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Estimates of the neutron emission during large solar flares in the rising and maximum period of solar cycle 24

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ABSTRACT

We searched for solar neutrons using the data collected by six detectors from the International Network of Solar Neutron Telescopes and one Neutron Monitor between January 2010 and December 2014. We considered the peak time of the X-ray intensity of thirty five $\geq$ X1.0 class flares detected by GOES satellite as the most probable production time of solar neutrons. We prepared a light-curve of the solar neutron telescopes and the neutron monitor for each flare, spanning $\pm$ 3 h from the peak time of GOES. Based on these light curves, we performed a statistical analysis for each flare. Setting a significance level at greater than 3σ, we report that no statistically significant signals due to solar neutrons were found. Therefore, upper limits are determined by the background level and solar angle of these thirty five solar flares. Our calculation assumed a power-law neutron energy spectrum and an impulsive emission profile at the Sun. The estimated upper limits of the neutron emission are consistent within the order of magnitude of the successful detections of solar neutrons made in solar cycle 23.

1. Introduction

Solar flares are a sudden flash observed on the surface of the Sun. This sudden flash may be interpreted as a large energy release of particles, such as X-rays, γ-rays, protons, electrons, ions and more, into space. During this release, ions are sometimes accelerated to very high energies. The interaction of these ions with the solar atmosphere may produce secondary neutrons through nuclear interactions. These secondary neutrons can arrive directly from the Sun to the Earth without being affected by the interplanetary magnetic fields. Moreover, solar neutrons reaching detectors on the ground give crucial information concerning the ion acceleration mechanism occurred at the Sun. The most important information will be whether the acceleration is impulsive or gradual, or a combination of both.

When a solar flare occurs, the released electromagnetic component will arrive at Earth faster than those particles which have mass. In particular X-rays are considered as a good indicator of the intensity of solar flares, and may also be used as a sign of solar neutron production. X-rays are mainly if not exclusively observed by satellites. One of these is the Geostationary Operational Environmental Satellite (GOES-15) [1] which records the soft X-ray (SXR) flux in the 1–8 Å band (1.5–12 keV) every minute. Now, if we assume that solar neutrons are emitted simultaneously as X-rays, their arrival time at Earth will depend upon their energies, because neutrons have mass. For instance, neutrons with energies of 1 GeV and 100 MeV require about 1.2 min and 11 min respectively longer than X-rays' travel time to reach the top of the Earth's atmosphere. Once in the atmosphere neutrons will be scattered or absorbed by the interactions they will suffer with air nuclei [2]. Eventually a few of them (those coming directly from the Sun) will reach the detectors located at high altitude observatories around the world.

Since its first ground-based detection made on 1982 June 3 [3], twelve solar neutron events associated with large solar flares have been detected until the last one occurred on 2005 September 7 [4]. What we learned so far is that the energy spectrum of neutrons can be reproduced by assuming that neutrons are emitted with the same time profile as X-rays and γ-rays ([5] and [6]). Giving such small number of positive detections, we continue striving to search for more solar neutron events.

In the present work the results of a search for solar neutrons with the data collected by the solar neutron telescopes and the neutron monitor during five years are presented. We could not detect any significant excess due to solar neutrons associated with SXRs detected by GOES-15 (hereafter GOES). We therefore estimated the upper limits of the neutron emission at the Sun. The paper is organized in the following way. We first describe our

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detectors. Then, we explain our analysis method to search for solar neutrons. After that, we describe our estimation method to calculate the upper limit of solar neutrons. Finally, we will discuss about the obtained results in comparison with the six successful detections made in the past solar cycle. We limit our work only to the SXR emission given by GOES and we do not search for solar neutrons associated with the γ-ray or hard X-ray emission.

2. The solar neutron detector

To reduce the attenuation effect, ground-based neutron detectors must be installed at high altitudes and low latitudes. Low latitudes are preferred because it provides us a longer daytime during the winter months and it also provides high cutoff rigidity that excludes most of the solar protons that come many times mixed with the neutrons. To have continuous monitoring detectors should also be located at different longitudes.

