ASTRONOMY & ASTROPHYSICS
SUPPLEMENT SERIES

Astron. Astrophys. Suppl. Ser. **97**, 349-353 (1993)

Detection of a long-duration solar gamma-ray flare on June 11, 1991 with EGRET on COMPTON - GRO

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Received June 3, 1992; accepted August 10, 1992

Abstract. — On June 11, 1991, the Energetic Gamma Ray Experiment Telescope (*EGRET*) on the *Compton Gamma Ray Observatory* (*COMPTON*) observed high-energy gamma radiation above 30 MeV from the sun following an intense flare around 2:00 UT. After the decay of most of the X-ray flare, which caused nearly complete deadtime losses in EGRET, high-energy emission was registered during the interval from about 3:30 UT to at least 10:30 UT. Gamma rays were detected up to energies above 1 GeV. The solar origin of this emission is assured by the time profile of the gamma-ray count rate and by time resolved sky maps, which show a clear maximum at the position of the sun. The gamma-ray lightcurve of the flare can be described with two-components: a fast decaying emission with an e-folding time constant of about 25 minutes and a slow decay with about 255 minutes. There are indications for a spectral evolution with time, such that the emission below 100 MeV fades away earlier than the 100-300 MeV radiation, roughly on the time scale of the fast component. The spectrum of the flare can be well fitted with a composite of a proton generated π^0 spectrum and an electron bremsstrahlung component. The latter can be identified with the fast decaying component of the lightcurve.

Key words: gamma rays — solar flares.

1. Introduction.

Solar flares have been observed in the high-energy gamma-ray range ($\geq$ 10MeV) from satellites since the early 1970's. An almost continuous coverage of the sun from 1980 to 1989 was provided by the Gamma Ray Spectrometer (GRS) on the Solar Maximum Mission (Forrest *et al.* 1980). About 250 flares were detected with SMM above 300 keV, 25 of which showed emission above 10 MeV and a few ($\sim$ 6) extended up to the limit of the spectrometer of 140 MeV (SMM catalogue in preparation, Vestrand *et al.* 1992). Ground level cosmic ray installations indicate that a few exceptional solar flares are capable of producing particles with energies exceeding about 20 GeV (e.g. review by Shea 1990).

Imaging gamma-ray telescopes, like SAS-2 or COS-B, have never been directed towards the sun, either due to a lack of solar activity during the mission or due to attitude constraints.

Emission mechanisms and observations of solar flare gamma rays have been reviewed by several authors (e.g. Ramaty & Murphy 1987, Chupp 1990). Flare accelerated energetic particles which interact in the solar photosphere cause gamma ray emission mostly through three processes: Excited or newly formed nuclei emit gamma-ray lines mostly below $\sim$ 8 MeV; bremsstrahlung from energetic electrons, which either result from direct acceleration or from the decay of charged pions from nuclear interactions, causes typically a power law spectrum that extends up to the energy of the primary particles; the decay of neutral pions from ion induced nuclear interactions results in the characteristic peaked spectrum with a maximum at 68 MeV. All three types of emission have been measured in flares with occasionally one component dominating the spectrum: line flares (Forrest & Murphy 1988, Rieger 1991), nearly pure electron bremsstrahlung flares (Rieger & Marschhäuser 1990) and flare phases with strong π^0 emission (Forrest *et al.* 1985). This latter observation of the flare on June 3, 1982 showed e.g. that π^0 radiation was emitted not only during the flash phase but following it for several minutes.

Akimov *et al.* (1991), detected gamma radiation extending to above 1 GeV from flares on March 26, and June 15, 1991. The latter showed emission lasting to about 2 hours after the flare peak and the time integrated spectrum above 30 MeV was derived. The spectral evolution of this late phase emission could however not be determined due to a lack of statistics.

Usually all high energy photon emissions are observed in close temporal coincidence, i.e. within minutes, with other manifestations of the flare, such as X-ray, optical and radio emissions. Neutral radiation, delayed by typically 10-20 minutes from the flash phase, has been observed in several flares and is generally attributed to the arrival of solar neutrons. The latest observation of neutrons was reported for the June 9, 1991 flare by the *COMPTEL* team (Ryan *et al.* 1992).

