Extended γ-Ray Emission in Solar Flares

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During the solar flare events on 11 and 15 June 1991, COMPTEL measured extended emission in the neutron capture line for about 5 hours after the impulsive phase. The time profiles can be described by a double exponential decay with decay constants on the order of 10 min for the fast and 200 min for the slow component. Within the statistical uncertainty both flares show the same long-term behaviour. The spectrum during the extended phase is significantly harder than during the impulsive phase and pions are not produced in significant numbers before the beginning of the extended emission. Our results with the measurements of others allow us to rule out long-term trapping of particles in non-turbulent loops to explain the extended emission of these two flares and our data favour models based on continued acceleration.

INTRODUCTION

Before the large solar flares in June 1991 occured, γ-ray emission from flares has been observed for no longer than about half an hour. For the 11 June flare EGRET detected emission > 50 MeV for more than 8 hours (1) and COMPTEL detected emission in the neutron capture line for about 5 hours (2) (3). The 15 June flare observations are not as detailed as those from 11 June. However, COMPTEL also measured emission of the neutron capture line for several hours for this flare. The GAMMA-1 instrument observed emission > 50 MeV (4) (5) for a different time period and reported significant emission during the following spacecraft orbit.

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A model for the 11 June flare (6) based on the EGRET measurements explained the extended emission by particles that were accelerated during the impulsive phase and trapped in non-turbulent coronal loops. A different explanation for the emission during the extended phase of a flare (7) favours continuous acceleration of particles in turbulent magnetic loops for long time periods.

Our results for the 11 and 15 June 1991 flares allow us to investigate the question whether long-term trapping or continuous acceleration better describes the prolonged emission. We analyze the COMPTEL measurements and compare them to the results of the EGRET and GAMMA-1 instrument to distinguish between these types of processes.

OBSERVATIONS

The COMPTEL Instrument

The Compton telescope COMPTEL onboard CGRO is sensitive to γ-rays in the energy range from 0.75 to 30 MeV. This energy range contains the major nuclear deexcitation lines and the neutron capture line. Continuum emission in this range is produced by nuclear emission originating from inverse nuclear reactions (broad lines) and electron bremsstrahlung from both primary electrons accelerated directly in the flare and secondary electrons produced by pion decay.

The COMPTEL telescope uses a double scatter technique to get both spectral and directional information of the incoming γ-rays (8). In the ideal case the photons undergo a Compton scattering in one of seven detector modules of the upper detector plane and the scattered photon is subsequently fully absorbed in one of fourteen modules of the lower detector plane. Measuring the energy deposits in both detector planes yields the energy of the photon. It also provides the scatter angle of the Compton interaction in the upper detector and together with the event location in the modules constitutes the imaging capability of COMPTEL.

For solar flare observations the position of the source is known and the imaging properties of the instrument are used for suppressing the instrumental background and for excluding events that are not fully absorbed in the lower detector. Consequently the instrument offers high sensitivity and a nearly Gaussian response for an uncomplicated deconvolution of spectra. The instrumental background of COMPTEL is mostly due to cosmic ray interactions. The intensity of the incident cosmic ray flux varies periodically according to the spacecraft orbit. For a model background we use time intervals about 15 and 16 orbits before and after the flares where the orbit conditions at the time of the flare are reproduced.

All detectors of COMPTEL are shielded by anti-coincidence plastic scintillators. While these scintillators are essential for normal observations, they cause dead time problems for very intense flares. Due to the enormously high flux in soft X-rays during the impulsive phase, these anti-coincidence shields are triggered at a high rate. The dead time fraction can be calculated from housekeeping data. The statistics, however, remain poor under high dead time conditions. Therefore, the sensitivity of the telescope is degraded during the impulsive phase of the flare on 11 June. On 15 June the CGRO observation window allowed only measurements beginning about 40 min after the onset of the flare. At this time the soft X-ray flux has alrady faded and dead time was not a problem.

Extended Emission on 11 and 15 June 1991

The flare on 11 June 1991 was a X12/3B event starting at 0156 UT according to GOES-7. This flare began shortly after orbital sunrise for CGRO and could be observed during the whole orbital daylight period until about 0300 UT. The emission in the 2.2 MeV line was detected by COMPTEL for three more consecutive orbits.

