New Measurements of the Anisotropy of Solar Flare Gamma-Rays

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Abstract

During the rise toward the 22nd Solar Maximum, the Gamma-Ray Spectrometer (GRS) aboard the Solar Maximum Mission (SMM) satellite detected gamma-rays from nearly 100 flares with energies greater than 300 keV. The position distribution for those flares shows a limb brightening over the distribution predicted for isotropic emission. The subset of events detected above 10 MeV shows an even larger fractional limb excess. In contrast, the sample of flares detected at 30 keV during the same period by the Hard X-ray Burst Spectrometer on (HXRBS) SMM shows a position distribution that is consistent with the predictions for isotropic emission. These Cycle 22 measurements therefore exhibit the same energy dependent limb brightening observed during Cycle 21. An important difference in the samples is that the Cycle 22 measurements at 10 MeV show several events that are located well on the disk. We argue that the detection of these disk events indicates that the transport of high energy particles in flare loops probably plays an important role in regulating the flare radiation pattern.

1.0 Introduction. Anisotropies in the velocity vector distribution of flare generated energetic electrons can provide important clues about the mechanism of particle acceleration and transport during solar flares. Unfortunately, at x-ray energies the combination of strong Compton backscattering from the solar atmosphere [1,2] and the relatively broad bremsstrahlung radiation pattern [3] make it difficult to detect energetic electron anisotropies. However, as the observation energy approaches 300 keV the backscatter component becomes small and the bremsstrahlung cross-section becomes more collimated. This gives one a low energy gamma-ray band in which to search for evidence of electron anisotropy that is bounded by the nuclear de-excitation component which starts to dominate the flux near 1 MeV [4,5,6]. The other effective energy band starts at ~ 8 MeV, where the nuclear de-excitation emission abruptly decreases, and continues up to energies of $\sim$50 MeV where neutral pion decay emission starts to dominate the flux [4,5]. Together, these two energy bands therefore act as windows through which one can search for the radiation directivity generated by electron anisotropies.

A statistical method that can be used to search for flare directivity is to study the distribution on the solar surface of flares detected in these windows. If the radiation is directed, an experiment with a fixed (or randomly varying) detection threshold will effectively sample the size-frequency distribution down to a level that is heliocentric angle dependent. For example, if the radiation is downwardly directed, then less luminous flares will be easier to detect at large heliocentric angles. Since the flare size distribution decreases monotonically with flare size, the fraction of events at large heliocentric angles will be larger than is predicted for isotropically emitting flares. Clearly, the size of the deviation from the position distribution for isotropic flares increases with the steepness of the size distribution and the directivity of the radiation pattern. The fraction of flares, f_L, that occur at a heliocentric angle, θ, such that $\sin\theta > 0.9$ is a practical indicator of radiation directivity which is rather insensitive to the precise nature of the event latitude distribution [7]. For isotropically emitting flares that occur primarily at solar latitudes b in the $5^o \leq |b| \leq 20^o$ band, the expected limb fraction is $f_L = 29.5\%$.

Measurements taken during the 21st solar cycle by the SMM showed a deviation from the predictions for isotropy that increased with photon energy [7,8]. At 30 keV, the sample of 424 HXRBS events with peak count rates greater than 10^3 counts s^{-1} had a limb fraction of $f_L = 25.9\%$. If the emission at that energy is isotropic then one expects a sample of that size to yield a limb fraction of $f_L = 29.5\% \pm 2.2\%$. This small limb deficit is consistent with the predictions for isotropic emission when one accounts for the non-uniformity of Hα visibility on the solar disk. In contrast, the events detected above 300 keV by the SMM GRS, which should also be influenced by the decreased Hα limb visibility, show a significant excess in the limb fraction. If the flares emit isotropically at 300 keV, one would expect 43.1 ± 5.5 of the 146 events detected to have heliocentric angles such that $\sin\theta > 0.9$. In fact, a total of 57 events were detected representing a 2.5σ excess beyond the isotropic prediction and a 3.0σ excess beyond the control sample [7]. The deviation from the limb fraction predicted for isotropic emission is even more dramatic when one examines the sample of events detected above 10 MeV [8]. Altogether, these results provided statistical evidence for energy-dependent flare radiation anisotropy during Cycle 21.