It should be noted that the observations with the *COMPTON* instruments allow for the first time a clear discrimination between solar neutrons and photons. The earlier scintillation detectors provided only circumstantial evidence for the type of neutral radiation and it was therefore difficult to separate photons and neutrons late in the flares.

In this paper we report the detection of high energy photon emission from the flare of June 11, 1991. The gamma radiation in the range around 100 MeV was observed for at least 8 hours following the flare. We briefly discuss some implications for the storage and release mechanisms of the primary particles with energy of typically a GeV implied by these gamma ray observations.

2. Observations.

2.1. The EGRET instrument

The *EGRET* instrument on *COMPTON* is a spark chamber telescope in the tradition of the SAS-2 and COS-B experiments flown in the 1970's. Its sensitivity is larger by about an order of magnitude with respect to the pioneering instruments due to the larger size and the extremely low internal background. The components of *EGRET*, typical for this type of instrument, are an anticoincidence system (ACS) to discriminate against charged particle radiation, a spark chamber to measure the tracks of the pair particles produced in the interspersed conversion foils, a triggering telescope to detect the presence of a pair creation event and finally an energy calorimeter (8 radiation lengths of NaI(Tl)) to measure the energy of the photon induced cascade. More instrumental details can be found in the descriptions by Hughes *et al.*,(1980), Kanbach *et al.*, (1988,1989) and Hartman et al.,(1992). The results of the instrument pre-flight calibration and performance in orbit are given by Thompson *et al.* (1992). The sensitivity of *EGRET* extends over the energy range from about 20 MeV to over 30 GeV with a broad maximum of the effective area of 1.5×10^3 cm^2 in the range 500 MeV to 1 GeV.

The *COMPTON* Gamma Ray Observatory was in a low earth orbit (altitude 430 km, orbital period 93 minutes, inclination 28.5 degrees) such that a target close to the equatorial plane will be occulted by the earth for half of the time. To suppress the registration of the strong earth albedo gamma radiation *EGRET* switches through a series of instrumental modes that inhibit the instrument when the atmosphere comes into the field of view. During a solar flare the intense X-ray emission leads to very high rates in the anticoincidence system of *EGRET*, which is sensitive down to several tens of keV. The high ACS rates introduced into the coincidence system lead to substantial deadtime which essentially precluded the registration of gamma-ray events in the spark chamber during the X-ray flaring phase of the solar event. Nevertheless there is a continuous monitoring of the radiation incident on the energy calorimeter: every 32.768 seconds the accumulation of a spectrum from this large NaI scintillator is being recorded between about 1 and about 200 MeV in a so-called Solar Mode. Data from this mode will be presented in a later paper.

2.2. The flare of June 11, 1991

On June 11, 1991 the GOES satellite registered in the 1-8 Angstrom X-ray band an intense flare from the prolific sunspot region no. 6659 commencing at 01:56, peaking at 02:09, and entering a gradual decay phase after a substantial decrease by 02:20 U.T. The flare reached an X-ray flux of about 10^{-3} Watts m^{-2} (Class X12.0), its optical brightness was classified as 3B and the location was 31° north of the solar equator and 17° west of the meridian. The heliocentric angle of this flare for the observer is thus about 35°.

COMPTON entered the sunlit part of the orbit on 1:57 U.T. Until spacecraft sunset around 2:38 U.T. the *EGRET* trigger was inhibited due to the high X-ray intensity which generated so much deadtime in the anticoincidence that only 3 events potentially coming from the sun could be registered in the spark chamber during this orbit. However, during the following orbits (until 12:00 U.T.) a strong flux of events was recorded in the spark chamber. Their directional distribution is consistent with the EGRET point spread function at the respective energies and their origin agrees with the position of the sun. In figure 1 a diagram of the temporal evolution of the flare above 50 MeV is shown. The deadtime loss during the time intervals with a positive solar flux varied from essentially 100% right after the flare peak (2:00 UT) to less than 30% after 3:40 U.T. The net solar flux depicted was derived by estimating the background from orbits offset from the corresponding flare orbit by $16 \times n$ orbits, where $n = -3, -2, -1, +1, +2, +3$. This method for background subtraction approximates similar geomagnetic conditions for the satellite and thus, despite the very low sensitivity to cosmic ray induced background in *EGRET*, any influence is minimized.

