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Arrival of solar neutrons from large zenith angle

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Abstract. Solar neutrons were detected by the Yangbajing solar neutron telescope located in Tibet(N$30°$, E$90°$, 4300 m above sea level) in association with X3.3 solar flare on November 28th 1998. The detection of solar neutrons was possible using a capability of the telescope which can identify the incoming direction of neutrons. In this event, solar neutrons arrived at the top of the the atmosphere with a large zenith angle $53°$. It has been shown by a Monte Carlo simulation in this paper that even solar neutrons with a large zenith angle can be detected owing to large angle scattering of neutrons by air nuclei. The energy spectrum of neutrons was obtained by assuming that solar neutrons were produced at the start time of BATSE hard X-rays.

1 Introduction

Solar flares are one of the most energetic and drastic phenomena in nature. In solar flares, electrons and ions are accelerated to high energies. X-rays and gamma-rays resulting from the acceleration of electrons, have also been observed. The acceleration mechanism for electrons has been revealed gradually, being based on several observational results. On the other hand, the acceleration mechanism of ions has been not well understood. Because ions have heavier masses than electrons, their radiations are quite faint. In order to elucidate the puzzle of how ions are accelerated to high energies near the solar surface, other information must be used.

Neutrons are also produced by flares. They result from nuclear interactions between accelerated ions and the solar atmosphere. Neutrons can travel directly from the flare site to the earth without being disturbed by the interplanetary magnetic field. Therefore, if we can measure the production time of neutrons, we will be able to reply to the question of whether ions are accelerated simultaneously with electrons or not. However neutrons have mass and cannot travel with the speed of light. A new capability was required for the new neutron detectors in order that they can measure the energy of neutrons. In addition, the solar neutron detector at Yangbajing has the capability of measuring incoming direction of neutrons. This capability can reduce the huge amount of background produced by galactic cosmic rays, which would otherwise swamp the signals from the sun. Other detectors installed at Gornergrat, Norikura and Mauna Kea also have the capability to measure the arrival direction of incident neutrons.

In this paper, after giving an interpretation of the solar flare of November 28th 1998 in Section 2, observational results are given in Section 3. The detection of solar neutrons is discussed in Section 4. In section 5 we summarize our results.

2 Flare of November 28th 1998

On November 28th 1998, a X3.3/3N solar flare was observed at N17E32 on the solar surface in Active Region 8395. According to GOES satellite data, the flare onset time and the maximum time were 4:54 UT and 5:52 UT respectively. A complicated loop structure was observed by the soft X ray telescope on board Yohkoh (Masuda, 1999). The loop started growing at $\sim$ 5:30 UT (Sakurai, 1999) and thermal emission from the loop reached a maximum intensity at $\sim$ 5:50 UT. Yohkoh detected hard X ray emissions (93 - 252 keV) between 5:39 UT and 5:43 UT (Yoshimori, 1999). CGRO/BATSE also detected hard X ray emissions (30 - 58 keV) with the peak intensity at 5:40:46 UT. The Nobeyama Radio heliograph detected radio emissions at a frequency of 17GHz and 34 GHz and the maximum emission was observed at 5:39:51 UT (Fujiki, 1999).

The NAO investigators have made an analysis based on their magnetogram, Hα and Yohkoh soft X-ray data. They proposed a scenario for this event in which the flare trigger had already started at 05:06 UT. The interaction between two loops drove a flow and triggered another intersection of two loops at 05:32 UT, and this becomes the origin of the large flare. Details can be seen in their paper (Hui Li et al., 2000).

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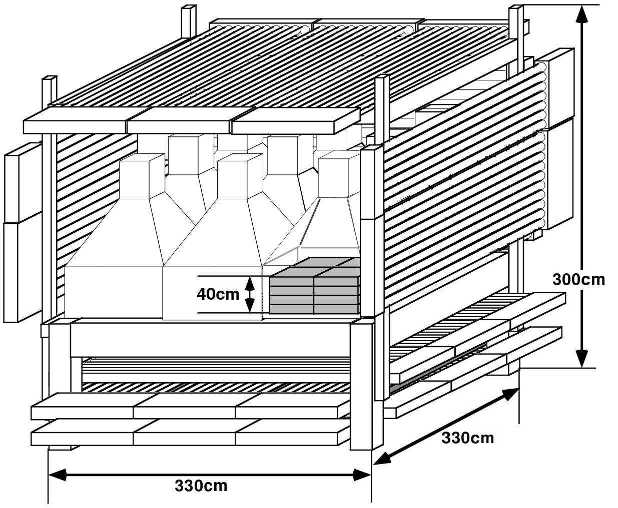

Fig. 1. Schematic view of the Tibet solar neutron detector. The detector has an area of 9 m^2 and scintillators with a thickness of 40 cm. Using the detector, observations of solar neutrons at Yangbajing have been made continuously since Oct., 1998.

