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Search for solar neutrons in association with large solar flares in July 2000 and March/April 2001

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Abstract. From March 29th to April 15th, 2001, a series of solar flares was observed. In this period nine large solar flares were reported by the GOES satellites with magnitude X > 1.0. For six of them, the most suitable positions to detect solar neutrons by detectors of the global solar neutron network were either Gornergrat, Switzerland or Mt. Aragats, Armenia. In this paper we report some candidates for solar neutron events detected by the new solar neutron detectors located on the European continent. We also report on a possible simultaneous observation of solar neutrons at Gornergrat and Mt. Aragats in association with the large solar flares on July 12th and 14th, 2000.

1 Introduction

The observation of solar neutrons is a very important subject in cosmic ray studies, since the data brings us improved knowledge of how ions are accelerated to high energies at the solar surface. However, solar neutrons can decay on their way from the Sun to Earth and are absorbed strongly in the Earth's atmosphere. Therefore solar neutrons were only rarely detected until recently. The first detection was made in space on June 21st, 1980 (Chupp et al., 1982), and the first detection on the ground was made on June 3rd, 1982 (Chupp et al., 1987). In the June 3rd, 1982 event the neutrons penetrated the atmosphere and arrived in the neutron monitors located at Jungfraujoch (Debrunner et al., 1983), Lomnický štít (Efimov et al., 1983), and Rome (Iucci et al., 1984).

After that no further solar neutron events were recorded in solar cycle 21. In solar cycle 22, in association with the solar flare on May 24th, 1990, a large ground level enhancement induced by solar neutrons was observed in the neutron monitors located on the American continent (Shea et al., 1991; Pyle et al., 1991; Debrunner et al., 1993; Kocharov et al., 1994). Then, in association with the March 22nd, 1991 flare (Pyle and Simpson, 1991), there were further ground level solar neutron observations. In association with the gigantic June 4th and 6th, 1991 flares, three different detectors observed solar neutrons (Muraki et al., 1992; Struminsky et al., 1994; Ramaty et al., 1994) . This was the first time that solar neutrons were detected by different types of detectors. Furthermore, observations were carried out successfully at two stations, Mt. Norikura and Mt. Haleakala, across the Pacific ocean (Muraki et al., 1995). The June 6th, 1991 event was the first solar neutron event that has been detected at two stations widely spread in longitude. Thus, by the end of solar cycle 22, quite a few solar neutron events were recorded.

However, the number of solar neutron observations was not enough to allow us to understand the processes of ion acceleration at the solar surface and the neutron production by collisions with the solar atmosphere. By comparison with X-ray and soft γ-ray emission time profiles, we should be able to understand when ions are accelerated and whether they are accelerated independently or together with electrons. For this purpose we have installed a new type of solar neutron detectors around the world (Matsubara et al., 1999).

On the European continent the locations are Gornergrat, Switzerland (7.78° E, 45.98° N, 3135 m asl (Flückiger et al., 1998; Bütikofer et al., 2001)) and Mt Aragats, Armenia (45° E, 40° N, 3500 m asl (Tsuchiya, 1998)). The Gornergrat and Mt. Aragats detectors consist of 4 m^2 plastic scintillator and surrounding anti-counters. The thickness of the plastic scintillator is 40 cm at Gornergrat and 60 cm at Mt. Aragats. In the case of Gornergrat, the detector also has the capability of determining the direction of incoming neutrons. Further details have been published elsewhere (Muraki et al., 1998; Tsuchiya, 2001).

A series of large solar flares was observed in the period between March 29th and April 15th, 2001. Simultaneous observations of a candidate for a solar neutron event were made by the Gornergrat and Mt. Aragats neutron telescopes in association with the large solar flare on April 12th, 2001. These results are presented here, together with a report of the events on July 12th and 14th, 2000.

