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A SEARCH FOR ENERGETIC ION DIRECTIVITY IN LARGE SOLAR FLARES

FINAL TECHNICAL REPORT
SMM GUEST INVESTIGATOR PROGRAM
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1.0 Introduction

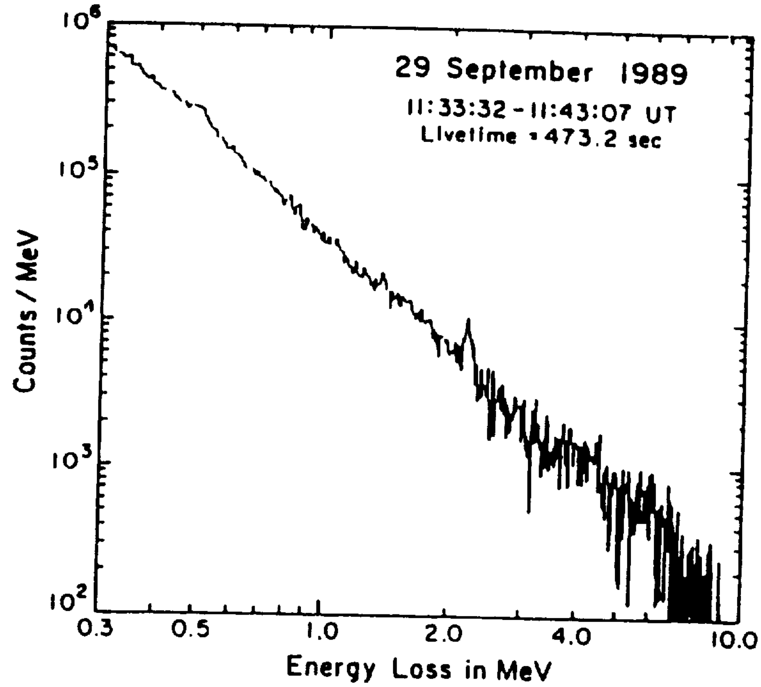
One of the key observational questions for solar flare physics is: What is the number, the energy spectrum, and the angular distribution of flare accelerated ions? The standard method for deriving ion spectral shape employs the ratio of fluences observed on the 4-7 MeV band to the narrow neutron capture line at 2.223 MeV. The 4-7 MeV band is dominated by the principal nuclear de-excitation lines from ^{12}C and ^{16}O which are generated in the low chromosphere by the direct excitation or spallation of nuclei by energetic ions. In contrast, the narrow 2.223 MeV line is produced by the capture of thermal neutrons on protons in the photosphere. These capture neutrons are generated by energetic ion interactions and thermalized by scattering in the solar atmosphere. In a series of papers, Ramaty, Lingenfelter, and their collaborators have calculated the expected ratio of fluence in the 4-7 MeV band to the 2.223 MeV line for a wide range of energetic ion spectral shapes (see, e.g. Hua and Lingenfelter 1987). Another technique for deriving ion spectral shapes and angular distributions uses the relative strength of the Compton tail associated with the 2.223 MeV neutron capture line (Vestrand 1988, 1990). This technique can indepently constrain both the angular and the energy distribution of the energetic parent ions. Combination of this tail/line strength diagnostic with the line/(4-7) MeV fluence ratio can allow one to constrain both properties of the energetic ion distributions.

The primary objective of our SMM guest investigator program was to study measurements of neutron capture line emission and prompt nuclear de-excitation for large flares detected by the SMM/GRS and to use these established line diagnostics to study the properties of flare accelerated ions.

2.0 Scientific Results.

This study of SMM/GRS flares led to the discovery of a remarkable component of neutron capture line emission in the giant 1989 September 29 flare. The flare was first detected at 10:47 UT by soft x-ray detectors on a GOES satellite which subsequently recorded a peak (X9.8) at 11:33 UT. Intense high-energy emission was measured by the Gamma-Ray Spectrometer (GRS) aboard the Solar Maximum Mission (SMM) satellite when the instrument was switched back on at 11:33 UT after a spacecraft South Atlantic Anomaly passage. The GRS flare measurements show a complex spectrum with an electron bremsstrahlung continuum, a positron annihilation line, prompt nuclear emission, high-energy emission extending to energies >50 MeV, and a strong neutron capture line at 2.22 MeV (see figure 1). The Hα observations for this period do not show any flare on the visible solar hemisphere that is likely to be associated with such a large ground level event. However, solar flare patrol observations (Swinson and Shea 1990) showed a "behind the limb" flare-like brightening indicative of major activity in NOAA region 5698 that was located beyond the southwestern limb. To estimate the flare position we studied the positions of AR5698 flares measured by three or more observatories as recorded in the Hα flare list of the NOAA Solar Geophysical Data comprehensive reports. Extrapolation of the linear least squares fit to that data yields the position for a AR5698 flare at 11:33 UT on 29 September 1989 of W97.9° $\pm$ 5.3° and S25.6° $\pm$ 2.0°. This places the nominal flare position well beyond the limb at a heliocentric angle of $\Theta = 100.0° \pm 4.7°$. Neutron capture line emission should not be visible from a flare that is this far beyond the solar limb.

