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GAMMA RAYS FROM PION DECAY: EVIDENCE FOR LONG-TERM TRAPPING OF PARTICLES IN SOLAR FLARES

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ABSTRACT

We analyze the energy spectrum and time dependence of the 50 MeV to 2 GeV gamma rays observed from the 1991 June 11 solar flare. We show that the emission detected at the late phase of this flare with EGRET on the *Compton Gamma-Ray Observatory* can be explained by a model in which the bulk of the particles were accelerated during the impulsive phase and subsequently trapped in coronal magnetic loops. We fit the observed spectrum with a combination of pion decay radiation and primary electron bremsstrahlung. We compare the 1991 June 11 data with data for the 1982 June 3 and 1991 June 15 flares from which pion decay emission was also observed. The fact that the fluxes from these three flares are ordered in time in accordance with the predicted time dependence of emission produced by trapped particles provides support for the model.

Subject headings: gamma rays: observations — Sun: flares — Sun: particle emission

1. INTRODUCTION

Gamma ray emission following the decay of pions has been observed with *SMM* for the flares of 1982 June 3 (Forrest et al. 1986), 1984 April 24 (D. J. Forrest 1988, private communication), 1988 December 16 (Dunphy & Chupp 1992) and 1989 March 6 (Dunphy & Chupp 1991), with *GAMMA-1* for the flare of 1991 June 15 (Akimov et al. 1991), and with EGRET on the *Compton Gamma-Ray Observatory* for the flare of 1991 June 11 (Kanbach et al. 1992). The *SMM* data cover the energy range from about 10 to 150 MeV, while the *GAMMA-1* and EGRET data range from about 50 to 2000 MeV. The distinguishing feature of the pion radiation is the characteristic flattening of the energy spectrum around 70 MeV. The emission observed with *SMM* was limited to time intervals near the impulsive phase of the flares. On the other hand, the higher sensitivities of *GAMMA-1* and EGRET allowed the detection of pion radiation at later times when the fluxes have diminished considerably. In particular, the EGRET observations revealed for the first time the existence of pion radiation as late as 8 hr after the impulsive phase.

Pions in solar flares are produced predominantly by protons and α particles of energies greater than a few hundred MeV/nucleon interacting with the ambient solar atmosphere. The neutral pions decay into two photons directly. The charged pions produce gamma rays by decaying (via muons) into electrons and positrons, which produce photons via bremsstrahlung and annihilation in flight (Murphy, Dermer, & Ramaty 1987). In a recent paper (Mandzhavidze & Ramaty 1992, hereafter MR) we treated the transport of high-energy protons and α particles in solar flare magnetic loops, calculated the production and propagation of the gamma rays resulting from pion decay, and applied these calculations to the 1982 June 3 observations. Ramaty et al. (1992) used our calculations to fit the energy spectrum of the 1991 June 15 flare.

The production of GeV gamma rays as late as 8 hr after the impulsive phase of a flare could be due to either the continuous acceleration of particles to GeV energies or the trapping of such particles in closed magnetic structures. While the possibility of continuous acceleration cannot be ruled out, we provide arguments that favor high-energy gamma ray production by particles accelerated during the impulsive phase and subsequently trapped in magnetic loops. We use the model for pion and bremsstrahlung production in a magnetic loop developed previously (MR) to analyze the energy spectrum and time dependence of the high-energy gamma ray emission observed from the 1991 June 11 flare.

2. ANALYSIS OF THE 1991 JUNE 11 FLARE

The 1991 June 11 flare was one of a series of X-class flares which occurred during the first two weeks of 1991 June. According to *GOES* observations, the soft X-ray emission started at 01^h56^m UT, reached maximum at 02^h09^m UT, and decreased substantially by 02^h20^m UT. Because of saturation during the intense early phase of the flare, EGRET data are available only after 03^h26^m UT. Lower energy gamma rays, including line emission, were also seen with the other instruments on the *Compton Gamma-Ray Observatory*, but these data are not yet available for analysis. From observations with Phebus on *GRANAT* (Trottet et al. 1992), the time of the peak of the 4–7 MeV emission was approximately at 02^h04^m UT. The emission in this energy range is a combination of nuclear lines and bremsstrahlung; the numerical values of the photon fluxes, however, have not yet been made available.

