GAMMA-RAYS AND NEUTRONS AS A PROBE OF THE PROTON SPECTRUM DURING THE SOLAR FLARE OF 1988 DECEMBER 16*

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ABSTRACT

We have previously reported on high-energy (> 10 MeV) γ–rays and neutrons from the flare of 1988 December 16 detected by the Gamma–Ray Spectrometer on the SMM satellite.[1] In this paper, we present results on γ–ray lines seen by the same detector during this flare. Together, these measurements constitute a powerful probe of the proton spectrum (> 10 MeV) that produces the flare neutrals. Analysis of the data suggests a Bessel-function proton spectrum with a shape parameter (αT) of 0.054 ± 0.004 and the number of protons above 30 MeV equal to $(9.0 \pm 0.9) \times 10^{32}$. The number of neutrons detected from this flare is much smaller than what is predicted from an isotropic distribution of the protons, indicating that the distribution may be non-isotropic.

OBSERVATIONS

We report on the observation of low-energy (0.3–10 MeV) γ-rays and high-energy (>10 MeV) γ-rays and neutrons from the flare of 1988 December 16. We 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).[2] 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).

Active region 5278 produced an X4.7/1B flare on December 16 at ~ 0830 UT. The flare was located at N27 E33 on the solar disk, corresponding to a heliocentric angle of 43°. Figure 1(a) shows the time history of the flare in the energy range 4.1–6.4 MeV, which is dominated by nuclear de-excitation line emission. Figure 1(b) shows the time history for "multiple"events in the HEM from the flare. The multiple events are "showering" events in both layers of the HEM and are produced primarily by γ-rays (> 25 MeV). The bulk of the high-energy γ-rays are produced in a peak that occurs well after (~ 7 minutes) the flare onset at lower energies.

Figure 1 in Dunphy et al. [1] showed a similar time history of the flare in the HEM for "singles" events (involving only one layer of the HEM). The emission that was seen to continue after the main peak is a signature of solar flare neutrons, delayed by their time of flight from the Sun.

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DATA ANALYSIS

Murphy et al. [3] have shown that the spectrum of solar flare protons can be evaluated by using the ratios of various γ-ray emissions, namely: (1) the line at 0.51 MeV from positron annihilation, (2) the line at 2.22 MeV from deuterium formation, (3) the emission between 4 and 7 MeV from nuclear de-excitation, and (4) the broad peak centered at 68 MeV from neutral pion (π^0) decay. The GRS main channel spectra were used to determine the fluences of the 0.51 MeV, 2.22 MeV, and 4-7 MeV photons.

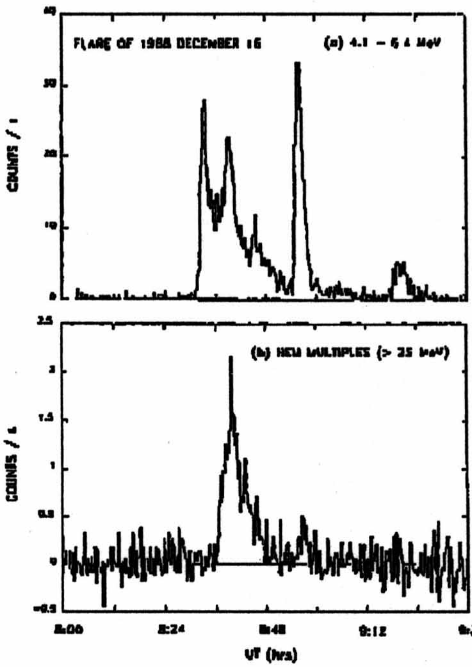

Figure 1. Time history of the 1988 December 16 flare in two GRS detector bands (background subtracted): (a) the 4.1-6.4 MeV band, sensitive to nuclear deexcitation γ-rays, and (b) the High Energy Matrix (HEM) multiple events, sensitive to γ-rays > 25 MeV.

