Accelerated-Particle Spectral Variability in the 1991 June 11 Solar Flare

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Abstract. The X12 solar flare that occurred on 1991 June 11 was well observed by the instruments on *CGRO.* Here we present observations of this flare obtained with OSSE. OSSE detected nuclear γ-ray lines, 2.223 MeV neutron-capture radiation, 0.511 MeV positron-annihilation radiation, >16 MeV γ rays and neutrons. We apply three techniques of measuring the accelerated-particle energy spectrum. Since each technique is sensitive to a different range of particle energies, comparison of the derived spectral indexes provides information about the shape of the particle spectrum over a broad energy range. We show that as the flare progressed, the particle spectrum clearly evolved. There were intervals when the particle spectrum was consistent with an unbroken power law from ~1 to 100 MeV. But there were also intervals when the spectrum deviated significantly from a simple, unbroken power law through this energy range.

INTRODUCTION

The 1991 June 11 solar flare was one of six large flares originating from AR6659. The GOES X12 flare was located at N31W17 solar heliographic coordinates and the soft X-ray flux peaked at ~2:09 UT (~7740 s UT). It was well-observed by the instruments on *CGRO*. Due to saturation of the anti-coincidence counter, the EGRET spark chamber could not observe the peak of emission and began monitoring after 3:26 UT. It detected γ-ray emission up to a GeV lasting for at least 8 hours after the peak (1) with a spectrum suggesting a pion origin. Data from the EGRET/TASC obtained during the peak of the flare showed evidence for spectral evolution (2). COMPTEL data also suggested that the >30 MeV ion spectrum hardened as the flare progressed (3). Nuclear lines were detected with *GRANAT*/PHEBUS (4).

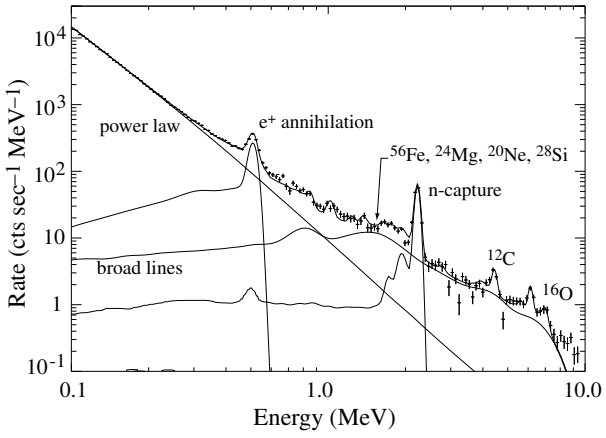

Figure 1. 1991 June 11 solar flare OSSE count spectrum from one detector.

OSSE covers γ-ray energies from 0.050 to 200 MeV and is sensitive to high-energy neutrons. Its good energy resolution allows spectroscopic study of γ-ray lines and its large area provides excellent sensitivity for weak emission. At the time of the June 11

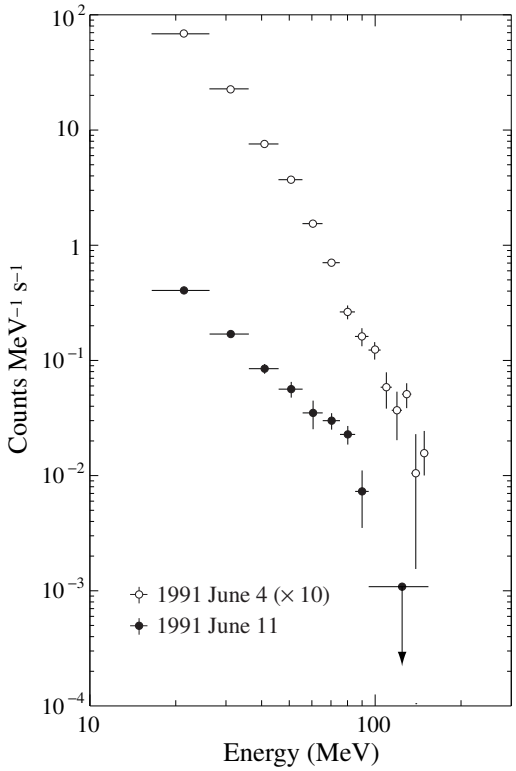

Figure 2. OSSE >16 MeV γ-ray count spectrum of the 1991 June 11 (solid) and 1991 June 4 (open) flares.