The loop models for gamma ray and neutron production (Ramaty et al. 1988; Miller & Ramaty 1989; Gueglenko et al. 1990; MR) are quite adequate for investigating phenomena on short time scales, such as those observed during the impulsive phase of flares. It has been suggested that the rapid decay of the gamma ray fluxes during this phase is the result of pitch angle scattering of the particles due to plasma turbulence in the corona. The high-energy gamma ray observations of the 1991

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June 11 flare, however, suggest different conditions later in the flare. As we shall see, to allow particles to be trapped for up to 8 hr the rate of pitch angle scattering must be much lower than that during the impulsive phase. On such long time scales the effects of particle drifts become important. Indeed, in a purely toroidal magnetic field the curvature of the coronal portion of the loop will produce drift velocities on the order of 10^6 cm s^{-1}, which could transport particles over distances on the order of the solar radius on times scales of hours. However, the addition of a poloidal component to the field (representing the twisting of the field lines) can reduce this drift (Galeev & Sagdeev 1979). Furthermore, the expansion of the loops on time scales of minutes to an hour after the flare (e.g., Poletto & Svestka 1992) will also reduce the curvature drift. Even if the particles would drift out of a loop, the existence of arcades of loops, or of a general area of closed, bipolar fields in active regions (e.g., Moore 1992), could allow them to remain trapped in the solar atmosphere. In the present paper we use the simple single loop model described in MR as a representation of an average trapping region.

The parameters of the model are the following: length of coronal part $\pi \times 10^9$ cm; coronal magnetic field, assumed to have constant magnitude, equal to 10 or 100 G; coronal density, also assumed constant, equal to 10^{10} cm^{-3}; photospheric to coronal magnetic field ratio, B_p/B_c, equal to 10 or 50; exponential density profile in the subcoronal region with scale height 200 km. The rate of pitch angle scattering is determined by the energy density of plasma turbulence $W_{\rm tot}$. We inject protons, α particles, and electrons into the loop impulsively at $t = 0$, which we take at the peak of the 4–7 MeV emission, i.e., at $02^{\rm h}04^{\rm m}$ UT. We assume power-law spectra for all particle species extending to 5 GeV, with indexes γ for the ions and γ_e for the electrons.

The spectra are shown in Figure 1, where the data represent the average spectrum of the 1991 June 11 flare above 50 MeV observed from $03^{\rm h}26^{\rm m}$ to $06^{\rm h}00^{\rm m}$ UT (Kanbach et al. 1992). The calculated curves represent spectra averaged over the range $\cos\theta > \frac{2}{3}$, where θ is the angle between the direction of observations and the outward radius at the flare location. This range includes the heliocentric angle of the 1991 June 11 flare (N31° W17°). The solid curves in Figure 1*a* are total time integrated pion decay spectra for three different γ's. We see that the closest fit is obtained with $\gamma = 3.5$. However, this fit underestimates the observed flux between 50 and 70 MeV, suggesting that there should also be a contribution from primary electron bremsstrahlung. Such a bremsstrahlung spectrum is shown by the dashed curve in Figure 1*a*. This spectrum was calculated for the same parameters of the loop as those used for the ions, except that $B_c = 10$ G.

However, to compare our calculation with the data more precisely, we must consider only spectra produced during the EGRET observing period. This is done in Figure 1*b*, where the dashed curves represent a pion decay spectrum and a bremsstrahlung spectrum produced 5000 s after the injection of the primary particles. These 5000 s represent the difference between the peak of the 4–7 MeV emission and the start of the EGRET observing period. These pion decay and bremsstrahlung spectra can be compared with the corresponding total time integrated spectra (the dashed-dotted curve in Fig. 1*b* and dashed curve in Fig. 1*a*). We see that the pion decay spectrum becomes somewhat flatter at late times caused by the hardening of the trapped particle spectrum due to ionization losses. On the other hand, the bremsstrahlung spectrum becomes much steeper at late times, due to synchrotron losses suffered by the electrons. Thus, since we are already using a low value for B_c and a hard electron injection spectrum, it is unlikely that the entire spectrum measured with EGRET could be attributed to electron bremsstrahlung alone. The sum of the pion decay and bremsstrahlung spectra (solid curve in Fig. 1*b*) does provide a good fit to the data. We have also carried out calculations with a cutoff energy at 10 GeV and found that the fit is not significantly different.

