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ON THE ORIGIN OF LONG LASTING GAMMA RAY EMISSION FROM SOLAR FLARES

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Abstract

We discuss the recently discovered long duration gamma ray emission from solar flares. We examine new data for the 1991 June 11 flare which suggest that, during at least the first 3 hours after the beginning of the flare, pure trapping cannot account for the observations.

1. Introduction

Gamma rays were observed from 6 X-class solar flares in June 1991 [1–7]. The new feature of these observations, revealed by the increased sensitivity of the CGRO (Compton Gamma Ray Observatory) and GAMMA-1 detectors, is the ability of flares to produce gamma rays for long periods of time. The most striking example of such long duration emission was provided by the June 11 flare from which 50–2000 MeV gamma rays were observed with the EGRET instrument on CGRO for 8 hours [3]. Gamma rays in the 30–3000 MeV range were also seen with GAMMA-1 from the June 15 flare for about 2 hours [1]. In addition, nuclear line emission was seen from the June 4 flare for about 2 hours [6], from the June 11 flare about 4 hours [4,5], and from the June 15 flare for slightly over an hour [4].

Two limiting possibilities exist as to the nature of the particles which produces these long duration emissions. The particles could either be accelerated in the impulsive phase and subsequently trapped at the Sun or be accelerated continuously over the duration of the emission. There are of course also intermediate possibilities, e.g. the particles are accelerated episodically and subsequently trapped between the acceleration episodes. These possibilities, as well as the arguments in favor and against particle trapping, have been discussed [8,9].

A fundamental property of long duration trapping is that emissions produced by different types of particles, or by particles of differing energies, should exhibit different time profiles. Gamma rays above 50 MeV are mainly due to the decay of pions produced by accelerated ions of energies greater than several hundreds MeV/nucleon. On the other hand, nuclear line emission is due to ions in the range 10–100 MeV/nucleon. As these ions lose

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energy much more rapidly than the pion producing particles, in the trapping scenario the line emission is expected to decrease faster than the pion decay emission. A complication, however, is introduced by drifts: the high energy ions could drift out of the trapping volume faster than the lower energy ones, thus counterbalancing the effect of the energy losses.

Comparisons of nuclear line and pion decay emissions were made for the June 15 flare. Here nuclear line emission was observed [4] for about 0.6 hours during a time period bracketed by two periods during which pion decay emission was seen [1,2]. We were able to fit these data with acceleration in the impulsive phase and subsequent trapping [10]. However, an argument against trapping was presented, based on the similarity of the combined pion decay–nuclear line time profile and microwave time profiles at 5.2 GHz [2] and 9.1 GHz [11]. Furthermore, the fact that the microwave emission from this flare shows considerable structure for close to 1 hour after the start of the flare, also argues against pure trapping.

The longest duration gamma ray flare (8 hours) was that observed on June 11 [3]. Gamma rays up to GeV energies were observed, showing that the bulk of the photons are of pionic origin. As the high energy protons that produce these pions have very long lifetimes against ionization losses and nuclear collisions, it was natural to apply [12] our previously developed pion production and trapping model [13] to this event. We have shown that the long term trapping of high energy ions requires loops with very low energy density in turbulent plasma waves ($W_a \lesssim 10^{-8}$ erg cm^{-3}) to reduce the precipitation rate of the particles through the loss cones due to pitch angle scattering. We also pointed out the potential difficulty caused by particle escape due to drifts. It was subsequently shown that the effects of the drifts can be reduced or eliminated if the loops are twisted [14] or if they are large enough [12,15]. While the observed spectrum is mostly pionic, the presence of an excess in the 50–70 MeV region above the calculated pion decay emission spectrum was found in a time interval centered about 2 hours after the impulsive phase but not in later time intervals [3] . This excess is most likely due to bremsstrahlung from primary electrons. As one of the predictions of the trapping model is the faster disappearance of such electrons relative to the high energy protons that produce pions, this result was considered as further evidence for trapping. However, the survival of the $\sim$ 100 MeV primary electrons against synchrotron losses for even 2 hours required a low magnetic field in the coronal part of the loop ($B_c \lesssim 10$ G).