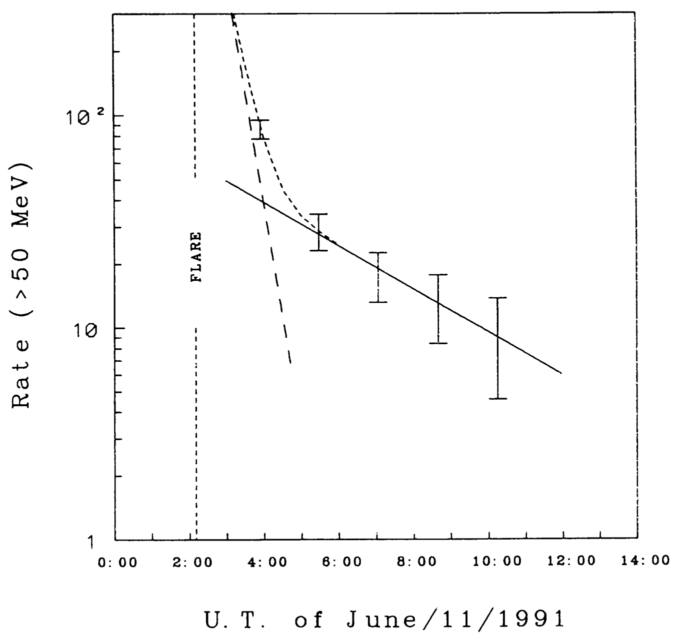

FIGURE 1. Time profile of the solar emission > 50 MeV on 1991, June 11, 1991. The two-component fit to the time profile is discussed in the text. The e-folding time constants derived are about 25 and 255 minutes.

The rate of solar emission shown in figure 1 falls off rather sharply from the first to the second measured point and then enters a gradual exponential fall-off. The slow component, that extends at least from 5:30 to 10:30 U.T., can be fitted with an exponential time constant of 255 minutes. It is reasonable to assume that this slow component is present already at 4:00 U.T. during the first measured point. The extrapolated value of the slow component rate around 4:00 accounts for about 45% of the count rate at that time. It is assumed that the rest of 55% of the rate (> 50 MeV) decays exponentially to an insignificant level until the next exposure at 5:30. The resulting two component description of the time profile has a fast component which decays from about 3:30 to 5:00 with a time constant of about 25 minutes and a continuous slow component which decays with a 255 minutes time-scale. This two-component fit is shown in figure 1.

A spectrum from the intense part of this flare from 3:26 to 6:00 hours UT is shown in figure 2. It is quite evident that no simple fit function can represent this spectrum. Mandzhavidze & Ramaty, 1992 and Ramaty *et al.*, 1992 have performed calculations in the frame of a coronal storage loop model with interactions taking place mostly at the photospheric footpoints of the loop. They derive the pion generated gamma-ray spectrum from nuclear interactions for the Akimov *et al.* measurement of the June 15, 1991 flare. Although this flare is at about 72° heliocentric angle and the June 11 flare is at 35° both can still be considered 'disk'-flares and are therefore comparable. Two cases for proton power law spectra have been calculated by Ramaty *et al.* (indices $s = 3$ and 4) and we include them in the spectrum after suitable normalisation at about 300 MeV. The number of energetic protons > 30 MeV required to produce the fluence of gamma rays between 3:26 and 6:00 U.T. is about 2×10^{30} and 6×10^{31} for $s = 3$ and 4 respectively. It is interesting to note that the different required normalisations have as a consequence markedly different fluences of prompt gamma-ray lines (4 - 7 MeV) and high energy neutrons: the steep s=4 proton spectrum generates about 60 times more prompt lines and about 6-9 time more neutrons with energies around 100 MeV than the $s = 3$ spectrum.

Both theoretical spectra fit the data well although $s = 4$ with its steeper high energy spectrum is slightly preferred. It is striking that the radiation of this flare between 200 and 2000 MeV can be completely explained by π^{o}-radiation.