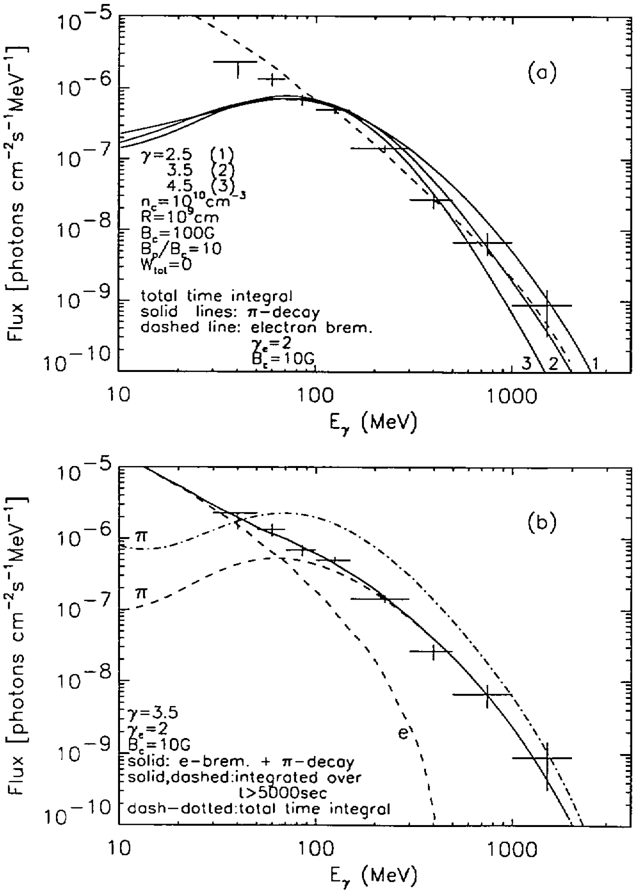

FIG. 1.—Average energy spectrum of the 1991 June 11 flare observed with EGRET from $03^{\rm h}26^{\rm m}$ to $06^{\rm h}00^{\rm m}$ UT (Kanbach et al. 1992). The calculated curves are arbitrary normalized to fit the data. The parameters of the loop are indicated in Fig. 1*a*.

The time dependencies are shown in Figure 2. The vertical bars were obtained by normalizing the EGRET count rates to the total gamma ray flux greater than 50 MeV observed from $03^{\rm h}26^{\rm m}$ to $06^{\rm h}00^{\rm m}$ UT (Kanbach et al. 1992). The calculated curves are also for energies greater than 50 MeV with the position of the flare taken into account. In Figure 2*a* the dashed curve corresponds to the pion decay radiation, while the solid curves are bremsstrahlung time profiles for $B_c = 100$ G and 10 G. The magnitude of the coronal field does not influence significantly the time profile of the pion decay emission above 50 MeV, since it is dominated by neutral pion decay. The pion decay curve fits the observations quite well, except for the earliest EGRET data point. By adding the bremsstrahlung time profile for $B_c = 10$ G we obtain the dash-dotted curve which provides an acceptable fit to all the EGRET data. The parameters of this fit are the same as those that were used to fit the spectral data in the Figure 1*b*. As we

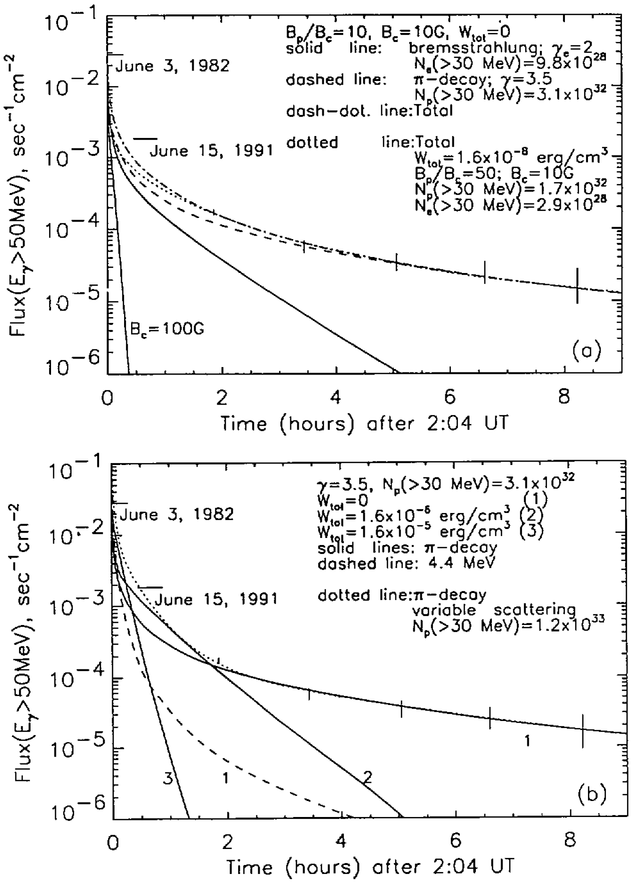

FIG. 2.—Measured (*vertical bars:* Kanbach et al. 1992) and calculated time-dependent fluxes of the greater than 50 MeV gamma rays. Also shown in Fig. 2*b* is the calculated flux of the 4.4 MeV gamma ray line. The parameters of the loop, except the ones indicated, are the same as in Fig. 1*a*.

