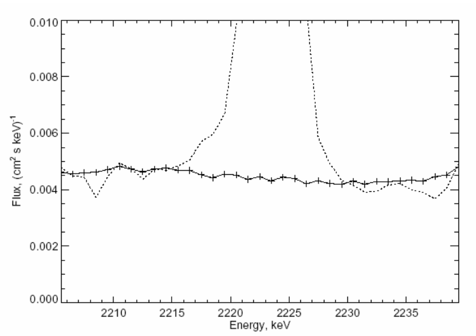
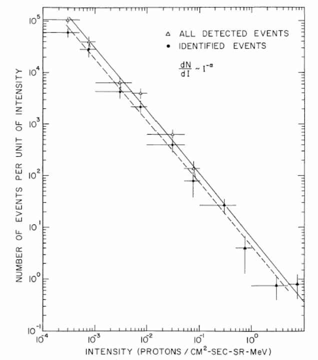


Figure 5. **Summed-epoch analysis**. To show how unusual a γ-ray flare really is, this compares the RHESSI observations of the flare of July 23, 2002, with the direct sum of the spectra of all other well-observed M and X-class flares in the sample. The summed spectrum (solid line) shows no 2.223 MeV excess emission. From this one gets the clear idea that γ-ray emission is an all-or-nothing proposition, that is that the variance of γ-ray flux to total flare energy is larger than for other flare parameters.

Figure 2. **Proton distribution**. The figure shows the "Log-N/log-S" distribution of peak proton intensities, from Van Hollebeke et al. (1974). The slope of this distribution was found to be α = 1.15+-0.15, which must be distinguished from the distribution of total flare energies (and many other parameters that reflect total energy, namely α = 1.7.



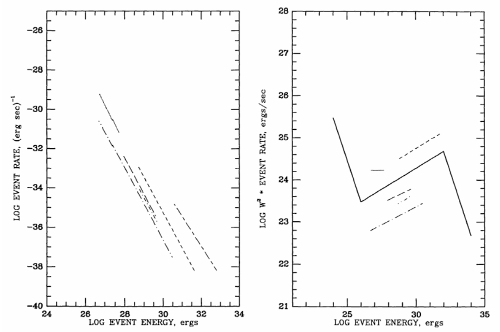


Figure 3. **Flare energy distributions**. The lines show fits to "Log-N/log-S" distributions of soft X-rays, including stellar flares (from Hudson, 1978). At the left are the raw observations, plotted directly. The plot on the right (multiplied for clarity by W^2) suggests a more complete picture: *nanoflares* on the left; a *high-energy cutoff* on the right.

TOO FEW γ-RAY EVENTS???

At the time of writing, the RHESSI data (which began in February 11, 2001) only contain two γ-ray events. Why is this? The data presented below show that it is not because of a lack of sensitivity. Instead the phenomenon of γ-ray emission is *not a universal property* of flaring.

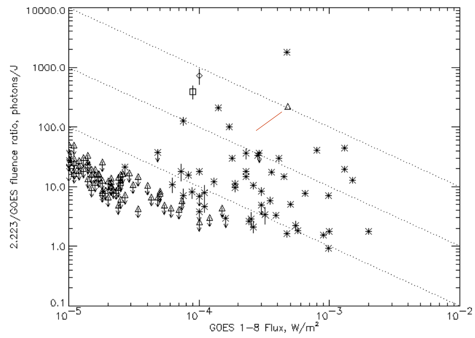


Figure 4. **Ratio of fluences**. The ratio of 2.223 MeV line fluence to total flare energy, for almost all of the events in the literature. The red arrow points to the RHESSI event of July 23, 2002. Some of the RHESSI upper limits are shown as triangles; the asterisks come from the SMM/GRS observations summarized by Vestrand et al. (1999). The sloping lines show constant ratios, approximately 0.001, 0.01, and 0.1 photon per Joule of soft X-ray energy.
The essence of the result here is that the fluence ratio has much more scatter than a typical correlation plot for other pairs of extensive parameters of flares. The γ-ray emission also appears to occur only in the most energetic events.

CONCLUSIONS: PROTON ACCELERATION IS NOT UBIQUITOUS

The RHESSI data and upper limits presented above show that the correlation between γ-ray emission and othe flare parameters, most definitively the total soft X-ray energy, has a different character from Kahler's "Big Flare Syndrome" suggestion. Most flares do not accelerate ions to 10-100 MeV in large numbers.

In the context of magnetic reconnection theories, this result suggests that the enormous electric field in the reconnection region does not systematically accelerate ions, and that the nature of this electric field may therefore be misunderstood by current theoretical work.

In the context of CMEs, we note above an odd property of the distribution function of solar protons observed in the heliosphere: α = 1.15+-0.15, as opposed to the larger values (around 1.7) associated with flare/microflare occurrence. This may represent a coincidence, but it does hint that the solar γ-ray emission results from a CME-related process such as flare ejection, rather than something intrinsic to the flare physics itself. It is unlikely that this process is the CME-drive shock wave implicated in the acceleration of interplanetary particles, because the solar γ-ray emission is known to arise from closed loop structures in a thick-target sense (e.g. Hudson et al., 1978).

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