

Simultaneous Observations of Solar Neutrons in Association with a Large Solar Flare on November 4, 2003

K. Watanabe^a, Y. Muraki^a, Y. Matsubara^a, T. Sako^a, T. Sakai^b, S. Shibata^c, C. Lopate^d, J.F. Valdés-Galicia^e, A. Hurtado^e, O. Musalem^e, L.X. Gonzalez^e, R. Ogasawara^f, Y. Mizumoto^f, M. Nakagiri^f, A. Miyashita^f, M. Gros^g

(a) Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya 464-8601, Japan

(b) College of Industrial Technologies, Nihon University, Narashino 275-0005, Japan

(c) College of Engineering, Chubu University, Kasugai 487-8501, Japan

(d) The University of New Hampshire, Space Science Center, New Hampshire 03824, USA

(e) Instituto de Geofísica, Universidad Nacional Autónoma de México, 04510, D. F. México, México

(f) National Astronomical Observatory of Japan, Hilo, Hawaii 96720, USA

(g) DSM/DAPNIA/SAP, CEA Saclay, 91191 Gif-sur-Yvette, France

Presenter: K. Watanabe (kwatana@stelab.nagoya-u.ac.jp), jap-watanabe-K-abs2-sh11-poster

On November 4, 2003, relativistic solar neutrons were observed in association with an X28 class flare, which is the largest solar flare on record. The detector onboard the *INTEGRAL* satellite observed a high flux of hard X-rays and γ -rays at the same time. It appears that neutrons were produced at the same time as the γ -ray emission. Solar neutrons were observed by the neutron monitors at Haleakala in Hawaii and Mexico City, and the solar neutron telescope at Mauna Kea in Hawaii, simultaneously. Clear excesses were observed at the same time by these detectors, with the significance calculated as 7.5σ for Haleakala, and 5.2σ for Mexico City. By fitting simulation results to these excesses we obtained a consistent energy spectrum as $1.5 \times 10^{28} \times (En/100 [\text{MeV}])^{-3.9} [\text{MeV}/\text{sr}]$.

1. Introduction

A solar neutron event is a rare event. Thus, it is important that one consistent model can explain the data of two or more (if possible, different type) detectors to derive an accurate spectrum of solar neutrons from the solar neutron event. Simultaneous observations of solar neutrons have been made for a few events on June 3, 1982 [1], on May 24, 1990 [2, 3, 4], and on June 4, 1991 [5, 6].

On November 4, 2003, solar neutrons were observed by NM64 type neutron monitors (NMs) located at different places, one at Haleakala in Hawaii and the other at Mexico City in Mexico. In addition, solar neutrons were also observed by the solar neutron telescope (SNT) located at Mauna Kea in Hawaii. In this paper, we report the analysis results of the November 4 event using data from the NMs, the SNT and the spacecraft.

2. Observations

On November 4, 2003, an X28 class solar flare occurred at 19:29 UT, located in NOAA active region 10486 at S19W83. This is the largest solar flare on record. At around 19:42 UT, an intense emission of soft X-rays was detected by the *GOES* satellite such that the detection was saturated. After 19:42 UT, intense emissions of hard X-rays and γ -rays were observed by the *INTEGRAL* spacecraft. In this event, although the components of the line emission produced by de-excited ions, C(4.443 MeV) and O(6.129 MeV), were not prominent, the 2.223 MeV neutron capture line can be clearly seen. Intense bremsstrahlung X-rays and γ -rays were also observed. Figure 1 shows the time profiles of γ -rays for different energy bins, that contain line γ -ray components produced as a result of the ion acceleration. There is a delay of the 2.223 MeV neutron capture γ -ray emission from that of the line γ -ray components produced by excited ions of C and O [7]. The γ -rays

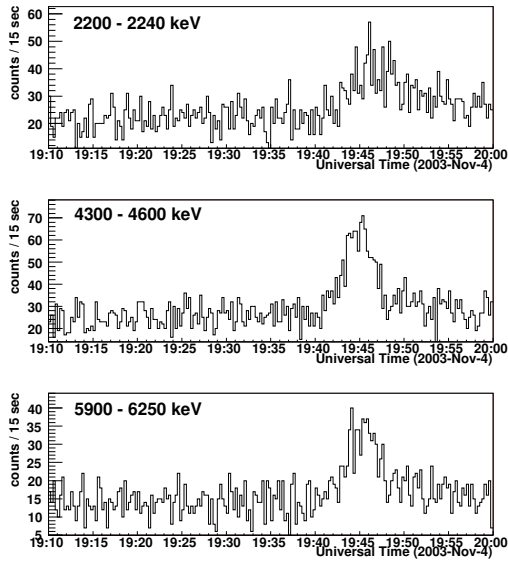


Figure 1. Time profiles of line γ -rays observed by the *INTEGRAL* satellite on November 4, 2003. The bremsstrahlung component has not been subtracted. The top panel shows the time profile of the 2.223 MeV neutron capture γ -ray. The second one gives the 4.443 MeV γ -ray of C nuclei, and the third one contains the 6.129 MeV γ -ray of O nuclei. These time profiles indicate the time profile of ion acceleration, although the dominant component is bremsstrahlung.