can see, the bremsstrahlung corresponding to $B_c = 100$ G decays too fast to provide any significant contribution at late times. Thus, to account for the observations the coronal magnetic field should be sufficiently low. On the other hand, for the mirror ratio of 10 that we used, this low coronal field leads to a photospheric field of only 100 G. In Figure 2*a* we also show the sum of the pion decay and electron bremsstrahlung fluxes calculated for $B_p/B_c = 50$ and $B_c = 10$ G (*dotted curve*). This calculation includes weak pitch angle scattering ($W_{\text{tot}} = 1.6 \times 10^{-8}$ ergs cm^{-3}). The corresponding spectrum is very similar to that shown in the Figure 1*b* for $B_p/B_c = 10$ and no pitch angle scattering.

Comparing the pion decay and bremsstrahlung time profiles in Figure 2*a*, we see that the ratio of these two emissions increases with time. This is consistent with the observed decrease of the ratio of the 50–70 MeV to greater than 70 MeV fluxes found by Kanbach et al. (1992) and their conclusion that after approximately 05$^{\text{h}}$00$^{\text{m}}$ UT the electron component has decayed completely.

Normalizing the calculated curves to the measured fluxes, we obtain the total numbers of the accelerated protons and electrons of energies greater than 30 MeV indicated in Figure 2. The derived values of $N_e(>30)$ depend strongly on the heliocentric angle of the flare. Since the 1991 June 11 flare was a disk flare, the bremsstrahlung radiation is considerably lowered due to the strong directionality of the emission (i.e., Miller & Ramaty 1989). This effect is less important for the pion decay radiation which is significantly less anisotropic (MR).

We also show in Figure 2 the average greater than 50 MeV fluxes for the 1982 June 3 and 1991 June 15 flares. The *SMM* observations for the 1982 June 3 flare were limited to the first 1000 s of the flare, while the flare of 1991 June 15 was observed with *GAMMA-1* during the time interval from about 1640 s to 3140 s after the beginning of the flare. We have obtained the total flux for this time interval by integrating the measured energy spectrum from 50 to 2000 MeV. We normalized the fluxes from both flares to the heliocentric angle of the 1991 June 11 flare, based on the calculated angular distributions of the pion decay radiation. We see that the data for the 1982 June 3 and the 1991 June 15 flares exceed the calculated fluxes given by both the dash-dotted and dotted curves which provide good fits to the 1991 June 11 observations. The discrepancy can be due to a higher number of accelerated particles in the 1982 June 3 and 1991 June 15 flares than in the 1991 June 11 flare. However, another explanation can be provided by a variable pitch angle scattering rate which decreases with time from an initially high value due to the dissipation of the plasma waves.

The effect of the pitch angle scattering of the ions on the time profiles of the pion decay emission is shown in the Figure 2*b*. We see that only in the case of no pitch angle scattering (*curve 1*) is the time profile sufficiently flat at late times to account for the EGRET observations. When scattering is taken into account with the indicated energy densities, the precipitation becomes too fast, resulting in the rapid drop of the emission (*curves 2 and 3*). These energy densities are much higher than the energy density we used in Figure 2*a*.

The dashed curve in the Figure 2*b* shows our predicted time dependence for the 4.44 MeV ^{12}C deexcitation line. We assume that the ion power-law spectrum with $\gamma = 3.5$, derived from the pion decay data for energies above a few hundred MeV, extends to lower energies. Because of the lower effective energies of the line producing particles, in the case of no or weak pitch angle scattering the flux of the 4.44 MeV line decays faster than that of the pion decay radiation. The corresponding total fluence of the 4.44 MeV line at the Earth is about 19 photons cm^{-2} for no pitch angle scattering and about 10 photons cm^{-2} for the case $B_p/B_c = 50$ and $W_{\text{tot}} = 1.6 \times 10^{-8}$ ergs cm^{-3}. These fluxes would be higher if the rate of pitch angle scattering early in the flare were higher than later on. An example of a pion decay time profile obtained with variable pitch angle scattering is also shown in Figure 2*b* (*dotted curve*). Here we assumed a time-dependent turbulent energy density, which, for the first 3000 s is of the same form as that used to fit the pion decay emission from the 1982 June 3 flare after its second peak (MR): $W_{\text{tot}} = 1.6 \times 10^{-4}/[0.1t + 1]$, where W_{tot} is in ergs cm^{-3} and t in s. After 3000 s we assumed that W_{tot} decays exponentially with time constant 100 s. The corresponding 4.44 MeV fluence for the 1991 June 11 flare is 61 photons cm^{-2}.