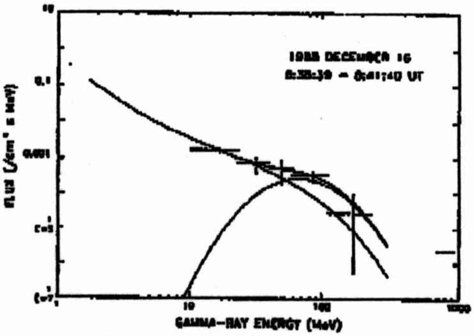

Figure 2. Gamma-ray spectrum in the GRS HEM during the peak of high-energy (> 10 MeV) γ-ray emission. A significant "bump" due to π^0-decay photons is present. The smooth curves are fits to the continuum (including the data < 10 MeV, which are not shown), to the π^0-decay peak, and to the total spectrum.

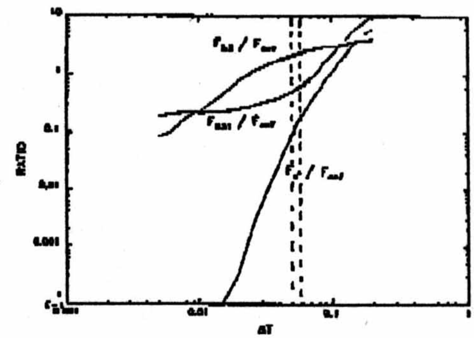

Figure 3. The calculated dependence of γ-ray fluence ratios on the parameter αT for proton spectra with a Bessel-function shape.[4] The 1σ ranges in the ratios are indicated by the darkened sections of the curves. The corresponding range of αT (0.054 ± 0.004) is also shown. The ratio $F_{2.2}/F_{4-7}$ depends on the heliocentric angle of the flare, which is 43°.

To determine the flux of the π^0-decay photons, we have used the GRS HEM data. 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). Figure 2 shows a γ ray spectrum in the HEM for one 180 s time interval with strong emission above 10 MeV. The spectrum shows a significant feature due to π^0 decay.

RESULTS

The relationship between γ-ray yields and solar proton spectral shapes has been calculated by Murphy and Ramaty [4] for the case of isotropic production in a thick-target model of the interaction environment on the Sun. We have used their results to calculate the expected fluence ratios, normalized to the the fluence in the 4-7 MeV band. Figure 3 shows the dependence of these fluence ratios on the parameter αT that describes proton spectra with a Bessel function shape. Also shown in Figure 3 are the ratios for the December 16 flare. These ratios were determined for the time interval 08:36-08:48 UT during which there was significant flux from π^0 decay.

The observed ratios are consistent with a Bessel-function proton spectrum with a shape parameter (αT) equal to 0.054 ± 0.004. The measured fluences can then be used to calculate the intensity of the proton spectrum. In this case, the number of energetic protons above 30 MeV (N_P > 30 MeV) is $(9.0 \pm 0.9) \times 10^{32}$.

Although the γ-ray data are consistent with a Bessel function proton spectrum, they are *not* consistent with a single, unmodified power-law spectrum. (The data might be consistent with a modified power law – e.g., a power law with a high-energy cutoff.)

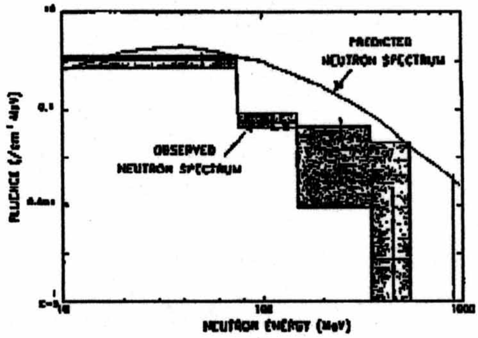

Figure 4. The time-integrated neutron spectrum observed by the GRS HEM, assuming δ-function neutron production at the time of peak γ-ray production > 10 MeV, is shown by the histogram. The shaded region encloses a range of spectra that depends on the range of assumed neutron production times (08:37-08:43 UT). The smooth curve is the neutron spectrum predicted from a Bessel-function proton spectrum interacting isotropically in a thick-target model.[5] The parameters of the proton spectrum, as determined from γ-ray line data, are $\alpha T = 0.05$ and N_P (> 30 MeV) = 9×10^{32}.