2.0 New Measurements. Cycle 22 measurements by SMM represent a new statistical sample that can be used to test the conclusions drawn from the Cycle 21 measurements. From the start of Cycle 22 (September 1986) until satellite re-entry in December 1989, a total of 98 flares were detected at energies above 300 keV by the SMM GRS. Most of those events were detected in 1988 and 1989 during the rise toward solar maximum. Hα positions were identified for 93 of the flares, 35 of which had heliocentric angles such that $\sin\theta > 0.9$. This limb fraction of $f_L = 37.6\%$ shows an excess that is very similar to the fractional excess measured during Cycle 21. However, due to the smaller sample size, the Cycle 22 excess has a statistical significance that is reduced to $\sim 2\sigma$. Joining the two samples together, we find a limb fraction that exceeds the prediction for isotropic emission by 3.1σ.

As a control sample, we once again examined the set of hard x-ray flares detected at energies near 30 keV by HXRBS on SMM since one expects the emission at that low energy to be essentially isotropic. A total of 198 flares with peak counting rates greater than 10^3 counts sec^{-1} were detected by HXRBS during Cycle 22. Associated Hα positions were identified for 177 flares and yielded a total of 52 flares at heliocentric angles with $\sin\theta > 0.9$. As expected, this limb fraction of $f_L = 29.4\%$ is consistent with the isotropic fraction predicted for the control sample.

If the limb excess observed near 300 keV is generated by bremsstrahlung from anisotropic electron distributions, then the cross-sections predict that deviations from the isotropic value should be even larger in the 8 MeV to 50 MeV band [e.g. 3,9]. In fact, the Cycle 21 measurements showed a remarkable limb enhancement for flares detected above 10 MeV. Of the fourteen flares detected, twelve occurred at heliocentric angles with $\sin\theta > 0.9$ [10]. This corresponds to a limb fraction of 85.7% and a limb excess with a significance of $\sim 4.6\sigma$.

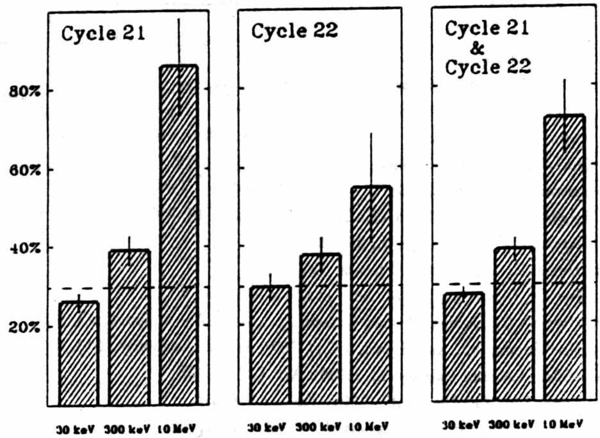
The new measurements provide another opportunity to test for increased anisotropy at high energies. Table 1 lists the flares detected at energies above 10 MeV with the exclusion of the very interesting 29 September 1989 event which seems to be associated with a flare that occurred beyond the solar limb. We have identified six of the eleven flares with Hα limb flares giving us a limb fraction of $f_L = 54.5\%$. The Cycle 22 measurements therefore show a limb excess, but with a statistical significance that has decreased to $\sim 2\sigma$. Combination of the measurements from the two cycles yields a limb fraction of $f_L = 72.0\%$ and a limb excess with $\sim 4.7\sigma$ significance.

Flare	Time (UT)	GOES/Hα	Location	Θ
16 Dec 1988	08:30-9:30	X4.7/1B	N27E33	43°
6 Mar 1989	13:56-15:43	X15/3B	N33E71	76°
7 Mar 1989	05:57-05:58	M2.9/1F	N30E69	76°
7 Mar 1989	13:19-13:21	M4.1/1B	N30E65	73°
10 Mar 1989	19:03-19:49	X4.5/3B	N32E22	44°
16 Mar 1989	15:23-15:32	X3.6/2B	N36W47	62°
17 Mar 1989	17:31-17:44	X6.5/2B	N33W61	70°
14 Jun 1989	13:52-13:54	M2.7/1N	S14W78	79°
16 Aug 1989	01:23-01:40	X20/2N	S18W84	87°
9 Sep 1989	09:09-09:15	X1.4/2B	N17E30	30°
19 Nov 1989	12:57-13:53	X13/4B	S25E09	32°

Table 1. A listing of flares detected at energies >10 MeV by SMM GRS during the 22nd Solar Cycle.

