OSSE Observations of the 4 June 1991 Solar Flare

R. J. Murphy[2], G. H. Share[2], D. J. Forrest[4], D. A. Grabelsky[3], J. E. Grove[2],
C. M. Jensen[1], W. N. Johnson[2], G. V. Jung[5], R. L Kinzer[2],.R. A. Kroeger[2],
J. D. Kurfess[2], S. M. Matz[3], W. R. Purcell[3], M. S. Strickman[2],
M. P. Ulmer[3], W. T. Vestrand[4]
[1]George Mason University, [2]Naval Research Laboratory, [3]Northwestern University,
[4]University of New Hampshire, [5]USRA

ABSTRACT

We present time profiles of the 2.223 MeV neutron-capture line and the 4.44 MeV ^{12}C nuclear-deexcitation line derived from observations of the 4 June 1991 X12+ solar flare obtained by the Oriented Scintillation Spectrometer Experiment (OSSE) on board the Compton Gamma-Ray Observatory *(CGRO)*. We discuss the OSSE instrument, the solar observation mode used during the June period, the data analysis technique employed, and derive an estimate of the accelerated-particle spectrum and a lower limit to the number of interacting particles.

1. INTRODUCTION

In this paper, we present time profiles of the 2.223 MeV neutron-capture and the 4.44 MeV ^{12}C nuclear-deexcitation lines derived from OSSE observations of the 4 June 1991 X12+ solar flare. Using a combination of data from on- and off-pointed detectors, we have determined these fluxes throughout most of the observable emission period, excluding only three short periods when the detectors were saturated due to intense emission. Measurement of these 2 line fluxes can provide information on conditions at the Sun during the flare. Since the ^{12}C line is prompt, its time profile represents the time profile of the nuclear reactions themselves. Also, the total, time-integrated fluence in either of these two lines is a measure of the number of interacting accelerated particles. Finally, the ratio of the total neutron-capture-line fluence to the total ^{12}C-line fluence is a measure of the flare-averaged kinetic-energy spectrum of the interacting particles.

In June of 1991, solar active region 6659 produced some of the largest *GOES* flare events ever recorded by the satellites. Fortunately, the *CGRO* Phase I Viewing Period 2 began on 30 May with the Sun accessible to the OSSE field of view (FoV). On 1 June, AR 6659 appeared at the East limb and produced an X12+ flare. At the time of flare onset, OSSE was shut down due to a South Atlantic Anomaly transit. However, as a result of the high probability for intense flare production, the Sun was declared an OSSE Target of Opportunity and replaced the existing secondary celestial target. On 4 June, AR 6659 produced a second X12+ flare while OSSE was viewing the Sun. Excellent observations were obtained of the rise, peak and decay of the event. The decay was interrupted by spacecraft night, but observations were resumed at sunrise of the next two orbits and additional observations were obtained.

In Section 2 we discuss the OSSE instrument and the solar observation mode used during the June period. In Section 3 we discuss the analysis technique and in Section 4 we present the data and discuss the results.

2. OSSE INSTRUMENT AND DATA COLLECTION MODES

OSSE consists of four, independently-oriented phoswich scintillation detectors with both passive and active shielding for reducing background and defining its aperture. The principal detector element is a 33-cm-diameter phoswich (effective area 480 cm^2 at 511 keV), consisting of 10.2-cm-thick NaI and 7.6-cm-thick CsI crystals, optically coupled to each other and viewed by seven photomultiplier tubes. The CsI and NaI pulses are electronically separated by pulse-shape discrimination, thus providing a compact anticoincidence system for charged particles and background γ-rays. The energy resolution is 3.8% full width at half maximum (FWHM) at 6.1 MeV, increasing to 8.2% at 662 keV. The combined sensitivity for narrow-line detection from a 1000-sec observation is 1×10^{-3} photons cm^{-2} sec^{-1}. A tungsten collimator above the phoswich defines a 3.8° × 11.4° FWHM FoV. Each detector is mounted in an independent elevation-angle gimbal which provides 192° of rotation about the spacecraft Y-axis. Surrounding the phoswich and collimator is a NaI annular shield, made up of four segments and having the capability of providing 0.1- to 8-MeV count spectra in 256 channels at ~10% FWHM energy resolution.

When viewing the Sun during the June 1991 period, the instrument was configured to obtain a range of solar data: (1) Count spectra covering the photon-energy range from 0.05 to >200 MeV in 528 channels along with 16 channels of neutron count spectra (>10 MeV) at a spectral accumulation time of ~8.2 sec; (2) Count rates at 16-msec accumulation times in four broad energy windows (200–450 keV, 570–750 keV, 4–7 MeV and >10 MeV); (3) If a BATSE burst trigger was received, 4096 16-msec shield count rates above threshold (~93 keV), with 256 of these accumulated prior to the trigger; and (4) If the BATSE trigger identified the burst as solar, 1000 seconds of shield count spectra at ~32-sec temporal resolution. Two of the detectors maintained a fixed orientation with the Sun in the FoV while the other two "chopped" (i.e., alternately pointed on and off the Sun at ~2-minute intervals) to facilitate background determination and to provide non-saturated spectra for intense flares. The Sun was therefore viewed by 3 of the detectors at all times, while one of the detectors was off-pointed.

