LONG-DURATION SOLAR GAMMA-RAY FLARES

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Abstract. Long-duration solar γ-ray flares are those in which high-energy photon emission is present well beyond the impulsive phase, indicating the presence of either stored or continuously accelerated ions. We review both the observations and the current theories or models that can explain this unusual phenomenon. The present situation favors either acceleration of protons and ions for long periods of time by second order Fermi acceleration in large coronal loops or acceleration in large-scale, CME-associated reconnection sheets. Observations in the upcoming solar maximum may resolve this problem.

1. Introduction

The concept of a long duration γ-ray flare (LDGRF) is a relatively new one despite the fact that the phenomenon has been observed and measured many times over the last twenty years. The imprecise definition that has developed (and will be used here) is that of a solar flare exhibiting γ-ray (and/or neutron) emission ($>$1 MeV) for time periods of a fraction of an hour to hours after the impulsive phase while other common flare emissions (e.g., X-rays) are absent or greatly diminished. The γ-ray emission can stand out above the background level while other emissions at longer wavelengths have since returned to normal intensities. The critical element of this definition is that emission in other wavelengths is reduced relative to the high-energy emission. This is noteworthy because if γ-ray and neutron emissions persist for hours it can represent one of the longest duration signatures of a solar flare. Although soft X-ray and radio emissions can last hours, they now compete with γ-ray emission in certain cases. The intuitive notion that energy degrades in form over time seems not to hold in these circumstances.

LDGRFs are not to be confused with γ-ray flares such as that which occurred on 27 April 1981. Although the flare of 27 April 1981 lasted approximately 20 min. (Forrest, 1988; Murphy et al., 1990), the γ-ray flux did not grow in importance relative to fluxes at other wavelengths as the flare progressed. This is to be contrasted with the extreme case of the 11 June 1991 solar flare. Here, γ-ray emission $>$50 MeV was measurable for 8 hours (Kanbach et al., 1993), and in this time the other flare emissions had dropped to normal levels or levels much lower than those during the impulsive phase.

The γ rays from these LDGRFs are the measurable signatures of the energetic proton and ion populations produced through some acceleration mechanism

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operating at the start of the flare (or shortly thereafter) and extending for some indefinite time. When these particles interact with the solar material, they produce γ rays and neutrons. However, the presence of γ rays does not necessary imply that particle acceleration is in progress. The acceleration of protons and ions gets intertwined with the transport or storage of these particles. Only when these particles interact with the target solar material is the measurable radiation produced. The target solar material is usually somewhere other than at the acceleration site. Generally speaking, proton acceleration requires low densities (so that collisions do not quench the process) while radiation requires high density. The conventional wisdom is that electrons and ions are accelerated in the corona and are transported downward to the solar chromosphere or lower corona, i.e., the thick target. (The exception to this is where γ-ray emission occurs high in the corona (Barat et al., 1994).) When γ radiation or neutron production persists for long periods of time, it becomes a problem to disentangle the combined effects of prolonged acceleration and any attendant transport. The problem becomes particularly thorny considering that some acceleration processes are inseparable from the transport processes, e.g., diffusive shock acceleration.

The γ rays can have many origins (Murphy et al., 1987). The bremsstrahlung of relativistic electrons produces a continuum spectrum, similar in shape to that of the parent electron spectrum (Brown, 1971; Hudson, 1972). Protons and ions, on the other hand, produce a rich spectrum of γ rays. Both protons and alpha particles excite heavy ambient nuclei (e.g., C, N, O) that then de-excite by way of γ-ray emission. The reverse process is also true, i.e.; accelerated heavy nuclei (with high velocity) interact with ambient hydrogen and helium producing the same line spectrum, although Doppler broadened due to the center-of-mass velocity in the observer's frame. Collisions of accelerated heavy nuclei with ambient heavies are rare, but α-α collisions are significant and produce ^{7}Be and ^{7}Li that are in turn responsible for $\sim$478 keV photons. In addition to electromagnetic decays of excited nuclei, positron emitters are also produced, eventually producing 511 keV radiation. Neutrons are generated through these same collisions. Free neutrons thermalize quickly in the solar photosphere and are captured by hydrogen or ^{3}He on a time scale of $\sim$100 s (Lingenfelter, 1994). The (n,p) capture forming deuterium produces narrow-line radiation at 2.223 MeV (Chupp et al., 1973; Ramaty et al., 1975). In intense and large flares the proton nature of the high energy emission is also confirmed by the detection of solar flare neutrons either at spacecraft altitudes (Chupp et al., 1987; Ryan et al., 1987, 1992) or at ground level with neutron monitors (Debrunner et al., 1983).

At relativistic energies π-meson production becomes important. Inelastic p-p and p-α scattering produces both charged and neutral pions. The neutral pions (99%) decay directly into two 67.5 MeV γ rays, appropriately Doppler shifted, while π^- mesons decay first into μ^- and then e^-. The π^+ mesons decay by the same scheme into positrons, that in turn annihilate. The electrons and positrons from the charged pion decays go on to radiate via bremsstrahlung in the process of slowing down. In this energy range, neutrons with energies up to $\sim$1 GeV are produced and can be measured by spacecraft or on the ground with neutron monitors. This rich zoo of neutral radiation provides the evidence that very energetic protons exist in the solar environment long after the impulsive phase of some flares.

Solar flares also accelerate protons in interplanetary space. However, for the most part, the protons and ions measured in space can be traced back to coronal mass ejections and the shocks associated with them (Gosling, 1993; Kahler, 1992). Particle events that are presumably traceable to the flare itself (so-called impulsive events), as discussed below, tend to be electron-rich and have chemical compositions similar to flare accelerated ions inferred from γ-ray measurements (Ramaty et al., 1993; Reames, 1990, 1994, 1996). Unfortunately, the general association of γ rays with interplanetary particles is poor (Cliver et al., 1989). The LDGRFs tend to be large events associated frequently with interplanetary shocks and CMEs (Kahler, 1982), although this conclusion may be biased by the sensitivity of the instruments that are used to measure them. In these large events protons or ions accelerated in the flare itself get confused with those accelerated by the shock associated with the CME. These remotely accelerated protons generally dominate those from the flare.

The spectrum of the protons that interact at the Sun (not those detected in interplanetary space) is best determined by the relative fluxes of γ rays from very different reactions with widely separated thresholds. Typically, these emissions are (1) the γ-ray flux in the narrow 2.223 MeV line from deuterium formation, (2) the 4$-$7 MeV range from the de-excitation of CNO nuclei and (3) the $>$50 MeV γ rays from the decay of π^0 mesons. The nuclear excitations (4$-$7 MeV) result primarily from protons $<$50 MeV. The pion production can occur only above $\sim$300 MeV (H(p; π,x)) (with an effective threshold close to 500 MeV). The production of neutrons, measured with the 2.223 MeV flux, occurs at all proton energies above a few MeV. LDGRFs are frequently characterized by small values of the 4$-$7 MeV/$>$ 50 MeV flux ratio and large values of the 2.223 MeV/4$-$7 MeV flux ratio, i.e., hard proton spectra (Murphy et al., 1987).

This new class of solar flares brings the theory of solar flare particle acceleration full circle, because it raises old concepts of particle trapping and slow and protracted acceleration. Prior to the Solar Maximum Mission the prevailing concept for the acceleration of solar flare particles, both at the Sun and in space, was that a first phase quickly accelerates electrons up to $\sim$100 keV after which a second phase, operating over a much longer time period, accelerates electrons up to relativistic energies and protons up to several MeV (Kane et al., 1980; Ramaty et al., 1980). As early as 1964 Elliot (1964) proposed that the flare process itself is the result of the catastrophic precipitation of stored energetic protons, accelerated over long periods of time high in the solar corona. At the time there was little need for rapid acceleration mechanisms for electrons or protons since γ-ray flare data were sparse and did not seem to require it. Thus, ‘standard’ acceleration mechanisms such as second-order stochastic acceleration as proposed by Fermi

(1949) (cf., Forman et al., 1986; Lee, 1994) were employed to explain the few and noisy observations of solar γ-ray flares. The data from the Solar Maximum Mission forced a revision of this concept with the measurement of both X-rays from relativistic electrons and nuclear γ rays from protons and ions approaching 100 MeV (Forrest and Chupp, 1983; Kane et al., 1986; Vestrand and Miller, 1999). For a large fraction of events the simple concept of a single acceleration of both electrons and protons to high energies was capable of explaining the observations. In some cases, the explanation of the intensity-time profiles of some flares had to include models of particle transport to account for peculiarities of the profile shapes and delays (Bespalov et al., 1987; Hulot et al., 1989; Ryan, 1986; Zweibel and Haber, 1983). However, beginning with the flare of 3 June 1982, and now with several flares measured by the Compton Observatory, the discussions of particle acceleration and transport increasingly use the language of proton trapping and second-phase acceleration, reminiscent of an earlier era.

