HIGH-ENERGY GAMMA RAYS AND NEUTRONS FROM THE SOLAR FLARE OF 1989 MARCH 6

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Abstract

We report on the measurement of γ-rays and neutrons (>10 MeV) from the large flare of 1989 March 6. The measurements were made with the Gamma-Ray Spectrometer (GRS) on the Solar Maximum Mission (*SMM*) satellite. The γ-ray flare began shortly after satellite sunrise at 13:55 UT, allowing both prompt and time-extended emissions to be observed by the GRS for 1 hour after flare onset.

This flare shows a number of bursts in the high-energy channels of the GRS. We focus our attention on one burst at ~14:07 UT, at which time there was a distinctive hardening of the γ-ray spectrum above 10 MeV. A detailed analysis of the spectrum shows that this was due to the emission of π^0-decay photons. High-energy neutrons, seen later by the GRS, can be associated with the time of the pion production. The fluence of the π^0-decay γ-rays at the Earth was 12.1 ± 2.6 cm^{-2}. The total observed neutron fluence (>50 MeV) was ~50 cm^{-2} with a total emissivity at the Sun of 4×10^{28} sr^{-1}, assuming isotropic emission.

We also present results on related γ-ray line fluences and proton spectra and compare the 1989 March 6 flare to other large flares known to have produced pions and neutrons.

1. Introduction. During its 10-year lifetime, the Gamma-Ray Spectrometer on the Solar Maximum Mission satellite (*SMM* GRS) detected more than 20 flares with γ-ray emission extending into the 10–100 MeV range. A subset of these were large flares from which flare-generated neutrons were detected. These were the flares of 1980 June 21, 1982 June 3, 1984 April 24, 1988 December 16, and 1989 March 6. In addition to neutrons, these flares exhibit a variety of phenomena (γ-ray lines, pion-decay γ-rays, electron bremsstrahlung) that probe the high-energy proton and electron spectra at the Sun. Here, we report on the observation of high-energy (>10 MeV) γ-rays and neutrons from the flare of 1989 March 6. We also apply the results from model calculations to the data to evaluate the proton spectrum that produced the γ-rays and neutrons.

The high-energy data are from the *SMM* GRS High-Energy Matrix (HEM). This mode of the GRS treats the seven 7.6 cm × 7.6 cm NaI(Tl) "main channel" scintillators as one layer of a two-layer detector. The second layer is a 7.5 cm thick × 25 cm diameter CsI(Na) "back shield." The HEM records energy-loss events in the range 10–100 MeV in broad energy-loss channels (~20 MeV wide). The time resolution is 2.048 s.

2. Observations. Active region 5395 crossed the solar disk between 1989 March 6 and March 19. During that time it produced 11 GOES X-class flares and numerous smaller flares [1]. The first X-class event was an X15/3B flare on March 6 at ~ 1350 UT, located at N35 E69 on the solar disk. Figure 1 shows the time history of the flare in the GRS HEM. The time structure is complex here and at lower energies, with fast bursts near the onset and extended features later on. The spectral evolution is equally complex with a relatively strong electron bremsstrahlung component in the early bursts and a stronger contribution from nuclear interactions afterwards [2].

3. Data Analysis. The emphasis of this paper is on data from the HEM, which is sensitive to γ-rays and neutrons >10 MeV. In order to distinguish solar γ-rays from neutrons and to determine their energy spectra, we have developed an iterative fitting technique using the calculated response of the HEM. In principle, both the γ-ray and neutron fluxes can be determined independent of any model of the functional form for the differential energy spectra. In practice, the HEM response is not sensitive enough to neutron energy to generate a stable, well-defined neutron energy spectrum unless the spectral shape is restricted. Therefore, we constrained the spectrum by assuming that all of the neutrons were produced at the Sun in a single, short time interval (*i.e.*, a

δ-function production model). Because of the velocity dispersion over the time of flight between the Sun and the Earth, this is equivalent to constraining the neutron energy to a fixed energy band that depends on the time interval over which the neutrons are observed. The uncertainty in the determination of the neutron spectrum caused by this δ-function approximation can be estimated. Furthermore, there are no restrictions on the γ-ray spectrum.

