EXTENDED GAMMA-RAY EMISSION OF THE SOLAR FLARES IN JUNE 1991

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ABSTRACT

In June 1991, a series of six X-class solar flares took place in the active region 6659. We present measurements of gamma-rays that were performed with the Compton telescope COMPTEL during the flares on 9, 11 and 15 June 1991. COMPTEL measured extended emission in the neutron capture line lasting for several hours after the impulsive phase. The time profiles of both flares 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 all three flares show the same long-term behaviour.

Comparing our results with those of other instruments we find that the decay times are independent of the energy of the accelerated protons. This favours the continuous acceleration of particles over long-term trapping as the explanation of the extended emission.

The first hour of the flare on 11 June 1991 was studied in more detail. We examine the evolution of the gamma-ray spectrum and the ratio between the intensities of the 2.2 MeV line and the prompt nuclear lines. We find that the spectrum during the extended phase is significantly harder than that during the impulsive phase. Pions are not produced in significant numbers before the beginning of the extended emission.

INTRODUCTION

During the period of high solar activity in June 1991 a series of six X-class flares occured. The instrument COMPTEL onboard CGRO observed the three flares on 9, 11 and 15 June 1991.

One of the most compelling findings from the June 1991 flare observations was prolonged gamma-ray emission after the flares: For the flare on 11 June the EGRET instrument measured >50 MeV radiation for more than 8 hours (Kanbach et al. 1993) and COMPTEL detected emission in the 2.2 MeV neutron capture line for about 5 hours (Ryan et al. 1993; Rank et al. 1993). Although the impulsive phase of the 15 June flare happened during orbital night for CGRO, COMPTEL measured gamma-ray emission for several hours. The GAMMA-1 instrument observed >50 MeV gamma-radiation later and detected emission during the following orbit (Akimov et al. 1991; Kocharov et al. 1994). For the flare on 9 June, a 20–200 MeV time profile measured by EGRET has been published for the flare orbit (Schneid et al. 1996). Here, we present the first results for the long-term 2.2 MeV line measured with COMPTEL.

An early model based on long-term trapping of accelerated particles was calculated by Ramaty & Mandzhavidze (1993) for the 11 June 1991 flare. However, from the CGRO and GAMMA-1 measurements it could be shown (Rank et al. 1995), that the measured gamma-ray time profiles are not compatible with a magnetic trapping scenario. This can also be shown directly from COMPTEL measurements of the first hour of the 11 June flare. Possible theories to explain the extended gamma-ray emission are the continuous acceleration throughout the extended phase or alternating periods of acceleration and short-term particle storage.

