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SOLAR FLARE NUCLEAR GAMMA-RAYS AND INTERPLANETARY PROTON EVENTS

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Abstract

We compared flare γ-ray line (GRL) events and solar energetic proton (SEP) events for the period from February 1980 - January 1985 and substantiated earlier results showing a lack of correlation between γ-ray-producing ions and interplanetary protons. This poor correlation results primarily from several large SEP events that originated in flares without detectable γ-ray emission. The converse case of GRL events unassociated with SEP events is rare. We present evidence which suggests that the ratio of trapped to escaping protons in GRL/SEP flares depends on the spatial scale size of the flare (cf., Cane et al., 1986; Bai, 1986). We affirm the result of Bai and Dennis (1985) that GRL flares are generally accompanied (75%) by metric Type II bursts.

1. Introduction. One of the more surprising results from the most recent solar maximum was the poor correlation observed between flare nuclear γ-ray fluences and the sizes of interplanetary proton events (Chambon et al., 1981; von Rosenvinge et al., 1981; Pesses et al., 1981; Cliver et al., 1983a; Yoshimori and Watanabe, 1985). This result is based on a relatively small number of events observed mainly during 1980-1981. The largest sample considered in any study to date was 16 events (Cliver et al., 1983a). In the present paper we compare γ-ray line (GRL) and solar energetic proton (SEP) events observed from February 1980 - January 1985 in order to substantiate this lack of correlation.

We also look for evidence that the time scale of a flare is an important parameter that might "order" the γ-ray/proton data as was recently indicated by Cane et al. (1986) and Bai (1986) (cf., Kocharov et al., 1983). Since SEPs are generally thought to be accelerated at coronal shocks, we determine the fraction of the γ-ray events during this period that were associated with metric Type II bursts to see if Type II shocks or their progenitors might be important for γ-ray-producing ions as well. Bai and Dennis (1985) and Bai (1986) have reported that Type II bursts were a characteristic feature of the GRL flares observed in 1980-1981.

2. Data Analysis.

2.1 Peak ~ 10 MeV Proton Fluxes vs. 4-8 MeV Gamma-Ray Line Fluences. The proton data are from the NASA GSFC experiments on IMP-8 and ISEE-3. For three events we used the Helios particle data published by McDonald and Van Hollebeke (1985) and McDonald et al. (1985). We identified a total of 66 prompt proton events with J(>20 MeV) > 10^{-3} pr cm^{-2} s^{-1} sr^{-1} MeV^{-1} for which we were able to make confident visible disk flare associations. The 4-8 MeV GRL fluences (or upper limits) were either measured directly by the UNH/NRL/MPI Gamma Ray Spectrometer on SMM or were inferred from hard X-ray observations from the U Cal/

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Berkeley experiment on ISEE-3 by making use of the relationship between the 4-8 MeV fluence and the >300 keV electron bremsstrahlung continuum flux (Forrest, 1983). Of the 66 proton events, 50 originated in western hemisphere flares. For 45 of these well-connected flares, γ-ray (hard X-ray) observations were available from either SMM or ISEE. These 45 events are plotted in Fig. 1 along with three well-connected GRL events that were associated with small ($J(>20) < 10^{-3}$) SEP events or lacked SEP association. As we had shown previously with fewer events, the γ-ray-producing and interplanetary ions do not appear to be closely related. We note that the largest GRL events (>10 γ cm^{-2}) are generally accompanied by significant SEP production. Conversely, there are seven large (> 4 x 10^{-1}) SEP events that lacked detectable > 300 keV emission. These seven events (23 Nov 80, 30 Mar 81, 10 May 81, 20 Jul 81, 05 Dec 81, 09 Dec 81, 19 Dec 82) are characterized by gradual 1-8 Å decay rates, weak (S_p(9 GHz) $\lesssim$ 100 sfu) to moderate (S_p(9 GHz) ~ 500 sfu) impulsive phases, and associations with metric and/or kilometric Type II bursts (6/7) (Kahler et al., 1978; Cliver et al., 1983b; Cane and Stone, 1984).