The proton spectrum calculated from the γ-ray data can be used to predict the neutron spectrum for the same isotropic thick-target model. We have used the neutron spectrum predicted by Murphy et al. [3] for a Bessel-function proton spectrum with an αT of 0.05. This is shown in Figure 4 with the neutron spectrum observed by the GRS at 1 AU on December 16. In the range 10-75 MeV, the predicted fluence is reasonably close to the observed fluence, but above 75 MeV, the observed fluence falls below the predicted fluence by a factor of ~5. Since the predicted neutron spectrum does not account for γ-ray (and neutron) production outside the time interval 08:36-08:48 UT, the discrepancy is at least as large as is shown in Figure 4.

A similar analysis of the large 1989 March 6 flare [5] also showed an observed neutron spectrum that was below the predicted spectrum, in that case by a factor of ~2. It is important to determine whether these discrepancies are due to beaming effects, [6] since the present model assumes an isotropic distribution of energetic protons. Further observations of solar flare γ-rays and neutrons (for example, by the Compton Gamma Ray Observatory) would be valuable for such studies.

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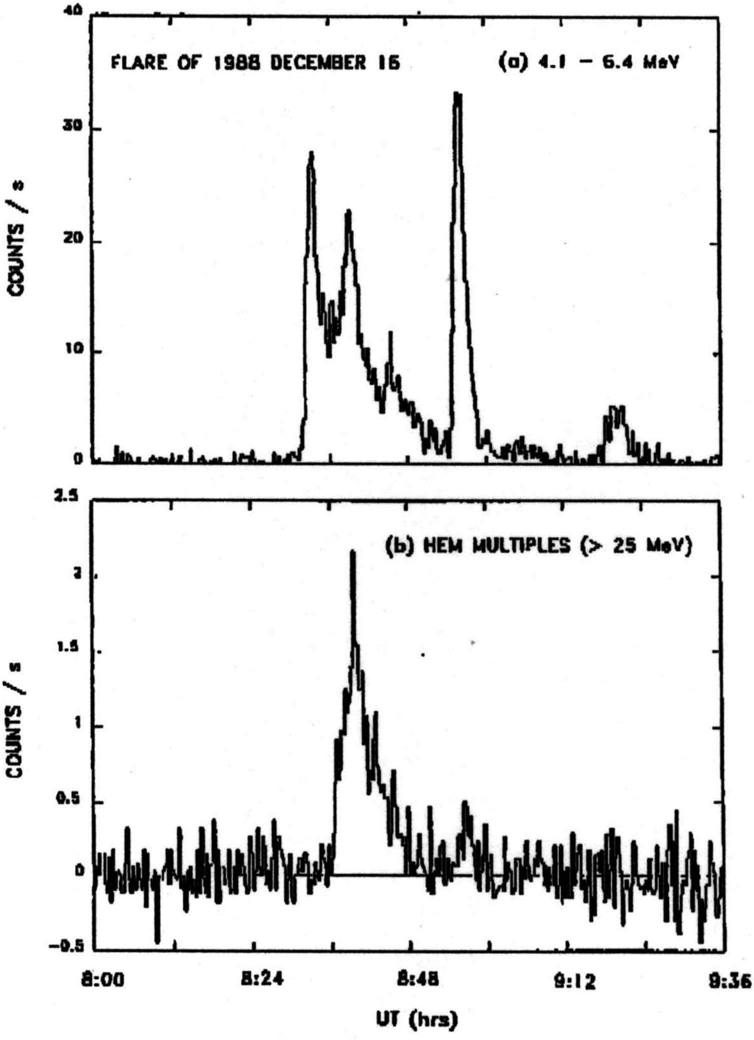