3 Observation of neutrons at Yangbajing, Tibet

Yangbajing is one of the most suitable places for observing solar neutrons because of its high altitude, with vertical atmospheric depth $600\mathrm{g/cm}^2$. The Tibet solar neutron detector was installed at Yangbajing in Oct. 1998. A schematic view of the Tibet solar neutron detector is shown in Figure 1. The Tibet solar neutron detector has three important capabilities for observing solar neutrons; (1) measurement of the kinetic energy of incident neutrons, (2) measurement of the arrival direction of incident neutrons and (3) rejection of charged particles, which are mainly composed of muons and electrons. The arrival directions are measured using 4 layers of proportional counters. Detailed descriptions have been published elsewhere (Katayose et al., 1999; Tsuchiya et al., 2001).

The Tibet solar neutron detector has a capability to measure the energy of neutrons in a wide range. The measurement of low energy solar neutrons is achieved using the 9 scintillation counters in the upper part (See Fig. 1), while the detection of high energy solar neutrons is realized in the lower part by a sandwich detector consisting of wood and proportional counters. The wood is used to absorb low energy protons. In this event, no remarkable enhancement was observed in the data obtained from the plastic scintillator. Probably, the weak neutron signals must have been masked by the large background.

3.1 Data analysis using the ability of measuring direction of incoming neutrons

Using the directional information, we compared the flux of neutrons from the north and the south directions. Three directional data for north and south were summed up independently (see Fig. 2). In this event, solar neutrons entered into the top of the atmosphere with a fixed incidence angle $53°$. According to a Monte Carlo simulation, the solar neutrons must have a broad angular distribution with a peak at $\sim 30°$. Thus it is reasonable to use the most southern data from the 25 directions. The results are shown in Figure 3 for comparison. Figure 3 represents the statistical significance of 3 minute counting rate for the solar direction (south) and the anti-solar direction (north). As shown in Figure 3, a 4.2σ excess was clearly seen in the data from the south in the time interval between 5:38 UT and 5:41 UT, while -0.4σ decrease was observed for the data of the northern direction. From this, we can say that solar neutrons certainly arrived and were detected by the Tibet neutron telescope, which has a high sensitivity.

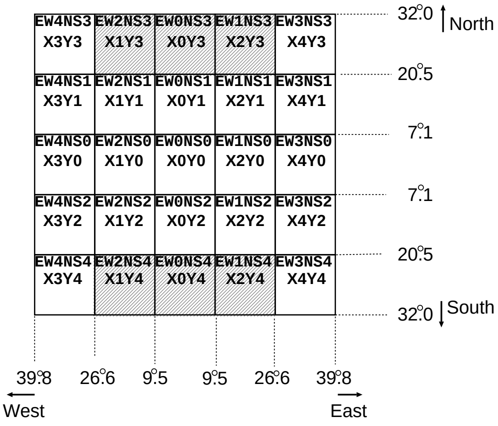

Fig. 2. Assembly of data which used in the analysis of directional data. The two shaded areas were compared. The number drawn in the figure represents the measurable range of the angle sustained by the telescope.

4 Discussion

4.1 Attenuation of solar neutrons at Yangbajing

Solar neutrons are attenuated by the atmosphere as a result of nuclear interactions with air nuclei. However, solar neutrons are not only absorbed in the atmosphere but also scattered elastically. Owing to scattering with air nuclei, the attenuation of solar neutrons decreases significantly and the effect is called “the refraction effect of solar neutrons in the atmosphere”. This was first pointed out by Smart et al.(1995) and compared with observational results obtained from the North American neutron monitors at the time of the 1990 May 24th solar flare. Furthermore, Galicia et al.(2000) applied the refraction effect to the same event as Smart et al. and found that the increases of the neutron monitors were consistent with their calculations taking into account the refraction effect. The refraction effect arises from the diffraction process between neutrons and the air nuclei and it makes the path length of solar neutrons shorter than otherwise expected. For exam-