flare, OSSE was observing Cygnus when it received a BATSE solar trigger. OSSE immediately slewed to the Sun and observed for ~3000 seconds until satellite night and during the following orbits.

Figure 1 shows the OSSE 0.1–10 MeV count spectrum accumulated after the peak of the June 11 ~MeV emission. Also shown is a fit to the data with a model consisting of narrow and broad γ-ray lines and a power law representing electron bremsstrahlung. We note the excess of the data over the model above ~7.5 MeV implying that there is emission continuing above 10 MeV not accounted for by a simple extrapolation of the power law from lower energies. OSSE also observed these high-energy γ rays in addition to neutrons from this flare. OSSE separates the γ-ray and neutron contributions using measured pulse shapes and Figure 2 shows the OSSE >16 MeV count spectrum attributed to γ-rays from this flare. Shown for comparison is the spectrum observed by OSSE from the 1991 June 4 flare. The June 11 spectrum is significantly harder, suggesting that some of this emission may be from pion decay rather than from electron bremsstrahlung as in the June 4 flare.

Figure 3 shows the derived time profiles of the >2 MeV narrow nuclear lines, the 2.223 MeV neutron-capture line, the 0.511 MeV positron-annihilation line, and the >16 MeV emission. (The relative normalizations are arbitrary for display purposes.) The nuclear lines, the neutron-capture line, and the positron-annihilation line peak at ~7450 s UT. The >16 MeV emission peaks ~850 s later. A secondary peak in the 0.511 MeV line at this time supports the claim that much of this >16 MeV emission is from pion decay rather than electron bremsstrahlung. Four emission intervals are defined in Figure 3. Interval I (7126–7650 s UT) covers the peak of the nuclear lines and electron bremsstrahlung. Interval II (7650–7913 s UT) corresponds roughly to the "Interphase" defined by Dunphy *et al.* (2) for this flare. Interval III (7913–8634 s UT) covers the >16 MeV emission peak. Interval IV (8634–9420 s UT) covers the decay phase.

MEASUREMENT OF SPECTRAL HARDNESS

The cross sections for the processes responsible for γ-ray line emission can have significantly different energy dependencies. Ratios of line fluences are therefore sensitive to the steepness of the accelerated-particle energy spectrum. Depending on where the