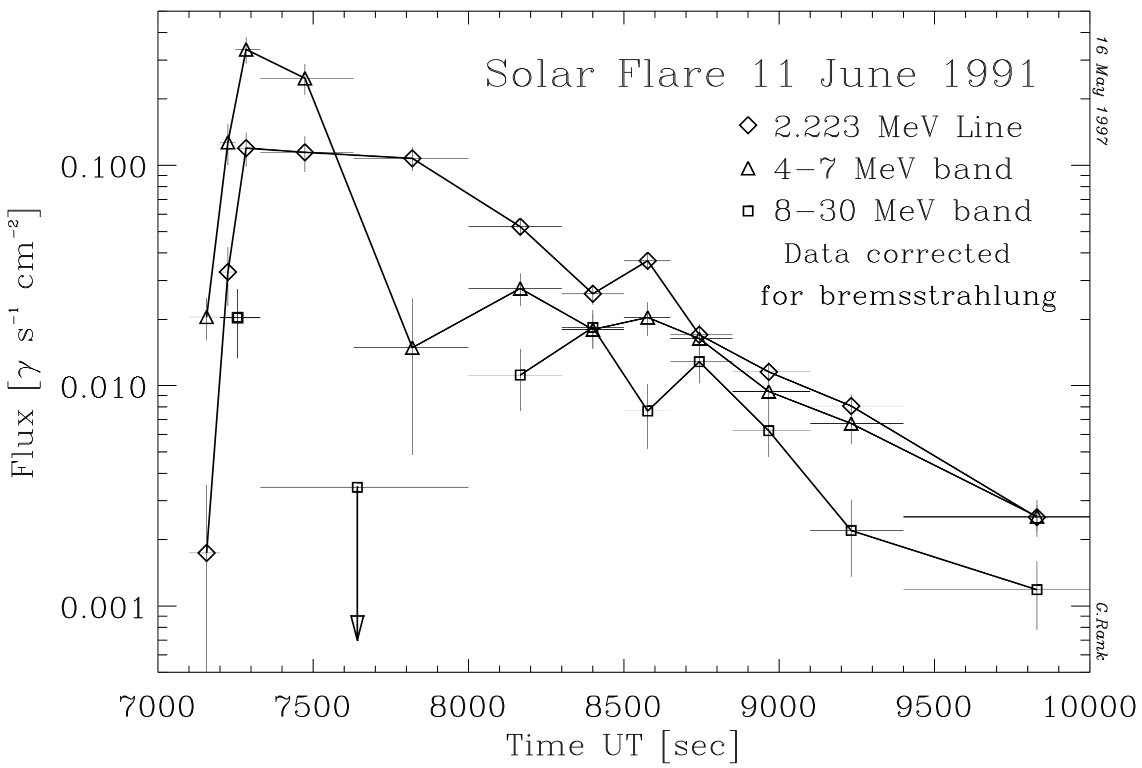

Fig. 1: Fluxes for three spectral components for the flare of 11 June 1991 (first hour).

OBSERVATIONS

The COMPTEL Instrument and Solar Flare Data Analysis

The Compton telescope COMPTEL is designed for imaging and spectroscopy of gamma-rays in the energy range 0.75 to 30 MeV (Schönfelder et al. 1993). For solar flares, the imaging capability of the instrument can be used to suppress background. Also the periodicity of the radiation environment with the satellite orbit is used for background estimation. We use a Monte-Carlo code to simulate the instrument response for every flare and then perform a maximum entropy deconvolution for the flare spectra.

The first hour of the 11 June 1991 Flare

This flare occured shortly after orbital sunrise. This permitted an uninterrupted observation of about one hour. The fluxes for the 2.2 MeV line, the 4–7 MeV band and the 8–30 MeV band for this time period are given in figure 1. The 2.2 MeV line originates from neutron capture onto hydrogen in the solar photosphere, the 4–7 MeV band is dominated by prompt nuclear deexcitation lines, while the 8–30 MeV band can be attributed to the bremsstrahlung of secondary electrons that are produced in the decay of charged pions. The spectrum obtained with PHEBUS/GRANAT (Trottet et al. 1993; Vilmer 1994) has been used to construct a bremsstrahlung spectrum with an index of 2.55 (Trottet 1995). We subtracted it from the COMPTEL flux values to obtain a spectrum of nuclear origin.

At the peak of the flare, nuclear lines are prominent and the fluence ratio $\Phi = \phi_{2.2MeV}/\phi_{4-7MeV}$ (time integrated for several 100 seconds) stays below 1. At later times, starting at 8000 s UT, the 2.2 MeV line is very prominent and the ratio increases to values between 1.0 and 2.0. The 8–30 MeV flux shows a short maximum early in the flare, but stays under the sensitivity limit until 8000 s UT. After about 8500 s UT all three curves show a smooth exponential decline with similar decay times.

From these measurements we can devide the flare into three stages: The impulsive phase from about 7000 s to 7630 s UT shows a small fluence ratio Φ, indicating a soft spectrum. Some evidence of pion production occurs at the beginning of the impusive phase. The extended phase after 8000 s UT shows a high value of Φ, together with a strong pion signal. The interval from about 7630s to 8000s, which might be called a transition phase, reveals a very reduced prompt line production but a strong 2.2 MeV signal. Modelling of this phase, using both telescope data and single detector data, indicates that a very long capture time for the neutrons is necessary to explain this ratio. While a high fluence ratio itself would point to a rather hard proton spectrum, the long capture time and the fact that no pion signal is detected during this phase argues for a very soft proton spectrum instead.

Long-Term Time Profiles

Figure 2 shows the long-term time profiles for all three flares. We present the flux in the 2.2 MeV line where COMPTEL is most sensitive. While the impulsive phases could be observed on 9 and 11 June, for the 15 June flare it occured during orbital night. The time profiles are aligned at flare onset in SXR according to the times given by the GOES-6 satellite (0134 UT for 9 June, 0156 UT for 11 June and 0810 UT for 15 June). We find that all three flares produce a very similar temporal behaviour on hour time scales and the decline can be described as a double-exponential decay. The 2.2 MeV line is the only significant feature in the COMPTEL

