Neutron–Capture Gamma–Rays Observed by EGRET from the Flare of 1991 October 27

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Abstract

The neutron–capture γ–ray line at 2.223 MeV was observed by the Total Absorption Shower Counter (TASC) section of the EGRET γ–ray telescope on the Compton Gamma Ray Observatory satellite from a solar flare on 1991 October 27. This flare, which produced γ–rays starting around 05:39 UT, was very intense in the energy range dominated by nuclear lines. This radiation was also relatively impulsive compared to other large flares observed by the TASC. The neutron capture γ–ray line at 2.223 MeV is clearly delayed relative to prompt γ–ray line emission in the energy range of 4–8 MeV. We find that the time history of the neutron–capture line at 2.223 MeV can be characterized by a single exponential decay–time of 78 ± 16 s. We use this parameter to constrain the ^{3}He/H ratio at the capture site to a level of $< 3 \times 10^{-5}$ at the 68% confidence level and $< 6 \times 10^{-5}$ at the 90% confidence level. The proton spectrum that produced the nuclear line emission is consistent with a power law with an index of -3.4 ± 0.15 in the range 10–100 MeV.

1 Introduction:

A γ–ray of energy 2.223 MeV is produced when deuterium is formed from a proton and a neutron in the exoergic reaction $\mathrm{p} + \mathrm{n} \rightarrow {}^2\mathrm{D} + \gamma$. The neutron–capture line from a solar flare was first observed by the Gamma–Ray Monitor on the OSO–7 satellite on 1972 August 4 (Chupp *et al.* 1973). Subsequent observations were made by detectors on HEAO–1 (Hudson *et al.* 1980), HEAO–3 (Prince *et al.* 1982), SMM (Prince *et al.* 1983; Rieger *et al.* 1983), HINOTORI (Yoshimori *et al.* 1983), GRANAT (Trottet *et al.* 1993), and CGRO (Rank *et al.* 1996). The 2.223 MeV line can be used to probe conditions in the solar photosphere. In particular, Prince *et al.* (1983) and Hua & Lingenfelter (1987) used the time history of the line during the large flare of 1982 June 3 to calculate the ^{3}He/H ratio in the solar photosphere. The capture line time history depends on the rate of production of solar neutrons, as well as on their rate of capture. The measured time–dependent flux of the 2.223 MeV line can be modeled as [using the notation of Prince *et al.* (1983)]

$$F_{2.2}(t) = \int_{-\infty}^{t} S(T) R(t,T) dT \qquad (1)$$

where $F_{2.2}(t)$ is the observed 2.223 MeV flux, $S(T)$ is the neutron production time history, and $R(t,T)$ is the response function giving the 2.223 MeV photon contribution at time t due to neutrons produced at time T. If the spectral shape of the energetic particles does not change during the flare, the neutron production time history, $S(T)$, is proportional to the

flux of prompt nuclear lines produced by the same population of energetic particles. Then equation (1) becomes

$$F_{2.2}(t) = \int_{-\infty}^{t} k_1 F_\gamma(T) R(t,T) dT \tag{2}$$

where $F_\gamma(T)$ is the observed flux of prompt γ–ray lines, and k_1 is a proportionality constant that relates $F_\gamma(T)$ to the neutron production rate.

Prince *et al.* (1983) have shown that the function $R(t,T)$ can be approximated by a single exponential function of the form

$$R(t,T) \approx k_2 \exp(-(t-T)/\tau). \tag{3}$$

In equation (3), k_2 is a constant that relates flux in the 2.223 MeV line to neutron production at the sun. The time constant, τ, is essentially the lifetime of the neutron in the capture region. The time constant is determined by $\frac{1}{\tau} = \frac{1}{\tau_H} + \frac{1}{\tau_{He^3}} + \frac{1}{\tau_d}$ where $\frac{1}{\tau_H}$, $\frac{1}{\tau_{He^3}}$, and $\frac{1}{\tau_d}$ are time constants for neutron capture by hydrogen, neutron capture by ^{3}He, and neutron decay, respectively.

Analysis of the large flare of 1982 June 3 by Prince *et al.* (1983) gave a best fit τ of 89 ± 10 for the first 150 s of the flare. They used this τ to derive an upper limit on the ^{3}He/H ratio of 3.8×10^{-5} (90% confidence level). Clearly, the value of the ^{3}He/H ratio can be further constrained by studying the decay times of the neutron–capture line from many flares. With this in mind, we report the results from a relevant study of the 1991 October 27 flare.

