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Solar Neutron Event Associated with an X8.3 Flare on 2003 November 2

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On November 2, 2003, in association with X8.3 flare, a solar neutron event was detected with high statistical significance (4.7σ) by the neutron monitor at Mt. Chacaltaya, Bolivia. Although large GLE event occurred and was observed by many neutron monitors in association with this flare, the start time of the neutron event was earlier than that of the GLE event. At this flare, the intense emission of γ-rays has been observed by the *RHESSI* satellite. The production time of solar neutrons was well correlated with those of γ-rays.

1. Introduction

The Sun was intensely active from late October to the beginning of November 2003. The solar flares that occurred in this period were observed by numerous satellites and detectors, and have been analyzed by many investigators. During the period when three active regions appeared simultaneously on the solar surface, the soft X-ray flux was very intense and a series of eleven X-class solar flares occurred in NOAA regions 10484, 10486 and 10488. At this time, solar neutrons were observed on November 2, 2003, in association with X8.3 class solar flare. In this paper, we report the analysis results of this event such as the energy spectrum of solar neutrons and accelerated protons in this solar flare, using the data of the neutron monitor and the satellite.

2. Observations

At 17:03 UT on November 2, 2003, an X8.3 class solar flare occurred in NOAA active region 10486. The location of the active region was S14W56 at the start time of the flare, which was a disk flare. The flux of soft X-rays did not increase smoothly between the start time and the flare maximum: a sudden increase of the flux was observed before the flux reached its maximum.

During this flare, large amounts of γ-ray emission were observed by the *RHESSI* satellite. The second highest energy γ-ray channel ($800 - 7000$ keV) of the *RHESSI* satellite showed a significant excess. The γ-rays in this energy range contained the 2.223 MeV photons resulting from the neutron capture and line γ-rays of de-excited ions between 4 and 7 MeV. Time profiles of the 2.223 MeV and 4 to 7 MeV γ-rays are shown in Figure 1. The γ-ray emission in the energy range of 4 to 7 MeV reached its peak at 17:17 UT and the neutron capture line peaked at 17:18:40 UT. There is a gap of 100 seconds between these peak times. Since it takes about 100 seconds for high energy neutrons to slow down and be captured by protons [1], we conclude that the solar neutrons were produced at 17:17 UT.

At the time of occurrence of this flare, the Sun was positioned over South America. The Chacaltaya observatory (292.0°E, 16.2°S, 5250 m a.s.l.) in Bolivia was accordingly the most suitable station to observe solar neutrons in the international network of solar neutron telescopes. At 17:17 UT, the zenith angle of the Sun was 14.9° at Mt. Chacaltaya, and the corresponding air mass along the line of sight to the Sun was $559\,\mathrm{g/cm^2}$. Unfortunately, during this time, blackouts often occurred at the observatory and the data from the solar neutron telescope was not recorded due to a power outage. However, the neutron monitor continued to record data until 18:00 UT, and clear excesses were detected between 17:25 and 17:50 UT (top panel of Figure 2). The statistical significance was 4.7σ at 17:30−17:35 UT with a 5-minute counting rate.

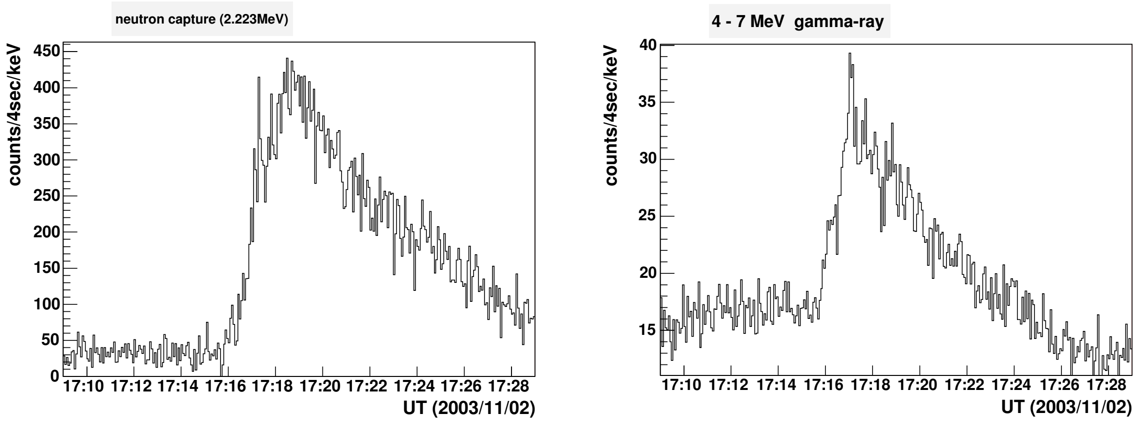

Figure 1. The 2.223 MeV (left) and $4-7$ MeV (right) γ-ray time profiles observed by the *RHESSI* satellite on November 2, 2003. The peak of the 2.223 MeV emissions is delayed by about 100 seconds from that of the $4-7$ MeV emissions.