Two flares have emerged as standard bearers for the definition of LDGRFs. These are the flares of 3 June 1982 and 11 June 1991. As discussed below, the 3 June 1982 flare stands out because of a clear episode of high-energy emission distinct from the impulsive phase occurring $\sim$2 min. earlier (Forrest et al., 1986). The intensity-time profile in several energy bands is shown in Figure 1. The flare of 11 June 1991 is remarkable because of 8 hour photon emission above 50 MeV (Kanbach et al., 1993). Although the detection of 8-hour emission is in part due to the sensitivity of the EGRET instrument (Schneid et al., 1996; Thompson et al., 1993), it underscores the difficulty in understanding the physics of the phenomenon. During the 4-hour period after the impulsive phase the soft X-ray flux measured by the GOES spacecraft had dropped by a factor of 200 to its background level. Figure 2 shows the EGRET image of galactic anti-center region of the sky (containing the Sun) before and after the 11 June 1991 flare at 01:58 UT (Kanbach et al., 1993). The Sun was luminous in γ-rays $>$50 MeV for 4 hours after the exposure as seen in Figure 2. Although the EGRET telescope was effectively disabled during the impulsive phase, the TASC detector recorded spectra from 1 to 100 MeV (Schneid et al., 1994). These data show that the count rate at 100 MeV is greater 20 min after the flare than during the most intense part of the impulsive phase, consistent with the data used to create the image over a much longer time scale. The question is ‘How does the Sun either store the protons (and perhaps electrons) so efficiently or how does it accelerate them without attendant emission at other wavelengths?’ We will explore these data and the questions that surround them in this review.

2. Observations

A list of LDGRFs is found in Table 1. The behavior of the emission has been characterized by first a short (τ_1) followed by a long exponential decay (τ_2). To

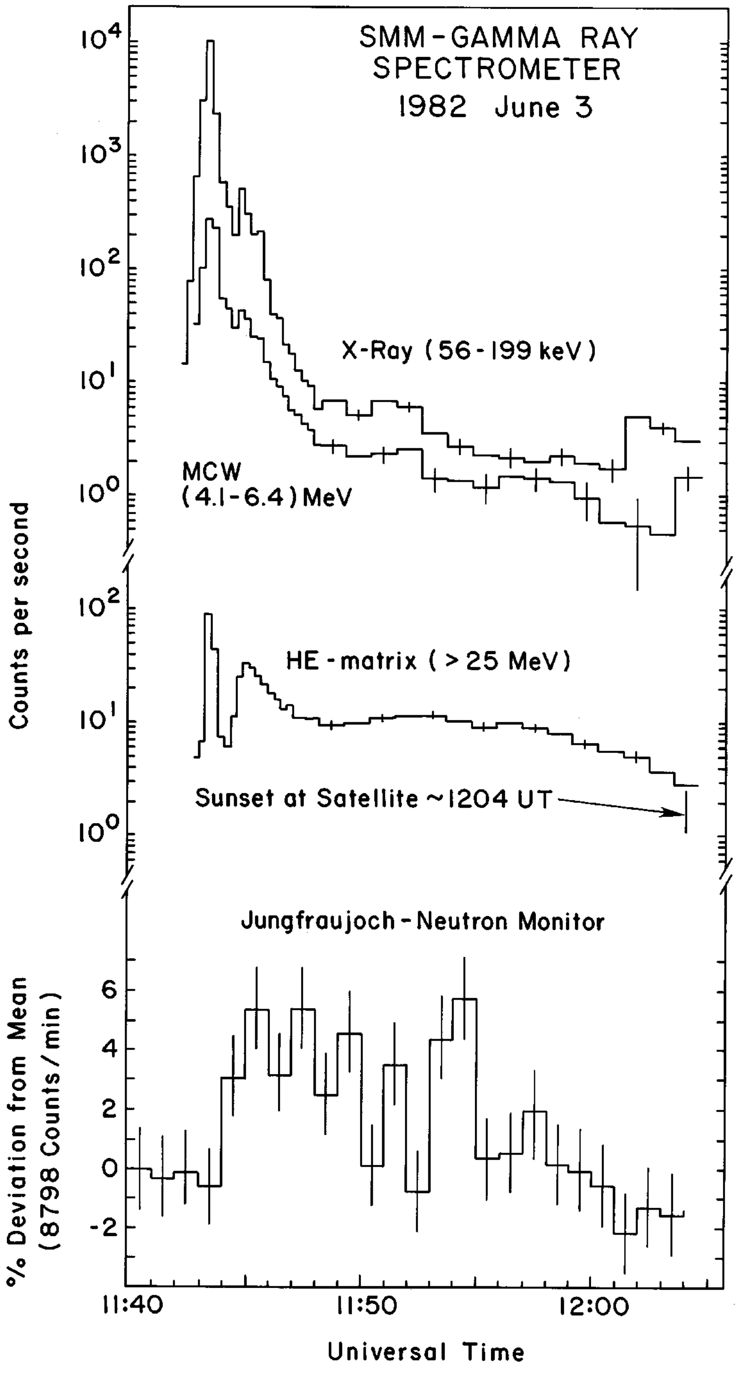
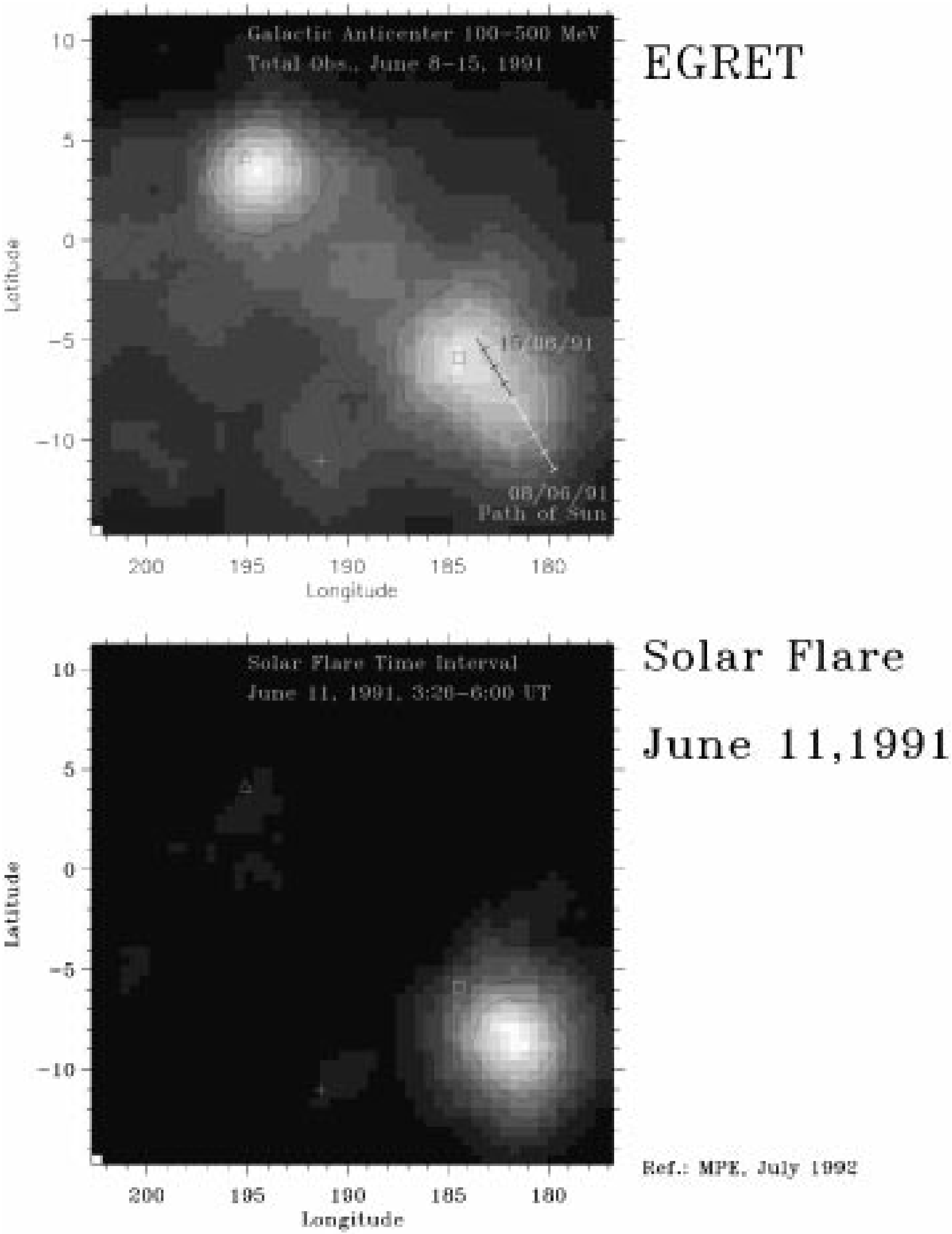


Figure 1. High-energy intensity-time profiles of the 3 June 1982 solar flare (Chupp et al., 1987).



Ref.: MPE, July 1992

Figure 2. The >50 MeV image of the sky including the Sun (*top*) for four days around the 11 June 1991 flare and (b) eight hours after the flare.