Since our previous analyses [8,12] total 2.22 and 4.44 MeV nuclear line fluences for the June 11 flare were derived from EGRET/TASC data [16], and this allowed the calculation of the spectrum and total number of interacting protons for this flare [17]. Using these results we have calculated the total pion decay emission and extended the >50 MeV time profile observed with EGRET back to the impulsive phase of the flare. It was not possible to observe the impulsive phase with the EGRET spark chamber because of the saturation of its anticoincidence dome. This extended time profile now allows us to perform a more meaningful comparison with the available (unnormalized) 2.22 MeV time profile for the June 11 flare [4,5]. We have also examined the 35 GHz microwave data during the time period in which the excess primary electron bremsstrahlung was observed. We discuss these new results and reexamine the issue of long duration trapping in the June 11 flare.

2. Analysis

The power law proton spectral index s and total number of interacting protons of energies >30 MeV, N_p(>30MeV), for the June 11 flare were determined [17]: $s \simeq 3.2$, N_p(>30MeV) $\simeq 2.3 \times 10^{32}$ or 6.3×10^{31}, depending on the composition of the ambient medium and accelerated particles [18]. We calculated the total >50 MeV pion decay emission for these parameters and the results are shown by the two horizontal bars in Fig. 1. Also shown are the >50 MeV flux observed with EGRET [3] and the time dependent count rates in the 2.22 MeV line from COMPTEL [4] and OSSE [5]. As the corresponding photon fluxes are not yet available, we arbitrarily normalized the 2.22 MeV count rates to the >50 MeV flux in the time interval from about 1.5 to 3 hours (after 2:04 UT) in which the two emissions overlap. Considering the entire time profile, we see that, within uncertainties, the >50 MeV emission and the 2.22 MeV line emission have similar time profiles. Since the lifetime of the high energy ions which produce the bulk of the >50MeV emission via pion decay is longer than the lifetime of the ions which lead to the 2.22 MeV line (via neutron production and capture), this result argues against long term trapping, at least for the first 3 hours of the flare.

In Fig. 2 we present the spectrum of the > 50 MeV gamma rays measured with EGRET from the June 11 flare, together with theoretical spectra of pion decay emission calculated for a power law in kinetic energy ion spectrum and two interaction models - isotropic thick target and magnetic loop [12]. The curve for the loop model differs somewhat from the one we presented previously [8,12]. The difference at high energies stems from the replacement of the pion production kinematics given in [19] with that of [20]; at the low energies we corrected an error affecting the secondary $e^{\pm}$ component. As the kinematics of [20] yields a somewhat softer photon spectrum at high energies, to fit the data we now have to extend the proton energy spectrum to at least 10 GeV. The excess flux (Fig. 2) above the theoretical spectra in the 50–70 MeV range can only be attributed to primary electron bremsstrahlung. This excess is somewhat higher for the loop model for which the secondary $e^{\pm}$ component is attenuated due to the directivity of this radiation and the position of the flare close to the disc center.

