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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. [1, 2] 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. For the flare on June 4, instruments onboard the *CGRO* satellite detected high energy γ-rays [4]. One of the instruments, OSSE, observed not only γ-rays, but also solar neutrons [1, 2]. Solar neutrons were also observed by the ground-based neutron detectors at Mt. Norikura, Japan [5, 6].

In this paper, we calculate predicted time-dependent neutron spectra arriving at the Earth using 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. (1997)

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 BATSE and OSSE onboard the *CGRO* satellite [4, 1, 2]. *CGRO*/OSSE clearly observed the γ-ray lines at 2.2 and $4.4\,\mathrm{MeV}$ and also solar neutrons.

Table 1: Parameters of the Hua's program for 1991 June 4 event [2].

Accelerated ion composition (impulsive)	$\alpha/\mathrm{p} = 0.5$ $^3\mathrm{He}/^4\mathrm{He} = 1$
Ambient composition (coronal)	$\mathrm{He/H} = 0.1$ $\mathrm{Ne/O} = 0.25$
Atmospheric model	Avrett, 1981 [7]
Photospheric $^3\mathrm{He/H}$	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	$74.5\,\mathrm{degree}$
Pitch angle scattering (λ)	300
Magnetic convergence (δ)	0.20
Power law index (s)	4.0
Cutoff energy (E_c)	$125\,\mathrm{MeV}$

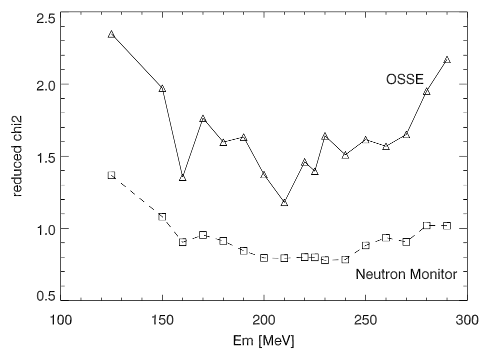

Figure 1: The reduced χ^2 distribution for the fit to the OSSE and neutron monitor neutron data for each cutoff energy.

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 [6]. At the flare start time, the zenith angle of the Sun was $18.5\,\mathrm{degrees}$ 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 the statistical significance of the event was 5.1σ.

Murphy et al. [2] analyzed the OSSE γ-ray data in detail and determined many parameters of Hua's model [3]. They used the $4.4\,\mathrm{MeV}$ line time history as the ion acceleration release time history and, for the accelerated ion composition, ambient composition, atmospheric model and photospheric $^3\mathrm{He/H}$ ratio, they used typical values estimated from observations of previous flares. Although they could not obtain the flare loop length directly from observations since there was no X- or γ-ray imaging at that time, they obtained the loop length along with the level of pitch angle scattering within the loop (λ), the magnetic convergence parameter (δ), and the accelerated-ion power-law spectral index (s) through a comprehensive analysis of the γ-ray data. Their derived values are shown in Table 1. Using these parameters, they then calculated the time history of neutrons arriving at Earth and, using the OSSE neutron response, compared predicted and observed neutron count rates. They found that the prediction overestimated the measurements, but reasonable agreement could be obtained if the accelerated-ion spectrum had a high-energy cutoff. They obtained a rough estimate of this cutoff, E_c, of about $125\,\mathrm{MeV}$.

Cutoff energy of solar neutrons

We first improve the determination of the cutoff energy E_c obtained from the OSSE neutron data, keeping the other parameters fixed at the values derived from the γ-ray analysis. From the reduced χ^2 distribution of the fit shown in Figure 1, we obtain $E_c = 210\,\mathrm{MeV}$. With this value of E_c, the observed OSSE neutron data is well fit with the predicted neutron profile as shown in Figure 2, with a reduced χ^2 of 1.18.

We now determine the cutoff energy E_c using the ground-level neutron observations for this flare. We calculate predicted neutron-monitor count rates using the solar neutron atmospheric attenuation obtained from the Shibata program [8] and the neutron monitor efficiency calculated by Clem and Dorman [9]. From the reduced χ^2 distribution of the fit shown in Figure 2, we obtain $E_c = 230^{+20}_{-50}\,\mathrm{MeV}$. With this value of E_c, the observed neutron-monitor data is well fit with the predicted neutron count rate as shown in Figure 3, with a reduced χ^2 of 0.78. We thus find that, within the uncertainties, the cutoff energy derived from the neutron-monitor data is consistent with that derived from the OSSE neutron data.

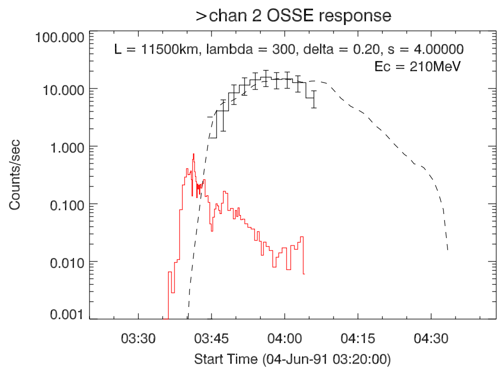

Figure 2: The observed and predicted neutron time histories by the OSSE on 1991 June 4. The black solid line is the observed counting rates from OSSE. The dashed line represent the predicted result of Hua's program with cutoff energy $210\,\mathrm{MeV}$. The red line represent the $4.4\,\mathrm{MeV}$ line time history as the ion acceleration release time history.

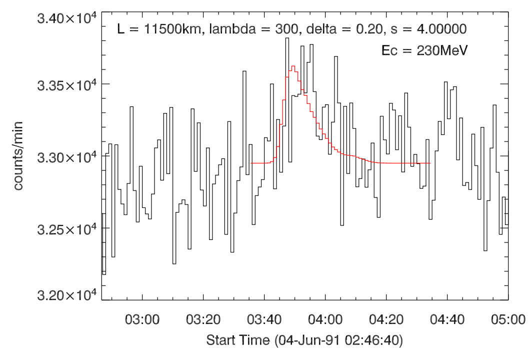

Figure 3: The observed and predicted neutron time histories by the Norikura neutron monitor on 1991 June 4. The black line is the observed one-minute counting rates from the Norikura neutron monitor. The red line represent the predicted result of Hua's program with cutoff energy $230\,\mathrm{MeV}$.

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 the cutoff energy is about $210\,\mathrm{MeV}$. 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.

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