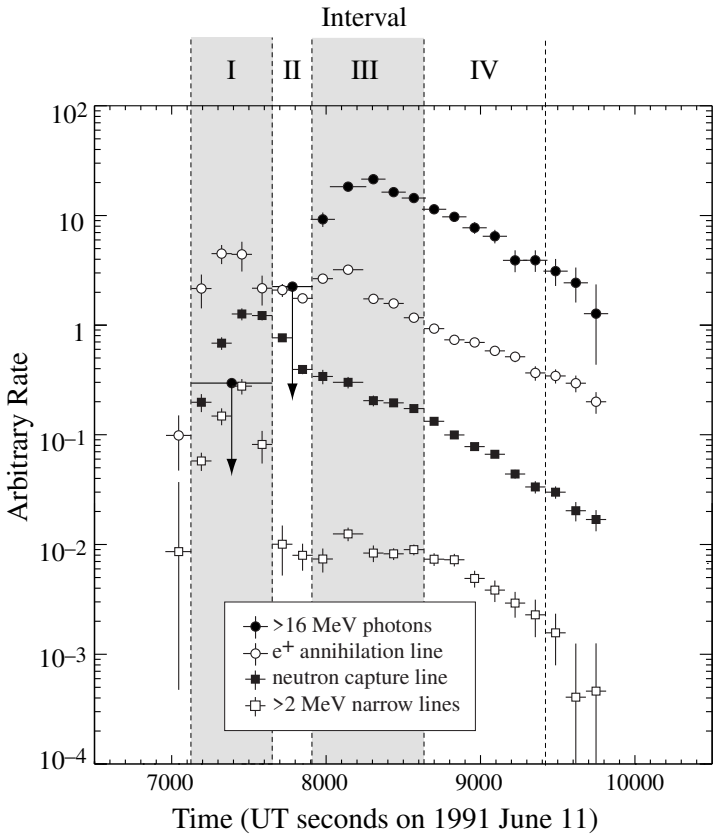

Figure 3. >16 MeV, 0.511 MeV line, 2.223 MeV line and >2 MeV narrow line fluxes.

specific cross sections peak, the ratios provide this information within relatively narrow energy bands. We use three ratios which together cover particle energies from ~1 to greater than several hundred MeV.

The first technique uses the **6.13-to-1.63 MeV line flux ratio**. The thresholds for the production of the $^{16}O^{*6.13}$ and $^{20}Ne^{*1.63}$ excited nuclei are ~2 and 8 MeV nucleon^{-1}, respectively, making the flux ratio quite sensitive to the particle spectral hardness. Both cross sections are falling rapidly by ~20 MeV nucleon^{-1}. As a result, this line ratio is sensitive to the steepness of the particle spectrum in the ~2–20 MeV nucleon^{-1} energy range.

The second technique uses the **0.511-to-4.44 MeV line ratio**. Positrons result from the decay of radioactive nuclei produced by interactions of ~10–50 MeV nucleon^{-1} particles. If the particle spectrum extends to several hundred MeV nucleon^{-1}, positrons can also result from the decay of pions produced. The positrons slow down in the solar atmosphere and annihilate with electrons to produce the 0.511 MeV line. On the other hand, the $^{12}C^{*4.44}$ excited nucleus is produced by ~10–30 MeV nucleon^{-1} particles. Therefore, this line ratio is sensitive to the steepness of the particle spectrum from ~10 to 50 MeV nucleon^{-1} or as much as several hundred MeV nucleon^{-1} if pions are produced. We assume a positronium fraction of 67%.

The third technique uses the **2.223-to-4.44 MeV line ratio**. Neutrons responsible for the 2.223 MeV neutron-capture line are produced primarily by 50–100 MeV nucleon^{-1}

particles. This ratio is therefore sensitive to the steepness of the particle spectrum in the 10–100 MeV nucleon^{-1} range.

Deexcitation γ rays such as those at 1.63, 4.44 and 6.13 MeV from ^{20}Ne, ^{12}C and ^{16}O are produced essentially instantaneously after production of the excited nuclei. Their fluxes therefore trace the nuclear interaction rate and so the 6.13-to-1.63 MeV line ratio provides an instantaneous measure of the particle spectral index. However, both the 0.511 MeV positron-annihilation and the 2.223 MeV neutron-capture lines are delayed. The 0.511 MeV line delay is due the decay time of the radioactive positron emitters and the subsequent slowing-down time of the positrons. Murphy and Ramaty (5) showed that for the 1981 June 21 *Solar Maximum Mission (SMM)* flare the slowing-down time was less than 16 s. The mean radioactive decay time, however, is on the order of a hundred seconds (6,7). The delay of the 2.223 MeV line is due to the slowing-down time of the neutrons to thermal energies and is also on the order of a hundred seconds (8,9). Because of these delays, spectral indexes determined using the 0.511 and 2.223 MeV lines are meaningful only if the data are accumulated over a long enough interval such as intervals I, III and IV defined for the June 11 flare. We note that interval II may be too short to provide a reliable index.

RESULTS

Power-law spectral indexes of the accelerated particles can be derived from the measured line ratios using calculations of γ-ray production (e.g., 5,10). Comparison of the indexes determined with the three techniques can then provide information about the overall shape of the particle spectrum from ~2 to as much as several hundred MeV.