Using an isotropic thick target bremsstrahlung model and assuming that the incident electron differential number is given by $N(E) = AE^{-\gamma}$ electrons MeV^{-1}, we calculate A as a function of γ, keeping the differential bremsstrahlung fluence at Earth equal to the observed excess in the 50–70 MeV range, $\simeq 2.7 \times 10^{-3}$ photons cm^{-2} MeV^{-1}. We take a total duration of 1.5 hours centered around 1.8 hours after 2:04 UT, equal to the time interval over which the excess bremsstrahlung was seen [3]; the derived A thus represents the average differential electron number at 1 MeV during this period. The steeper the electron spectrum the more electrons are required at 1 MeV to produce a given bremsstrahlung fluence at 50–70 MeV; thus A increases with increasing γ. For $\gamma = 3$ we obtain $A \simeq 2 \times 10^{32}$ electrons MeV^{-1}. When integrated over the time profile implied by the data shown in Fig. 1, this implies that for the total interacting electrons $A_t \simeq 5 \times 10^{33}$ electrons MeV^{-1}. In comparison, for the June 4 flare, for which the bremsstrahlung at ~ 1MeV is among the largest ever observed [17,18], and for which the total 2.22 MeV line fluence was about 7 times larger than for the June 11 flare [16,17], A_t is about 2×10^{34} for $s = 3$. We thus conclude that to account for the 50–70 MeV excess in the June 11 flare, γ cannot be larger than 3 because otherwise the total number of electrons at 1 MeV is too large.

We have calculated the 35 GHz gyrosynchrotron flux density at Earth produced by electrons with $N(E) = 2 \times 10^{32}$ and compared it to the observed average flux density in the 1.5 hour time period mentioned above, ~ 150 sfu (S. Enome and H. Nakajima, private communication 1993). We use the gyrosynchrotron code [17,21], assume a constant magnetic field, take the angle between the field and the direction of observation equal to 45° and assume that the source is optically thin. We find that to account for the observed flux density, the magnetic field has to be at least 60 G. The lifetime of 100 MeV electrons against synchrotron losses in such a field is only about 0.2 hours. This is then another argument against trapping, at least for the relativistic electrons which produce the primary electron bremsstrahlung excess and gyrosynchrotron radiation late in the June 11 flare.

3. Conclusions

The nuclear line emission data that became available for the impulsive phase of the June 11 flare from EGRET/TASC allowed us to show that, at least for a time period of about 3 hours after the beginning of the flare, the 2.22 MeV line and pion decay emission have similar time profiles. We also show that the magnetic filed of 10 G that is needed to allow trapping of the high energy electrons responsible for the bremsstrahlung that is present for about 2 hours after the impulsive phase of the flare is inconsistent with the observed microwave flux. Therefore, we conclude that the currently available data for the June 11 flare are not consistent with a single acceleration during the impulsive phase followed by particle trapping. There probably were multiple acceleration episodes that produced additional gamma ray fluxes at later times. For another flare that exhibited long duration gamma ray emission, that of June 4, evidence for a second major acceleration episode that occurred about 40–50 minutes after the impulsive phase was provided by neutron, nuclear line and microwave data [6,22].

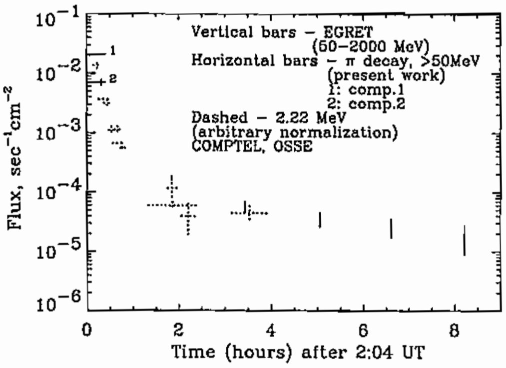

Fig. 1 Gamma ray time profiles for the June 11 flare.

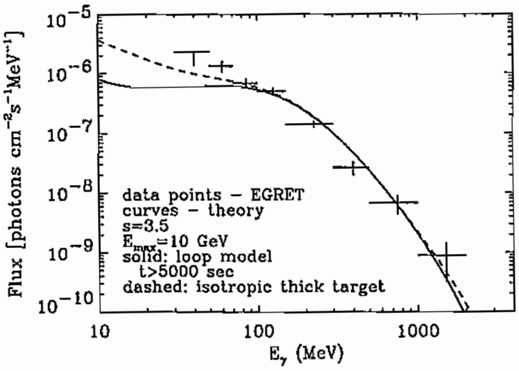

Fig. 2 Gamma ray energy spectrum for the June 11 flare.

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