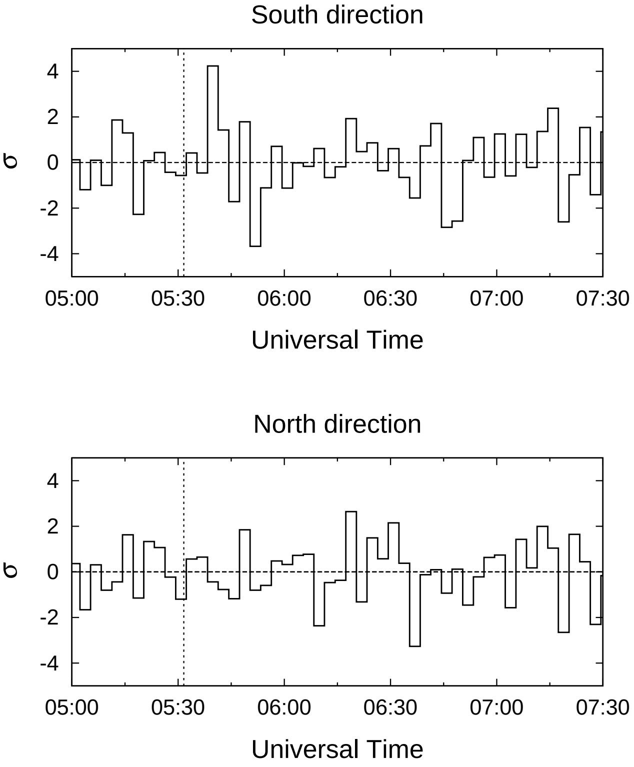

Fig. 3. The statistical significance of 3 minute average counting rates are shown for the south (top panel) and the north (bottom panel) direction. The horizontal and vertical axes show universal time and significance. The vertical dashed line represents the BATSE flare onset time (5:31:36 UT). A 4.2σ excess can be seen from the data of the south direction.

ple, in this event, the air mass along the line of sight from the sun to the detector was $997\mathrm{g/cm^2}$, if we use a simple formula $600/\cos 53°$. However, if solar neutrons are scattered by $6°$ after each scattering with an attenuation length $100\mathrm{g/cm^2}$, the total path length turns out to be $747\mathrm{g/cm^2}$. Therefore, even on the basis of a simple model, it is found that the path length is shorter than the result obtained without considering the refraction effect.

Indeed, Monte Carlo simulations taking account of the refraction effect show an interesting result concerning the attenuation of solar neutrons at Yangbajing. In Figure 4 we present the results of a Monte Carlo simulation. As shown in Figure 4, the attenuation of solar neutrons with an incident angle of less than $30°$ is almost the same in both calculations. However, for solar neutrons with the incident angle over $30°$, the results of the calculations deviate strongly. In this event, the incident angle of solar neutrons was $53°$. It was found from the present calculation that solar neutrons with the energies of 200, 500 and 800 MeV had a higher survival probability than the previous estimations. For neutrons with an angle of incidence $53°$, the probabilities are 3, 7, 10 times higher than they would be without including the refraction process. Thus, it appears likely that solar neutrons arrived at Yangbajing with a flux detectable by the neutron telescope even with an incident angle $53°$ and in winter.

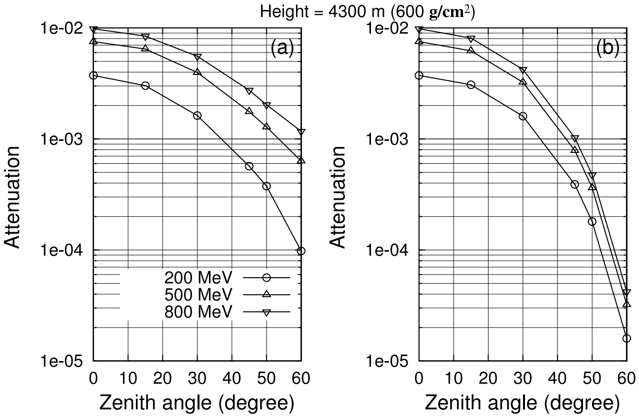

Fig. 4. Attenuation curve expected for solar neutrons at Yangbajing. Figure (a) represents the result of a Monte Carlo simulation taking account of the refraction effect, while Figure (b) corresponds to the result without taking account of the refraction effect.

4.2 Neutron spectrum at the top of the earth's atmosphere

The energy spectrum of neutrons at the top of the atmosphere was derived using 1 minute counting rate data from the southern direction. The results are given in Figure 5. When the spectrum of neutrons was derived, we assumed that protons and electrons were accelerated at the same time and the production of neutrons took place at the rise time of X ray emission (30 - 60 keV) impulsively. Thus, the neutron production time was assumed to have occurred at 5:37:50 UT. The time is shown in the top panel of Figure 5 by the dashed lines. The counts within the two vertical solid lines were used for deriving the energy spectrum of the neutrons. The interval corresponds to the time between 5:38:19 UT and 5:41:19 UT. This implies that solar neutrons with the energy between 400 MeV and 2 GeV were observed. The threshold energy of the higher part of the detector was set at 230 MeV, so the observed ranges of neutron energies are consistent with each other.