Figure 4 shows spectral indexes derived by applying the three techniques to the June 11 data accumulated during the four Intervals of Figure 3. Technique 1 could not be used during the peak of the ~MeV emission (Interval I) due to saturation effects caused by the intense flux. Each Interval is discussed, starting with the two intervals (I and III) covering the peaks of the ~MeV and the >16 MeV emissions.

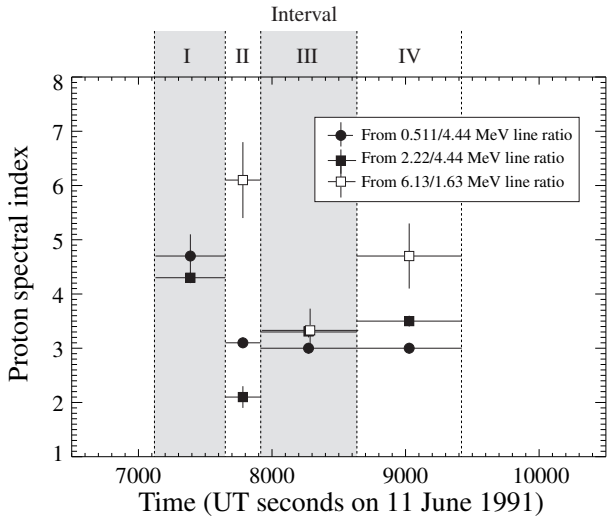

Figure 4. Accelerated-particle spectral indexes derived by the three techniques for the four intervals defined in Figure 3.

Interval I (peak of ~MeV γ-ray emission). The two available techniques give consistent spectral indexes, implying that the spectrum during this interval is an unbroken power law from ~10 to ~100 MeV. The derived index of ~4.5 is consistent with the index of ~4 derived by Dunphy *et al.* (2) for this interval.

Interval III (peak of >16 MeV γ-ray emission). All three techniques give nearly consistent indexes, implying that the spectrum is essentially an unbroken power law from ~2 to >100 MeV. The index (~3.2) is harder than that of Interval I and is consistent with the index of 3.35 ± 0.10 derived by Dunphy *et al.* (2) for this interval. Such a harder index is expected since the >16 MeV emission is probably from pion decay.

Interval II (Interphase). The indexes derived with the three techniques are *not* consistent, suggesting that the particle spectrum is *not* an unbroken power law during this interval. There appears to be a low-energy component with a soft spectrum and a high-energy component with a hard spectrum.

Interval IV (decay phase). The indexes derived with the three techniques again do not agree, suggesting that the spectrum again is not an unbroken power law. The hard, high-energy component may be that seen by EGRET late in the flare.

CONCLUSION

We applied three techniques of determining the steepness of the accelerated-particle energy spectrum, each sensitive to a different energy range, to OSSE data from the 1991 June 11 solar flare. We showed that the particle spectrum evolved as the flare progressed. During both the peak of the ~MeV emission and the peak of the >16 MeV emission, the spectrum was consistent with an unbroken power law from a few MeV to 100 MeV. The spectral indexes during these two intervals were ~4.5 and ~3.2, respectively. During the interval between these two emission peaks and during the decay phase, the spectrum deviated from a simple power law, showing a steeper low-energy component.

The peak of the >16 MeV emission was not coincident with that of the ~MeV line emission but occurred ~850 seconds later. The energy spectrum of this high-energy emission was very hard, suggestive of pion-decay radiation rather than electron bremsstrahlung. An enhancement of the 0.511 MeV positron annihilation radiation at the time of the >16 MeV peak supports this conclusion (see Figure 3). The arrival time of the neutrons (not shown here) was delayed relative to the ~MeV line radiation as compared to other flares such as the 1991 June 4 flare. A significant fraction of the neutrons were therefore probably produced during this delayed high-energy episode. This second acceleration episode is similar to the 1982 June 3 and 1984 April 24 flares observed with *SMM*.

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