Fig. 1. A background-subtracted energy-loss spectrum from *SMM/GRS* for the flare of 1989 September 29.



The neutron capture line flux and the prompt 4-7 MeV de-excitation flux were the important quantities for our study. The strength of the neutron capture line in each background subtracted spectrum was determined by subtracting the average of counts in adjacent regions below and above the photopeak region from counts in the photopeak region. The photon power-laws that best fit the bremsstrahlung component below 800 keV were extrapolated to derive the expected number of bremsstrahlung counts in the 4-7 MeV band. The number of the prompt nuclear counts was then determined by subtracting this bremsstrahlung component from the total number of 4-7 MeV flare counts observed for each record. The time dependences of the neutron capture line flux and the 4-7 MeV nuclear flux were then obtained by dividing the number of flare counts per second by the respective instrumental effective areas.

Since the SMM/GRS was switched off during the intense early phase of the flare due to a South Atlantic Anomaly passage, derivation of the diagnostic fluence ratio $\Re = \phi(2.22MeV)/\phi_{nuc}(4-7MeV)$ requires modeling of the flux time histories. This followed because the delayed nature of neutron capture line emission means that some of the neutrons that generate the observed capture line emission were produced when the GRS was not capable of observing the associated prompt emission. Straightforward derivation of the fluences from such a temporally truncated spectrum would therefore overestimate $\Re$. To correct for this we made the reasonable assumption that the exponential decay constant for neutron capture line emission, τ, does not vary during the event, so that we could derive $\Re$ by jointly studying the time dependences of the capture line flux, $F_{2.22}(t)$, and the prompt nuclear flux in the 4-7 MeV band, $F_{4-7}(t)$. In that case, one can phenomenologically model the time dependence of the neutron capture line flux with the relation

$$F_{2.22}(t) = A \exp(-\frac{(t - t_o)}{\tau}) + \int_{t_o}^{t} \frac{\Re}{\tau} F_{4-7}(T) \exp(-\frac{(t - T)}{\tau}) dT \tag{1}$$

The first term describes the emission from neutrons generated before the gamma-ray observations began at t_o and has an amplitude constant A that is fixed by the relative strength of the emission before t_o. The second term relates the measured time dependence of prompt nuclear emission to the predicted capture line flux. The parameters were then determined by systematically varying them until the model for the capture line flux which provides the best χ^2 fit to the observed time dependence was found. To improve the statistical precision of our analysis, the observed 2.22 MeV line fluxes were accumulated over 163.84 second intervals and the model line fluxes were summed to the same time resolution. Studies of other flares using the same phenomenological model find that those data are well fit by a decay constant of τ ~100 seconds (Prince et al. 1983). When we adopted the value τ =100 seconds for the 1989 September 29 flare, we found the 70% confidence interval for the fluence ratio was given by $\Re = 0.19 \pm 0.09$. Smaller (larger) values of τ yield slightly increased (decreased) values of $\Re$. For example, τ =10 seconds requires $\Re \simeq 0.3$ and τ =200 seconds requires $\Re \simeq 0.1$.

While the fluence ratio $\Re \simeq 0.2$ derived from our temporal study of 29 September 1989 is less than the value one would naively derive directly from the integrated spectrum, it is still much higher that one would expect for an event at such a large heliocentric angle. Figure 2 shows the fluence ratio as a function of heliocentric angle predicted by Hua and Lingenfelter (1987) for "point-like" flares with a range of ion spectral shapes. The measurements for most flares are bracketed fairly well by the predictions for Bessel function proton spectra with αT =0.015 and 0.04. Notice, however, that the ratio we derived for 1989 September 29 is much higher than predicted.