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2 Data Analysis

Large solar flares were observed on July 12, 2000, at 10:18 UT, and on July 14, 2000, at 10:03 UT, at heliographic locations N17E27 and N22W07, respectively. The X-ray intensities measured by GOES for these events were reported as X1.9 and X5.7, respectively. The best sites for solar neutron detection of these flares by the international solar neutron network were Gornergrat and Mt. Aragats. From March 29th to April 15th, 2001, nine large solar flares were observed by the GOES satellites with magnitude X $>$ 1.0. For six of them, the most suitable positions to detect solar neutrons by detectors of the global solar neutron network were again either Gornergrat and Mt. Aragats. Therefore we have concentrated our efforts on analyzing the data from the July 2000 and the March and April 2001 events, including two more M $>$ 5 solar flares in the 2001 time period.

Unfortunately BATSE data from the CGRO satellite are no longer available. We therefore assume that the ion acceleration occurred at the beginning of the flare as indicated by the GOES X-ray data. This naturally assumes that the ions were accelerated at the same time as the electrons, and of course this is not necessarily true. It should be noted that the GOES start time is defined when 4 minutes of continuous enhanced intensity were observed in the X-ray channel. So the beginning of ion acceleration should be considered as being at or before the GOES start time.

We have searched for an excess in the Gornergrat and Mt. Aragats solar neutron detector data within $\pm$ 8 minutes of the GOES start time. The scoring is summarised in Table 1. In this table we present the GOES start time, the statistical significance of the neutron channel count rate, the atmospheric depth taking into account the refraction effect (Smart et al., 1995), and finally the situation of the Yohkoh satellite (whether it could observe the flare or if it was in the shadow of the Earth or in the South Atlantic Anomaly). As a result we find an excess at (more or less) the 3 sigma level at least at one of the two stations in almost every event. No count rate enhancement due to solar neutrons could be identified for the flare on July 14, 2000. As can be seen from Table 1 it is quite difficult to get a solar neutron event with a high statistical significance at two stations. This can be understood by considering the magnitude of the events and the difference in the zenith angle of the Sun at the different locations.

Observations at different longitudes provide us with another strong confirmation of the arrival of solar neutrons, even when the signal is weak. We have presented the data of the April 12th, 2001 event in Fig.1. Fig. 1a shows the one minute data of Mt. Aragats and Fig. 1b the 30 second data. Fig. 1c shows the one minute data obtained by the Gornergrat detector and Fig. 1d the 30 second data. The vertical line in each panel represents the flare start time obtained from the GOES X-ray data. The time of both solar neutron detectors is based on GPS time signals. We believe our clocks are exact within $\pm$30 seconds to GPS time at any given moment. The data at the two solar neutron telescopes are sampled every 10 seconds.

3 Results and Discussion

3.1 Simultaneous observations

Simultaneous observations of solar neutrons were achieved previously at Mt. Norikura (4.6 σ) and Haleakala stations in Hawaii (5.7σ) for the June 6th, 1991 flare. The events presented here include probably the second (July 12th, 2000) and third (April 12th, 2001) successful two-station observations, although the statistical significance was only at the 3 σ level. Probably this low statistical significance arises because of the relative weakness of the corresponding flares (X1.9, X2.0) in comparison with the June 6th, 1991 flare (X12.0).

It is not certain whether the observed X-ray intensity reflects the intensity of the accelerated protons. But in comparison with the enhancements observed on June 6th, 1991 at Mt. Norikura and Haleakala, and taking into account the difference in the attenuation length and the difference in the X-ray intensities, the enhancements in the neutron detector count rates recorded on April 12th, 2001, are consistent with the observation of solar neutrons.

3.2 The start time estimation

Here we discuss the start time of ion acceleration based on the data in Table 1. When we compare the onset times of the excesses in the neutron channels with the start times of the corresponding flares in X-rays or Hα, the differences in the start times can be classified into three groups. In the events of 3/29, 4/2, 4/10, 2001, the neutron excess starts about 5-7 minutes after the start time of the flare in X-rays or Hα. We call these 'Category I' events. Since the excesses were observed in the channels $>$ 80 MeV and $>$ 120 MeV, the initial neutrons that arrived at the detector must have had an energy $>$ 250 MeV. Neutrons with an energy of 250 MeV take 5 minutes more than light when they travel from the Sun to the Earth. So this group could be explained by the hypothesis that neutrons were produced together with electrons in the flare. However for the event on April 10th, 2001, if we assume the acceleration start time of electrons to be 05:06 UT (X-rays), then this event should belong to the 'Category II'.

