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Solar Flare Nuclear Gamma Rays and Energetic Particles in Space, 1980-1989

E.W. Cliver[a], W.T. Vestrand[b] and D.V. Reames[c]

(a) Air Force Research Laboratory, AFRL/VSBXS, 29 Randolph Rd, Hanscom AFB, MA 01731-3010 USA
(b) Los Alamos National Laboratory, NIS-2, MS D436, Los Alamos, NM 87545 USA
(c) NASA Goddard Space Flight Center, Code 661, Greenbelt, MD 20771 USA
Presenter: E.W. Cliver (edward.cliver@hanscom.af.mil), usa-cliver-E-abs1-sh11-poster

From February 1980 - November 1989, 52 solar gamma-ray-line (GRL; 4-8 MeV) flares ($\geq 2\sigma$) were recorded by the Gamma Ray Spectrometer (GRS) on the Solar Maximum Mission. During the same interval, 121 $\sim$10 MeV solar energetic proton (SEP) events with front side flare associations were observed. In general, when a GRL flare occurred during a time that the SEP background was not already elevated due to an earlier proton event, a new SEP event was observed near Earth (17 of 18 cases for western hemisphere flares; 29/33 overall). GRS observed the associated flare for 50 of the 121 SEP events. Of these 50 flares, 17 had detectable gamma-ray lines. Gamma-ray-fluences and SEP peak fluxes are poorly correlated; the 24 SEP events associated with western hemisphere flares for which only an upper limit flare GRL fluence ($\leq 1\ \gamma\ \mathrm{cm}^{-2}$) could be determined had peak $\sim$10 MeV fluxes that spanned more than three orders of magnitude. The ratio of interacting (GRL producing) to interplanetary protons (SEPs) is inversely proportional to flare time scale. In general, GRL flares are more impulsive than SEP flares; the median e-folding decay times of the associated 1-8 Å bursts are 14 minutes and 24 minutes, respectively. These results substantiate those in Cliver et al. (ApJ 343, 953, 1989), that were based in large part on GRL fluences or upper limits inferred from proxy (microwave, X-ray) data.

1. Introduction

Prompt gamma-ray-line emission is formed during flares when accelerated protons bombard and excite C, N, and O nuclei in the solar atmosphere. These excited nuclei decay to their ground states by emitting 4-8 MeV gamma rays. The 4-8 MeV de-excitation lines provide direct information on the protons accelerated during flares for comparative analysis with the solar energetic protons subsequently observed in space. We have previously [1] reported a comparison of solar flare nuclear GRL fluences and the peak fluxes of associated $\sim$10 MeV proton events at 1 AU for the period from February 1980 - January 1985, corresponding to the first five years of the Solar Maximum Mission (SMM). We found that these two parameters were poorly correlated, primarily because of a subset of large SEP events for which the associated flares lacked detectable GRL emission. In addition, we noted that the ratio of interacting (gamma-ray-producing) to interplanetary $\sim$10 MeV protons varied with flare time scale, with the ratio decreasing with flare duration. Our earlier study was based in part on proxy gamma-ray data that we used to compensate for the $\sim$50% effective duty cycle of the Gamma Ray Spectrometer [GRS; 2] on SMM. In a scatter plot of SEP event peak flux vs. GRL fluence of the associated flare in [1], 31 of 52 GRL fluences (or upper limits) were based on microwave or hard X-ray data. Here we extend our analysis through the end of the SMM lifetime in November 1989. This extended time interval includes the rise to maximum of cycle 22 and enables us to test our previous results without the use of proxy data.

2. Analysis

Proton data were obtained by the Goddard Space Flight Center experiments on ISEE-3 and IMP 8. Gamma ray data were taken from the SMM atlas [3]. During the $\sim$10-yr SMM lifetime, GRS observed 52 ($\geq 2\sigma$ above

