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THE SOLAR FLARE ON 15 JUNE 1991

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ABSTRACT

In June 1991 the Sun produced a series of six X-class flares. For the flare event on 15 June 1991 there exists a rich set of measurements, including H_α, radio and microwaves, X-rays, gamma-rays, neutrons and interplanetary protons.

Using some of these measurements we are able to obtain a composite photon spectrum spanning the energy range from about 25 keV to 4 GeV.

From the gamma-ray and neutron results of COMPTEL and GAMMA-1 we can determine the spectrum of the accelerated protons. We find that COMPTEL gamma-ray data are consistent with a proton power law spectrum with index 3.3 over the energy range 10–200 MeV. To simultaneously fit the higher energy GAMMA-1 measurements, the spectrum must steepen at a few hundred MeV.

INTRODUCTION

The flare on 15 June was one in a series of six X-class flares that all originated from the same active region, NOAA 6659. The event was well observed including photons in different energy regimes and particle data. For three of these flares, extended gamma-ray emission on time scales of many hours was measured by different instruments (see Rank et al., this volume).

We used gamma-ray measurements of the instruments BATSE and COMPTEL onboard CGRO and GAMMA-1 on the GAMMA satellite to construct a composite gamma-ray spectrum over a wide energy range. We also used the different gamma-ray measurements of COMPTEL and GAMMA-1 and the neutron measurements of COMPTEL and GAMMA-1 to construct the spectrum of the accelerated particles during the extended phase. Basic data on the instruments and the observations are given in table 1.

Table 1: Energy Ranges and Observation Times

Instrument	Measurement	Energy	Time Interval
COMPTEL	γ-rays	1 – 30 MeV	9:02 - 9:40 UT
	Neutrons	10 – 100 MeV	9:02 - 9:40 UT (arrival)
			8:10 - 9:10 UT (production)
BATSE	HXR/γ-rays	25 keV – 2 MeV	9:02 - 9:40 UT
GAMMA-1	γ-rays	30 MeV – 5 GeV	8:37 - 9:00 UT

OBSERVATIONS AND RESULTS

A Composite Gamma-Ray Spectrum of the Extended Phase

We used the data from three gamma-ray telescopes with different energy ranges to construct a combined photon spectrum ranging over four decades in energy from 25 keV to 5 GeV. The spectrum reflects the emitted gamma-ray flux during the extended phase of the 15 June flare and is shown in figure 1.