TABLE I

Year	Month	Day	Duration (s)	τ_1 (min)	τ_2 (min)	Ref.
1982	6	3	1200	1.15 ± 0.14	11.7 ± 3.0	1, 2
1984	4	24	900	3.23 ± 0.07	≥ 10	2
1988	12	16	600	3.34 ± 0.30		2
1989	3	6	1500	2.66 ± 0.27		2
1989	9	29	>600			3
1990	4	15	1800			5
1990	5	24	500	0.35 ± 0.02	22 ± 2	4, 5, 6
1991	3	26	600			7, 8
1991	6	4	10000	7 ± 0.8	27 ± 7	9, 10
1991	6	6	1000			9
1991	6	9	900			9, 11
1991	6	11	30000	9.4 ± 1.3	220 ± 50	9, 12, 13
1991	6	15	5000	12.6 ± 3.0	180 ± 100	7, 8, 12

[1] Chupp (1990); [2] Dunphy and Chupp (1994); [3] Vestrand and Forrest (1993); [4] Debrunner et al. (1997); [5] Trottet (1994); [6] Debrunner et al. (1998); [7] Akimov et al. (1991); [8] Akimov et al. (1994c); [9] Schneid et al. (1996); [10] Murphy et al. (1997); [11] Ryan et al. (1994a); [12] Rank et al. (1996); [13] Kanbach et al. (1993)

different degrees they all exhibit the phenomenon of protracted γ-ray emission with indications that other forms of emission are at a reduced level. The flares of 3 June 1982, 11 June 1991 introduced above and the flares of 24 May 1990, 4 June 1991, 9 June 1991 and 15 June 1991 were the best measured and are discussed below in greater detail. (The flares of June 1991, including those on 1 June and 6 June, all originated from the same active region, 6659.)

A common feature among these flares, and contributing to the definition of these events, as we will see below, is the proton or ion nature of the prolonged radiation. For example, for the 11 June 1991 flare observed by the Compton Observatory, the *relative* intensity of the high-energy flux (>50 MeV) compared to the flux at 1 MeV was a factor of ~ 20 greater 15 min after the impulsive phase as compared to the same ratio 2 min after the impulsive phase (Schneid et al., 1994). The high-energy flux is normally attributed to proton interactions creating neutral and charged π mesons (cf., Murphy et al., 1987; Ramaty and Mandzhavidze, 1994). However, in some flares, now known as electron-dominated γ-ray flares, electron bremsstrahlung emission extends into this energy interval (Rieger and Marschhäuser, 1990), but is not necessarily accompanied by prompt nuclear line radiation or an increase in the flux of 2.223 MeV radiation (Lingenfelter, 1994).

Typical of the largest (and best measured) of the events listed in Table 1 is a two-component intensity-time profile in the highest energy band above 50 MeV.

The more extended of the two decays is typically several times that of the shorter one. Table 1 lists the published values for the two decay times of various LDGRFs compiled from a number of sources (e.g., Dunphy and Chupp, 1994; Lockwood et al., 1997). For the smaller events the decay times could not be measured, but high-energy neutrons and/or γ-rays well after the impulsive phase identifies them as LDGRFs. As described below, sometimes the decay time must be inferred from a surrogate emission, e.g., the 2.223 MeV line.

3 June 1982

The solar flare of 3 June 1982 was the first clear example of a distinct second, delayed and prolonged high-energy phase of a flare. Several measurements of the flux from this flare have been reported (Chupp, 1990; Chupp et al., 1987; Debrunner et al., 1983; Forrest et al., 1986; Trottet et al., 1994). The γ-ray emission consisted of a $\sim$100 s impulsive phase (with emission extending from X-rays to γ-rays above 25 MeV), typical of many flares observed early in the Solar Maximum Mission. It was followed $\sim$2 min later by a separate high-energy phase accounting for the majority of the high-energy emission. In Figure 1 the count rate of the High Energy Matrix ($>$25 MeV) of the Gamma Ray Spectrometer (GRS) shows a significant minimum between the impulsive and ‘high energy’ or ‘time-extended’ phases. However, the count rate in the energy range of the nuclear lines (4.1–6.4 MeV) shows no clear fall and rise at the time of the dip in the high energy count rate. Similarly, at the time of the high-energy phase maximum, the hard X-ray flux shows only a secondary peak on the decline from the impulsive phase maximum.

The high-energy phase was deconvolved into photon and neutron components (Forrest et al., 1986). The GRS was capable of identifying energetic solar neutrons ($\sim$100–500 MeV) on a statistical basis, but with little spectroscopic information. Also detected with little spectroscopic information were the $>$200 MeV neutrons that evoked an atmospheric response at ground level (Debrunner, 1994; Debrunner et al., 1983, 1990). The background-subtracted count rate of the Jungfraujoch neutron monitor is also shown in Figure 1. In modeling the neutron emission the intensity-time profile of photons attributable to π^0 decays (including both the impulsive and high energy phases) was used successfully as an injection profile for energetic neutrons emitted into interplanetary space (Chupp, 1990; Chupp et al., 1987). This injection profile can successfully reproduce the GRS neutron signal and the neutron monitor count rate profile if one assumes a neutron production spectrum above 100 MeV of the form $\propto E^{-2.4}$ (Chupp et al., 1987). Forrest et al. (1986) concluded that 80% of the pion-produced γ rays and neutrons are related to the late phase of the flare. This neutron spectrum merges smoothly with that inferred from the measurement of interplanetary neutron-decay protons (Evenson et al., 1983, 1990). However, these neutron spectra do not agree with the neutron spectra published by Shibata (1994) for this flare. Using neutron monitor data alone and assuming an impulsive neutron production at the Sun, Shibata arrived at a neutron spectrum at the Sun more than 10 times as intense below 100 MeV than the combined results of Chupp et al. (1987) and Evenson et al. (1990). Other uncertainties surround the analysis and calculations of Shibata (1994) making the reconciliation of these spectra difficult.

The association of the high-energy neutrons with the gradual phase establishes that the gradual phase had a significant hadronic component. Although Murphy et al. (1987) speculated that the protons responsible for the time-extended phase are not the same as those responsible for the impulsive phase, the data are ambiguous and, as will be shown later, can be interpreted in several ways.

11 June 1991

The other extraordinary flare exhibiting a long-duration high-energy phase and the one that created much of the interest in this phenomenon is that of 11 June 1991. The flare was well observed with instruments on the Compton Observatory (Kanbach et al., 1993; Rank et al., 1993, 1994; Ryan et al., 1993b; Ryan, 1994; Schneid et al., 1994). The spectrum was measured with the EGRET instrument in its *telescope mode* beginning ∼90 min after the flare onset. The spectrum extended at least up to 1 GeV. Comparing the emission 15 min after the impulsive phase to that of the impulsive phase, the high-energy emission >50 MeV was enhanced by 20× relative to that at 1 MeV (Schneid et al., 1994). It was also accompanied by a strong line at 2.223 MeV from the neutron capture on photospheric hydrogen. The line was detected with COMPTEL (Rank et al., 1994) for a period of 4 hours after an initial exponential decay rate of $(9\text{ min})^{-1}$ (Rank et al., 1996) after the impulsive phase. Within uncertainties, the flux at 50 MeV decayed at the same rate (Kanbach et al., 1993) shortly after the impulsive phase suggesting that this component is also of a hadronic nature and not a result of primary electrons as first reported (Mandzhavidze and Ramaty, 1992a). A spectral analysis of the EGRET data (Dunphy et al., 1999) supports the claim that a different acceleration process is at work in the gradual phase of this flare. Based largely on the pion-decay γ rays, the gradual phase spectrum requires a significantly harder spectrum of protons than that of the γ-ray spectrum of the impulsive phase to produce the observed emission.

24 May 1990

The γ-ray flux was measured with instruments on the GRANAT spacecraft, in particular, the shields and central detector of the SIGMA experiment (Pelaez et al., 1992) and the PHEBUS experiment (Terekhov et al., 1993; Trottet, 1994; Vilmer, 1994). The flare emitted the largest measured flux of solar neutrons with estimates ranging from 7 to 100× the fluence of the 3 June 1982 flare (Debrunner et al., 1997). By itself, the presence of solar neutrons detected at ground level does not establish this event as a LDGRF, but when coupled with γ-ray measurements makes a convincing case for one. Gamma rays >50 MeV that may be associated with π meson decay exhibited a strong double-peaked impulsive phase followed by emission extending for at least 10 min at a much lower level. The prolonged high-energy radiation measured with the PHEBUS experiment began at most 2 min after the impulsive phase. The radiation was an admixture of high-energy γ rays and neutrons; however, Debrunner et al. (1997) concluded that at most 30% of the late high-energy emission is attributable to neutrons. The ground-level neutron event was detected at a variety of stations, showing up most clearly at Climax at approximately local noon, the ideal location for detecting solar neutrons. Both Kocharov et al. (1994) and Debrunner et al. (1993a) concluded that a protracted production of neutrons is necessary to explain both the high-energy measurements by PHEBUS and the ground-level neutron measurements proposed earlier by Shea et al. (1991). Muraki et al. (1992) using the neutron monitor efficiencies of Shibata (1994) found, however, that the neutron emission is consistent with neutron production contained entirely within the impulsive phase. However, Debrunner et al. (1997), using the atmospheric neutron response of Shibata, could only obtain the neutron intensity-time profile from a totally impulsive phase production by assuming a solar neutron spectrum that is very steep below 500 MeV, in conflict with the intense π^0 emission in the impulsive phase. This is in conflict with the γ-ray analysis of Debrunner et al. (1997). Using the time-extended neutron production indicated by the γ rays, Debrunner et al. (1997) found that the flare-integrated solar neutron spectrum drops off in intensity above approximately 1–3 GeV.