3. DATA ANALYSIS TECHNIQUE

During the three orbits associated with the OSSE observations of the 4 June X12+ flare, the instrument was viewing the Sun during 3:01:56–4:04:52, 4:36:00–5:37:27, and 6:09:32–7:09:53 UT. The corresponding times of satellite day were 3:06:04–4:08:57, 4:39:32–5:42:28 and 6:12:59–7:15:59 UT. OSSE was therefore already viewing the Sun at satellite sunrise for each of these orbits. The onset, peak and end of the *GOES* soft X-ray event was reported to be 3:37, 3:52 and 8:00 UT, respectively. The flare was located at N30E65.

The flare saturated the *GOES* detectors for more than 30 minutes during the peak of the emission. Similarly, the OSSE detectors suffered from several saturation effects. The effects addressed in this analysis are:

(1) Extremely low livetimes were experienced due to the large event rates suffered by both the shields and the central detectors. In this analysis, we have eliminated data for which the fractional livetime fell below 25%. This occurred during three intervals at the peak of the emission: 3:38:23–3:40:35, 3:40:59–3:41:40 and 3:43:27–3:44:08UT.

(2) Pulse-pile-up distortion of the central-detector pulse shapes due to low-energy flare photons interacting simultaneously with an event of interest can cause the event to be rejected by pulse-shape discrimination. The result is a reduction of detector efficiency and a distortion (hardening) of the count spectrum. Pulse pile-up occurred during the intense portions of the flare in those detectors directly viewing the Sun. The off-pointed detector was adequately protected by absorption of the low-energy photons in the shields and collimator. We therefore use data only from the one off-pointed detector during these times, with the count rate adjusted for the off-axis response. We determine the time after which data from the on-pointed detectors can be used by comparing the on-pointed rates of a "chopping" detector to its off-pointed rates (adjusted for off-axis response). When the two rates are in agreement, we use data from the three on-pointed detectors to improve the sensitivity. This occurred for times after 3:53:20 UT.

Background spectra were obtained by propagating an initial background spectrum forward through time using a technique based on the measured variations of background spectra observed in orbit. The initial background spectrum was obtained by summing 8-sec spectra accumulated during the Sun-viewing portion of the orbit prior to the flare-onset orbit. This previous orbit was free of significant solar activity, as determined by inspection of the *GOES* flare reports. Background-subtracted count spectra were then used in the subsequent analyses.

Summed count spectra for each of the 4 detectors were constructed, derived from 8-sec spectra obtained during 3:53:20–4:04:52 UT when the data problems mentioned above were minimal. Each of the 4 summed spectra were fit for the 2.223 and 4.44 MeV lines to provide a fitting template for the 8-sec spectral fits. To improve statistics during the second and third orbits, the 8-sec spectra for each detector were summed into ~2 minute spectra (16 8-sec spectra each). For each detector, the 8-sec spectra from the first orbit and the 2-minute spectra from the last two orbits were then fit for the two line amplitudes, with each line's central energy and width held fixed at the best-fit values obtained from the fit to the summed-spectra. To obtain the corresponding photon fluxes, the line amplitudes were divided by the photopeak effective area (derived from calibration measurements and Monte Carlo calculations) appropriate for the line energy and source position in the FoV. For times when data from the 3 on-pointed detectors could be used, a weighted mean of the 3 fluxes was calculated.

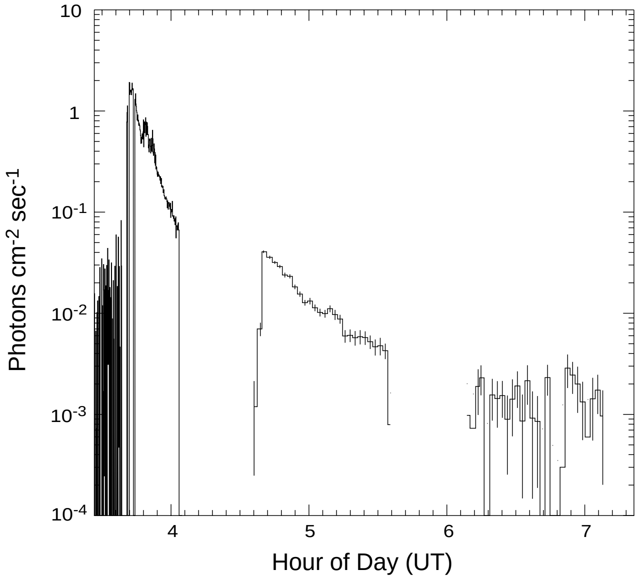

Figure 1. Time profile of the 2.223 MeV neutron-capture line.