Once the high-energy γ-ray spectrum has been determined, we fit it using a model which is the sum of a π^0-decay peak and an exponentially decreasing continuum. The continuum shape is constrained by requiring it to be consistent with the main channel spectrum <10 MeV. The main channel spectrum is fit with a model that combines a power-law continuum, a nuclear line spectrum, and an exponential continuum determined from the HEM (>10 MeV) γ-ray spectrum (*c.f.*, "Model 1" of Murphy et al. [3]). To model the time-integrated neutron spectrum, we use neutron spectral shapes produced by isotropic Bessel-function or power-law proton spectra in thick-target interactions at the solar surface [4].

4. Results. A crucial step in constraining the spectrum of solar neutrons seen by the GRS is to determine when they were produced. One clue is the association of high-energy neutrons with pions that are produced in the same interactions. In Figure 1, we plot a time history of the ratio of the γ-ray fluence from 60–110 MeV to the fluence from 10–60 MeV. The sudden increase of this ratio at ~14:07 UT is evidence of pion decay photons which produce a much harder spectrum than electron bremsstrahlung, which is the other likely source of photons in this energy range. Two high-energy γ-ray spectra from the flare are shown in Figure 2. Both are fitted with a model spectrum that is a sum of an exponential continuum and a π^0-decay peak. The spectrum observed before 14:06 is dominated by the continuum (presumably due to electron bremsstrahlung), while the spectrum observed after 14:06 shows clear evidence of a π^0-decay peak. The time history of the π^0-decay radiation indicates that ~60% of the pion production, and therefore the bulk of the high-energy neutron production, occurred between 14:06–14:12 UT. Two other pieces of information can be used to locate the time of neutron production. First, the HEM has enough energy resolution for neutrons to constrain the production time (for a δ-function emission model) over a broad time period. The neutron data itself limits the likely period of neutron production to 14:06–14:15 UT. Second, the GRS main channel detector observed the 2.223 MeV γ-ray line from the capture of neutrons by hydrogen. This showed that most of the neutrons were produced between 14:00–14:09 UT.

Having bounded the time period of neutron production, we can calculate the flare neutron spectrum from the GRS HEM data with the simplifying assumption of δ-function production at the time of maximum production, taken to be 14:07 UT. The resulting neutron spectrum at the Earth is shown in Figure 3. Since errors in the assumed production time distort the derived spectral shape, we have calculated the neutron spectrum for two limiting-case production times (14:04 and 14:13 UT). These are shown in Figure 3 in the form of an envelope around the "most likely" spectrum. The total neutron fluence (>50 MeV) at the Earth was ~50 neutrons cm^{-2}. This implies a neutron emissivity (>50 MeV) at the Sun of ~4 × 10^{28} neutrons sr^{-1} if the neutrons were emitted isotropically.

An important use of the high-energy γ-ray and neutron measurements is as a probe of the proton spectrum that produced them. When used in conjunction with measurements of nuclear emission at lower energies, the intensity and spectral shape of the protons can be determined [5]. For the period of significant pion production (14:06–14:18 UT), the total fluence in the π^0-decay peak was 12.1±2.6 photons cm^{-2}. For the same time period, the fluence in the 2.223 MeV neutron-capture peak was 43.8±2.2 photons cm^{-2} and the fluence in the 4–7 MeV energy band from nuclear de-excitation γ-rays was 42.7±6.4 photons cm^{-2}. Ratios of the π^0-peak fluence and 2.223 MeV peak fluence (after correcting for limb-darkening effects) to the 4–7 MeV fluence can be used to find the proton spectrum at the Sun that produced them.

The relationship between these ratios and solar proton spectra with power-law and Bessel-function shapes has been calculated by Murphy and Ramaty [5] for the case of isotropic production in a thick-target model of the interaction environment. Our measured ratios are consistent with a single Bessel-function proton spectrum with an intensity $N_P(>30 \text{ MeV})$ of $(4.5\pm1.2)\times10^{32}$ protons and a shape parameter αT of 0.062 ± 0.007. The ratios are *not* consistent with a single power-law proton spectrum, but the power law that comes closest to describing the data has an intensity $N_P(> 30 \text{ MeV})$ of $(3\pm2)\times10^{32}$ protons and a power-law index of -3.2 ± 0.4.

The proton spectrum calculated from the γ-ray data can be used to predict the neutron spectrum for the same isotropic thick-target model [4]. The neutron spectrum produced by a Bessel-function proton spectrum with $\alpha T = 0.06$ was not reported by Murphy, Dermer, and Ramaty [4], so we have used their predicted neutron spectrum for an αT of 0.05. This is shown with the observed neutron spectrum in Figure 3. The predicted spectrum lies above the envelope of the observed spectrum and exceeds the most likely spectrum by about a factor of 2. However, the predicted spectrum is based on a model of isotropic neutron production. Hua and Lingenfelter [6] have shown that the shape and intensity of the neutron spectrum can be affected strongly by beaming of the protons. It appears possible that protons beamed (on the average) away from the observer could explain the discrepancy between the observed and predicted neutron spectra for this flare. We note that any power-law proton spectrum that could be allowed by the γ-ray data produces a neutron spectrum that is much too hard and intense to explain the spectrum observed by the *SMM* GRS (see Figure 3).

