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Upper limits on high-energy solar neutrons from satellite-detected flares with the Yangbajing neutron monitor

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Abstract: We report a systematic search for solar neutrons using the Yangbajing neutron monitor. Making use of the onset times of $>\sim$ 25 keV hard x-ray emissions detected by BATSE, we search the Yangbajing neutron monitor data for possible count enhancements due to solar neutrons from the BATSE-detected flares. As a result, statistically significant signals from individual flares were not found. We hence deduced 99 % confidence level upper limits on $>$ 50 MeV solar-neutron flux at 1 AU, comparing them with absolute neutron fluxes deduced from past positive detections.

Introduction

Solar neutrons are one of the best tools to deeply understand acceleration mechanism of ions in solar flares, because they are produced via nuclear interactions between the accelerated ions and the solar ambient plasma. High-altitude detectors, including neutron monitors [1] and neutron telescopes [2], provide a good opportunity to detect $>$ 50 MeV solar neutrons. Actually, such high-altitude detectors has accomplished positive detections of the high-energy solar neutrons associated with X-class solar flares. On the other hand, None, including space satellites, has succeeded in detecting solar neutrons from C- and M-class flares.

Near earth satellites actually detected bremsstrahlung photons from many C- and M-class flares, revealing that such flares can accelerate electrons to high energies. This fact allows us to consider that solar neutrons may be produced in such less intense flares, because usually it is very natural that ions are simultaneously accelerated at the same time as electrons. Therefore, a systematic search for solar neutrons from the less intense flares, as well as very strong ones, are important to strictly constrain some key parameters of the ion acceleration process, including numbers, pitch angle distributions, and energy spectra of accelerated ions, In this paper we hence perform a systematic search for solar neutrons from 164 M and X-class flares.

Yangbajing neutron monitor

The Yangbajing neutron monitor (NM) has been in operation at Yangbajing ($90^\circ.522$E, $30^\circ.102$N) in Tibet, China, since 1998 October [3, 4]. Installed at an altitude of 4300 m above sea level, it has an advantage of a much reduced air mass, 606 gcm^{-2}. Furthermore consisting of 28 NM64 type detectors, it has a total area of 32 m^2 which is currently the largest one in the world-wide NMs. In addition to these advantages, the Yangbajing NM has the highest geomagnetic cutoff rigidity, 14 GV, among the world NMs. These conditions allow the Yangbajing NM to be one of the most sensitive detectors for solar neutrons.

Analysis

We briefly explain an analysis method in this paper. The detailed information are described in Tsuchiya et al. [5].

Flare sample

The BATSE aboard CGRO observed more than 7,000 solar flares in the hard X-ray range above $\sim$ 25 keV until its re-entry to the atmosphere on 2000 June 4th. Among them 164 events satisfy conditions with the GOES peak flux higher than 1.0×10^{-5} Wm^{-2} which corresponds to the GOES class of M1, detected over a period of 1998 October and 2000 June. The 164 events are composed of 157 M- and 7 X-class flares, constituting our "preliminary sample". Extracting a set of flares with the zenith angles of the Sun at the flare onset time smaller than 60° from our preliminary sample, we prepare our "final sample" consisting of 2 X- and 16 M-class flares as shown in Fig. 1.

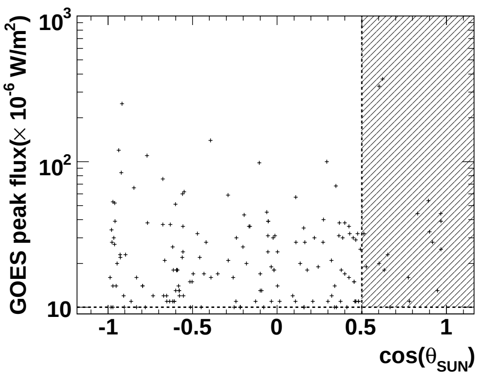

Figure 1: The cosine of the zenith angle of the Sun at Yangbajing (θ_{SUN}) at onset time of individual flares in our preliminary sample, plotted against their GOES peak flux in units of 10^{-6} Wm^{-2}. The vertical and horizontal dashed lines correspond to $\theta_{\mathrm{SUN}} = 60^{\circ}$ and the GOES flux of 1 $\times10^{-5}$ Wm^{-2}, respectively. The 18 events in the hatched area constitute our final sample.

