OSSE satellite and neutron monitor observations of solar neutrons in association with 1991 June 4 flare

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Abstract: In association with the X12.0 flare on 1991 June 4, solar neutrons were observed in space by OSSE onboard the *CGRO* satellite and by ground-based detectors, such as the $12\,\mathrm{m}^2$ neutron monitor at Mt. Norikura, Japan. The γ-ray lines were also observed by *CGRO*/OSSE, and we can use the $4.4\,\mathrm{MeV}$ line time history as the ion acceleration release time history. Using these γ-ray line emissions, Murphy et al. [6, 5] calculated predicted time-dependent neutron spectra arriving at Earth using the solar-flare magnetic-loop transport and interaction model of Hua et al. [3]. Using the OSSE neutron response function, they compared predicted count rates with the observed OSSE count rates. We compare predicted count rates with the neutron signals observed by the Norikura neutron monitor, and successfully explain all observed signals.

Introduction

Ions accelerated in solar flares interact with the solar atmosphere to produce γ-ray lines and neutrons. Some of the neutrons that escape from the Sun into interplanetary space can survive to the Earth and be observed both by satellite detectors and by ground-based neutron detectors. Lower energy neutrons (kinetic energies below $100\,\mathrm{MeV}$) can only be observed in space because they are strongly attenuated in the Earth's atmosphere and cannot reach the ground. Neutrons with kinetic energies higher than $100\,\mathrm{MeV}$ can be observed on the ground and hence with simultaneous observations in space and on the ground, it is possible to obtain the energy spectrum of solar neutrons and of accelerated particles, in a wide energy range.

In June 1991, a series of six X-class solar flares which were larger than X10 occurred in NOAA region 6659. At the flare on June 4, the detectors onboard the *CGRO* satellite detected high energy γ-rays [7]. One of the detector onboard the *CGRO* named OSSE observed not only γ-rays, but also solar neutrons [6, 5]. Solar neutrons were also observed by the ground-based neutron detectors at Mt. Norikura, Japan [4, 9].

In this paper, we calculate predicted time-dependent neutron spectra arriving at the Earth using the Hua's model [3], and compare these predicted rates with rates observed both by OSSE and neutron monitor.

Observations and previous results of Murphy et al.

An X12.0 class solar flare occurred at 3:37 UT in NOAA region 6659 (N30 E70) on June 4, 1991. In this case, intense emission of γ-rays was observed by the BATSE and OSSE onboard the *CGRO* satellite [7, 6, 5]. The γ-ray lines at 2.2 and $4.4\,\mathrm{MeV}$

Table 1: Parameters of the Hua's program for 1991 June 4 event [5].

Accelerated ion composition (impulsive)	$\alpha/\mathrm{p} = 0.5$ $^3\mathrm{He}/^4\mathrm{He} = 1$
Ambient composition (coronal)	$\mathrm{He}/\mathrm{H} = 0.1$ $\mathrm{Ne}/\mathrm{O} = 0.25$
Atmospheric model	Avrett, 1981 [1]
Photospheric $^3\mathrm{He}/\mathrm{H}$	3.7×10^{-5}
Acceleration release time history	$4.4\,\mathrm{MeV}$ γ-ray line profile
Loop length	$11,500\,\mathrm{km}$
Flare heliocentric angle	74.5 degree
Pitch angle scattering (λ)	300
Magnetic convergence (δ)	0.20
Power index (s)	4.0
Cutoff energy (E_c)	$125\,\mathrm{MeV}$

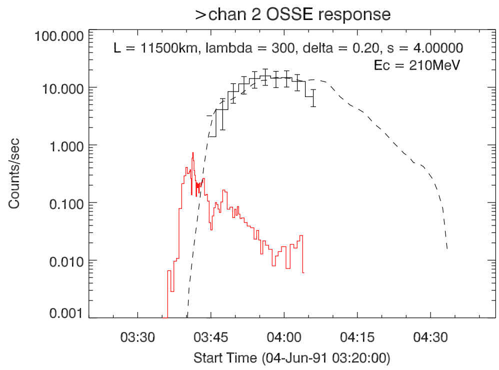

Figure 1: The observed and predicted neutron time histories by the OSSE on 1991 June 4. The black solid line is the observed counting rates from OSSE. The dashed line represent the predicted result of Hua's program with cutoff enegy $210\,\mathrm{MeV}$. The red line represent the the $4.4\,\mathrm{MeV}$ line time history as the ion acceleration release time history.

were clearly observed by *CGRO*/OSSE, and solar neutrons were also observed.