To study the emission, the orbit was divided into twelve time intervals each with approximately equal statistics. Data for the subsequent orbits are time integrated. Each spectrum was corrected for background and dead time effects and was deconvolved using a SVD matrix inversion technique.

To estimate the bremsstrahlung of the primary electrons we use the data of the PHEBUS/GRANAT instrument, that measures photon energies down to 75 keV. The bremsstrahlung continuum as measured by PHEBUS can by described by a power law index of 2.55 ± 0.4 (9) (10). The hard X-ray time profile of PHEBUS in the energy range $310 - 540$ keV (9) is used to represent the time dependence of the bremsstrahlung emission. This bremsstrahlung model is necessary to determine the excess flux in the nuclear line region.

The impulsive phase consisted of several maxima, seen also in microwaves and hard X-rays. After the last peak of the impulsive phase at 0206 UT the prompt nuclear emission fades away and falls below the sensitivity limit at about 0209 UT. At 0213 UT the prompt emission returns. We define this to be the beginning of the extended emission.

The analysis reveals different emission characteristics during impulsive and extended phases: The fluence ratio of the 2.2 MeV line and the $4-7$ MeV range increases from 0.80 ± 0.12 to 1.24 ± 0.12. This indicates that the spectrum is significantly harder in the extended phase of the flare. Furthermore, the emission in the energy range $8 - 30$ MeV can be explained by the bremsstrahlung of the primary electrons during the impulsive phase. In the extended phase, however, the $8-30$ MeV flux exceeds the level expected from primary eletrons. We conclude that this additional component originates from secondary electrons of pionic origin. This observation shows that the major pion production does not begin during the impulsive phase, but is better associated with the extended processes. The time behaviour of prompt nuclear emission and emission at energies $8 - 30$ MeV is correlated during the extended phase. From 0227 UT until the end of the first observation period at 0300 UT the $4-7$ MeV and $8 - 30$ MeV emission decay exponentially with constants of (6.4 ± 0.9) min for the nuclear emission and (7.0 ± 1.2) min for the $8 - 30$ MeV emission.

The impulsive phase of the flare on 15 June 1991, also a X12/3B event, was not observable by CGRO. The observation window opened some 50 min after flare onset. Nevertheless, the γ-ray emission could still be detected by COMPTEL and the flux in the 2.2 MeV line was measured for several hours.

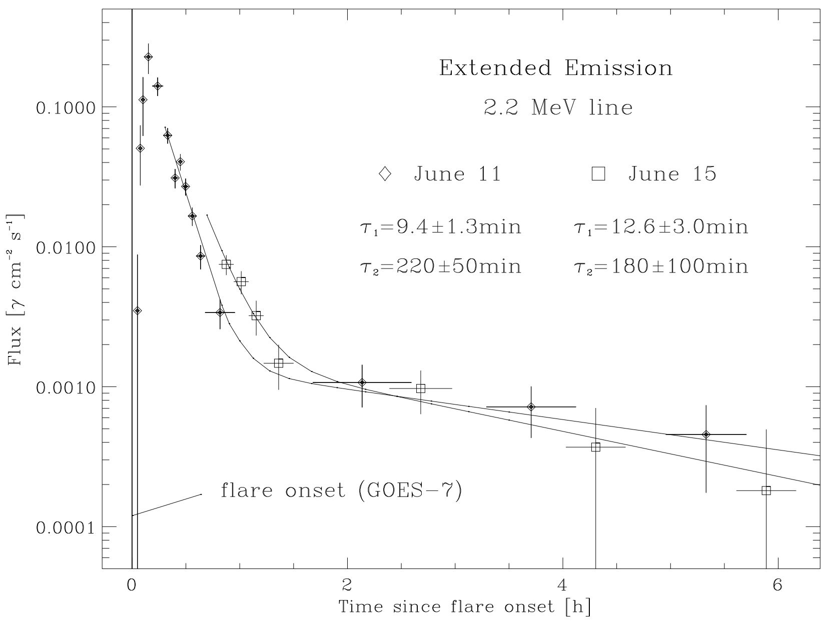

FIG. 1. Extended emission of the flares on 11 and 15 June 1991 in the neutron capture line as measured by COMPTEL.