Below 200 MeV a significant excess can be noted. It cannot be due to secondary bremsstrahlung from $\pi^{\pm}$ produced electrons since this component is included in Ramaty *et al.*'s calculation. If one subtracts the pion component from the data between 50 and 300 MeV one obtains a spectral component, the excess, that can be reasonably well described by an $E^{-2.4}$ power law. In the given energy interval this power law component contains about 50% of the flux from the sun, which agrees well with the intensity contained in the fast component of the time profile. A tentative interpretation of this power law component is of course that it is generated by a population of electrons with a similar power law spectrum and energies extending to several hundred MeV.

The relative spectral evolution of the flare can be analysed quite independently from uncertainties in the instrument's calibration by a two-color photometry method: the number of 'background corrected counts' above and below a chosen energy result in a hardness ratio. We chose 70 MeV for the dividing energy. The counts registered from a 67% enclosure cone around the sun (energy dependent follow-

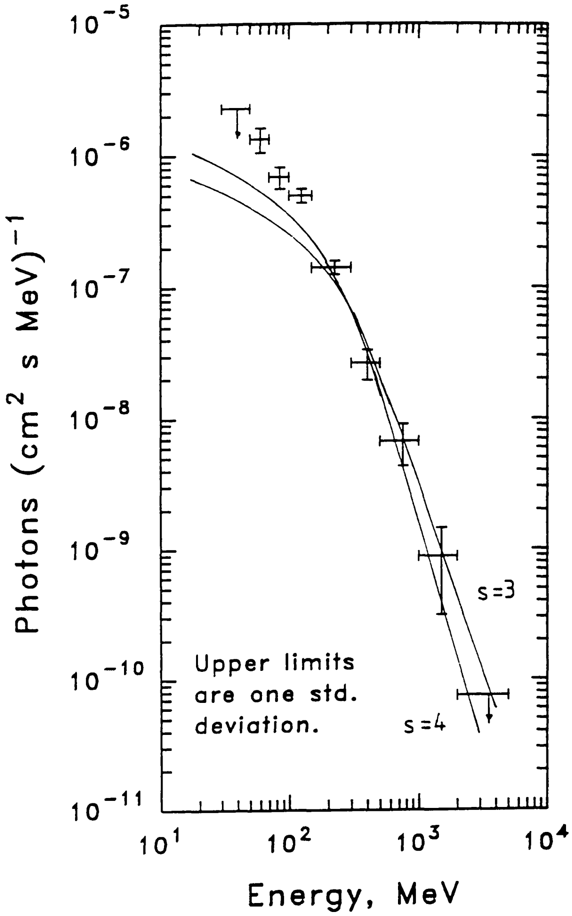

FIGURE 2. Spectrum of the solar flare on 1991, June 11 between 3:26 and 6:00 U.T. The theoretical spectra were calculated by Ramaty *et al.*, 1992.

ing the instrument's point spread function) corrected for background are given in Table 1.

TABLE 1. *Background corrected solar counts in two energy intervals.*

Time U.T.	> 70 MeV	50-70 MeV
3:08 - 4:42	129 ± 12	32.0 ± 6.1
4:42 - 7:52	68 ± 9	0.4 ± 3.5
7:52 - 11:02	22 ± 6	-0.2 ± 2.8
11:02 - 14:02	2 ± 4	1.2 ± 2.7

From the numbers in Table 1 it is clear that the low energy part of the flare emission has completely decayed after about 5:00 U.T.

3. Discussion and conclusions.

3.1. ELECTRON BREMSSTRAHLUNG

The flare of June 11, 1991 at 2:00 U.T. was well observed by the Toyokawa Radio Telescope in Japan at frequencies ranging between 1.0 and 9.4 GHz. (Monthly report of the Toyokawa Observatory and Shinzo Enome, private communication). After the initial flash the radio flare decays between 3:00 and 4:00 U.T. with exponential time constants of 20 to 30 minutes, the latter applicable to the higher frequencies. This radio emission (presumably synchrotron emission in the top part of a coronal loop) might be associated with the gamma ray bremsstrahlung component detected in the same time interval with approximately the same time dependence. As an order of magnitude example, a 100 MeV electron moving with an angle α relative to the magnetic field of strength B (Gauss) emits a synchrotron spectrum with a maximum at about $50 \cdot B \cdot \sin\alpha$ GHz.