'Category II' events have the typical feature that the neutron excess starts at the same time as the increase in X- and γ-ray emissions. We could provide two possibile explanations for this group, to which the events of 4/1, 4/2 (earlier one), 4/12, and 4/15, 2001, belong. One hypothesis is that the neutrons causing the increase in the detector count rate have an energy around 250 MeV and that the acceleration of ions started earlier than that of electrons. Another possibility is that the neutrons might have a higher energy (1 GeV) and that they reach the Earth at almost the speed of light. Since we do not have an absorber under the telescopes, we are unable to distinguish between the two cases. A precise analysis of the 4/15, 2001 event using the Yohkoh soft X-ray images will clarify this question.

'Category III' events are those in which the neutron excess begins about 6-10 minutes before the X-ray or optical flare

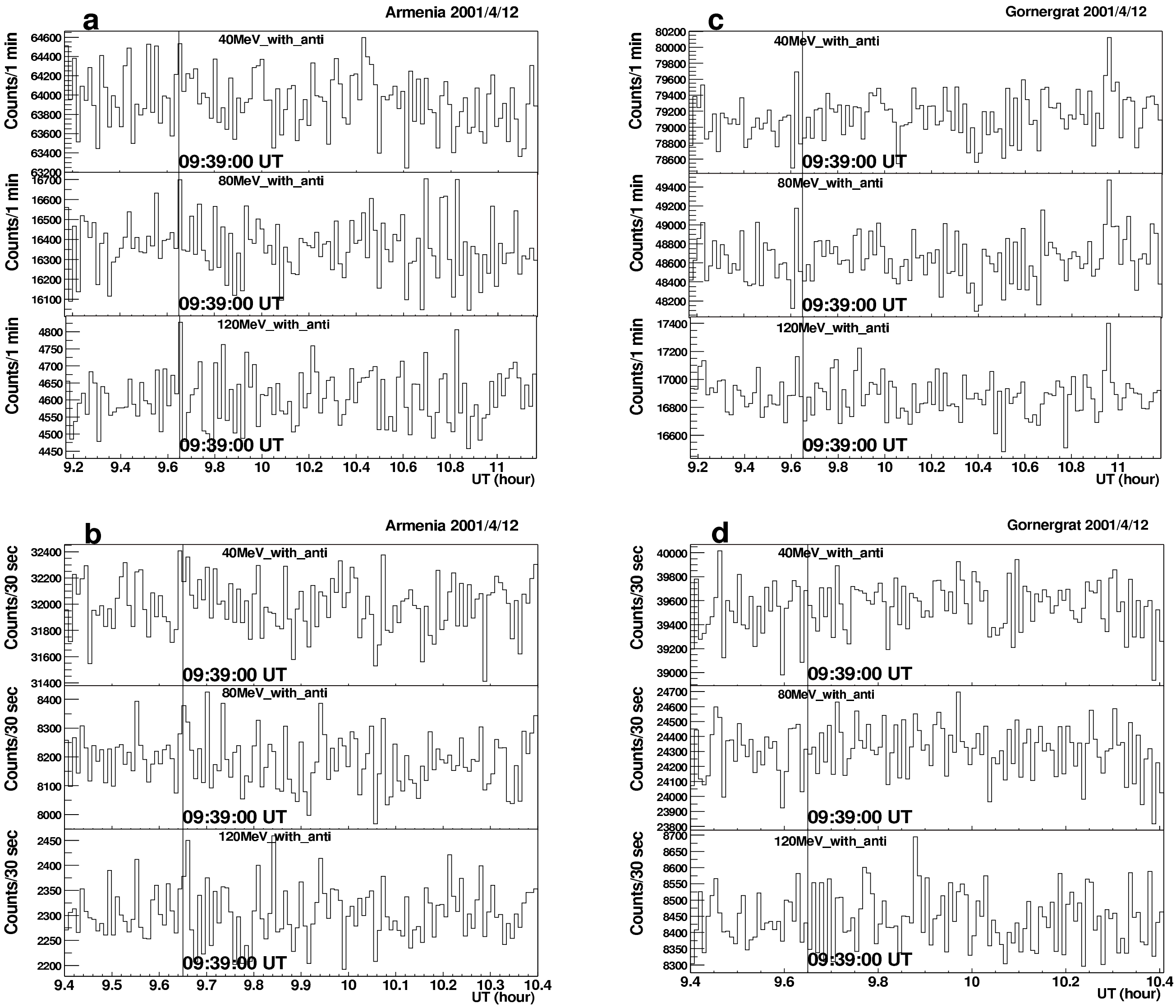

Fig. 1. The time profiles of the neutron channel counting rates of the April 12th, 2001 event at Mt. Aragats (a: 1 minute values; b: 30 second values) and Gornergrat (c: 1 minute values; d: 30 second values). The vertical line in each panel represents the flare start time obtained from the GOES X-ray data.

start time. The events of 7/12, 2000, and 4/9, 2001, belong to this category. However, in the July 12, 2000 event, if we take the flare start time as 10:15 UT instead of 10:18 UT, the difference is not so big, and the event might be reclassified as a ‘Category II’ event. The GOES start time may not always reflect the correct time of commencement of particle acceleration. Further careful study of the ‘Category III’ events using the Yohkoh X-ray image data must be very interesting.

4 Summary

The international solar neutron network has probably succeeded in detecting several solar neutron events in association with large solar flares in July 2000 and March/April 2001 . These solar neutron events can be classified into three categories, one of which is consistent with a picture that ions are accelerated at