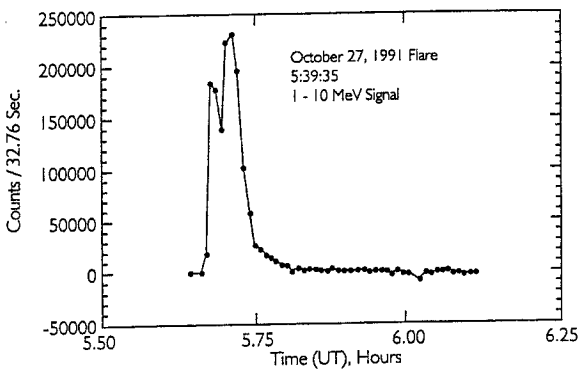

Figure 1: Response of the TASC in the 1–10 MeV energy–loss band during the flare of 1991 October 27.

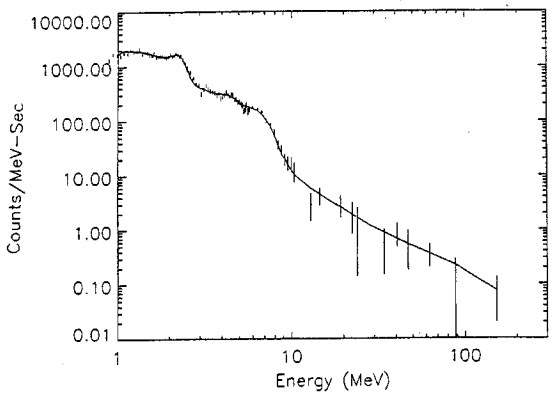

Figure 2: TASC energy–loss spectrum during the time interval 05:41:11–05:41:44. Solid line is a multiparameter fit.

2 Flare Observations:

The flare of interest began at 05:38 UT on 1991 October 27 in soft x–rays (NOAA, Solar Geophysical Data). The flare had an H_α brightness 3B and was an X6–class GOES flare. It was located in active region 6891 with solar coordinates S 13°, E 15° and a heliocentric angle of 23°. The October 27 flare was observed over a range of wavelengths (radio, optical, x–ray, and γ–ray). This flare produced a particulary strong signal in the TASC spectrometer, the most intense of several flares that occurred in October. Figure 1 shows the TASC response in the energy–loss range of 1–10 MeV.

3 Analysis:

To model the behavior of the 2.223 MeV flux as described by equation (2), we need the flux of photons from prompt nuclear lines. In practice, we fit the TASC spectra with a multi–component model source spectrum which is folded through the detector response. The components of the model are: (1) a power–law γ–ray spectrum, (2) the 2.223 MeV γ–ray line, (3) a prompt nuclear γ–ray spectrum, (4) a γ–ray spectrum from activation of Fe nuclear levels by neutron interactions in the spacecraft material, (5) a γ–ray spectrum from pion decay and (6) a spectrum from solar neutrons interacting in the detector. Figure 2 shows a fit of one of the TASC spectra. The time intervals used for the analysis must be discrete, so equation (2) can be modified to

$$F_{2.2}(t_n) = \sum_{i=1}^{n} \frac{k' F_{4-7}(t_i)\Delta t_i}{\Delta t_n} \int_{t_i-\Delta t_i/2}^{t_i+\Delta t_i/2} \exp(-T/\tau) dT, \tag{4}$$

where $F_{4-7}(t_i)$ is the flux from nuclear lines in the energy interval 4–7 MeV for a time interval centered on t_i, $F_{2.2}(t_n)$ is the calculated flux in the 2.223 MeV line for a time interval centered on t_n, and k' is the appropriate proportionality constant.