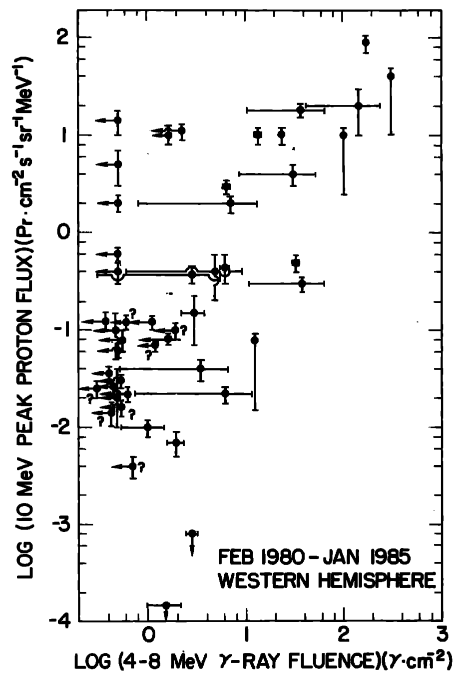

Fig. 1. Peak ~ 10 MeV Proton Flux vs. 4-8 MeV GRL fluence

2.2 The Ratio of γ-Ray-Producing Ions to Interplanetary Protons vs. the Soft X-ray Decay Rate. For a sample of 10 GRL/SEP flares, not all of which were well-connected, Bai (1986) showed that the ratio of the number of γ-ray producing protons to the number of interplanetary protons varies greatly from event to event but that, on average, impulsive flares have a higher ratio than gradual flares. Since Pallavicini et al. (1977) have associated impulsive soft X-ray flares with low-lying (< 10^4 km) sources and gradual events with extended (~ 5 x 10^4 km) structures, Bai's result suggests that the probability of proton escape is dependent on the scale size (loop height) of the flaring region (cf., Cane et al., 1986). To test this result, we have plotted in Fig. 2 the ratio R (= (4-8 MeV GRL fluence / 9-23 MeV peak proton flux)) vs. τ, the e-folding time of the flare associated soft X-ray burst for the events in Fig. 1. We measured τ from the peak of the GOES 1-8 Å profile. For a given flare, R is proportional to the ratio, near 10 MeV, of the number of γ-ray-producing (trapped) ions to the number of interplanetary (escaping) protons. Despite the uncertainties, the data in Fig.

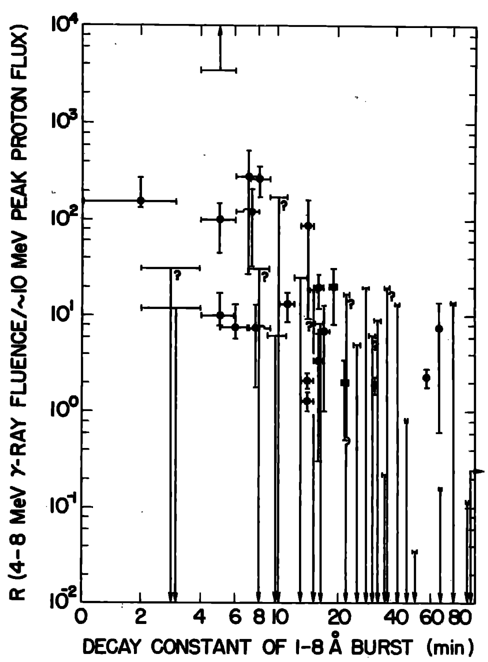

Fig. 2. Ratio of GRL to SEP Protons vs. Soft X-ray Decay Rate.

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2 display an apparent trend. If we take the limiting values of R to be the actual values for the events with upper (or lower) limits, then the median value of R for the 14 most impulsive events ($\tau < 10$) is 66, compared to R = 11 for the 16 intermediate ($10 < \tau < 30$) events and R = 2 for the 13 most gradual ($\tau > 30$) events. We also determined the R values of the 16 eastern hemisphere SEP events in our sample and found them to be, for the most part, consistent with the above trend, after taking the propagation effect into account. There are three eastern hemisphere events, however, with τ values ~ 20 minutes that have lower than expected R values. The data for these events are as follows: 30 Jan 1982, E13°, $R = 2.4 \pm 2.1 \times 10^{-2}$; 04 Sep 1982, E38°, $R < 1.7 \times 10^{-1}$; 25 Dec 1982, E45°, $R < 8.3 \times 10^{-1}$. Presumably R would be even smaller if these events had been well-connected. The 30 Jan and 04 Sep flares were associated with interplanetary Type II bursts (Cane, 1985) and the 25 Dec flare was followed within 48 hours by a sudden commencement at Earth (Cane et al., 1986).