Recent work by (Debrunner et al., 1998) on the evolution of the γ-ray spectrum supports the conclusion that this was a LDGRF. The impulsive phase had two resolvable spikes at γ-ray energies $>$36 MeV, each of $\sim$60 s duration. When examined closely, the second spike becomes more pronounced as one progresses to higher energies (Figure 3). The authors and Talon et al. (1993) concluded that the first spike in the impulsive phase was electron dominated, i.e., the high-energy radiation was produced by primary electron bremsstrahlung, while the second spike contained a strong hadronic component, giving rise to the π^0 peak in the impulsive phase.

After both impulsive phase spikes have given way to the prolonged phase, the spectrum above 35 MeV exhibits a clear π^0 peak. The π^0 peak decays slowly with respect to the emissions at lower energies, becoming an increasingly dominant feature in the spectrum as shown in Figures 4 and 5. The hadronic component is the dominant feature well after the impulsive phase and it remains so until the observation ceased after 10 min. The decay rate of the π^0 peak was estimated to be ($\sim$20 min)$^{-1}$ (Debrunner et al., 1997) (Table 1). The smooth exponential decay of the count rate at high energies in the extended phase shows no sign of fluctuations beyond statistical, constrainting the possibility that the prolonged emission is due to numerous small episodes of particle acceleration.

Both studies of the GLE neutron signal (Debrunner et al., 1997; Kocharov et al., 1995) reached the conclusion that the prolonged component of the neutron emission was softer than the component arising from the second spike of the impulsive

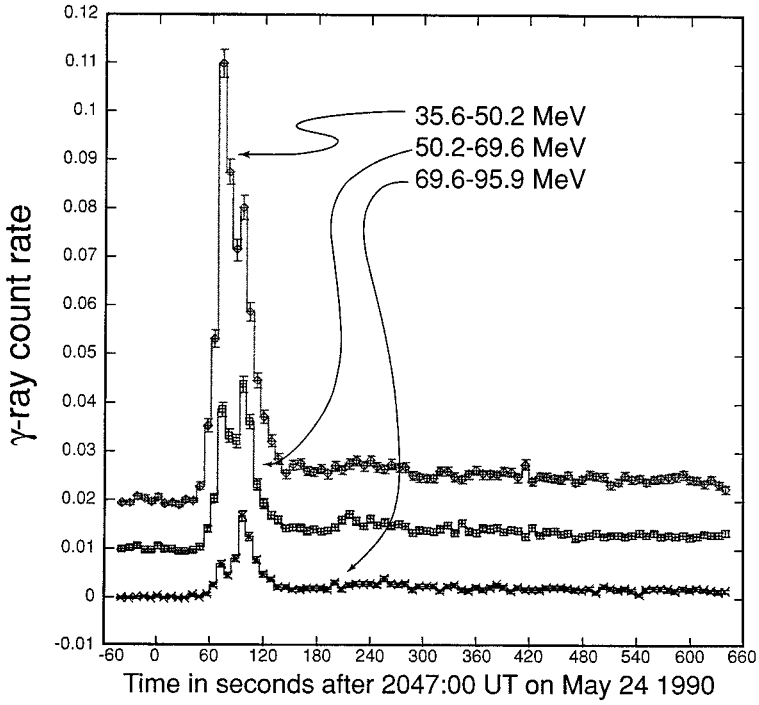


Figure 3. The intensity-time profiles of the highest energy channels of the PHEBUS instrument showing the hard spectral shape of the second spike and the contribution from neutrons and delayed high-energy γ rays.

phase. This, on its face, contradicts the conclusion from the γ-ray data (Debrunner et al., 1998) that the proton spectrum hardens in the extended phase. However, the energy ranges of these studies only have a small overlap. The GLE neutron signal derives from a significantly higher energy part of the proton spectrum than the π^0 signal, making a quantitative comparison difficult

4 June 1991

This flare (03:37 UT) was well measured only by the OSSE instrument on the Compton Observatory. Murphy et al. (1993, 1994) reported that proton precipitation and neutron production occurred during three successive orbits of the spacecraft, i.e., >2 hours. This conclusion was drawn from the measured flux of the 2.223 MeV nuclear line over this time period. Supporting this concept is the long duration of the 4.43 MeV carbon de-excitation γ-ray line paralleling that of the 2.223 MeV line. The decay of the line flux in this flare is on the order of $\sim 160 \pm 30$ s. The detection of ground level neutrons was reported by Muraki et al. (1992) and Takahashi et al. (1991). Because the flare was near the east limb (N30 E70), no prompt protons were expected that could be confused with neutrons at ground-level stations. Using only data from the first ~ 15 min of the event and using the NM

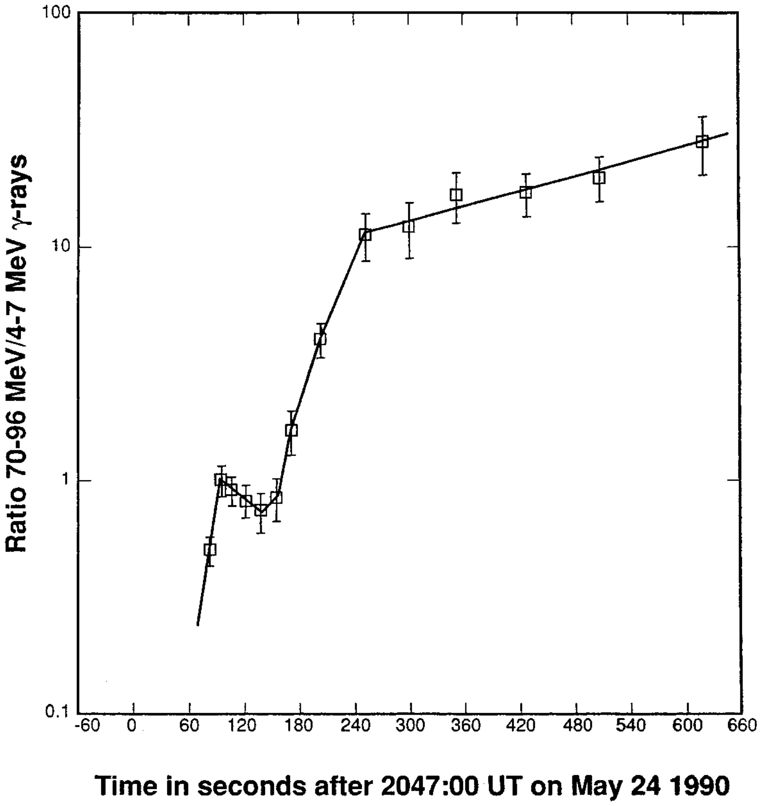


Figure 4. The ratio of the γ-ray intensities in the π^0 and nuclear de-excitation channels.

efficiencies of Shibata (1994), Muraki et al. concluded that neutrons were produced impulsively at the flare onset (03:41 UT). Their resulting spectrum for neutrons at the Sun is soft ($E^{-5.4}$ to $E^{-7.5}$) and is probably a direct result of assuming only an impulsive production. Furthermore, the efficiencies of Shibata (1994) and those of Debrunner et al. (1993a; 1997) diverge significantly at low energies. As mentioned above, the spectrum reported by Shibata (1994) for the 3 June 1982 flare differs markedly from others (Evenson et al., 1983, Chupp, 1987, #21), being more than 10× greater where they overlap. However, an excess of low energy neutrons is necessary when assuming an impulsive neutron production in order to explain the late arrival of neutrons at earth. An extended production would produce what seems to be a harder neutron spectrum at the Sun.