3. DISCUSSION AND CONCLUSIONS

We have shown that it is possible that the late phase emission observed with EGRET from the 1991 June 11 flare was produced by ions and electrons accelerated during the impulsive phase of the flare and subsequently trapped in magnetic loops, provided that the strength of the magnetic field and the level of the plasma turbulence in the coronal part of the loops are sufficiently low. The other necessary conditions are mirror ratios of the order of 10 or higher and coronal densities not exceeding 5×10^{11} cm^{-3}. These conditions are quite reasonable. However, if they are not satisfied, continuous acceleration of particles during several hours is required. This process should be capable of accelerating particles to at least several GeV, but the acceleration mechanism should be different from those which operate in the impulsive phase of flares. Indeed, acceleration during the impulsive phase is always accompanied by intense and highly variable radio and X-ray emissions. But the time profiles of the radio and X-ray emissions during the late phase of the 1991 June 11 flare decayed smoothly (Kanbach et al. 1992), arguing against multiple impulsive acceleration events. Continuous acceleration by a single shock seems also unlikely. Moving with the speed of approximately 1000 km s^{-1}, by the time of the EGRET observations the shock would be at a very large distance from the Sun, so that the particles would not be able to return to the Sun to interact and produce the gamma rays.

Although we expect the plasma turbulence resulting from the primary energy release to decay with time, self-generated Alfvén waves resulting from the loss cone instability during the late phase of the flare (e.g., Bespalov, Zaitzev, & Stepanov 1987) could scatter the trapped particles and cause their precipitation. However, Landau damping of the waves can stabilize the particles in a magnetic structure with curved field lines (Wentzel 1976). Besides, as we discussed in the previous section, the energetic particles could be distributed over many loops due to drifts, in which case their densities would fall below the threshold for the excitation of the waves. Another consequence of the drifts would be the expansion with time of the high energy gamma ray emitting area. On the other hand, since the drift velocities of the electrons and nonrelativistic ions are much smaller than those of the pion producing ions, the bremsstrahlung and gamma ray line emitting regions are expected to be much more confined. These effects could, in principle, be verified by the future imaging observations.

We have shown that the ion spectral index for the 1991 June 11 flare from a few hundred MeV to a few GeV is close to 3.5. This value is in good agreement with the ion spectral index derived for the same flare from the ratio of the 2.223 MeV line flux and the 4–7 MeV nuclear emission (Trottet et al. 1992). The fit to the observed gamma ray spectrum also requires a small contribution from bremsstrahlung. But because this contribution is limited to the 50–70 MeV range, the electron spectrum cannot be deduced uniquely. The shapes of the energy spectra of the greater than 50 MeV gamma rays for the 1991 June 11 and 15 flares are very similar. For the 1991 June 15 flare the data can be fit with an ion spectral index between 3 and 4, with a bremsstrahlung contribution below 100 MeV (Kocharov et al. 1992; Ramaty et al. 1992). A similar conclusion has been obtained for the 1982 June 3 flare (MR). Our results indicate that this bremsstrahlung addition does not necessarily require the continuous acceleration of the electrons. Similar to the ions, the electrons can be stored in the magnetic loop for a long time, although we expect bremsstrahlung to decay faster than the pion decay radiation. The fact that in the 1991 June 11 flare greater than 50 MeV bremsstrahlung decayed faster than the pion radiation is perhaps the strongest argument against continuous acceleration. Another consequence of particle trapping is the faster decay of the deexcitation line emission compared to the pion decay emission.

Our analysis of the 1991 June 11 flare is limited to the high-energy data from EGRET. As we have seen, these data alone can be fitted with different numbers of accelerated particles depending on the parameters of the model. This results in different predictions of nuclear gamma ray line fluxes. Data on nuclear lines, bremsstrahlung, and neutrons from the other instruments on the *Compton Gamma-Ray Observatory* and *GRANAT* will help to further constrain the parameters of the loop.

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