the same time as electrons (‘Category I’). However, we saw several candidates for solar neutron events where the observation would require that the ion acceleration must have started before the electron acceleration (‘Category II’ and ‘Category III’). But no event was observed which suggests that ion acceleration started at the time of the flare maximum.

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Table 1. Scoring Table

Date	X-ray class	Flare location	Start time (UT)	Score			Statistical Significance		Atmospheric depth	
				Gornergrat	Mt. Aragats	Yohkoh	Gornergrat	Mt. Aragats	Gornergrat	Mt. Aragats
2000.7.12	X1.9	N17E27	10:18 (10:15)	○ *1 (10:12)	○ *2 (10:15)	○	3.3 σ (4 min)	3.5 σ (1 min)	716	704
2000.7.14	X5.7	N22W07	10:03 (10:03)	×	×	△ *3	–	–	724	705
2001.3.29	X1.7	N20W19	09:57 (09:55)	⊙ (10:01)	△ (09:54)	○	4.2 σ (1 min)	2.2 σ (3 min)	850	803
2001.4.1	M5.5	?	10:55	△ (10:42)	○ (10:43)	△	2.8 σ (2 min)	3.2 σ (1 min)	808	826
2001.4.2	X1.4	N17W60	10:04 (10:05)	△ (09:57)	⊙ (09:57)	○	2.7 σ (2 min)	4.7 σ (25 min)	831	794
2001.4.2	X1.1	N17W61	10:58	○ (11:03)	△ (11:12)	×	3.1 σ (1 min)	2.4 σ (5 min)	804	826
2001.4.9	M7.9	S21W04	15:20 (15:24)	⊙ (15:09)	evening	○	4.9 σ (6 min)	–	large angle	–
2001.4.10	X2.3	S23W09	05:06 (04:59)	morning	⊙ (05:06)	×	–	4.5 σ (6 min)	–	large angle
2001.4.12	X2.0	S21W04	09:39 (B11:12)	○ (09:38)	○ (09:39)	△	3.0 σ (1 min)	3.4 σ (1.5 min)	821	767
2001.4.15	X14.4	S20W85	13:19 (13:36) *4	△ (13:19) *5	evening	○	2.8 σ (6 min) *6	–	808 [g/cm^2]	–

⊙ observed at 4.5 σ or higher significance
○ observed at 3.0 – 4.5 σ significance
△ claimed signals with less than 3 σ
× not seen

∗1 A peak was observed 6 minutes before GOES start time.
∗2 A peak was observed 3 minutes before GOES start time.
∗3 The triangle mark of Yohkoh represents partially observed events.
∗4 The number within the brackets implies the start time determined from the optical flare.
∗5 The number within the brackets represents the neutron start time.
∗6 The number within the brackets shows the duration of the observed excess.

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