Struminsky et al. (1994) used the neutron monitor data of Mt. Norikura, that show an excess persisting for approximately one hour, to model the time-extended neutron production. Their model predicts neutron spectra at the Sun that are much harder ($E^{-3.5}$ to $E^{-5.2}$) than those reported by Muraki et al. and are in better agreement with the proton spectrum ($E^{-2.8}$) at the Sun reported by Murphy et al. (1994). The interpretation of these data is complicated by two facts: (1) that there

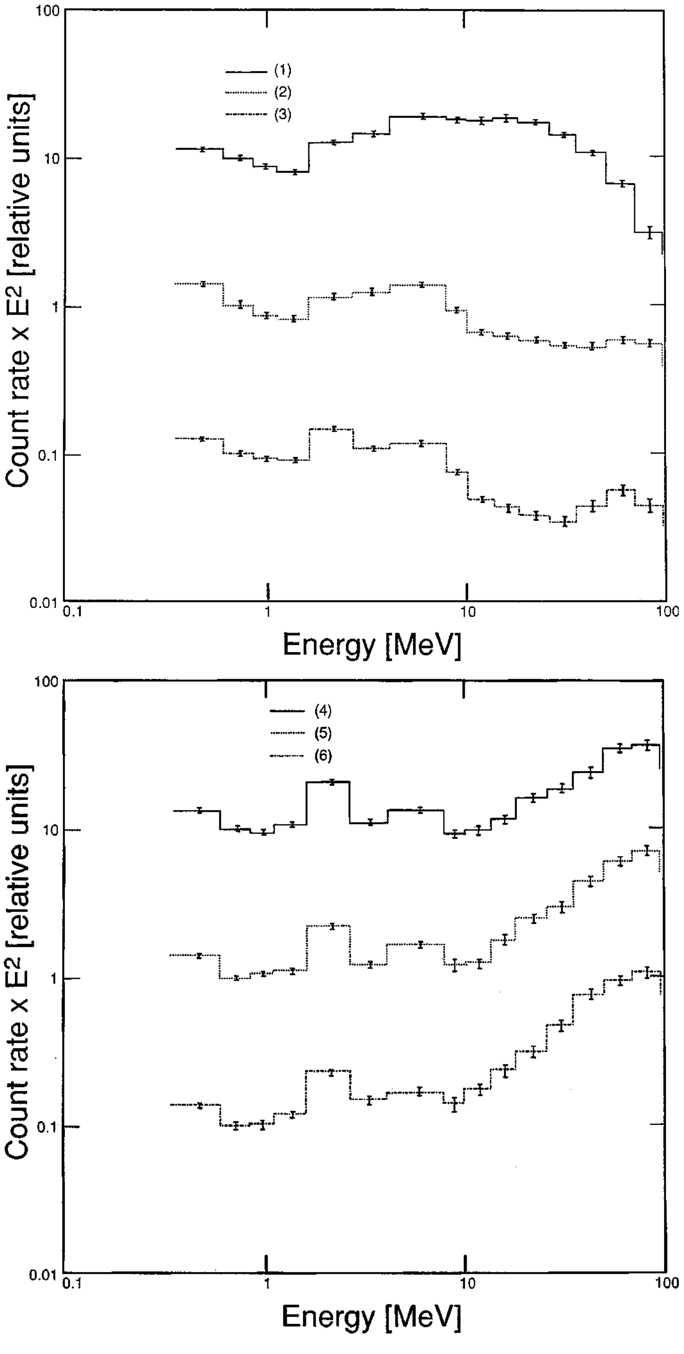


Figure 5. The γ-ray spectrum (weighted by E^2) from the (a) impulsive and transitional and (b) the gradual phase periods of the 24 May 1990 flare.

appears to be a second and distinct acceleration episode that occurred during an epoch when the Compton Observatory was occulted, and (2) 5 min NM data have inadequate resolution to measure spectra that are produced on the same time scale. Struminsky et al. reported that 17 GHz Nobeyama microwave data also indicate two acceleration episodes. This second acceleration (with an accompanying proton precipitation) helps explain the observed discontinuity in the intensity-time profiles of the 2.2 MeV γ-ray line emission (Lockwood et al., 1997). They conclude that both proton accelerations represent the beginnings of independent and protracted neutron and γ-ray production, each lasting longer than 30 min. It is not clear whether this second episode of proton acceleration (with significant emission of neutrons and γ rays) is directly related to the flare that occurred 45 min earlier. Conceivably, this could be an entirely different flare. However, Struminsky et al. derive a much harder neutron spectrum from the second episode than from the first perhaps representing a discrete jump in the spectral shape of the accelerated protons (Ramaty et al., 1994).

15 June 1991

Although the COMPTEL instrument on the Compton Observatory and the GAMMA-1 experiment both detected this flare, neither spacecraft measured the emissions during the impulsive phase, believed to have occurred around 08:20 UT, the maximum in the soft X-ray flux. Both spacecraft were occulted during the impulsive phase. In almost mutually exclusive observations, GAMMA-1 measured γ-ray emissions up to 1 GeV (Akimov et al., 1991) after which COMPTEL measured the γ-ray flux $<$30 MeV until 09:45 UT (McConnell et al., 1993; Ryan et al., 1993 b). (The EGRET instrument was disabled at this time.) In this period after the impulsive phase both the high-energy flux and that at 2.223 MeV decayed away with a decay constant of $\sim$13 min (Rank et al., 1996). In a second observation of the Sun on the subsequent orbit GAMMA-1 again measured a statistically significant flux $>$50 MeV. There was also a significant detection of 2.223 MeV γ rays and 15–80 MeV neutrons by COMPTEL on its second orbit after the impulsive phase. This event may also have produced a solar proton ground level event in neutron monitors (Smart et al., 1994) and probably a solar neutron ground level event (Nieminen, 1997; Usoskin et al., 1995).

Akimov et al. (1994a, 1996b,) compared the γ-ray intensity-time profile with μ-wave emissions and found good agreement between the two, supporting the assumption that the impulsive phase occurred around 08:20 UT. They also used these observations to conclude that the production of γ rays $>$50 MeV was a result of extended acceleration rather than trapping plus precipitation. COMPTEL also measured neutrons between 15 and 80 MeV from this flare (Debrunner et al., 1993b; McConnell, 1994; Nieminen, 1997; Rank, 1996; Rank et al., 1993a, 1997a, b). By studying the measured energy of the detected neutrons, Debrunner et al. (1993b) concluded that neutrons were also produced for at least $\sim$90 min after the impulsive phase. This coupled with the measurement of the 2.223 MeV neutron-capture line and nuclear de-excitation lines above 4 MeV over similar periods of time indicate that the long-duration flux was due almost entirely to protons or ions. Long after the flare relatively little flux was measured below 1 MeV where primary electrons would have their strongest signatures. However, evidence of energetic electrons can be seen in the γ-ray continuum below 50 MeV, presumably from the decay of charged pions (Rank et al., 1997b).

Two studies independently concluded that a separate ion-dominated acceleration mechanism was responsible for the extended phase emission (Akimov et al., 1996; Kocharov et al., 1998). Akimov et al. supported this claim with the arguments that (1) the microwave signal was variable in the late phase indicating acceleration, (2) decimetric and meter wave activity was high during the same time, indicating acceleration at high altitudes, (3) the microwave and the γ-ray intensity-time profiles are very similar and (4) the prolonged escape of high-energy particles into interplanetary space is not consistent with a single impulsive phase acceleration.

Kocharov et al. and Nieminen (1997) also associated the microwave emission with the extended γ-ray emission. Kocharov et al. deduced a two-component ion spectrum dominated by protons ($\alpha/p = 0.5$) with each component having a similar power law shape, but with the low-energy component stronger by a factor of $\sim$10 with a cutoff at several hundred MeV. No primary electron spectrum was necessary in this model. (The spectrum was constructed from both low- and high-energy γ-ray data and neutron data and thus it represents a flare average.) Akimov et al. attributed the interplanetary particles and the late-phase γ-ray emission to a dc electric field acceleration in a large (10^{10} cm) reconnection sheet (RCS) formed behind a CME (Litvinenko, 1996b; Litvinenko and Somov, 1995; Somov, 1996), although there was no reported CME.

3. Theory of long duration gamma-ray flares

The characteristic properties of LDGRFs as described above are (1) ion-rich particle precipitation for periods that extend long after the impulsive phase, remaining strong well into or after the decline in soft X-ray emission, and (2) relatively high-energy photons, associated with π meson production. There are a limited number of possibilities consistent with such phenomena. The first of these is that proton, ion and electron acceleration occurs during the impulsive phase, after which these particles are stored in high altitude magnetic structures. They subsequently precipitate onto the lower solar atmosphere to produce high-energy photons. The particles can also interact with the ambient medium in these magnetic structures rather than at lower altitudes in the chromosphere or lower corona. Conditions must be such that within the high altitude coronal structures there is little MHD turbulence that scatters particles into loss cones and that the magnetic geometry is such that curvature and gradient drifts do not prematurely deplete the population of trapped particles. The combined loss effects of pitch angle diffusion, collisional braking in the ambient medium and drifts determine the characteristic trapping time.

The second scenario is that particle acceleration takes place over long periods of time after the flare, but is decoupled from the impulsive flare. The picture of a receding shock is one such scenario, where the shock, which may have produced the original fast particles seen in the impulsive phase, continues to produce energetic protons and ions. The particles, once accelerated at the shock, must make their way back in sufficient numbers to the lower corona or chromosphere to produce detectable γ rays. For γ-ray production of $\sim$1 hour this implies that the shock that produced these particles can be as far away as 5 R_0 (solar radii) when the γ rays are produced.

The third scenario also relies upon a CME for prolonged particle acceleration, but here the acceleration takes place in a reconnecting current sheet (RCS) behind the CME (Litvinenko, 1996a, b; Litvinenko and Somov, 1993, Somov, 1996). The RCS is capable of generating large potential drops for high-energy ions and the temporal behavior of establishing the RCS fits the time scales of LDGRFs.

The final scenario is an admixture of the first two mechanisms outlined above, i.e., particles are both trapped in high altitude magnetic structures but are accelerated continuously while being trapped. Since the geometry implied here is static, this rules out any dynamic shock acceleration process. The energy to accelerate the particles must, most likely, come from turbulence or mini-flaring within these magnetic structures.