4-8 MeV background fluctuations) GRL flares. During the same interval 121 9-12 MeV SEP events (with peak fluxes $\geq 10^{-2}$ pr cm^{-2} s^{-1} sr^{-1} MeV^{-1}) that could be reliably linked to solar flares were observed. In general when a GRL flare occurs, it is followed by a SEP event at 1 AU. Of the 33 cases when a GRL flare occurred when the SEP background was not high due to a previous event (that might mask a fresh SEP injection), in 29 an associated ~10 MeV SEP event was observed (17 of 18 cases for western hemisphere flares). GRS observed the associated flare for 50 of the 121 SEP events. Of these 50 flares, 17 had detectable gamma-ray lines. Figure 1 contains a scatter plot of peak fluxes of all western hemisphere SEP events vs. 4-8 MeV GRL fluences, or upper limit values, for their associated disk flares. In all there are 35 such SEP events, of which only 11 were associated with flares with detectable GRL emission. [In some cases the GRL observations were truncated at the beginning or the end of the event because of SMM eclipse as it orbited the Earth; we included these events if it appeared from the microwave burst timing that the bulk of the line emission was recorded.] In the figure it can be seen that ~10 MeV SEP peak flux and the flare 4-8 MeV GRL fluence are not well correlated; in particular, the SEP peak flux spans more than three orders of magnitude for the 24 source flares for which no GRL emission was recorded above the somewhat arbitrary background upper limit fluence of 1 γ cm^{-2} (see [4]). Since smaller SEP events tend to be associated with shorter flares, integrating background for all upper limit cases will cause data points associated with small SEP events to shift to the left relative to those linked to larger SEP events. We note, however, that 12 of the 24 SEP events with upper limit GRL fluences,

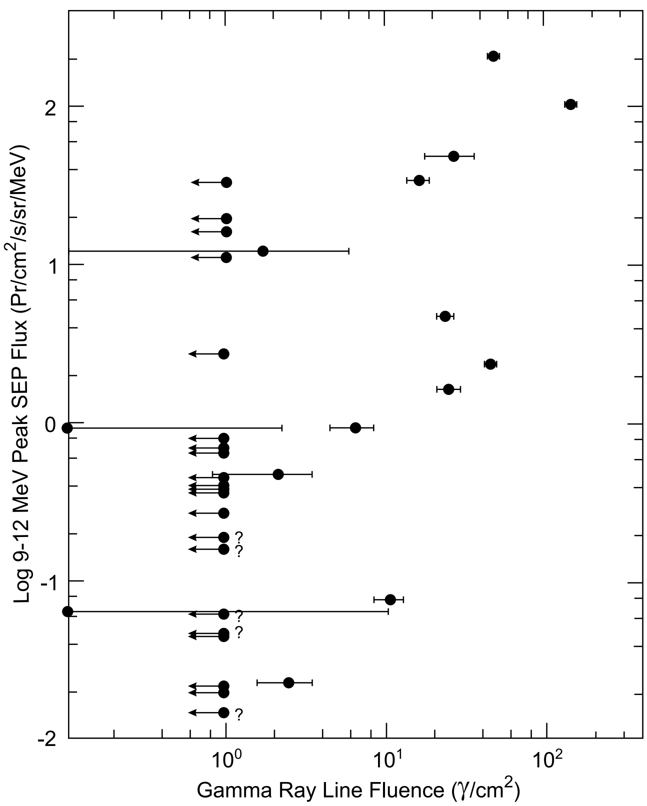

Figure 1. Scatter plot of peak interplanetary proton flux near 10 MeV vs. the associated flare 4-8 MeV GRL fluence (or an upper limit) for well-connected (W00-W90) SEP flares occurring from February 1980 to November 1989.

including the two largest SEP events of this group (20 July 1981 and 9 December 1981), lacked detectable 300 keV emission, the nominal lower energy for gamma ray continuum. If we only consider the 10 SEP events in Figure 1 that were associated with flares with $\geq 2\sigma$ GRL emission, we obtain a correlation with $r^2 = 0.6$.

As noted in [1] and evidenced in Figure 1, large SEP events, having peak $\sim$10 MeV fluxes $>$ 10 pr cm^{-2} s^{-1} sr^{-1} MeV^{-1}, can originate in solar eruptions unaccompanied by detectable GRL emission. An example of an event of this type is shown in Figure 2. On 23 March 1989, a moderate $>$ 300 keV gamma ray continuum burst without a 4-8 MeV counterpart was followed by a SEP event at 1 AU that extended to $>$ 100 MeV.

In our previous study [1], we found that the ratio of the number of interacting protons to the number of interplanetary protons was inversely proportional to the flare time scale (τ) as given by the e-folding time of the flare 1-8 Å burst, measured from the peak. This analysis is repeated in Figure 3 for all events in Figure 1. For the expanded data set, and without the use of proxy data, our earlier finding is confirmed. In general, SEP-associated flares have longer time scales (median τ = 24 minutes) than GRL-flares (τ = 14 minutes).