5 Summary

A X3.3 solar flare took place at 4:54 UT on 1998 November 28th. Yangbajing in Tibet was the most suitable place for observing solar neutrons. Fortunately, the Tibet solar neutron detector was installed just before the November 1998 flare and could obtain data at the time of the solar flare. In the data from the plastic scintillator (40 $\sim$ 160 MeV), only a weak excess of solar neutrons was found. The signal obtained from the detector was the same level as the background to less than $2\sigma \sim 3\sigma$. However, a clear excess was found when we use the capability of the telescope to measure incoming direction of neutrons and discriminate the background. A clear signal was observed only in the data from the solar direction (with 4.2σ statistical significance), but not in the data from the anti-solar direction. This is a definite confirmation of the detection of solar neutrons. However, there appeared to be a

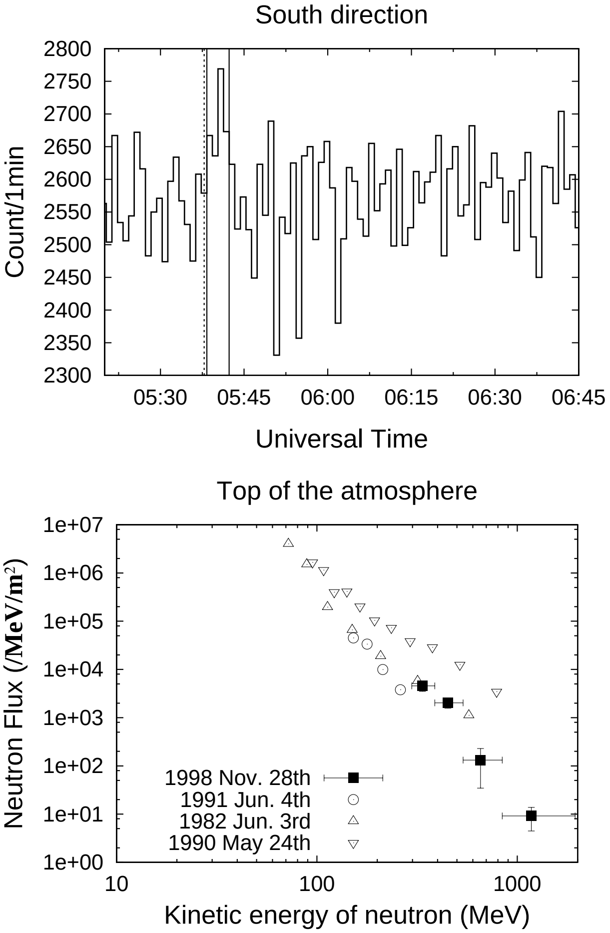

Fig. 5. Top panel represents 1 minute counting rate. In the bottom panel,the neutron spectrum obtained by the present experiment was shown in comparison with past events. We can observe from the figure that present spectrum was hard but the intensity was low. In the top panel, the vertical dashed line indicates the production time of neutrons (assumed to be 5:37:50 UT). The energy spectrum of neutrons was derived using the events detected in the period defined by the two solid lines.

problem associated with the attenuation of solar neutrons in the atmosphere since the solar neutrons had entered with a large incident angle (53°). In this paper, it has been demonstrated that solar neutrons can penetrate the thick atmosphere and arrive at the detector if account is taken of a ‘refraction’ effect. The refraction effect is significant not only for this event, but could be important for other solar neutron observations which have been made in the early morning, late evening and also in the winter season.

In the time interval between 5:38 UT and 5:41 UT when a clear signal was obtained, radio and hard X-ray emissions were also detected. This correlation between X-ray and radio data suggests to us that the commencement of the proton and electron acceleration happens at the same time. If the simultaneous acceleration and impulsive production of neutrons took place at the solar surface, solar neutrons detected by the Tibet solar neutron telescope must have an energy between 400 MeV and 2 GeV.

The detection of solar neutrons in this event was made possible by the measurement of the arrival direction of solar neutrons. Therefore, it was demonstrated that the ability to measure the arrival direction of solar neutrons is very useful for solar neutron observations. We believe that solar neutrons were produced in such a moderate level solar flare (X3.3) and arrived at Yangbajing due to the refraction effect in the atmosphere. This was determined by using the directional information from the Tibet solar neutron telescope.

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