The possibilities for producing LDGRFs encompass the very same processes as those for the impulsive phase, i.e., electric fields and first and second order Fermi acceleration mechanisms. However, it is important to strive for, if possible, a single model to explain this phenomenon. Given that there is a wide range of duration of these events, it will be possible to explain some of them with passive trapping while others require continuous acceleration. Occam's razor demands that we first attempt to explain all these LDGRFs with a single process with variable parameters before resorting to models tailored to individual events. In this section we will explore the current models for each of these scenarios and discuss the ramifications in terms of other observable solar phenomena.

3.1. PASSIVE TRAPPING OF IMPULSIVE PHASE HIGH ENERGY PROTONS

For studying the time behavior of γ-ray emission, the simple picture of passive trapping was examined by Zweibel and Haber (1983) and Ryan (1986) where protons are stored in a bipolar loop and are scattered into a loss cone by way of pitch angle scattering at some point within the loop. This concept has always been attractive since we see long term trapping of protons in the radiation belts of the planets. The size of the loss cone and the intensity of the pitch angle scattering determine the decay rate of the population within the loop and consequently the rate of proton precipitation into the lower corona or chromosphere. The proton precipitation is observed by way of γ-ray and neutron emission if the protons are sufficiently energetic. If the pitch angle diffusion is confined to an isolated turbulent region and is strong enough so that the proton population is isotropized with each transit, then the loss is entirely determined by the size of the loss cone. If there is no pitch angle scattering in this loop then the radiation decays because the protons lose energy in collisions in the local medium. The other extreme case is where the pitch angle scattering is intense and distributed throughout the loop. The protons are transported by spatial diffusion eventually arriving at the loop ends to produce the neutron and γ radiation (Ryan, 1986). Various combinations or intermediate cases have also been studied (Fletcher, 1997).

Regardless of the dynamics within a loop, energetic protons will lose energy by way of collisions with ambient electrons. This energy loss rate tracks the γ-ray and neutron production from within the same volume. Non-relativistic protons lose energy via collisions with ambient electrons on a characteristic time scale (per unit number density) $E/(\mathrm{d}E/\mathrm{d}t) = 2 \times 10^{11} E^{0.5}$ (MeV cm^{-3}) s for subrelativistic energies and $2 \times 10^{12} E$ (MeV cm^{-3}) s for relativistic protons. To achieve a one hour lifetime for 100 MeV protons the mean coronal density can be no greater than about 5×10^{8} cm^{-3}. Relativistic protons (1 GeV) fare better, requiring a density $<5 \times 10^{11}$ cm^{-3}. A natural hardening of the proton spectrum occurs over time due to this effect. However, the effect of nuclear interactions at relativistic energies is comparable to that of energy loss through ‘ionization’. This tends to soften the proton spectrum over time.

These processes were examined in detail by Hua et al. (1989). They modeled a coronal loop with an ambient matter density that smoothly merges with the matter density at the ends of the loop. They assumed a level of MHD turbulence within the loop that scatters the protons into a loss cone. The protons were tracked by way of a Monte Carlo calculation as they adiabatically mirror within the loop and change their pitch angle according to the assumed turbulence intensity. The protons also gradually lose energy by way of normal collisions with ambient electrons. The inelastic collisions of the protons with matter within the loop or at the ends of the loop where the density is high results in the observable photon emission. The picture although much more detailed yields results similar to analytical calculations (Ryan, 1986; Zweibel and Haber, 1983).

The dynamic behavior of protons in a bipolar field was examined by several investigators. Except for the effects described above, the lifetime of protons in a static loop is largely determined by the size of the loss cone and the rate at which the loss cone is replenished. The expression for the half angle α of the loss cone is $\sin^2 \alpha = B_0/B_m$, where B_m is the magnetic field strength at the mirror point and B_0 is the magnetic field strength at the apex of the loop. Particles that are initially in the loss cone penetrate the lower corona or the dense chromosphere and are capable of emitting γ rays or neutrons. They do not return to the energetic proton distribution once having entered the loss cone. The remainder of the protons interacts with the ambient medium or gets scattered into the loss cone. Coulomb scattering, directly related to the energy loss, is in principle capable of filling the loss cone. However, small angle scattering experienced by protons does not compete with the energy losses and is therefore negligible (Benz and Gold, 1971; Fletcher, 1997). The loss cone can be filled more efficiently by MHD wave-resonant pitch angle scattering. The wave field can arise from external sources or can be self-generated by the distorted pitch-angle distribution due to the depleted loss cone. The case of a self-generated field has been studied by Meerson and Rogachevskii (1983). They found that under certain conditions (large enough plasma $\beta = p/(B^2/8\pi)$) an Alfvén wave field that is resonant with the energetic protons can develop quickly, keeping the loss cone filled and thereby depleting the proton population. The diffusion starts out weak with the protons scattering into the loss cone. The wave intensity finally develops into a condition of strong pitch angle diffusion, i.e., the loss cone is filled (and emptied) with each bounce of the particles. Under these conditions proton loss rate is proportional to $\exp(-t(\sin^2\alpha)/\tau_b)$, where τ_b is the proton bounce time. If the ratio of the magnetic field at the footpoint to that at the loop apex is not larger than $\sim$5, then the characteristic loss time through pitch angle diffusion is only about a factor of 10 greater than τ_b. For a 10^{10} cm loop and a proton with a velocity of $c/3$, τ_b is on the order of 5 s. The trapping that results from this situation is sufficient to smooth out the impulsive nature of the particle acceleration as seen in γ-ray emission, but not nearly long enough to provide the containment for a one hour long duration flare. To achieve a 1 hour trapping time the diffusion must be much weaker than that necessary to isotropize the proton population with each bounce. However, this may not be possible with turbulence generated by other means.

Also affecting the lifetime of the protons within the trap are guiding-center particle drifts, in particular, curvature and gradient drifts (Northrop, 1963). From curvature drift alone a 500 MeV proton in a 100 G loop of length 10^{10} cm will drift $\sim 10^9$ cm per hour in a direction orthogonal to the plane of the loop. The drift rate is inversely proportional to the magnetic field strength. With $B = 10$ G a 500 MeV proton will therefore drift in one hour one loop length away from the loop, removing itself from the trap. Lau and Ramaty (1993, 1994) proposed that twisted (force-free) loops are capable of containing energetic protons if the loops are either large enough or have sufficient twist ($<2\pi$).

Thus, in order to contain trapped relativistic protons or ions for extended lengths of time three conditions must be met. (1) Loop densities must be low. For 100 MeV protons and one hour trapping this implies an ambient hydrogen number density $<5 \times 10^8$ cm^{-3}, and a corresponding ambient density $<5 \times 10^{11}$ cm^{-3} for 1 GeV protons. (2) MHD turbulence must be very low. For the 11 June 1991 flare Ramaty and Mandzhavidze (1994) pointed out that the Alfvén wave energy density can be no larger than $(\delta B)^2/8\pi < 2 \times 10^{-6}$ ergs cm^{-3}, assuming a 1-d Kolmogorov wave spectrum ($k^{-5/3}$) integrated down to a wave number corresponding to a 10 GeV proton Larmor radius in a 100 G field. The low Alfvén-wave energy density proposed by Ramaty and Mandzhavidze (1994) for the 11 June 1991 flare should be compared to the value of $\sim 10^{-2}$ ergs cm^{-3} in turbulent wave energy if Alfvén waves heat coronal loops (Hollweg, 1984). The mean free path of such a proton is of order 1000 AU. However, we would expect the wave spectrum to continue down to a wave number corresponding to a wavelength $2L$, where L is the length of the coronal loop. This would increase the total wave field energy density to $\sim 10^{-3}$ ergs cm^{-3} in a loop with $L = 10^{10}$ cm and $B = 100$ G. However, this is still much smaller than one would expect in a post-flare environment. (3) The arcade of coronal loops containing the protons and ions must be force-free so that particle drifts do not deplete the proton and ion population. This is important for loops on the order of 2×10^{9} cm or smaller for trapping of 1 GeV protons (Lau et al., 1993).

3.2. SEPARATE AND REMOTE ACCELERATION

The protons that produce the long-duration high-energy emission need not be accelerated during the impulsive phase of the flare. In principle they could arise from a separate and distinct acceleration process occurring at a later time. Separate and remote acceleration processes take two forms: electric fields and coronal shocks. We first discuss the electric field models.

Electric field acceleration of protons and ions are often based on the picture constructed by Speiser (1965) and later by Martens (1988). However, the special case of long duration, high-energy proton and ion acceleration by electric fields was specifically addressed by Litvinenko and Somov (1993) and Litvinenko (1996a) and later employed by Akimov et al. (1996) to explain the high-energy gamma emission from the 15 June 1991 flare. The general picture is that a large magnetic reconnection current sheet (RCS), established behind a receding CME, accelerates particles in the electric field along the sheet. The dimensions of the RCS, the strength of the merging magnetic field and the flow velocities are more than sufficient to generate large electric fields and accelerate protons well above GeV energies. The problem is the dynamics of retaining the particles in the electric field. The protons will naturally drift out the inhomogeneous field before acquiring relativistic energies. However, with a small (0.1%) magnetic field normal to the RCS (and the accelerating electric field), the protons drift back into the accelerating electric potential (several V m^{-1}). With approximately 100 such exits and re-entrances of the protons into the electric potential, they can attain GeV energies. The model is attractive because it relies upon the creation of a CME, a common feature of large solar flares. Not only does the CME-large flare association exist, but also the time scale for the development and evolution of the CME matches that of the long-duration γ-ray emission. Moreover, the polarity of the field would naturally exclude high-energy electron bremsstrahlung when protons and ions precipitate to the chromosphere.