3. Discussion and Summary. The Cycle 22 measurements clearly follow the energy dependent pattern found in the Cycle 21 measurements (see Figure 1). This increase of the limb fraction with energy is consistent with the predictions for bremsstrahlung from energetic electron distributions which, on average, have an intensity in the upward hemisphere that increases as a function of angle from the outward normal.

Figure 1. The observed limb fraction f_L as a function of energy for each of the Cycle 21 and Cycle 22 samples as well as the combined samples.



An interesting difference between the two >10 MeV samples is the presence of a number of events at smaller heliocentric angles in the Cycle 22 observations (see figure 2). At those energies, the bremsstrahlung cross-sections are approaching their ultra-relativistic limit where the radiation from an electron with Lorentz factor γ is strongly beamed forward within a cone of width $\sim \gamma^{-1}$. Therefore, the >10 MeV radiation from those flares at positions with $\sin\theta \ll 0.9$ must be associated with the decay of pions from energetic ion interactions or bremsstrahlung from energetic electrons that are moving away from the Sun. The pion decay spectra have a characteristic shape that shows a very flat bremsstrahlung component ($\propto E^{-1}$), generated by electrons and positrons from charged pion decay, that merges with the well-known "hump" centered near 68 MeV generated by the decay of neutral pions [11,12]. Two of the disk events (9 Sep 1989 and 10 Mar 1989) have spectra that are too steep to have their >10 MeV integral fluxes dominated by pion decay emission. Those events therefore seem to require electron bremsstrahlung from upwardly moving electrons. Rapid variability in the 9 September 1989 flare also allows us to place a limit on the density in the interaction region of $\sim 8 \times 10^{12}\mathrm{cm}^{-3}$. If we assume that the events are not part of a small group of flares that emit isotropically, then the simplest explanation for their detection is that the upwardly moving electrons have been reflected at mirror points below the transition region. These observations therefore support models [e.g. 13,14,15] that include mirroring and trapping in loops within their theoretical framework.

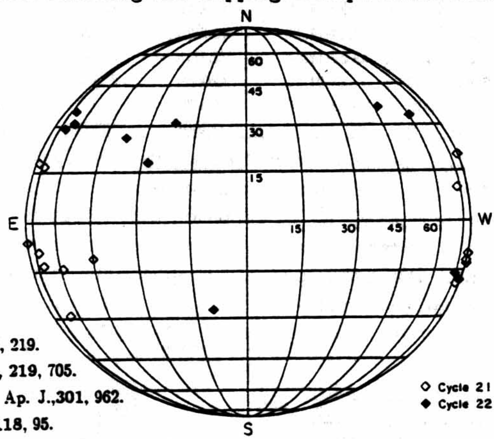


Figure 2. The positions of flares detected at energies >10 MeV by SMM GRS during the entire mission.

References

1. Henoux, J.C., (1975), Solar Physics, 42, 219.
2. Bai, T. and Ramaty, R., (1978), Ap. J., 219, 705.
3. Dermer, C.D. and Ramaty, R. , (1986), Ap. J.,301, 962.
4. Vestrand, W.T., (1988), Solar Physics,118, 95.
5. Ramaty, R. and Murphy, R.J., (1987), Space Sci. Rev., 45, 213.
6. Chupp, E.L., (1990), Science, 250, 229.
7. Vestrand, W.T. et al., (1987), Ap. J., 322, 1010.
8. Rieger E. et al., (1983), in 18th ICRC (Bangalore), 10, 338.
9. Petrosian, V., (1985), Ap. J., 209, 987.
10. Rieger, E., (1989), Solar Physics, 121, 323.
11. Forrest, D.J. et al., (1986), Adv. in Space Research, 6, 115.
12. Murphy, R., Dermer, C., and Ramaty, R., (1987), Ap. J. Suppl., 63, 721.
13. MacKinnon, A.L. and Brown, J.C., (1989), Astron. Astrophys., 215, 371.
14. Miller, J.A. and Ramaty, R., (1989), Ap. J., 344, 973.
15. Ryan, J.M. and Lee, M.A., (1991), Ap. J., 368, 316.

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