A "point-like" neutron capture patch located in the photosphere cannot explain the strong neutron capture line emission detected from the 29 September 1989 flare. The problem is that the column depth along the line-of-sight to this flare that occurred nearly 10° beyond the western limb is so large that gamma-rays generated in either the chromosphere or the photosphere could not reach the earth. A possible explanation is that the 2.2 MeV line is generated by low energy (<2 keV) neutrons from the over-the-limb flare which are trapped in the gravitational well of the Sun. Gravitationally trapped neutrons can follow ballistic trajectories that return them far from the flare site producing a diffuse patch of neutron capture emission (Kanbach et al. 1975; Hua and Lingenfelter 1987). However, since typically only $\sim 10^{-3}$ of the total neutron capture emission is generated by gravitationally trapped neutrons, this mechanism is rather inefficient. Nor does it explain the bremsstrahlung continuum and the prompt nuclear emission that were observed during the flare. An additional coronal component might explain that emission, but then the observed value of the fluence ratio $\Re$, which is comparable to that observed for unocculted flares, would be a coincidence.

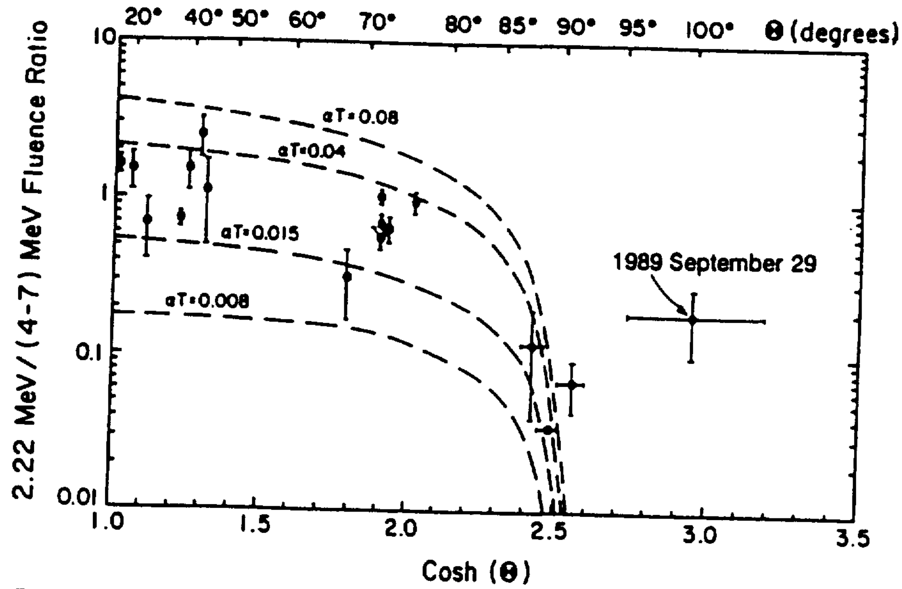


Fig. 3. The fluence ratios measured for a number of flares plotted versus the heliocentric angle of the flare. The dashed curves show the predictions for Bessel function ion energy spectra with a horizontal fan beam angular distribution[1].

We found that a more straightforward explanation for the 29 September 1989 gamma-ray measurements is that, in addition to the relatively compact region at the flare site normally measured in flares, there was an interaction region that was quite extended in heliolongitude. This could take the form of a large diffuse interaction region or a giant magnetic loop that reaches around the limb to place a footpoint in the visible hemisphere of the sun.

A number of other interesting phenomena associated with this flare led us to favor the idea that line emission is generated in a diffuse interaction region that is powered by particles accelerated at a shock driven by a Coronal Mass Ejection (CME). Several interplanetary spacecraft measured SEPs with energies >30 MeV (Cliver, Kahler, and Vestrand 1993). Images taken by the Coronagraph/Polarimeter on SMM showed evidence for a CME with an inferred velocity which is consistent with the formation of a coronal/interplanetary shock (Burkepile and St. Cyr 1990). A metric type II radio burst that is indicative of a coronal shock was also detected. The relative timing of the CME, metric radio bursts, and the inferred injection profile for the 20 GeV protons responsible for the ground level event suggest that a CME driven shock was the source of the SEP event. The "back-diffusion" into the solar atmosphere of some SEP particles on open field lines makes an attractive explanation of our results.

3.0 Publications Describing Grant Supported Research.

1. "Evidence for a Spatially Extended Component of Gamma Rays from Solar Flares", W.T. Vestrand and D.J. Forrest, 1993, Ap. J. Letters, **409**, L69.
2. "On the Origin of Gamma-Ray Emission From the Behind-the-Limb Flare on 29 September 1989", E.W. Cliver, S.W. Kahler, and W.T. Vestrand, 1993, Proc. of 23rd ICRC, **3**, p. 91.
3. "Gamma Rays from an 'Over-the-Limb' Flare", W.T. Vestrand and D.J. Forrest, 1994, in High-Energy Solar Phenomena—A New Era of Spacecraft Measurements, eds. J.M. Ryan and W.T. Vestrand (New York:AIP), p. 143.

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