3. Discussion: The current flares vs. shocks debate

How to interpret these results? The lack of correlation between SEP peak flux and GRL line fluence is consistent with the current view [5, 6] that the bulk of the $\sim$10 MeV protons observed in space is not accelerated in a flare but rather at a coronal/interplanetary shock. While big SEP events have been observed without detectable GRL emission [Figure 2], such SEP events are invariably accompanied by coronal mass ejections [7] and strong shocks [8]. The fact that nearly 90% (29/33) of GRL flares (from anywhere on the disk) were followed by protons at Earth admits the possibility that for some large SEP events, solar and interplanetary protons originate in a common acceleration process in a flare. Alternatively, this association may reflect the

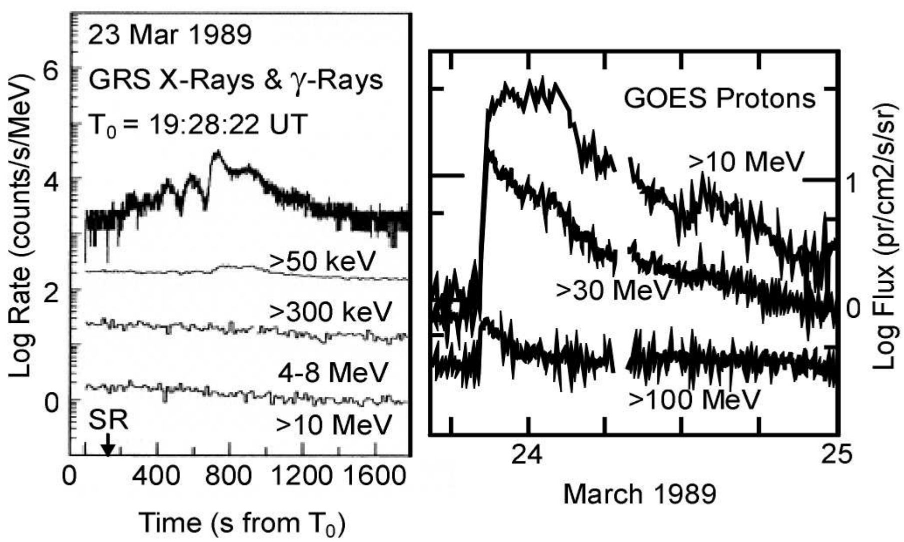

Figure 2. GRS X-ray/γ-ray data and GOES proton data for the 23 March 1989 SEP event.

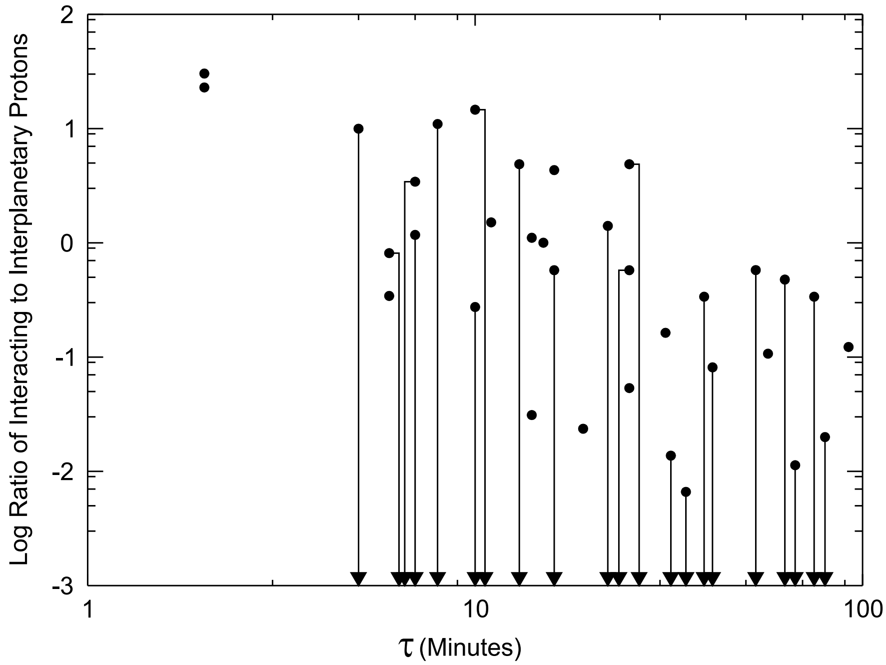

Figure 3. Ratio of solar to interplanetary protons vs. flare time scale.

Big Flare Syndrome (median GRL flare 1-8 Å X-ray class = X2). The case for a direct flare contribution to large SEP events will require comparisons of GRL and SEP spectra, composition, and timing, as well as SEP charge state measurements. The inverse correlation in Figure 3 might be due to a narrower SEP "cone of emission" for more impulsive flares. However, flare time scale has also been related to e/p ratio [10, 11, 12], Fe/O ratio [13], and electron spectra [14], and its role in SEP physics remains unclear.

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