Another possibility, also involving CMEs, is that a secondary shock wave from the powerful impulsive phase or a coronal mass ejection accelerates protons at a distance from the original flare site. Murphy et al. (1987) and Ramaty et al. (1987) suggested that the protons responsible for the pion-related emission in the late phase of the 3 June 1982 flare could have the same origin as the protons measured in interplanetary space. Less than 10% of the interplanetary proton flux is required to yield the measured pion-related emissions (McDonald and Hollebeke, 1985). (A revision of the proton spectral shape (Van Hollebeke et al., 1990) increased the required fraction of the interplanetary proton population to 25–50%.)

Shock accelerated protons are frequently detected and measured in space (Lee, 1994; Reames, 1996). Most often they are associated with coronal mass ejections (Lee, 1997), but not always associated with flares (Gosling, 1993; Kahler, 1992). The typical ionization state of ions detected is representative of quiet coronal conditions, i.e., 10^6 K. Some interplanetary protons and ions are however associated with the flare itself. The association is also established by way of the ionization states and the composition of the measured ions. The characteristics of these flare-associated particles are (1) a relatively high abundance of energetic electrons, (2) a large abundance of ^{3}He with respect to ^{4}He and (3) ion charge states representative of $10–30 \times 10^6$ K. Although the CME-related particles are clearly shock accelerated, the case is not so clear for the so-called impulsive phase particles. However, we assume for the moment that the flare-associated protons and ions have been accelerated by a CME-driven shock wave (or a coronal blast wave) and that they diffuse back to the Sun through the turbulent downstream region of the shock to produce the γ rays and neutrons in the LDGRF. The dynamics of proton shock acceleration in a coronal blast wave was described by Lee and Ryan (1986), but a proper theoretical treatment of the problem of protons diffusing to the solar surface from a receding shock apparently has not be attempted, nor are there any published measurements that might address the problem.

Two scenarios that might allow shock-accelerated protons to precipitate back to the solar surface for periods of hours after a large flare are the following. We first can imagine that a coronal blast wave or a CME sets up a shock that accelerates particles for long periods of time. In that time, however, the shock, the source of the energetic particles, is receding from the target Sun. The particles must either diffuse back to the Sun through the turbulent downstream region of the shock or find efficient, i.e., relatively scatter-free, magnetic field lines that connect the regions of great energetic particle density back to the Sun. The energetic particles concentrate near the shock interface that moves across new field lines as it propagates. If scatter-free transport of ions occurs along quiet field lines, it must occur on a large number of them in order to maintain the connection and keep the precipitation going for hours. However, the connecting field lines must only connect a limited fraction of the accelerating region to the Sun, because the intensity of the γ-ray emission falls off exponentially whereas the energetic proton population integrated over the entire shock front falls off more slowly, or even grows with time (Lee and Ryan, 1986).

Evidence is strong, through compositional studies of a small number of flares (Murphy et al., 1990; Share and Murphy, 1995), that the chemical composition of ‘gradual event’ interplanetary ions is not similar to those of interplanetary ions from impulsive events (Reames et al., 1994) or the that of the γ-ray producing ions, as inferred from the γ-ray spectra (Cliver, 1996). In addition, the onset times of the GLE protons are much later than the γ-ray emission at the equivalent energy (Lockwood et al., 1999). Thus, GLE proton emission at the Sun is *not* created in the impulsive phase of the flare. If the highest energy interplanetary protons and ions are not related to the impulsive phase and the chemical composition of the extended phase ions resembles that of the impulsive phase we can safely rule out the transport of remotely accelerated shock-associated ions as the source of the high energy ions responsible for the pion-related γ-ray emission. However, there is limited spectral data on the high-energy delayed γ-ray emission. The first analysis of the 11 June 1991 event (Mandzhavidze and Ramaty, 1992a, b) indicated a dominant primary electron bremsstrahlung component in qualitative agreement with the strong electron component in impulsive event particle spectra. A subsequent analysis showed that the 2.223 MeV emission decay curves are identical to the high-energy decay curves (Rank, 1996; Rank et al., 1996, 1997a). This belies the conclusion that primary electrons contributed significantly to the high-energy emission. The great difference that one would expect in the trapping efficiencies of electrons and ions would naturally lead one to conclude that primary electron bremsstrahlung and ion signatures would diverge in the late phase of the flare.

For the 15 June 1991 event Kocharov et al. (1998) limited the ^{4}He abundance to be less than half that of the protons, while Debrunner et al. (1998) excluded the composition II of Ramaty et al. (1993), i.e., enriched in heavy elements (and primary electrons) for the 24 May 1990 event. These limited studies do not support the hypothesis that the composition of the long-duration, high-energy proton spectrum has a composition similar to that deduced from the γ-ray spectrum of the 27 April 1981 flare (Murphy et al., 1990) or that of impulsive interplanetary particle events (Kahler, 1992; Ramaty et al., 1993; Reames et al., 1994). This singular similarity of the 27 April 1981 composition and that of impulsive interplanetary particle events led Cliver (1996) to conclude that LDGRFs derive from the same particle acceleration process as impulsive flares. We believe, however, that the 27 April 1981 flare should not be classified as a LDGRF, as we have defined them here, but rather a merely drawn out impulsive phase event with no significant high-energy emission.

On the experimental side a positive detection of high-energy γ rays following a CME, especially without the occurrence of a flare, would be strong evidence that remotely accelerated shock-associated particles are precipitating back to the solar surface. The first results of such a search with the data from the COMPTEL instrument on the Compton Observatory are negative (McConnell et al., 1997) and there was no report of emission from the disk following the large flare on 1 June 1991 (Barat et al., 1994; Ramaty et al., 1997; Murphy et al., 1999). Furthermore, Kahler et al. (1999) saw no evidence for interplanetary particles associated with post-eruptive coronal loop structures in the absence of flares. However, it is not clear that the proper observation has been performed. The instruments on the Compton Observatory would be those that would provide the greatest probability of detecting such an unambiguous γ-ray and, thus, proton or ion acceleration signal. To summarize, the evidence seems to indicate that few or no shock-associated ions are responsible for the long duration γ-ray emission, but a positive detection after a thorough search of existing data or new data from the upcoming solar maximum would indicate otherwise.

3.3. TRAPPING AND EXTENDED ACCELERATION

Given the difficulty of maintaining a MHD-quiet environment for long periods of time with low densities and the proper geometry to prevent or manage drifts and the difficulty of transporting accelerated protons back from a receding shock, we now examine a scenario in which the protons and ions remain in the near-Sun environment and are continuously accelerated well after the impulsive phase. Such a situation was examined analytically by Ryan and Lee (1991) in order to explain the delayed high-energy phase of the 3 June 1982 event. The hypothesis is that protons accelerated during the impulsive phase are trapped in an isolated magnetic loop. The material interior to the loop is turbulent as a result of the flare, but the loop maintains its general shape and size ($\beta \ll 1$). The transport of the protons within a loop of length L and out of the loop is mediated by the intense turbulence ($\lambda \ll L$) and is characterized by spatial diffusion (as opposed to 'ballistic' trajectories in the passive trapping model). The slow diffusion, resulting from the intense turbulence, 'traps' the protons in the loop. They leak out the ends of the loop that are tied to the chromosphere and photosphere and the precipitation results in γ-ray emission. The decay time of the population in the loop has a characteristic value of $\tau_D = L^2/\pi^2\kappa_{\text{para}}$, where κ_{para} is the spatial diffusion coefficient (parallel to **B**) that can be a function of energy. (This level of turbulence is far above that of the 'saturated' turbulence case assumed by others (e.g., Hua et al., 1989), where the scattering time is on the order of the particle bounce time, i.e., $\lambda \approx L$.) Even though diffusion along the loop is slow, it is far more efficient than that transverse to the loop. The cross-field resonant diffusion coefficient is $\kappa_{\text{perp}} = \eta v^4(3\Omega_{\text{i}}\kappa_{\text{para}})^{-1}$ (Lee, 1982, 1983), where η is on the order of unity, Ω_{i} is the ion gyrofrequency and v is the particle velocity. For typical values, κ_{perp} is orders of magnitude smaller than κ_{para}.

This diffusion alone is not responsible for the prolonged high-energy emission from LDGRFs. Accompanying the slow spatial diffusion in a natural way is rapid diffusion in momentum space through second-order Fermi acceleration (Schlickeiser, 1986). As the particles are trapped they are also accelerated. The diffusions in real space and momentum space are inseparably linked. In this model the delayed high-energy emission does not rely explicitly on high-energy protons being present in the impulsive phase. The characteristic times for space and momentum diffusion, τ_D and τ_F, respectively, are inversely related by $\tau_\mathrm{D}\tau_\mathrm{F} = (3L/V_\mathrm{A})^2$, where L is the scale length and V_A is the Alfvén speed (Schlickeiser, 1986). The spatial diffusion is due to pitch angle scattering *along* the field lines. Cross-field diffusion is much slower and can be safely neglected. While the spatial diffusion depletes the proton population within the loop, the remaining protons experience Fermi acceleration, thereby increasing the number of protons above some high-energy threshold, e.g., pion production. The weak link in this scenario is the origin of sustained, intense turbulence required to trap and accelerate the particles. We will return to this point.