Murphy et al. [5] analyzed these OSSE data in detail, and obtained many parameters of Hua's model [3] as shown in Table 1, which explain observed $2.2\,\mathrm{MeV}$ γ-ray data. They use the $4.4\,\mathrm{MeV}$ line time history as the ion acceleration release time history. For the accelerated ion composition, ambient composition, atmospheric model and photospheric $^3\mathrm{He}/\mathrm{H}$ ratio, we use typical values estimated from observations of previous flares. Although they could not obtain flare loop length from observed data since there is no imager of the X-ray or γ-ray at that time, they obtained loop length by fitting observed $2.2\,\mathrm{MeV}$ time history, combination with values of the level of pitch angle scattering within the loop (λ), magnetic convergence ratio (δ) and spectral power-law index(s).

By using Hua's model with these parameters, they calculated neutron time history at the OSSE, and by comparing observed neutron data. They determine the upper cutoff energy of accelerated ions to fit the observed neutron data. That gave $125\,\mathrm{MeV}$, but such a value is too low energy to observe solar neutrons on the Earth.

The Sun was over Japan during this flare, and hence the observatory at Mt. Norikura was the most suitable place for observing solar neutrons, which were indeed detected by the Norikura neutron monitor [9]. At the flare start time, the zenith angle of the Sun was 18.5 degrees and the air mass along the line of sight to the Sun was $770\,\mathrm{g/cm^2}$. Neutron signals were observed by the 12NM64 Norikura neutron monitor, and statistical significance of the event was 5.1σ.

Cutoff energy of solar neutrons

Now we can compare ground-level neutron observations with neutron fluxes predicted from the γ-ray observation. The parameter that can be changed from Murphy et al. [5] is the cutoff energy of the accelerated ions. When we use $E_c = 125\,\mathrm{MeV}$, predicted profile significantly underestimates the observed neutron-monitor count rate.

Thus, at first, we recalculate the cutoff energy for the OSSE neutron data. When $E_c = 210\,\mathrm{MeV}$, predicted neutron profile is well fitted to the observed data of OSSE as shown in Figure 1, and the reduced χ^2 is 1.18.

Next, we calculate the resulting neutron-monitor count rates due to these arriving neutron spectra by using the solar neutron atmospheric attenuation ratio from the Shibata program [8] and the neutron monitor efficiency calculated by Clem and Dor-

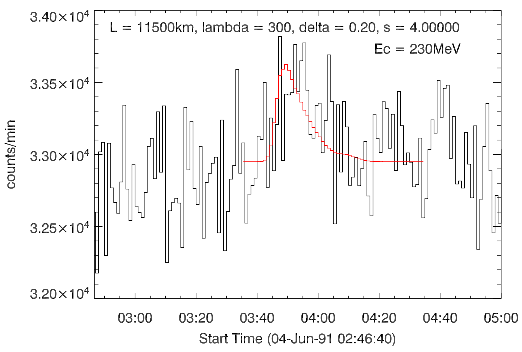

Figure 2: The observed and predicted neutron time histories by the Norikura neutron monitor on 1991 June 4. The black line is the observed one-minute counting rates from the Norikura neutron monitor. The red line represent the predicted result of Hua's program with cutoff energy $230\,\mathrm{MeV}$.

man [2]. We compare the predicted count rate with the observed count rate in Figure 2. When $E_c = 230\,\mathrm{MeV}$, the predicted neutron profile is well fitted to the observed neutron monitor data as shown in Figure 2, and the reduced χ^2 is 0.78.

From the reduced χ^2 distribution of this fit as shown in Figure 3, we obtain errors of these cutoff energy as $E_c = 210 \pm 10\,\mathrm{MeV}$ for fitting to the OSSE data, and as $E_c = 230^{+20}_{-50}\,\mathrm{MeV}$ for the neutron-monitor data. We thus find that the predicted rate is well fitted both observed neutron data within the range of error.

Summary

We have compared observed neutron count rates for the 1991 June 4 solar flare obtained with the OSSE and Norikura neutron monitor simultaneously with calculated count rates based on γ-ray data obtained with *CGRO*/OSSE. We find that the predicted rates fit the observed data when cutoff energy is $210\,\mathrm{MeV}$. This is the first event for which the predicted neutron profile from Hua's model can explain all observed data of line γ-rays plus neutron data from both space and ground.

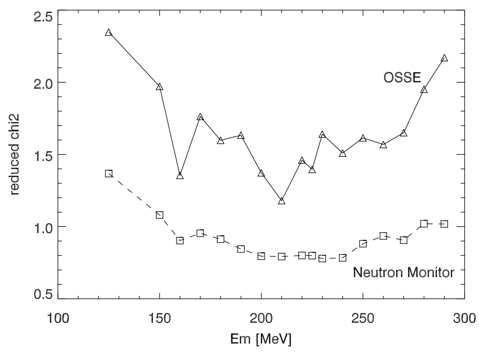

Figure 3: The reduced χ^2 distribution for the fit to the OSSE and neutron monitor neutron data for each cutoff energy.

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