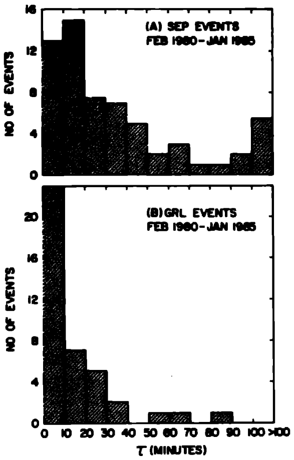

Fig. 3. Histograms of τ

Cane et al. (1986) separated interplanetary electron events into two classes on the basis of the time scale of the soft X-ray emission of the associated flares. Similarly, from a consideration of hard X-ray ray burst time profiles, Bai (1986) argued for two distinct classes of GRL/SEP flares. Events with $\tau < 10$ minutes correspond to the class of impulsive events of Cane et al., while those with $\tau > 10$ minutes approximate their gradual events. There is no indication of a sharp division between the events in Figure 2 near $\tau = 10$. Nor is there evidence for bimodality in the histograms of τ for either SEP or GRL (2σ) events (Fig. 3). The lack of evidence for two classes of events in either Figures 2 or 3 may be due to "mixed" events in which both acceleration processes are operating. The two distributions in Fig. 3 are not mutually exclusive; there are 17 common events. The GRL events are more impulsive, with a median τ value of 9 minutes compared to 22.5 minutes for the SEP events. Detectable (2σ) GRL events with τ values > 30 minutes are rare.

2.3 Type II Bursts and Gamma-Ray Line events. Through January 1985, ~ 150 γ-ray continuum events were observed by SMM; 45 of these had 4-8 MeV line emission at the 2σ level. The Type II burst associations for the continuum and line events are shown in Table 1. In 1(A) it can be seen that the relatively high degree of association found by Bai and Dennis (1985) for GRL events from 1980-81 persists for the larger sample. In Table 1(A) we considered only reports of metric Type II in SGD by Culgoora, Weissenau, and Fort Davis. Relaxing these criteria in 1(B) to include such events as metric Type IVs, possible Type IIs, or unclassified activity, in addition to reports of Type II or Type II-like activity by other observatories, increases the percentage of IIs without 2σ lines. The distributions in Table 1 may be a consequence of the Big Flare Syndrome (Kahler, 1982); in Table 1(B) the median >300 keV fluence of the 74 events with Type II or possible Type II emission is 31 γ cm^{-2}, compared to 4.5 γ cm^{-2} for the 70 events that lacked Type II association. Alternatively, the presence of an additional, Type II - related, acceleration mechanism could be the cause

γ-Ray Events (>300 keV)

		> 2σ (4-8 MeV)	< 2σ (4-8 MeV)
(A) Type II	Yes	32	20
	No	10	73
		> 2σ (4-8 MeV)	< 2σ (4-8 MeV)
(B) Type II	Yes	37	37
	No	8	62

Table 1.

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of the larger γ-ray fluences observed in the events with associated Type II bursts. For 28 of the 33 2σ 4-8 MeV GRL events that had associated Type II bursts, the Type II began within six minutes after the onset of the γ-ray emission. A disturbance propagating from the low corona at a characteristic speed of 1000 km s^{-1} will reach the 100 MHz plasma level (a typical Type II starting frequency) in a 10 x Baumbach-Allen atmosphere within approximately six minutes. We note that the line emission in the eight GRL events that lacked any evidence for Type II emission tended to be weak; only one of these eight events had a 2.2 MeV fluence at the > 2σ level.

3. Discussion. The poor correlation between γ-ray-producing ions and interplanetary protons is caused primarily by a number (seven) of large SEP events from flares that lacked detectable γ-ray emission. The absence of strong impulsive phases in these events, coupled with the fact that 6 of the 7 events had associated coronal and/or interplanetary Type II bursts, argues that the protons observed in space following these flares resulted from shock acceleration (cf., Cliver *et al.*, 1983b). The persistent high degree of association between Type II bursts and GRL events leads us to question if the Type II shock or its progenitor, i.e., the low coronal propagating disturbance eventually observed as a Type II burst, might play an important role in accelerating the *bulk* of the impulsive phase γ-ray-producing ions as well. The Type II shock is a common thread linking the SEP and GRL flares considered in this study. Approximately 75% of the events in each sample had associated Type IIs. We speculate that in impulsive events shock acceleration begins low in the corona where energetic ions are trapped on closed loops while in gradual flares this "second phase" acceleration occurs primarily in the high corona where the protons have greater access to open field lines. This picture is appealing because of its simplicity but significant questions remain concerning the speed of shock formation and subsequent acceleration (Ellison and Ramaty, 1985; Decker and Vlahos, 1985), the cause of the variation of e/p ratios (Evenson *et al.*, 1984) and electron spectra (Evenson *et al.*, 1985) with τ, and the nature of the recently discovered delayed, or extended, pion emission observed in the 03 June 1982 neutron flare (Forrest *et al.*, 1985; Murphy *et al.*, 1987).

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