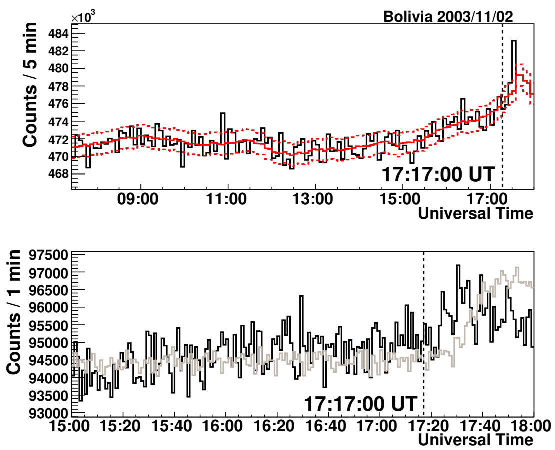

Figure 2. Time profiles of the counting rate observed by the neutron monitor located at Mt. Chacaltaya, Bolivia on November 2, 2003. Top: the 5-minute counting rate observed on November 2, 2003. The solid smooth line is the averaged background and the dashed lines are $\pm 1\sigma$ from the background. Bottom: The 1-minute counting rate of the Bolivia neutron monitor (black line) and the time profile of the McMurdo neutron monitor (gray line) on November 2, 2003.

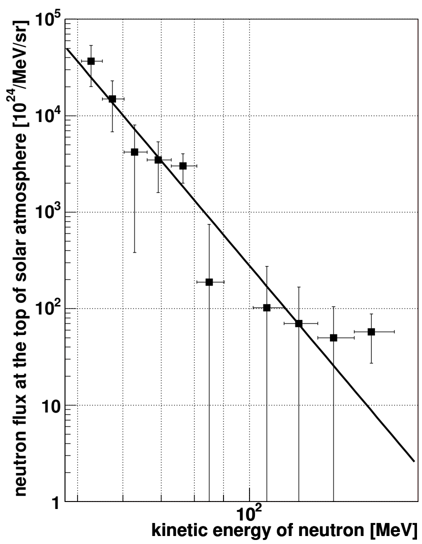

Figure 3. The energy spectrum of solar neutrons at the surface of the Sun in the case of the flare of November 2, 2003.

High energy protons were produced in association with this flare and large ground level enhancements (GLEs) occurred around the world. Thus it is possible that the excesses were due to the energetic ions rather than neutrons. However, the cutoff rigidity at Mt. Chacaltaya is very high (12.53 GV) so that it is difficult for such ions to enter the magnetosphere of the Earth. Furthermore time profile of the McMurdo neutron monitor is plotted together with that of the Bolivia neutron monitor (bottom panel of Figure 2). The GLE event began after 17:30 UT, that is, about 5 minutes later from the start time indicated by the neutron monitor at Mt. Chacaltaya. It is therefore clear that these excesses observed by the neutron monitor at Mt. Chacaltaya were due to the solar neutrons.

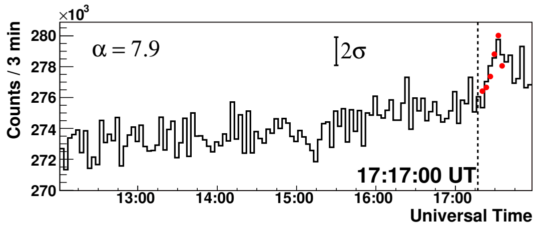

Figure 4. The simulated time profile (dots) of three minute counting rate of the Bolivia neutron monitor on November 2, 2003, superposed on the observational data. The start time of this time profile is 17:17 UT, corresponding to the peak time of γ-ray emission. Data obtained during 17:16−17:37 UT are used in this fitting.

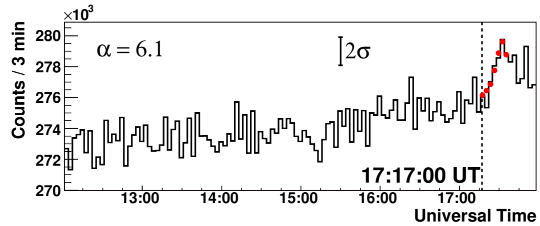

Figure 5. The simulated time profile (dots) of three minute counting rate superposed on the observational data. In this fitting, the data obtained during 17:16−17:37 UT are used. The simulated time profile is based on the assumption that solar neutrons were produced with the same time profile as the 4 − 7 MeV γ-rays shown in Figure 1.

3. Analysis Result

3.1 Energy Spectrum

To derive the energy spectrum of neutrons at the solar surface from the observed time profile with the neutron monitor, the survival probability of neutrons in propagation between the Sun and the Earth, the attenuation of solar neutrons in the Earth's atmosphere and the detection efficiency of the neutron monitor must be taken into account. The attenuation of solar neutrons passing through the Earth's atmosphere at Chacaltaya at 17:17 UT on November 2, 2003, was calculated using the Shibata model [2], and we used the detection efficiency calculated by Clem & Dorman [3].