To monitor solar neutrons, in this paper we mention two types of detectors. The first one is the Neutron monitor (NM) [7], which is the standard device to continuously measure the by-products of the cosmic-ray intensity and it can also detect solar cosmic rays. In fact, the first detection of solar neutrons on the ground was performed by the NM [3]. Although NMs are more efficient at the time to observe solar neutrons, and the number of detectors positioned around the world is also large [8], they are however, unable to measure the energies of the incident neutrons and there is also the experimental problem known as the multiplicity effect [9]. The second detector is the solar neutron telescope (SNT) [10], which is designed especially to detect solar neutrons. This detector measures the energy and the direction of recoil protons produced by the interaction of neutrons in the detector. If we can determine the arrival direction of solar neutrons, we can compare the data obtained from the solar direction with those from the anti-solar direction, these feature allow us to decide if an excess in the counting rate was produced in association with a solar flare or not [5,11]. In addition, this type of detector can discriminate between incident charged particles and neutral particles. Around the world seven SNTs in total have been installed at very high mountains. In Table 1 the geographical location and the starting of observation time of each detector are shown along with the vertical line-of-sight air mass.

2.1. Method of detection of the SNT

Details of each SNT were described in [12,13]. In this paper, we briefly explain the SNT components and measurement strategy. To begin, all SNTs have a target layer which consists of a thick plastic scintillator (20 to 60 cm). To discriminate charged particles, proportional counters (PRC) or thin plastic scintillators (we call this veto counters) are put before incident particles come to the target layer. Underneath the target layer, some of the detectors have an array of PRCs to determine the arrival direction.

The process of detection is as follows. Incoming neutrons are converted into protons by nuclear interactions in the target. Recoiled protons which are subjected to a charge exchange process tend to be scattered in the direction of incident neutrons, almost conserving its energy. The ionization energy loss of the protons is measured by photomultipliers (PMT) located on top or side of the target. In Table 2 the discriminator thresholds of the PMTs are shown. Four SNTs are set at the same energy levels, the others are set at different energy levels. NRJP, ARAM, GOSW and YACH are set at $>$40 MeV, $>$80 MeV, $>$120 MeV, and $>$160 MeV. CHBO is set at $>$40 MeV, $>$80 MeV, $>$160 MeV, and $>$240 MeV. MKUS is set at $>$12 MeV (PMT-L) and $>$20 MeV (PMT-H). Finally, SNMX is set at $>$30 MeV, $>$60 MeV, $>$90 MeV, and $>$120 MeV. The variation of the energy levels is related to the thickness of the target.

The particle discrimination is done in the following way: In the case veto counters give signals coincident with the target, they are denoted by the operation mode called “with veto”. Thus, these signals are recognized as the sum of neutral and charged particles, this mode can be also called “neutral and charged”. On the other hand, the anti-coincidence of the veto counter signals are recognized as neutral particles. This operation mode is called “neutral” or “without veto”.

2.2. Performance of the SNT

The performance of the SNT has been examined by different authors. In the present work we will use their results. To

Table 1
The geographical locations of the detectors from the International Network of Solar Neutron Telescopes. A four-letter code has been assigned to each detector.

	Location	Longitude	Latitude	Height [m]	Air mass [g/cm^2]	Operation
ARAM	Mt. Aragats, Armenia	40.5°E	44.2°N	3200	670	1997 Jun ~
CHBO	Mt. Chacaltaya, Bolivia	68°W	16.2°S	5250	540	1992 Sep ~
GOSW	Gornergrat, Switzerland	7.8°E	46.0°N	3135	690	1998 Jan ~
MKUS	Mauna Kea, USA	156.3°W	19.8°N	4200	610	1997 Apr ~
NRJP	Mt. Norikura, Japan	137.5°E	36.1°N	2770	730	1996 Oct ~
SNMX	Mt. Sierra Negra, Mexico	97.3°W	19.0°N	4580	575	2003 Jun ~
YACH	Yangbajing, China	90.5°E	30.0°N	4300	600	1999 Sep ~

Table 2
Characteristics of the SNTs.

SNT	Area [m^2]	Target thickness [cm]	Threshold level [MeV]				Anti counter	Directional mode
ARAM	4	60	>40	>80	>120	>160	Top	Yes
CHBO	4	40	>40	>80	>160	>240	Top + Side	No
GOSW	4	40	>40	>80	>120	>160	Top + Side	5NS
MKUS[a]	8	20	>12	>20			Top	3NS
NRJP	64	20	>40	>80	>120	>160	Top + Side	5EW × 5NS
SNMX	4	30	>30	>60	>90	>120	Top + Side	5EW × 5NS
YACH	9	40	>40	>80	>120	>160	Top + Side	9EW × 9NS

[a] >12 MeV corresponds to PMT-L and >40 MeV to PMT-H.