Pion Decay and Nuclear Line Emission From the 1991 June 15 Flare

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ABSTRACT

We analyze the flux of very high energy (0.03-3 GeV) gamma ray emission measured with GAMMA-1 during the 1991 June 15 solar flare. The energy spectrum of this emission, resulting from pion decay, allows us to derive for the first time the spectrum of the accelerated particles at the Sun at energies up to few GeV. Combination of the GAMMA-1 data with the COMPTEL/CGRO data on nuclear line emission allows to further constrain the spectral parameters. We also analyze the time dependences of the nuclear line and pion decay emissions, which lasted for at least 2 hours after the flare. We show that although continuous acceleration of particles cannot be ruled out, it is possible to account for the observations by assuming that after impulsive acceleration the particles are trapped in magnetic loops.

1. INTRODUCTION

High energy emissions from the series of X-class flares that occurred in June 1991 were detected with various instruments on CGRO [1,2,3], with GAMMA-1 [4] and with SIGMA/GRANAT [5]. Among the most important results of these observations is the detection for the first time of gamma rays with energies up to 2-3 GeV with EGRET/CGRO from the 1991 June 11 flare [1] and with GAMMA-1 from the 1991 June 15 flare [4]. The remarkable feature of these very high energy emissions is their unusually long durations, especially in the case of 1991 June 11 flare, when the GeV emission lasted for at least 8 hours. In [6] it was argued that the continuous acceleration of particles during an entire time period is unlikely. It was shown that the EGRET data can be fitted with the combination of primary electron bremsstrahlung and pion decay emission resulting from particles that were accelerated in the impulsive phase of the flare and subsequently trapped in coronal magnetic loops. Analysis of the GAMMA-1 data [7] revealed an essentially pionic shape of the spectrum observed from the 1991 June 15 flare, but no scenario for gamma ray production was considered.

In the present paper we analyze the time dependence and the energy spectrum of gamma rays with energies 0.03-3 GeV measured with GAMMA-1 during the 1991 June 15 flare. According to GOES data the soft X-ray emission started at 08^h10^m UT and reached maximum at 08^h21^m UT. No gamma ray observations were made during the impulsive phase of the flare because it occurred during the satellite nights of both GAMMA-1 and CGRO. The GAMMA-1 measurements started at 08^h37^m UT and continued through the next orbit of the satellite (Figure 1). COMPTEL/CGRO observations [2] of nuclear lines were made between the two orbits of GAMMA-1 (08^h59^m UT to 09^h39^m UT) (Figure 1b). Here we combine the GAMMA-1 and COMPTEL data to test the possibilities of trapping and continuous acceleration and to derive the energy spectrum of accelerated ions at the Sun over a broad energy range ($\approx$ 10 MeV - 5 GeV).

2. ANALYSIS

We first consider the possibility that particles were accelerated impulsively and subsequently trapped in magnetic loops. There are indications based on neutron monitor data for this flare that particle acceleration to high energies lasted for 10-15 minutes [8]. However, since we do not know the exact duration of the acceleration, as a first approximation we assume that all the particles were injected into the loop at the time of maximum of the soft X-ray emission (08^h21^m UT). The description of the model and the physical processes was given in [6,9]. We take into account all the relevant losses (ionization, nuclear, synchrotron) except possible particle escape from the loop due to curvature drift. The importance of drifts for extended high energy gamma ray emission was pointed out in [6]. Recently, it was shown [10] that in a loop with a sufficiently twisted magnetic field the drifts are strongly reduced. In the present calculations we consider a loop with radius of 10^9 cm, magnetic field in the coronal part of 100 G, mirror ratio of 10, and two values for the coronal matter density $N_c=10^8$ and 10^{10} cm^{-3}.

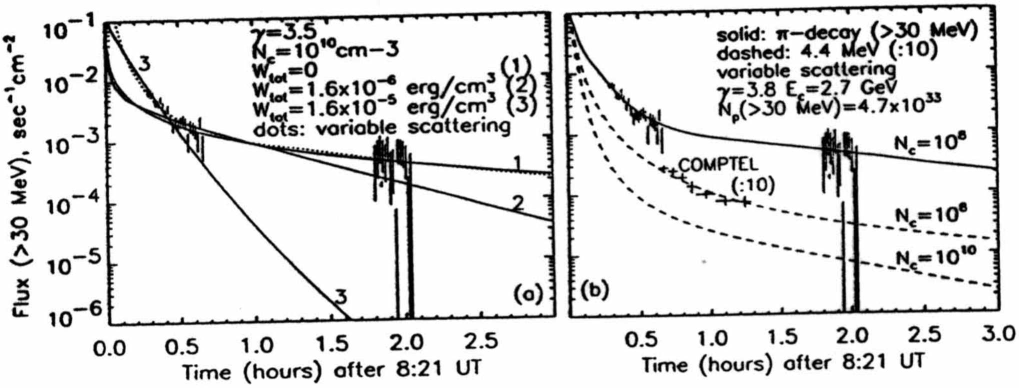

Fig. 1a,b: Pion decay and 4.44 MeV time profiles. Bars: pion decay data (GAMMA-1); crosses: 4.44 MeV data (COMPTEL); N_c is in cm^{-3}.