Assuming that solar neutrons were produced at 17:17 UT when large fluxes of γ-rays were observed by the *RHESSI* satellite, the energies of the solar neutrons detected by the neutron monitor is estimated in the range $51 - 180\,\mathrm{MeV}$. Although these energies are very low, solar neutrons in this energy range can penetrate to the ground level through $559\,\mathrm{g/cm^2}$ of atmosphere. For Example, 0.6% of incident $100\,\mathrm{MeV}$ neutrons can reach the ground level at this time while the survival probability for $50\,\mathrm{MeV}$ neutrons is 0.03 %.

The energy spectrum is calculated by dividing the response (attenuation, efficiency and so on) into general bins, each characterized by a mean energy. For the survival probability of solar neutrons, as well as the attenuation of neutrons and detection efficiency of the neutron monitor, the values at these discrete energies are used. Figure 3 shows the energy spectrum of solar neutrons at the solar surface calculated under the assumption that they were produced at 17:17 UT. We calculated the energy spectrum at the solar surface from the time profile of the 1-minute counting rate. It can be fitted by a power law above $50\,\mathrm{MeV}$ as

$$(2.8 \pm 1.6) \times 10^{26} \times \left(\frac{E_n}{100\,[\mathrm{MeV}]}\right)^{-7.0\pm1.3} \quad [/\mathrm{MeV/sr}]. \tag{1}$$

For this fit, $\chi^2/\mathrm{dof} = 6.94/8 = 0.87$, and the χ^2 probability is 54 %. The spectral index is softer than those of the solar neutron events observed thus far ($-3 \sim -4$). The total energy of neutrons emitted from the Sun in the energy range $51 - 180\,\mathrm{MeV}$ was estimated to be $2.6 \times 10^{25}\,\mathrm{erg/sr}$.

3.2 Simulation Using the Impulsive Model

In order to calculate the energy spectrum of the solar neutrons in detail, we include an assumption about the time profiles of solar neutrons but still assume a power law spectral index at the solar surface. Using this method, we can investigate whether the neutrons are produced continuously. To clarify the consistency with the conventional method, we begin by assuming that all the neutrons are produced at the same time.

The time profiles of solar neutrons, assuming their spectral index at the solar surface, can be simulated if all the neutrons were produced at the same time. In this simulation, the assumed spectral index of neutrons produced at the Sun is changed from -1.5 to -9.0 in steps of 0.1 and the energy range of the incident neutrons is $50 - 1500\,\mathrm{MeV}$.

The minimum χ^2 for the simulated counting rate to the observed excess of the Bolivia neutron monitor is obtained when the power index is -7.9, and $\chi^2/\mathrm{dof} = 8.77/6 = 1.46$, as shown in Figure 4. From this fitting, the energy spectrum is determined as follows:

$$(1.9 \pm 0.3) \times 10^{26} \times \left(\frac{E_n}{100\,[\mathrm{MeV}]}\right)^{-7.9^{+0.8}_{-1.0}} \; [/\mathrm{MeV}/\mathrm{sr}]. \tag{2}$$

This provides good agreement with the observations as shown in Equation (1). The total energy flux of solar neutrons with energies in the range $50 - 1500\,\mathrm{MeV}$ was calculated to be $(3.1^{+0.5}_{-0.4}) \times 10^{25}\,\mathrm{erg/sr}$.

3.3 Simulation by Neutron Production Using the γ-ray Model

Next we simulate the neutron time profile measured by the Bolivia neutron monitor on November 2, 2003, assuming that the neutrons were produced within a finite time. In this calculation we used the $4 - 7\,\mathrm{MeV}$ γ-ray profile observed by the *RHESSI* satellite during 17:15:54−17:22:22 UT, which is shown in Figure 1.

The minimum χ^2 for the simulated time profile to the observed excess of the Bolivia neutron monitor is obtained when the power index is -6.1, and $\chi^2/\mathrm{dof} = 5.35/6 = 0.89$, as shown in Figure 5. From this fitting, the spectral index is determined to be $-6.1^{+0.6}_{-0.8}$. The spectral indices calculated by assuming neutrons were produced with a time spread, tend to be harder than those derived by assuming neutrons were produced impulsively. The total energy flux of solar neutrons was calculated as $(2.4^{+0.5}_{-0.3}) \times 10^{25}\,\mathrm{erg/sr}$.

4. Summary

We have detected solar neutrons in association with the X8.3 flare that occurred on November 2, 2003. This detection was made by the neutron monitor at Mt. Chacaltaya. In order to determine the production time of neutrons, we compared the solar neutron data with the γ-ray data obtained by the *RHESSI* satellite. When assuming that the neutrons were produced impulsively, spectral index of solar neutron is calculated as $-7 \sim -8$, and if these were produced gradually with γ-ray time profile, spectral index is calculated as -6.1. Time profile of solar neutrons were explicable with the assumption that solar neutrons were produced with the same time of γ-rays.

5. Acknowledgments

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