The time profile of the 2.2 MeV line for both flares is given in figure 1. The origin of the time axis refers to the onset of the flares, i.e. 0156 UT on 11 June and 0810 UT on 15 June. The decay curves are fit by a double exponential decay. The decay constants for 11 June are (9.4 ± 1.3) min and (220 ± 50) min. For 15 June they are (12.6 ± 3.0) min and (180 ± 100) min. Both flares show a similar time profile. Their flux values are of the same order as are their time constants. The transition from the fast to the slow component occurs in the 15 June event about 20 min later than in the 11 June event.

DISCUSSION AND CONCLUSIONS

Our results are not in agreement with an explanation of the extended emission by long-term trapping of particles. The most important implication of a storage model in this context is, that we expect the trapped particles to suffer energy dependent losses (e.g. energy losses due to Coulomb collisions). Particles with MeV energies are removed more quickly than particles with GeV energies. Hence, different spectral components that originate from different energy ranges of the parent spectrum should have different decay times. In our case, the nuclear emission, produced mainly by $10-40$ MeV/nucl. particles, should decay about 30-times faster than the pionic emission, originating from particles with > 300 MeV/nucl. (6).

The COMPTEL measurements of the prompt nuclear emission (from protons with energies between $10-40$ MeV) and the excess in the $8-30$ MeV range from secondary electron bremsstrahlung from pion decay (requiring several 100 MeV protons) have similar temporal behaviours indicating a constant proton spectral shape. This does not agree with the predictions of a storage model. Thus, we conclude that particle trapping cannot play a dominant role in the extended phase of the 11 June flare up to 0300 UT.

For the flare on 11 June the long-term behaviour in the 2.2 MeV line can be compared to the emission > 50 MeV measured by EGRET. The time constants are 25 min and 255 min (1). However, these measurements are based on the spark chamber data only and are restricted to times after 0400 UT due to dead time effects. Therefore, the determination of the short time constant is not very reliable. By also using the TASC data the time profiles show a much steeper decay (11). This shows that both time constants measured by EGRET are consistent with the 2.2 MeV profile measured by COMPTEL. Since the neutrons responsible for the 2.2 MeV line are produced from lower energy protons than pions, their similar intensity-time profile further supports our conclusion that the parent proton spectrum was constant in shape during the extended phase.

The faster decaying component in the EGRET data was explained with primary electron bremsstrahlung (1). Our $8-30$ MeV measurement during the extended phase is above what we expect from primary electron bremsstrahlung. Furthermore, if we assume that this emission is due to primary electrons we expect different time evolution for the $8-30$ MeV emission and the EGRET > 50 MeV measurement and for the 2.2 MeV line or the nuclear emission between $4-7$ MeV (both of nuclear origin). Since we measure a correlated time behaviour, we conclude that the fast decay during the extended phase is dominated by pionic emission rather than primary electrons.

For the 15 June flare the scenario is not as complete, but the data have a similar interpretation. The COMPTEL data of the neutron capture line show the same temporal characteristics as the emission at > 50 MeV as measured by GAMMA-1. Recall that the COMPTEL measurements were made in a time interval after the GAMMA-1 observations. Also in the GAMMA-1 data there is a signal in the following orbit that indicates that there exists an additional slow component declining with a time constant > 100 min. As with the 11 June flare data, these similar time profiles in two different spectral components argue against long-term trapping.

Our data favour an explanation by continuous or episodal acceleration (7). In these models the plasma turbulence does not inhibit the establishment of long time scales but serves to accelerate a new particle population.

Both flares are characterized by at least two components showing different exponential decay times. This may be interpreted in terms of several large scale loops of different sizes. In a highly turbulent environment the particle transport is dictated by diffusion. If the diffusion constant does not vary within the loops, the decay constants are proportional to the square of the loop length. An impulsive loop of 10^9 cm and extended phase loops of $(0.5-1)\cdot 10^{10}$ cm are in the proper ratio to explain the measured time behaviour. Indeed, these are typical loop length for the extended phase that were observed for the 15 June flare in H_α (12). Moreover, both flares show similar time profiles. It appears that the magnetical loop structure on large scales remains stable for several days and the same regions offer the most efficient sites for particle acceleration in both flares.

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