In Figure 1a we show the measured background subtracted time profile of gamma rays with energies >30 MeV and calculated time profiles of pion decay emission for various rates of particle pitch angle scattering (determined by the energy density in plasma turbulence W_{tot}). We see that the precipitation rate must have decreased at later times. This can be caused, for example, by the expansion of the loop (reduction of the loss cones), or by the damping of the turbulence. The dotted curve, which provides a good fit to the data, was calculated by assuming that the energy density in the turbulence decays exponentially from an initial level of 1.6×10^{-5} ergs/cm^3 with a characteristic time constant of 250 s. In Figure 1b we show time profiles of pion decay and 4.44 MeV ^{12}C deexcitation line emissions calculated with the same variable pitch angle scattering rate and two values of N_c. Also shown is the time profile of 1-10 MeV gamma rays measured with COMPTEL [2]. Since this region is dominated by nuclear line emission, we assume that these data also represent the time profile of the 4.44 MeV line. We obtained the absolute normalization from the measured 4-7 MeV fluence of 12.1 ph/cm^2 (M. McConnell, private communication 1993) and the theoretical ratio $F_{4-7}/F_{4.4}=3.7$. We see that to simultaneously fit the time profiles of nuclear line and pion decay emissions we need a relatively low matter density in the coronal part of the loop. On the time scales considered here, pion decay emission is practically insensitive to this parameter because the bulk of the pion producing ions interact in the subcoronal part of the loop. On the other hand, because of the much higher importance of the Coulomb losses, a significant fraction of nuclear lines are already produced in the corona.

The energy spectrum of the accelerated ions used in Figure 1b is the one that provides the best fit to the energy spectrum of the gamma rays measured with GAMMA-1. We analyzed the spectral data by folding theoretical pion decay emission spectra through the GAMMA-1 response function, adding the background and comparing the result with the data. We have mostly used the spectral data obtained during the first orbit, since the data for the second orbit is less accurate. The theoretical spectra were also integrated over the corresponding time interval and the position of the flare was taken into account. We tested spectra resulting from accelerated ions with various spectral shapes, such as power laws, power laws with exponential cutoffs (characteristic energy E_c), Bessel functions and numerical solutions of the Fokker-Plank equation which describes stochastic acceleration [11]. Unlike Bessel functions, these numerical solutions are valid at all energies. Some of the results are shown in Figures 2a,b and 3a,b and are summarized in the Table. In Figures 2a,b we show the case of power law spectra with exponent $\gamma = 3.5$. In Figure 2a we see that without a cutoff, the theoretical spectrum is too hard at high energies. With E_c=2 GeV we can obtain an acceptable fit, while for E_c=1GeV the spectrum becomes too steep. In Figure 2b we show the corresponding photon spectra. Also shown is the spectrum that corresponds to a Bessel function. We see that even if we take αT=0.1, which is much higher than the typical values obtained from nuclear line ratios [12], the resulting spectrum is too steep at high energies. However, if instead we take the numerical spectrum [11], we can obtain an acceptable fit for the large value of αT=0.085 (see the Table).

In Figures 3a,b we show our best fit which corresponds to a power law with $\gamma = 3.8$ and E_c=2.7 GeV. Here we also show the fit to the spectrum measured during the second orbit and the evolution of the energy spectrum of pion decay emission with time. The prediction that the spectrum becomes harder with time can in principle be used to distinguish between continuous acceleration and trapping. However, currently available spectral data are not sufficiently accurate to test this prediction.