Ryan and Lee (1991) explained the delayed high-energy phase of the 3 June 1982 flare as the result of not only the trapping and acceleration of protons but also the threshold effects of the SMM/GRS instrument and pion production. As the trapped proton spectrum hardened, this increased the number of protons above the pion production threshold and secondary neutrons above the detection threshold of the GRS. The net result is a clear and distinct *observed* second or delayed phase of high-energy emission. Whereas the trapping and acceleration process is continuous and smooth, the physical and instrumental threshold effects exaggerate or enhance the effect.

The general expression for the one-dimensional spatial diffusion and coupled three-dimensional momentum diffusion is

$$\frac{\partial f}{\partial t} = p^{-2}\frac{\partial}{\partial p}\left\{p^2\left(D(p)\frac{\partial f}{\partial p} - \dot{p}f\right)\right\} + \frac{\partial}{\partial x}\left(\kappa\frac{\partial f}{\partial x}\right) + Q(x, p, t)\ ,$$

where x is the distance along the loop, t is time, p is momentum, D is the diffusion coefficient in momentum space, κ is the spatial diffusion coefficient, f is the particle distribution function, and Q is the injection or source function. Conceivably, κ can be a function of space and momentum, and consequently so would D. The quantity $\dot{p}$ is a momentum or energy loss term arising from proton collisions with ambient electrons. The case of κ independent of energy ($D \propto \mathrm{p}^2$) and $\dot{p} = 0$ was examined by Ryan et al. (1991) and Bennett et al. (1994) for the case of the 3 June 1982 flare. With a 20 MeV impulse injection of protons at a point x' Ryan et al. (1991) calculated the precipitation of protons $>$300 MeV. A distinct delayed high-energy phase could be produced with spatial diffusion time scales on the order of $\sim$100 s and momentum diffusion time scales on the order of $\sim$500 s in a loop of length 10^{10} cm. The required level of turbulence is on the order of 10 erg cm^{-3} assuming a 100 G magnetic field, i.e., $\delta B/B \sim 0.5$.

For the purpose of studying the delayed high-energy phase we can reduce Equation (1) to a leaky box equation (Ryan et al., 1994b). Temporal features related to the inhomogeneous nature of the particle population are lost in this treatment. The spatial diffusion effects are imbedded in a characteristic global escape time T. The equation for this diffusion process is

$$\frac{\partial f}{\partial t} = p^{-2}\frac{\partial}{\partial p}\left[p^2 D(p)\frac{\partial f}{\partial p}\right] - \frac{f}{T} + Q(p)\delta(t)\ .$$

Ryan et al. neglected energy loss terms and all spatial dependence. They also assumed that $D = D_0 p^2$, requiring that κ be independent of p. The injection spectrum was assumed to be of the form

$$Q(p) = \frac{N_0}{4\pi p_t^3}(\gamma - 3)\left(\frac{p}{p_t}\right)^{-\gamma} S(p - p_t) \ ,$$

where p_t is the low-end cutoff of the particle momentum spectrum and S is the Heaviside function. Similar results were obtained as those of the case where space dependence is included. That is, once the energetic particle population is built up through the Fermi acceleration process it eventually attains a constant spectral shape with losses out the ends of the loop. After this time the relative energetic particle distribution does not change within the loop but the entire population monotonically decreases in magnitude as spatial diffusion depletes the population. This is the limiting case of the time-dependent problem.

The photon spectrum that results from the precipitating protons in either of these models, i.e., leaky box or explicit spatial diffusion, is in qualitative agreement with the deduced spectrum from the 11 June 1991 event (Mandzhavidze and Ramaty, 1992a). However, the theoretical spectrum predicted from the explicit loop model is too hard relative to measurements, but can be brought into agreement by weighting with the power law input spectrum rather than the monoenergetic distribution studied by Ryan and Lee (1991).

The nagging question with regard to prolonged acceleration is the maintenance of the required level of turbulence. For a 10^{10} cm loop a 10^3 km s^{-1} velocity Alfvén wave will exit the loop in 100 s–far short of the 10^4 s required for long flares such as that of 11 June 1991. Two phenomena seem relevant to this question. The first is observational: Comparisons of the radiative cooling time of large coronal loops with the intensity-time profiles of the thermal X-ray emission have long been known to be in disagreement, indicating that energy in some invisible form is feeding the loop for long periods of time to maintain the temperature (Jakimiec et al., 1986). MHD turbulence may be associated with this energy input and would be the energy source of the accelerated particles (Bornmann, 1987).

The second phenomenon that may preserve the turbulence is one where the loop behaves as a resonant cavity for Alfvén waves. If the MHD turbulence is generated in the corona, a likely situation, then the waves can be contained because of poor transmission through the transition region. The index of refraction for Alfvén waves changes dramatically and abruptly from the corona to the transition region. This almost discontinuous change in phase velocity results in almost all the wave energy being reflected at the boundary, effectively producing a cavity with a high quality factor Q for the Alfvén waves (Hollweg, 1984; Hollweg and Sterling, 1984). The reflection coefficient, and thus the quality factor, depends on the abruptness of the density change in the transition region, i.e., the scale height. The quantity Q, however, is not dependent on the wave number k. An impulsive point-like disturbance can be expanded into a series of modes under the condition of perfect reflection off the boundary. With no dissipation the power spectrum is harmonic in nature with maximum amplitude at $k = m\pi(2x_0)^{-1}$ where $m = 1$, 3, 5, ..., and x_0 is the shortest distance to the end of the loop (the transition region). In reality, the power spectrum does not extend to infinity but truncates at $1/\lambda_D$, where λ_D is the Debye length, and long wavelength modes will be excited by the mass motions associated with the flare. However, the initial power spectrum is hard. The lowest mode has a wavelength of $2L$, where L is the length of the loop. Cascade processes will soften the spectrum over time and will attempt to smooth out the harmonic nature of the power spectrum. The quantity $Q = L/4\pi h_{av}$, where h_{av} is the average scale height of the corona at the two end points of the loop. If $L = 10^{10}$ cm and $h_{av} = 2 \times 10^7$ cm then $Q = 40$. To relate this to the residence time of the turbulence, Q can be expressed in terms of τ_{free}, the decay time of the wave energy in the undriven state, i.e., $\tau_{free} = QP/2\pi$, where P is the wave period. This works to the advantage of high-energy particle acceleration since the long wavelength modes are the ones that resonate with the highest energy particles, i.e., for a given Q the waves with the smallest wave number will have the longest residence time. If the wave transit time is 100 s, then the e-folding time for the energy in the loop in this mode will be on the order of 4000 s, a period of time long enough to produce the effect necessary for all but the longest duration flares.

We should not expect that the wave energy is lost out the sides of the loop since there is large mismatch between the wave numbers of the Alfvén waves in the loop and the acoustic waves that might be radiated from the loop. Therefore the particles and the waves will be constrained to the loop – the particles by the small cross-field diffusion coefficient and the waves by the ‘impedance’ mismatch between the Alfvén waves and the acoustic waves.

A great deal of work remains to be done on this problem. In addition to not knowing how the turbulence decays in time, we must investigate the effect of a momentum-dependent diffusion coefficient, a stratified corona, the depletion and refilling of the wave spectrum as particles tap the waves’ energy for acceleration, and a spatially-dependent diffusion coefficient since the magnetic loop is not uniform in cross section. Other effects could be important too.

4. Conclusions

The phenomenon of long-duration, solar γ-ray flares has focused attention on the properties of the corona and the behavior of energetic particles long after the impulsive phase of the flare. The abundance of relativistic protons and the relative absence of electrons provide clues about the nature of acceleration and the transport processes of these two species. Great difficulties plague the hypothesis of the particles being accelerated early in the flare and persisting in quiet loops. The demanding geometry, species independent diffusion coefficients and remarkably quiet coronal conditions all but rule out passive trapping as a general explanation of the phenomenon. Even if one allows for episodic accelerations, in the absence of any other flare signature, the smooth nature of the flux decay forces these acceleration episodes to be small, frequent and exponentially declining in intensity. A continuous acceleration process embodies the essential elements of the problem and employs theory that is well developed. Therefore, the current available data and models seem to favor second-order stochastic acceleration in static coronal loops or CME-related dc electric field acceleration. We cannot rule out, however, the prospect that a receding shock is responsible for the prolonged particle precipitation. Since only large solar flares have exhibited this phenomenon, we must search the data for CME-associated particle events *without* any accompanying flare that exhibit γ-ray emission. Future measurements and observations may set strong limits on this option. The upcoming solar maximum could provide those opportunities. EGRET and COMPTEL, the instruments that have shed the most light on this subject will still be operating and if funded for operation should be able to collect more data on LDGRFs and the CME shocks that possibly are the origin of the late and prolonged high-energy protons.

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