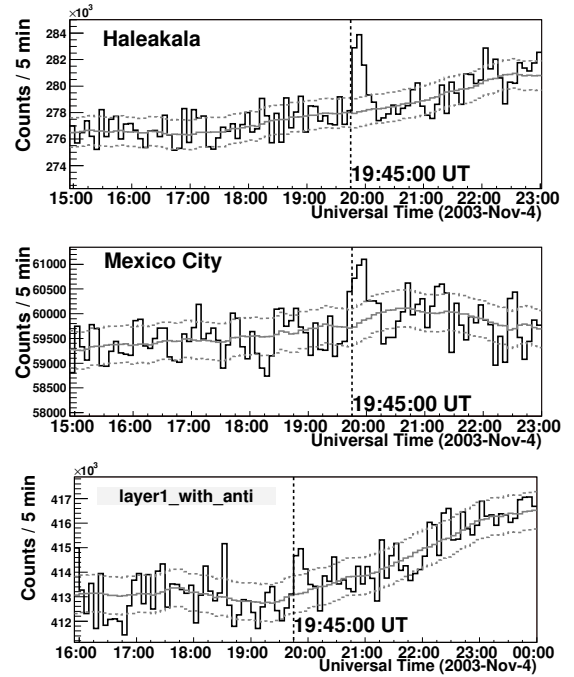


Figure 2. Five minute averages of the counting rate observed by the Haleakala (top), Mexico City (middle) NMs, and layer1_with_anti channel of the Hawaii SNT on November 4, 2003. The solid smooth line is the averaged background and the dashed lines are $\pm 1\sigma$ from the background.

are mainly emitted via bremsstrahlung; however we may assume that ion acceleration occurred at the line γ -rays were emitted and that this was when neutrons were produced. We may assume that the ion acceleration occurred at the same time as the line γ -rays of excited ions were emitted, although the main component of these γ -rays is bremsstrahlung, and that solar neutrons were also produced at the same time.

At 19:45 UT, the Sun was located between Hawaii and South America. Among the stations of the international network of solar neutron observation, solar neutrons were observed by the 18NM64 NM at Haleakala in Hawaii (203.7°E, 20.7°N, 3030 m a.s.l.), the 6NM64 NM at Mexico City (260.8°E, 19.33°N, 2274 m a.s.l.) and the 8 m² SNT at Mauna Kea in Hawaii (203.7°E, 19.8°S, 4200 m a.s.l.). The zenith angle of the Sun was 49.9° at Mauna Kea, 50.5° at Haleakala, and 40.52° at Mexico City. The air mass along the line of sight to the Sun was 947 g/cm², 1112 g/cm² and 1026 g/cm², respectively.

Figure 2 show the five minute binning of the counting rate observed by these detectors on November 4, 2003. Excesses were seen after 19:45 UT, lasting for 15 minutes in all detectors. The total significance for the fifteen minutes is 7.5 σ for Haleakala and 5.2 σ for Mexico City.

Although Mauna Kea should be a better place to observe neutrons in this event than Haleakala and Mexico City, only some small excesses were seen after 19:45 UT by this telescope as shown in the bottom panel in Figure 2 (layer1_with_anti channel). This apparent discrepancy between NMs and the SNT is discussed in the next section considering the surrounding environment of the detector.

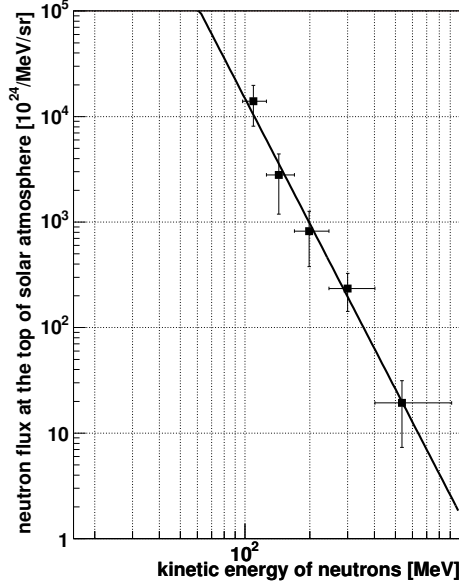


Figure 3. The energy spectrum of neutrons at the solar surface on November 4, 2003, calculated from the data of the Haleakala NM.