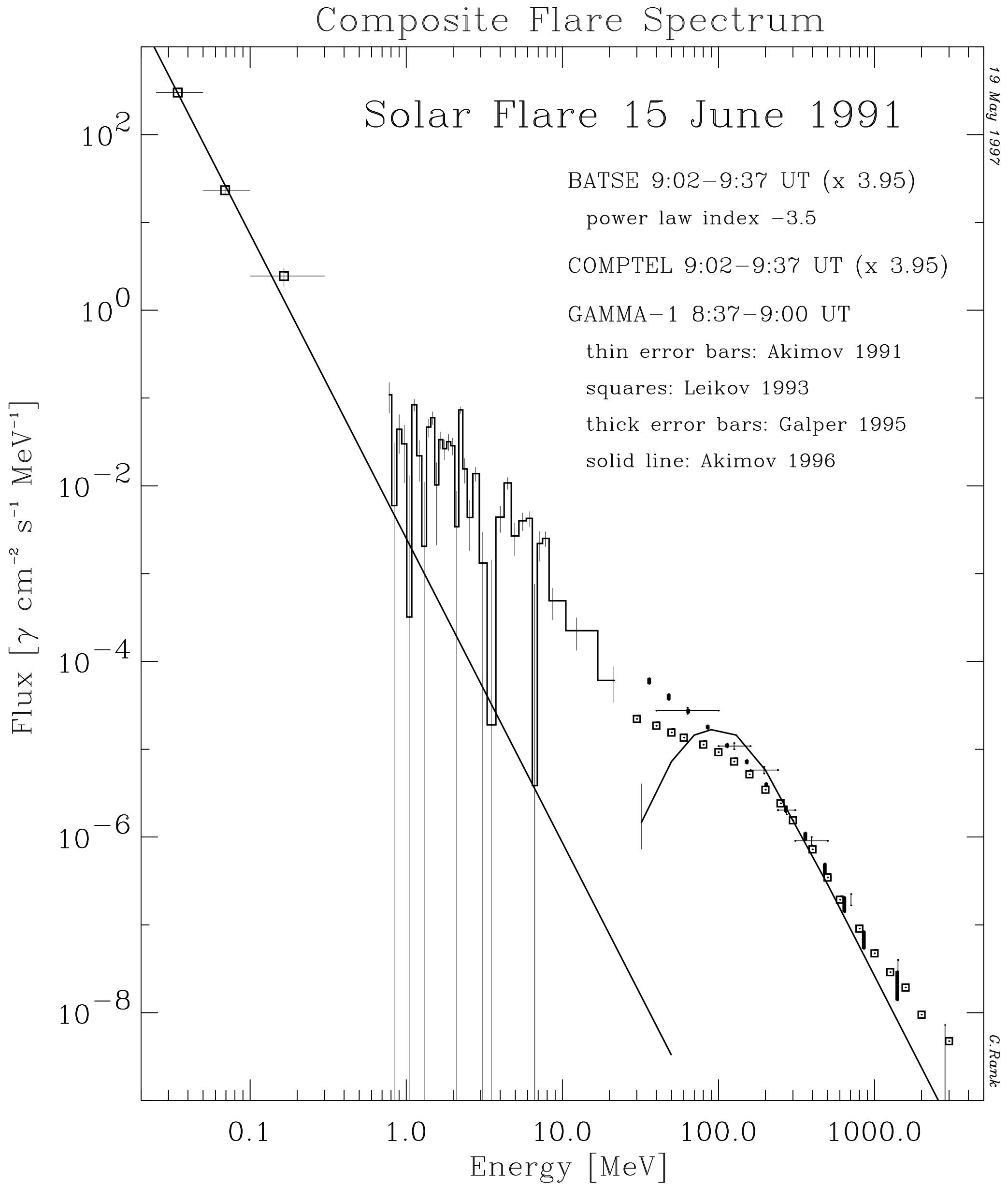

Fig. 1: Composite spectrum for the extended phase of the 15 June 1991 flare. The CGRO spectra have been scaled up by a factor of about 4 to compensate for the different observation times.

The spectra cannot be compared directly, since CGRO and GAMMA-1 did not observe the Sun concurrently. It has been pointed out by Akimov et al. (1994) and others that both gamma-ray time profiles follow the measured microwave emission at different frequencies remarklably well. We integrated the microwave curve at 9.1 GHz as measured at Zimenki station (published in Kocharov et al. 1994) for both observation intervals. From this we conclude that the emission has decreased by a factor of about 4 from the earlier (GAMMA-1) to the later (CGRO) observation.

The BATSE results are from the public data archive and we use spectra of the most sunward LAD detector consisting of four energy channels. The three lower channels contain predominantely source signal and the background can be easily accounted for. The highest channel from 300 keV to 1.9 MeV, however, needs a more sophisticated background subtraction treatment and is omitted here. The BATSE data points can be represented by a power law of index -3.5.

The COMPTEL datapoints are given as a histogram with about 2σ energy resolution. All data above 8 MeV are combined into three data points.

Different deconvolved spectra of the GAMMA-1 data have been published. We have included the deconvolution of four authors in the plot (see the references for further details on the methods).

The spectrum shows a power law continuum of the primary electrons below about 1 MeV and lines dominate over this continuum in the MeV range. The BATSE and COMPTEL spectra fit well together, although the actual increase of the nuclear emission around 800 keV is not represented. The GAMMA-1 spectra differ by more than an order of magnitude on the low end of the sensitivity range. While the spectrum of Akimov et al (1996) looks like an almost pure π^0 spectrum with a sharp turnover at lower energies, all others have a monotonically decreasing shape and imply a strong component of charged pions. COMPTEL also measures significant emission over the electronic continuum in the 8–30 MeV band. This fits well with the GAMMA-1 deconvolutions that predict a stronger emission at lower energies but agrees poorly with the Akimov et al (1996) spectrum.

The Accelerated Proton Spectrum

To investigate the accelerated proton spectrum between about 10 and 200 MeV we first use gamma-ray and neutron results from COMPTEL. The proton spectrum is assumed to be a power law of the form $N_P \propto E^{-S}$. The methods are probing proton energies in the range of 10–200 MeV.