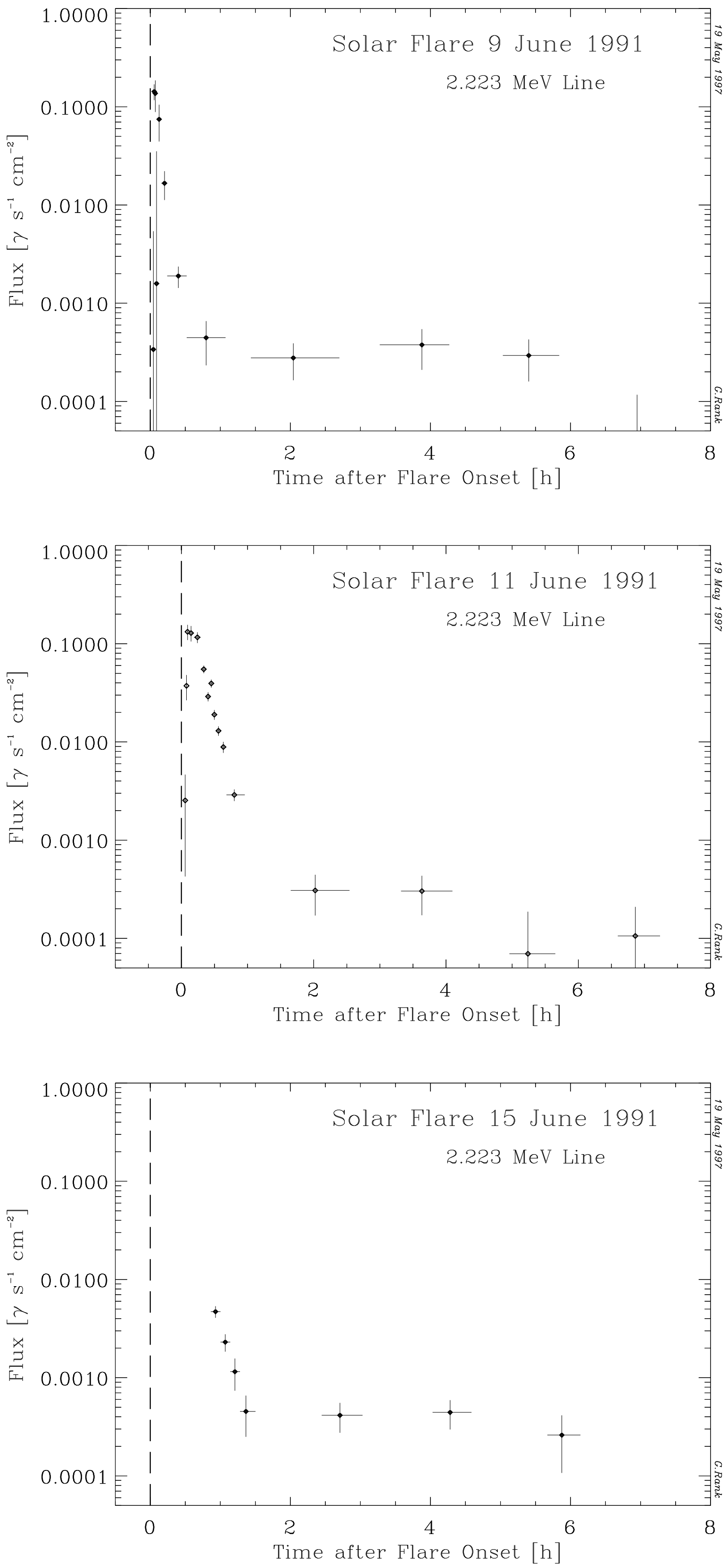

Fig. 2: Long-term time profiles in the 2.2 MeV neutron capture line for all three flares. All times are aligned to flare onset. See text for further details.

spectrum, but a 4–7 MeV signal is present at later times with a value of Φ that does not appear to change dramatically during the extended phase.

DISCUSSION

The first orbit of the 11 June flare (figure 1) shows a smooth decay of the emission during the early extended phase. The profiles can be described by an exponential decay with a decay constant on the order of 10 minutes for all shown energy bands. As these spectral features originate from quite different parts of the parent proton spectrum, this shows that the shape of the proton spectrum does not change significantly during the extended phase. This contradicts the scenario of trapped particles that would suffer energy-dependent energy losses. The same argument can be used when comparing the COMPTEL results to the $>$50 MeV gamma-ray time profiles as measured by EGRET for the 11 June flare and GAMMA-1 for the 15 June flare. In both cases the low-energy and high-energy gamma-ray signal decays with a similar time constant over time scales of hours. Models to explain the observations have been proposed to be the continuous acceleration of particles throughout the extended phase in turbulent magnetic loops (Ryan & Lee, 1991) and the episodal acceleration of particles followed by short-term trapping in magnetic loops with non-turbulent conditions. Given the time resolution available from our data, no distinction can be made between the models.

All three time profiles show the same overall time profile. It is interesting to note, that there seems to be even a slight enhancement in the emission about 2 to 3 hours after flare onset, producing a late maximum about 4 hours after onset, before decaying more rapidly. This can only be explained by newly accelerated particles, but not by storage alone. The remarkable similarity between the three flares, that span a period of six days, raises the question as to whether an expanding post-flare loop system goes through reproducible stages of particle acceleration after each of these flares, or if there are stable loops that remain unchanged during and between the events and can then be populated repeatedly in the acceleration process.

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