3. Analysis of observations

In order to estimate the energy spectrum of solar neutrons at this event, we begin with the data from the Haleakala monitor, because it recorded the largest excess with the best time resolution. We determine the neutron energy using the time of flight method, assuming that all the solar neutrons were produced at 19:45 UT, the peak time of the intense emission of high energy γ -rays observed by *INTEGRAL* as shown in Figure 1. Under this assumption, the energy of neutrons observed by the Haleakala NM between 19:51:20 and 19:56:20 UT ranged from 59 – 913 MeV.

To derive the energy spectrum of neutrons at the solar surface from the observed time profile by the NM, the survival probability of neutrons between the Sun and the Earth, the attenuation of solar neutrons passing through the Earth's atmosphere and the detection efficiency of the NM must be taken into account. The attenuation was calculated using the Shibata model [8], and we used the detection efficiency calculated by Clem & Dorman [9].

Using these observational and simulation results, we calculated the energy spectrum of neutrons at the solar surface using the method developed for the analysis of the solar neutron event observed on November 24, 2000 [10]. The result is shown in Figure 3. This spectrum was derived from two minute averages of the counting rate, the vertical errors shown are only statistical. By fitting these data points with a power law, the energy spectrum of solar neutrons was obtained. The fitting region is chosen as 100 MeV and above, because there the errors from neutron attenuation in the Earth's atmosphere are small. The energy spectrum is well fitted by a power law as:

$$Q = (1.5 \pm 0.6) \times 10^{28} \times \left(\frac{E_n}{100 [\text{MeV}]} \right)^{-3.9 \pm 0.5} \quad [/\text{MeV}/\text{sr}]. \quad (1)$$

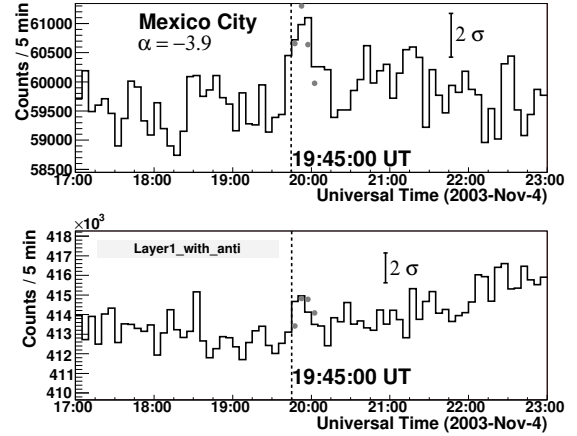


Figure 4. The simulated time profiles (dots) of five minute counting rate of the Mexico City NM (top) and layer1_with_anti channel of the Hawaii SNT (bottom) on November 4, 2003, superposed on the observational data. Equation (1) is used as the energy spectrum of the incident neutrons, which was obtained from the data of Haleakala NM. The start time of this time profile is 19:45 UT, corresponding to the peak time of γ -ray emission.

For this fit, $\chi^2/\text{dof} = 0.9/3 = 0.3$ and the χ^2 probability is 82 %. This spectral index is typical of solar neutron events observed thus far. The total energy flux of neutrons emitted from the Sun in the energy range 59 – 913 MeV is estimated to be 3.4×10^{26} erg/sr.

We then simulated the time profiles of neutrons which should be observed from the Mexico City NM and the Hawaii SNT using the energy spectrum of incident neutrons obtained from the data of the Haleakala NM as shown in Equation (1). The detection efficiency of the Hawaii SNT is calculated using Geant3, FLUKA–COLOR model. In this calculation we have taken into account that the Hawaii SNT is surrounded by the 20 cm concrete walls, since it is constructed within the building housing of the SUBARU telescope. The simulated results are shown in Figure 4. For this fitting, $\chi^2/\text{dof} = 6.6/3 = 2.2$ for the Mexico NM and $\chi^2/\text{dof} = 1.2/3 = 0.4$ for the Mauna Kea SNT, so the simulation result is consistent with the observed excess.

4. Summary

Relativistic neutrons were detected in association with the X28 solar flare on November 4, 2003. This detection was made simultaneously by the NMs at Haleakala and Mexico City, and also by the SNT at Mauna Kea.

In order to investigate the production time of solar neutrons, we compared the solar neutron data with the γ -ray data obtained from *INTEGRAL*. Assuming that solar neutrons were produced impulsively at 19:45 UT, when the high energy γ -rays peaked, the energy spectrum of solar neutrons at the solar surface was obtained for the data of the Haleakala NM as shown in Equation (1). By using Equation (1), time profiles of the Mexico City NM and the SNT at Mauna Kea are also explained. The calculated solar neutron energy spectrum is consistent with observations of the three stations.

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