• 10–100 MeV Neutrons

COMPTEL can image solar neutrons (see McConnell et al. 1993) and measure the individual neutron energies. The measured neutron spectrum depends on both N_P and S. However, as the neutron spectrum at these energies flattens out, it is not very sensitive on S. The deduced values span a wide range with $S < 4.2$ (Nieminen 1997).

• Fluence in the 4–7 MeV band

The emission in the 4–7 MeV energy band is dominated by prompt nuclear lines. By comparing with theoretical models of nuclear emission (Ramaty et al. 1993) we determined the combinations of N_P and S that can explain the observed fluence.

• Fluence ratio between 2.2 MeV line and 4–7 MeV band

This ratio sets rather narrow limits on the spectal index. However, it only is sensitive to the spectral shape and provides no information on the absolute number of protons. Using the calculations of Hua & Lingenfelter (1987) we find a fluence ratio of 0.8 ± 0.15. For isotropically interacting protons, this indicates a spectral index for the protons of $S = 3.3 \pm 0.2$.

The resulting parameter space for the extended phase spectrum of the 15 June 1991 flare with all three estimates is shown in figure 2. We obtain a best-fit proton spectrum with an index of $S = 3.3 \pm 0.1$ and a number of interacting protons of $N_P(> 30\text{MeV}) = (2.9 \pm 0.4)10^{32}$.

The power law spectrum for the 10–200 MeV protons obtained from COMPTEL data predicts a higher $>$100 MeV gamma-ray fluence from pion decay than is actually measured by GAMMA-1. To explain both measurements, we assume a broken power law of the form

$$N_P \propto E^{-S} \quad \text{for} \quad E < 300\text{MeV}$$

$$N_P \propto E^{-(S+D)} \quad \text{for} \quad E > 300\text{MeV}$$

where D is on the order of 2. Such a proton spectrum has a turnover at a few hundered MeV. From spectral studies of the GAMMA-1 data alone, a hard spectrum ($S = 3$) seems to be required for gamma-energies above 1 GeV (Galper et al. 1995).

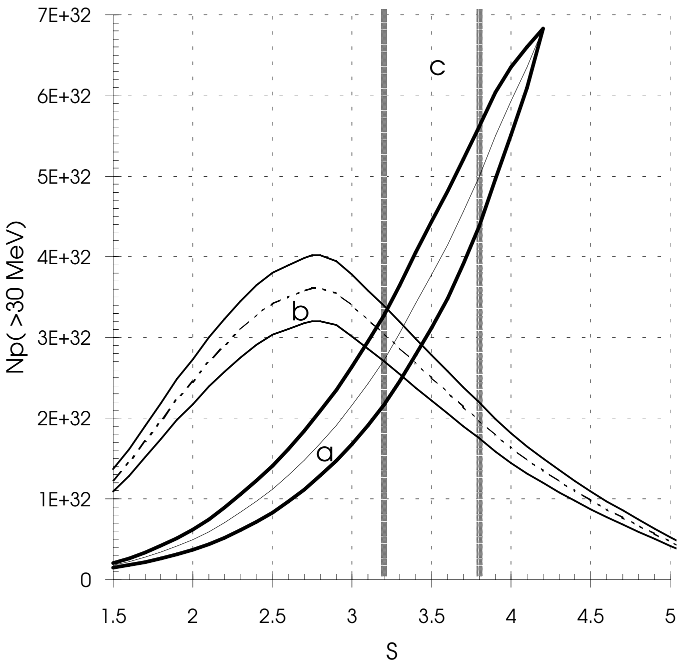

Fig. 2: Parameter space in number of accelerated protons (N) and spectral index (S). Method (a) uses 10–100 MeV neutron measurements, method (b) the fluence of the 4–7 MeV band and method (c) the 2.2 MeV line / 4–7 MeV band fluence ratio.

One possible explanation is a two-component spectrum: One is the broken power law, producing gamma-rays with energies below 1 GeV and neutrons. The other one, which dominates above 1 GeV, could be either an unbroken $S = 3$ power law, or have the turnover at an energy above the sensitivity of our measurements. As we know from COMPTEL measurements (Rank et al. 1995 or this volume) the long-term time profile of the June 15 flare shows a double-exponential decay of the MeV gamma-radiation, indicating the presence of two different particle populations. The two-component spectrum might refer to these two populations, with one spectrum turning over at lower energies (as observed), the other one stretching out to higher energies.

ACKNOWLEDGEMENTS

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