Emission profile of solar neutrons

In this analysis, we search the Yangbajing NM data for possible enhancements associated with solar flares. Thus we prepared 5-minute count histories from the Yangbajing NM, ranging over $\pm$ 1.5 hours from the onset time determined by the BATSE data and corrected them for atmospheric pressure changes.

In order to quantitatively constrain neutron signals from individual flares, we need to define for each flare an "ON time window", i.e., a time interval when solar neutrons might arrive at the Yangbajing NM, and use the remaining two time intervals (before and after the flare) to calculate the background. For this aim, a time profile of the solar-neutron production at the Sun in each flare as well as the minimum and maximum kinetic energies of solar neutrons are assumed. Then the "ON time window"opens at the arrival of the most energetic neutrons ejected at the beginning of the neutron emission at the Sun, and closes at that of the least energetic ones ejected at the end of the production interval. In this work, the most energetic neutron assumes the kinetic energy of 10 GeV, while the least energetic one 50 MeV.

The following two neutron-emission time profiles are employed; δ-emission and continuous-emission. The δ-emission simply means that solar neutrons are radiated from the Sun instantaneously at the BATSE hard X-ray emission peak, while the continuous-emission profile assumes that neutrons are continuously and constantly emitted from the Sun throughout the BATSE hard X-ray emission. Using these injection profiles, we can define the ON time window for each injection profile. Examples of the ON time windows specified by the two profiles are shown in Fig. 2.

Results

Statistical significances of neutron signals

With Equation (2) of [5], we evaluated the statistical significances of the 164 preliminary sample flares. The results are shown in Fig. 3, implying all null detections. Fitted a Gaussian curve with each histogram in Fig. 3, we obtain two important consequences. One is that the obtained Gaussian

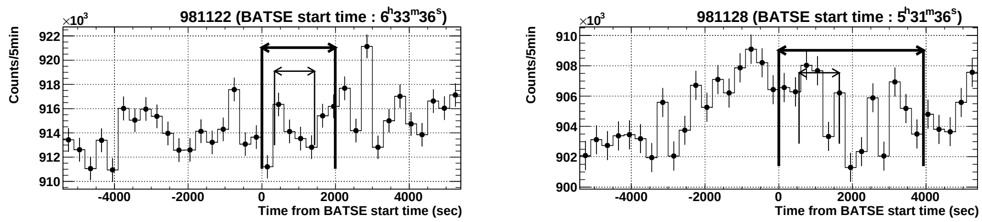

Figure 2: The 5-minute counting-rate histories of the Yangbajing NM for two X-class flares. Left and right panels show the counting-rate histories for an X3.7 (981122) and X3.3 (981128) flares, respectively. Abscissa in all panels shows the time measured from the BATSE start time, ranging over $\pm$ 5400s, where zero corresponds to the BATSE start time. The intervals of individual ON time windows specified by the δ- and continuous-emission profiles are shown by horizontal thin and thick arrows, respectively.

centroids are consistent with 0 within the fitting errors. Hence, there is no evidence for apparent neutron signals from the 164 flares. The other point is that the obtained standard deviations are consistent with 1.0, suggesting that the significance scatter among the 164 flares can be fully described by statistical fluctuations.

The flux upper limits of the final-sample flare

Because of null detections, we calculated 99% confidence level (CL) flux upper limits for individual final sample flares using Equations (3) and (4) of Tsuchiya et al. [5], assuming that an energy spectrum of solar neutrons at the Sun is a power-law form with the spectrum index of 3, 4, and 5.

Figure 4 shows the upper limits on the $>$ 50 MeV solar-neutron flux for the two (X3.7 and X3.3) of our final sample flares. For comparison, the previous positive detections are also plotted. As can be seen in Fig. 4, a strong positive correlation between the GOES peak flux and the absolute neutron flux appears, also given in Tsuchiya et al. [5] with $>$ 100 MeV neutron fluxes.

Figure 5 show s all upper limits on $>$ 50 MeV neutron flux for each final sample flare, consisting of the most and the least stringent ones. The most stringent upper limits are obtained assuming that the spectrum index is 3 and the emission model is the continuous-emission, while the least stringent ones are calculated assuming that the spectrum index is 5 and the emission model is the δ-emission.