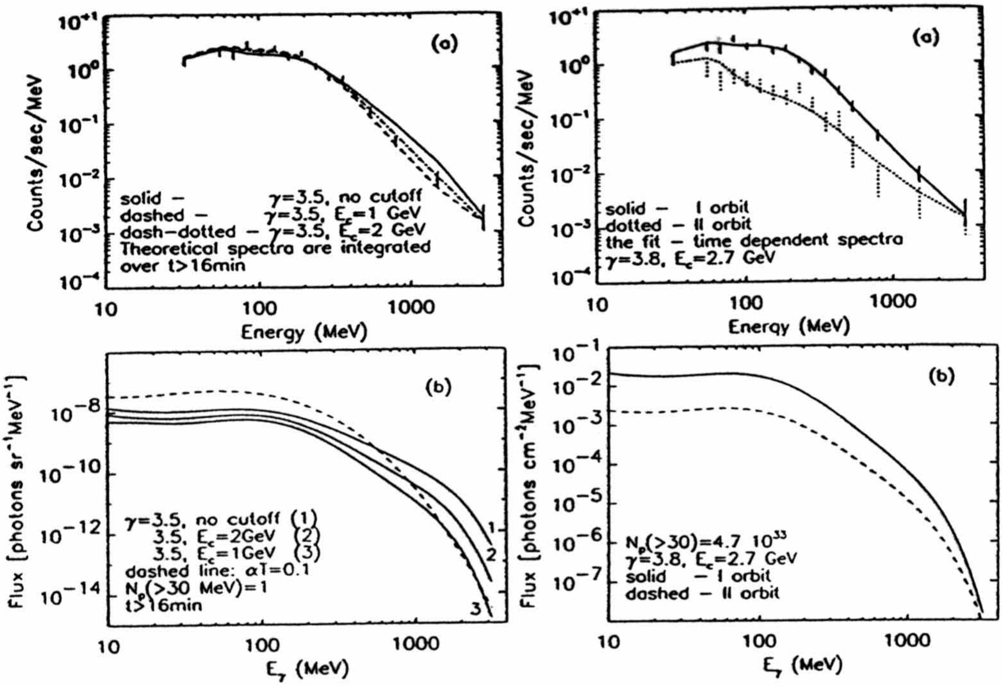

Fig. 2a,b (left panels) and 3a,b (right panels): Measured and calculated energy spectra of pion decay emission. The fits in Figures 2a, 3a were obtained by folding theoretical spectra through the GAMMA-1 response function and adding the background.

As can be seen from the Figure 3a and from the Table the quality of the fit is very good. As we have shown above, the same spectrum allows us to simultaneously fit the time profiles of nuclear line and pion decay emissions. We conclude that the high energy emission measured with GAMMA-1 was purely pionic, i.e. the combination of π^o decay and radiation from secondary $e^{\pm}$.

The Table shows the possible range of spectral parameters. The values of χ^2 (15 degrees of freedom), probabilities and the total number of protons above 30 MeV ($N_p(> 30)$) were derived from the fitting of the GAMMA-1 data. We see that we can exclude power laws with indexes < 3 and > 4.5, as well as the Bessel function. The remaining range can be further narrowed if we incorporate information on nuclear line emission. In the Table we give the calculated total 4.44 MeV line fluence and the fluence in this line integrated over the COMPTEL observing period. These calculations are for the variable pitch angle scattering rate and N_c=10^8 cm^{-3} (Figure 1b). Comparing with the measured fluence, which we estimated to be $\approx$ 3.3 ph/cm^2 (see the discussion above), we see that hard spectra ($\gamma < 3.5$) and the numerical spectrum do not yield enough fluence. On the other hand, the steep spectra ($\gamma > 4$) result in unacceptably high total fluences. Thus, we are left with a power law spectrum with γ=3.8 and E_c=2.7 GeV which is consistent with both the GAMMA-1 spectral data and the GAMMA-1/COMPTEL flux ratio.

We now consider briefly the possibility of continuous acceleration. Interpolating the pion decay flux between the two GAMMA-1 orbits and integrating over the COMPTEL observing period we obtain $F_\gamma(\pi)$=2.15 ph/cm^2. Thus, $F_\gamma(\pi)/F_{4-7} \approx 0.18$. We calculate this ratio for power law spectral indexes of 3.5, 3.6 and 3.7 using [12] with photospheric abundances. We obtain values of 0.19, 0.14 and 0.10, respectively. The corresponding fits to the GAMMA-1 spectral data give χ^2's of 36.7, 34.4, 25.8 and probabilities of 0.1%, 0.3%, 4%. Thus, the spectrum that can provide a good fit to the GAMMA-1 spectral data ($\gamma > 3.7$) is steeper than the one that gives the correct $F_\gamma(\pi)/F_{4-7}$ ratio at later times. However, a power law with γ=3.5 and E_c=2.7 GeV gives $F_\gamma(\pi)/F_{4-7}$=0.18 which is consistent with the measured value and at the same time fits the energy spectrum of the high energy gamma rays quite well (χ^2=19.3, P=20%).

Spectral Parameters	χ^2	P (%)	$N_p(> 30)$	$F_{4.44}$ (cm^{-2}) total	$F_{4.44}$ (cm^{-2}) (COMPTEL)
γ=3.5	40.8	0.034	7.7×10^{32}	72	0.47
" E_c=2 GeV	18.5	24	1.6×10^{33}	147	0.96
" E_c=1 GeV	22.2	10	3.3×10^{33}	310	2.0
γ=3.8, E_c=2.7 GeV	17.0	32	4.7×10^{33}	540	2.7
γ=4.0	28.2	2	6.0×10^{33}	864	3.3
" E_c=3 GeV	19.0	21	7.0×10^{33}	1008	3.8
γ=4.5	18.8	22	3.0×10^{34}	8704	15.
γ=5.	21.2	13	1.3×10^{35}	87040	150.
αT=0.1 (Bess.)	32.2	0.6	4.7×10^{32}	24.8	0.73
αT=0.085 (Num.)	22.1	10	1.1×10^{32}	4.6	0.14

3. CONCLUSIONS

We have shown that the GAMMA-1 and COMPTEL data on pion decay and nuclear line emission are consistent with impulsive acceleration and subsequent trapping of the particles in magnetic loops. We require an energy density in plasma turbulence which decreases with time, and a low ambient coronal density. We determine the spectrum of accelerated particles over a broad range ($\approx$ 10MeV - 5GeV), which can be represented by a power law with γ=3.8 and exponential cutoff at 2.7 GeV. The data is also consistent with the assumption of continuous acceleration, in which case the derived energy spectrum is a power law with γ=3.5 and E_c=2.7.

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