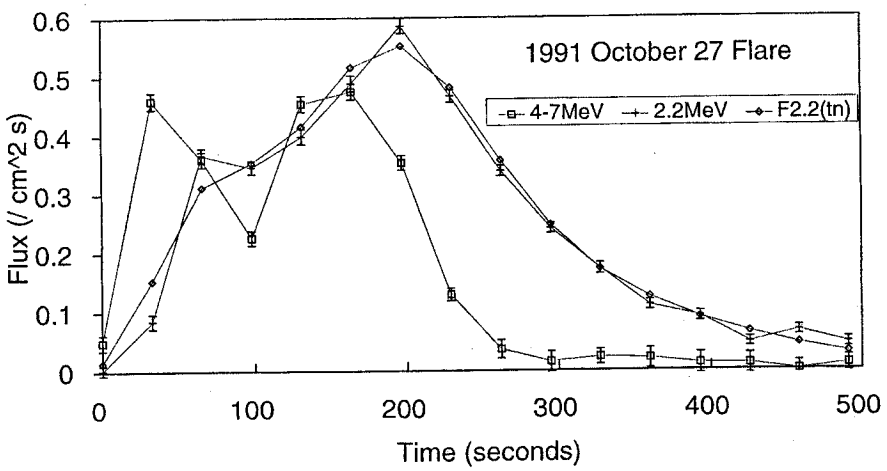

Figure 3: The time histories of the observed fluxes in the 2.223 MeV line and in the 4–7 MeV energy range. Also shown is the calculated 2.223 MeV flux, $F_{2.2}(t)$, from equation (4).

The calculated flux, $F_{2.2}(t_n)$, for each time interval depends on τ and k'. These parameters can be varied to get the best agreement between $F_{2.2}(t_n)$ and the observed flux in the 2.223 MeV line. Figure 3 shows plots of the time histories of the fluxes in the 2.223 MeV line and in the prompt lines (4–7 MeV). The time scale is relative to 05:39:33 UT, the beginning of the time bin during which γ–rays were first detected. Also shown in the figure is a curve representing $F_{2.2}(t_n)$ calculated from equation (4). The values of τ and k' were varied to minimize the sum of the weighted squared residuals between the observed and calculated 2.223 MeV fluxes. An acceptable fit was obtained for a constant k' and τ in equation (4). The "best fit" parameters are $\tau = 78 \pm 16$ s and $k' = 1.52 \pm 0.12$, where the uncertainties are at the 68% (1 σ) confidence level. These are the parameters used for calculating the curve in Figure 3.

4 Conclusions:

Observation of the time history of neutron–capture γ–rays from the solar flare of 1991 October 27 shows that it is consistent with behavior described by equation (4). That is, the instantaneous production of neutrons is proportional to the production of prompt nuclear lines, and the neutron–capture γ–rays are convolved through a single time constant, τ. The time constant that describes the neutron–capture γ–ray time history is 78 ± 16 s (68% confidence level). This can be compared with the time constant of 89 ± 10 s for the 1982 June 3 flare (Prince *et al.* 1983) and values of 70 ± 10 s and 97 ± 40 s for the 1991 June 11 flare found by Trottet *et al.* (1993) and Dunphy *et al.* (1999), respectively. Simulations have shown that the time behavior is expected to be more complex, with a time "constant," $\tau(t)$, that itself is a function of time (Kanbach *et al.* 1981; Hua & Lingenfelter 1987). However, over a limited time span, a constant τ can be used to approximate the decay.

The time dependence is a function of a number of flare parameters: the proton spectral shape, the proton angular distribution, the flare's heliocentric angle (viewing direction), and the ^{3}He/H ratio. Hua & Lingenfelter (1987) have evaluated the effect of these parameters on the time dependence of the 2.223 MeV γ–ray. Using their results, we estimate that the time constant for the 1991 October 27 flare implies an upper limit of 3×10^{-5} for the ^{3}He/H ratio at the 68% confidence level and 6×10^{-5} at the 90% confidence level. This can be compared with a limit of 3.8×10^{-5} at the 90% confidence level derived by Prince *et al.* (1983) and a value of $(2.3 \pm 1.2) \times 10^{-5}$ derived by Hua & Lingenfelter (1987), both for the flare of 1982 June 3, and the value of $(3^{+2}_{-1}) \times 10^{-5}$ found for the 1991 June 11 flare by Trottet *et al.* (1993).

The ratio k' can be used to characterize the spectral shape of the protons (over a range of kinetic energies approximately 10 to 100 MeV) that produce the nuclear line emission. Using the calculations of Ramaty *et al.* (1993) and Ramaty (private communication), we find that the proton differential energy spectrum is consistent with a power law shape with index $s = -3.4 \pm 0.15$ or a Bessel function shape described by the parameter $\alpha T = 0.024 \pm 0.002$. This assumes that the protons are moving approximately "horizontally" when they interact in the photosphere (see Ramaty *et al.* 1993). The derived shape is quite similar to what is found from other large γ–ray flares (Ramaty *et al.* 1993).

This work was supported in part by NASA grants NAG 5-2420 and NAG 5-3158 (UNH) and by NASA contract NAS 5-31210 (Northrop Grumman).

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