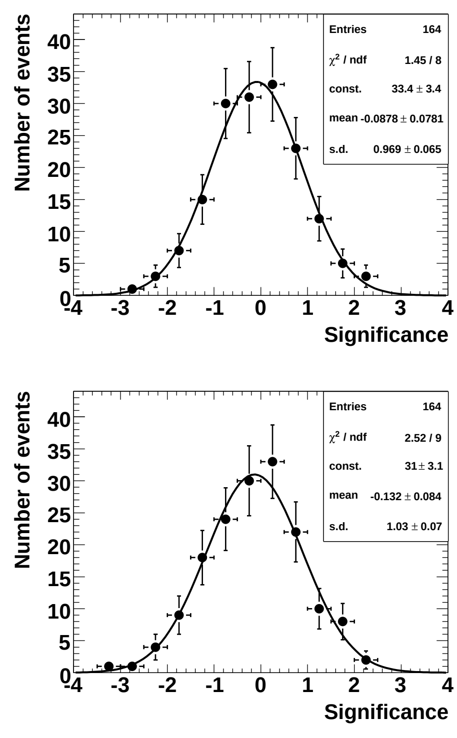

Figure 3: Significance distributions of neutron signals from our preliminary-sample flares, calculated assuming the two neutron-emission profiles. Top panel corresponds to the δ-emission model while bottom one continuous-emission model. Vertical error bars are Poissonian. The best-fit gaussian curves to individual histograms are drawn by solid lines.

The most stringent upper limits seem to indicate that the > 50 MeV neutron flux associated with M-class flares may be below $\sim 0.03\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ at one AU, with a 99% CL.

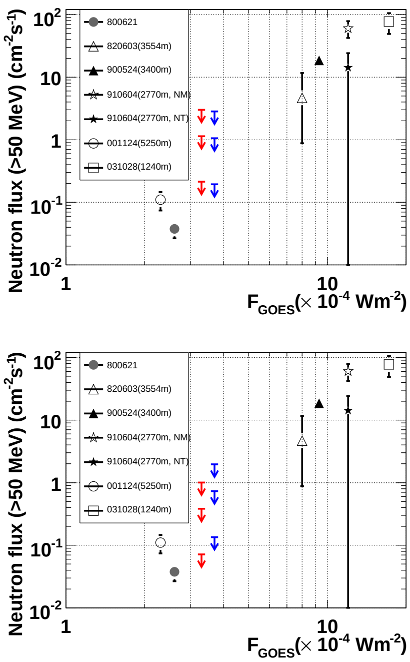

Figure 4: The 99 % CL upper limits on the $>$ 50 MeV solar-neutron flux at the top of the Earth atmosphere, from 981122 (red arrows) and 981128 (blue arrows) flares, are plotted as a function of F_{GOES}. Past positive detections are also plotted. The horizontal axis gives the GOES peak flux in units of $10^{-4}\ \mathrm{Wm}^{-2}$. Top and bottom panels correspond to δ- and continuous-emission, respectively. Upper limits from low to high correspond to assumed power-law index of solar neutrons at the Sun of 3, 4, and 5, respectively. The reference lists and detailed information for previous positive detections are given in Fig.5 of [5].

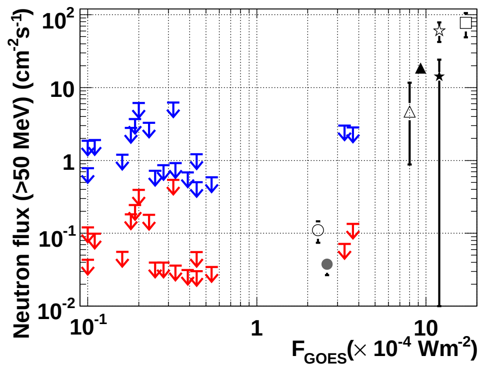

Figure 5: The same as Fig. 4, but including all flares in our final sample. Individual red arrows show the most stringent upper limit for individual final sample flares, while the least stringent ones are shown by blue arrows. The detail information on each data point are shown in Fig. 4.

Summary

Utilizing the Yangbajing NM data obtained between 1998 October and 2000 June, we derived 99% CL upper limits on $>$ 50 MeV solar neutron flux from 2 X and 16 M-class flares with reasonable assumptions.

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