It is not known if the time profile indicated for the 50-300 MeV radiation is caused solely by precipitation from a storage region or if continuing acceleration of electrons is present and shapes the lightcurve. In the following discussion it is assumed that no new particles are produced in this phase of the flare. The smoothness of the radio and X-ray time profiles could be an indication that the flare acceleration processes, which often produce highly fluctuating intensities, have ceased after 3:00 U.T.

The lifetime of an energetic electron population in a coronal loop is determined by the size of the storage region, the magnetic field and the turbulence and gas density conditions in the loop. The magnetic field and its geometry determine the synchrotron losses whereas the latter factors influence the direct escape from the storage region and the bremsstrahlung losses. Modelling of the transport and bremsstrahlung production of relativistic electrons has been performed by Miller & Ramaty, 1989. The flares considered by Miller & Ramaty exhibit decay time constants for the bremsstrahlung components in the range of 5-15 seconds. The present data show much longer time scales and require therefore new calculations which are beyond the scope of this paper. Suffice it to point out that the synchrotron lifetime of a 100 MeV electron (as in the above example) is $1.5 \times 10^6 \ (B \sin\alpha)^{-2}$ seconds. If the synchrotron loss dominates the time constant of these electrons in the present flare the magnetic field in the storage region ($B_\perp$) should be about 30 Gauss.

It should be noted that the X-ray emission from 1-8 Angstroms between about 2:30 and 4:30 also shows this characteristic decay time of about 25 minutes. One could interprete this X-ray component as a thermal plasma emission that is heated by the energetic electron population.

3.2. Protons

Protons capable of generating pions in nuclear interactions (threshold 300 MeV) must be present in this solar flare for an extended period of time. The observed time constant of about 255 minutes exceeds by about a factor of 5 any previously recorded high energy decay time constant of a flare. Two cases for the generation and maintenance of such a proton population can be envisioned: one based on the idea of a continous acceleration and diffusion in a turbulent storage loop (recently treated by Ryan & Lee, 1991), or the other alternative with the injection of flare accelerated particles into a coronal loop with subsequent release of particles into the photosphere (see Miller & Ramaty, 1989, Ramaty *et al.*, 1992, Mandzhavidze & Ramaty, 1992). The release time constant is determined by the size of the loop, the pitch-angle scattering characteristics and the depth of the mirror points in the transition zone to the photosphere.

Continous re-acceleration of particles does not seem to happen late into the flare of June 11, 1991 since the electron population disappears without being replenished at about 4:30. Consequently, the following discussion concentrates on the quiet coronal loop storage model.

If nucleon-nucleon interactions and ionisation losses are the only mechanisms determining the proton population at energies between 500 and 1000 MeV the effective density (averaged over the particle trajectories) allowable in the storage loop cannot exceed a value of about 6×10^{10} H-atoms/cm^3. This density is typical for a height over the photospere of 5000 km and the scale height of the solar atmosphere around this altitude is about 700 km. This indicates already that the particles must be trapped in a storage region that extends to a height of above 5×10^8 cm.

The model calculations of Mandzhavidze & Ramaty, 1992 showed clearly that wave turbulence in the storage area, which causes pitch angle scattering, will curtail the lifetime of the trapped particles significantly. Lifetimes in the range of seconds are expected for the case of saturated scattering, i.e. when the characteristic time for pitch angle scattering across the loss cone half angle is comparable to the transit time of the particle through the loop. When the energy density in the turbulence is reduced, the timescale of the emission at late times in the flare is lengthened. In one of the calculated examples the level of turbulence is reduced to about 0.003 of the saturation energy density. The decay time scale about an hour after the flare is then around 400 seconds. Only the model calculations with no pitch angle scattering assumed reproduce approximately the time scale of several hours observed late in the flare of June 11, 1991.

Acknowledgements.

The authors thank the referee for helpful comments. The German contribution to the EGRET project was funded by the Bundesministerium für Forschung und Technologie under grant 50 QV 90955.

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