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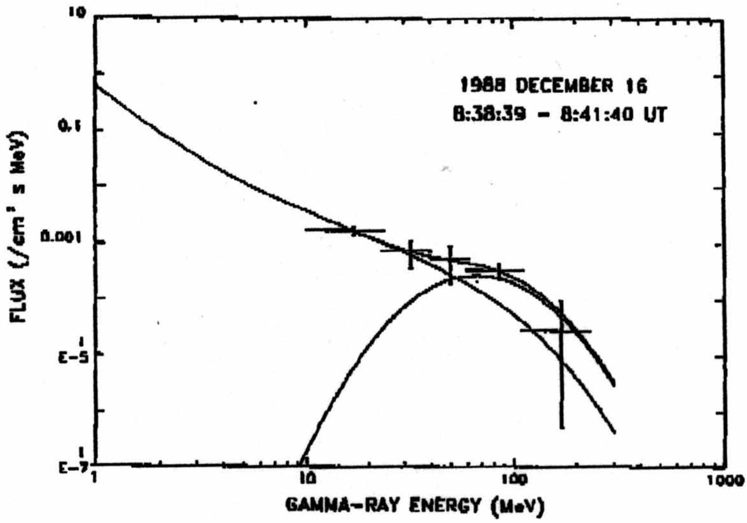

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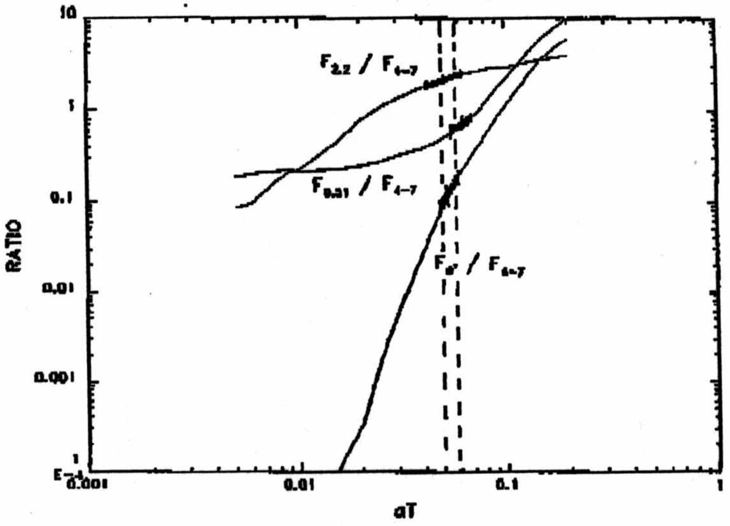

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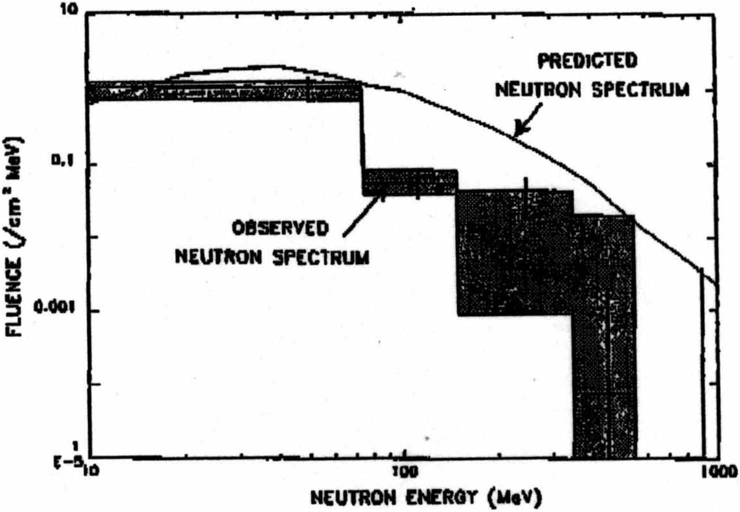

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