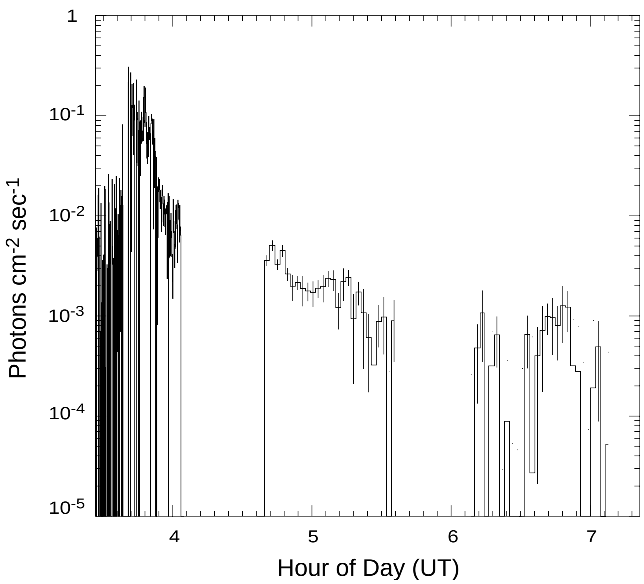

Figure 2. Time profile of the 4.44 MeV ^{12}C nuclear deexcitation line.

4. RESULTS AND DISCUSSION

The results are shown in Figures 1 and 2 for the 2.223 and 4.44 MeV lines, respectively, where the derived line fluxes are plotted versus time. The error bars represent 1-σ statistical uncertainties; systematic uncertainties associated with background subtraction are not included. A study of the level of this uncertainty is in progress.

Figures 1 and 2 show that nuclear interactions and the resultant γ-ray emission continue after the peak of the emission (at about 3:42 UT) for more than 110 minutes (until at least 5:37 UT, corresponding to the end of the second daylight period). Measured flux during the third orbit may only represent the level of systematic uncertainty associated with background subtraction rather than actual flux from the flare.

The total, time-integrated fluences of the 2.223 and 4.44 MeV lines are 692 ± 9 and 68 ± 4 photons cm^{-2}, respectively. This 2.223 MeV line fluence is a factor of two larger than the lower limit reported at the January 1992 American Astronomical Society meeting in Atlanta (Share *et al.* 1992). That estimate was based on fits to data obtained from the on-pointed detectors whose sensitivities had been significantly reduced by pulse-pile-up effects as discussed above. The fluence values reported here, of course, must be still be considered lower limits since we have not accounted for any emission occurring during the data gaps due to satellite night and detector saturation. If the emissions are interpolated linearly between the measured values bracketing each data gap, an additional 230 and 32 photons cm^{-2} would be added to the 2.223 and 4.44 MeV line fluences, respectively. The 2.223 MeV fluence of 692 photons cm^{-2} can be compared to the 314 photons cm^{-2} observed by the Solar Maximum Mission *(SMM)* Gamma-Ray Spectrometer (GRS) from the 3 June 1983 flare (Prince *et al.* 1983).

We use recent theoretical calculations (Ramaty, *et al.* 1993; Kozlovsky, Murphy and Ramaty 1994) to derive estimates for the flare-averaged kinetic-energy spectrum of the interacting, accelerated particles (using the 2.223-to-4.44 MeV line fluence ratio) and the total number of interacting protons (using the total 2.223 MeV line fluence). Since the data coverage is incomplete, the total-number estimate will be a lower limit. The ratio, however, should be reasonably independent of the unknown emission profile during the data gaps. Assuming a power-law form for the particle spectrum, we find that the measured ratio (10.2 ± 0.6) implies an index of ~2.8, independent of either the assumed angular distribution of the interacting particles or the assumed abundances. This can be compared to indices calculated for a number of flares by Ramaty *et al.* (1993) using a similar technique. Their values ranged from 2.7 (for the 16 December 1988 flare) to 4.5. (Note: Their derived index for the large flare of 4 August 1972 was 3.4–3.7.)

The implied number of interacting protons with energy greater than 30 MeV [N_p(>30 MeV)] depends somewhat on the assumed abundances at the interaction site. Using photospheric abundances (Anders and Grevesse 1989) for both the ambient and accelerated particles, the measured 2.223 MeV line fluence (692 photons cm^{-2}) implies $N_p(>30\ \mathrm{MeV}) \cong 1.5 \times 10^{33}$. Using the enhanced-heavy-element abundances derived (Murphy, *et al.* 1991) for the 27 April 1981 flare observed by *SMM*/GRS, we find $N_p(>30\ \mathrm{MeV}) \cong 4 \times 10^{32}$. We emphasize again that these are lower limits since we have not accounted for emission during data gaps. These values can be compared to those derived for a number of flares by Ramaty *et al.* (1993) which ranged from 1.6×10^{30} to 1×10^{33} (for the 4 August 1972 flare). We see that the 4 June 1991 flare was comparable in size to the 4 August 1972 flare but had a significantly harder spectrum.

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