5. Discussion. The *SMM* GRS has seen at least 5 flares in which high-energy neutrons and/or pions were observed. We compare three of the flares in Table 1. One interesting aspect of the comparison is the range of proton spectral shapes inferred from the parameter αT. Hua and Lingenfelter [7] have reported values of αT for 15 flares that range from 0.014 to 0.04. Since significant production of pions has only been seen from flares with proton spectra that are at the upper end of spectral hardness (i.e., the flares of 1982 June 3 and 1989 March 6), it appears that pion production is important in only a small fraction of flares. Alternatively, it may be that proton spectra are sufficiently hard for pion production during certain sub-intervals of a flare (i.e., bursts), as was the case for the delayed bursts of the June 3 and March 6 flares.

Table 1

Comparison of Three Large Flares

Date	Heliocentric Angle (degrees)	Fluence F(2.2 MeV) (cm^{-2})	Fluence F(4–8 MeV) (cm^{-2})	Neutron Emissivity (>50 MeV) (sr^{-1})	Observed π^0 Radiation	Proton Spectral Shape (αT)
6/21/80	89	3.1 ± 0.2	98 ± 2	3×10^{28}	No	0.02
6/3/82	72	314	305 ± 30	20×10^{28}	Yes	0.035
3/6/89	77	43.8 ± 2.2	45.4 ± 6.6	4×10^{28}	Yes	0.062

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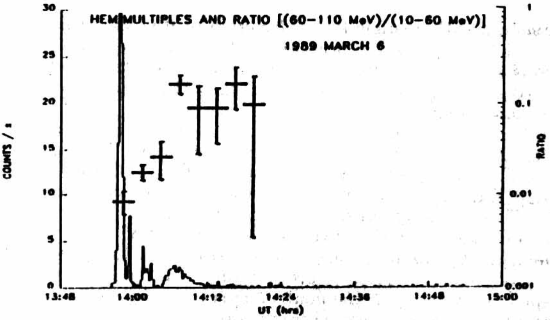

Figure 1. Time history of the GRS HEM "multiple" events (events in both layers >25 MeV). Also shown is the ratio of γ-ray fluence above 60 MeV to fluence below 60 MeV (heavy line and right axis). The ratio increases significantly at 14:06 UT.

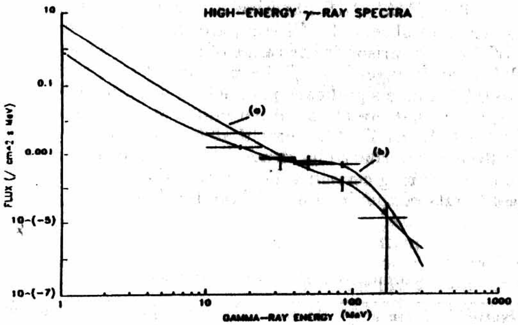

Figure 2. Gamma-ray spectra for 2 time intervals during flare. (a) 14:03–14:06 UT shows only weak evidence for π^0-decay peak at 70 MeV. (b) 14:06–14:09 UT shows significant π^0-decay peak. Data are fit with exponential continuum and peak at 70 MeV.

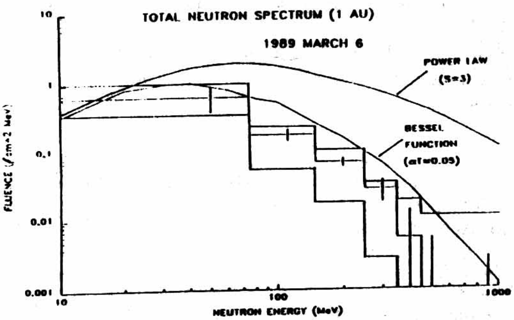

Figure 3. Time-integrated neutron spectrum at the Earth from the flare of 1989 March 6. Spectrum and "envelope" depend on production time as described in text. Curves labeled "Power law" and "Bessel function" are spectra predicted from γ-ray data using those proton spectral shapes in an isotropic, thick-target model.