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SOLAR NEUTRON EVENTS THAT HAVE BEEN FOUND IN SOLAR CYCLE 23

E. O. FLÜCKIGER,[1] R. BÜTIKOFER,[1] A. CHILINGARIAN,[2] G. HOVSEPYAN,[2] Y. H. TAN,[3] T. YUDA,[4] H. TSUCHIYA,[4] M. OHNISHI,[4] Y. KATAYOSE,[4] Y. MURAKI,[5*] Y. MATSUBARA,[5] T. SAKO,[5] K. WATANABE,[5] S. MASUDA,[5] T. SAKAI,[6] S. SHIBATA,[7] R. OGASAWARA,[8] Y. MIZUMOTO,[8] M. NAKAGIRI,[8] A. MIYASHITA,[8] P. H. STOKER,[9] C. LOPATE,[10] K. KUDELA[11] and M. GROS[12]

[1] *Physikaliches Institute, University of Bern, Bern, CH 3012 Switzerland*
[2] *Yerevan Physics Institute, Yerevan, AM-375036 Armenia*
[3] *IHEP, Academia Sinica, PO Box 918, Beijing, China*
[4] *ICRR, University of Tokyo, Kashiwa, 277-8582 Japan*
[5] *Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya, 464-8601 Japan*
[6] *College of Industrial Technologies, Nihon University, Narashino, Japan*
[7] *College of Engineering, Chubu University, Kasugai, Japan*
[8] *National Astronomical Observatory of Japan, Hilo, Hawaii, 96720 USA*
[9] *School of Physics, Potchefstroom University, South Africa*
[10] *University of New Hampshire, Space Science Center, USA*
[11] *Institute of Experimental Physics SAS, Kosice, Slovakia*
[12] *DAPNIA, Service de Astrophysique, CEA Sacley, Gif-sur-Yvette, 91191 France*
[*] *muraki@stelab.nagoya-u.ac.jp*

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In this paper, we report solar neutron events detected in the solar cycle 23, especially three interesting events detected on November 23rd and 28th 1998 in Tibet and October 28th 2003 in Tsumeb.

Keywords: solar neutron events; solar cycle 23; neutron telescope

1. Introduction

We have proposed in 1990 to study the particle acceleration mechanism at the solar surface by measuring solar neutrons at ground level on Earth. If we measure the energy of neutrons, we can know the acceleration time of ions into high energies.

However neutron detection had been considered to be difficult. Because (1) neutrons are attenuated strongly in the atmosphere of the Earth, (2) neutrons decay during the travel from the Sun to the Earth, and (3) the detection of neutrons is complex. Even if they leave the Sun at the same time, the arrival time of neutrons spreads. High energy neutrons arrive faster than low energy neutrons. Neutrons with energy about 1 GeV arrives one minute later than the light, while neutrons with energy 100 MeV arrive at the Earth 10 minutes later than the light. It is necessary to measure the energy of neutrons in order to identify their departure time at the solar surface. This is one of the main motive forces of us to install a new type of solar neutron detector that can measure the energy of neutrons.

During the solar cycle 23, we have prepared several solar neutron telescopes at the high altitude laboratories over the world and waited the occurrence of large solar flares. We observed 16 remarkable solar neutron events with use of these detectors and traditional neutron monitors. In this paper we report those results and interesting features.

2. Neutron monitors and neutron telescopes

The detection of solar neutrons has been made during the solar cycle 21st and 22nd by the neutron monitors. The solar neutron monitor has high detection efficiency for neutrons and a good S/N ratio for the background charged particles like muons and electrons. For details see the papers by Hatton, Shibata, and Clem and Dorman.[1–3]

On the contrary, neutron telescope design is based on a principle that solar neutrons will collide with the hydrogen target of the scintillator. By the n-p charge exchange process, the momentum of neutrons will be transferred to protons. The kinetic energy of protons is

$$\mathrm{T}_p = \mathrm{T}_n \cos^2 \theta .$$

Therefore if we measure the energy of protons, we will be able to know the energy of neutrons. In case neutrons collide with the carbon target, their energy is dissipated into protons and neutrons, so that the energy detected by the scintillator does not always reflect the energy of incident neutrons. However, the n-p charge exchange process allows to estimate the maximum energy of incident neutrons. By the quasi elastic charge exchange process, protons are emitted into a cone with an opening angle up to about 15 degrees.

Using the fact that protons are emitted into the forward cone, we can separate neutrons coming from the Sun from background. Generally speaking, if we divide the sky into 5×5 regions, we can reduce the background to about $1/25$. This is the principle of the neutron telescope.

3. Solar neutron events detected in the solar cycle 23

In Table 1, we present the list of solar neutron events detected in the solar cycle 23. The underlined locations represent the events detected by the neutron monitors.[4] The other events are detected by the neutron telescopes. We have observed about 40 excesses of events in coincidence with the GOES start time, but in this Table, we have only presented events with $\geq 4\sigma$ statistical significance. We searched for neutron events during flares of size greater than X1.4.

Let us describe here how we define neutron events. We have searched an excess due to neutrons before and after 13 minutes of the GOES flare start time. Within this time, if we see an excess of events higher than 4σ statistical significance, we define it as a solar neutron event. In case the data of photons of BATSE, RHESSI, or Yohkoh HXT are available, we used the start time of those data instead of the GOES start time, because the photon energies observed by these instruments are higher than those measured by GOES. In some events, the time difference between the GOES start time and soft gamma-ray start time turned out to be 10 minutes. Why do we choose a time interval within ± 13 minutes? Solar neutrons with energy of 70 MeV arrive at the Earth about 13 minutes later than the light. Neutrons

Table 1. List of solar neutron events detected during solar cycle 23 (flare size > X1.4 and neutron enhancement > 4.0σ). Detectors in the parentheses showed enhancement of 3.0–4.0σ.

Date	start time	max time	location	class	observatory where neutrons were detected
1998.11.23	06:28	06:44	S28W89	X2.2	Tibet
1998.11.28	04:54	05:52	N17E32	X3.3	Tibet
2000.11.24	14:51	15:21	N22W07	X2.3	Bolivia
2001. 3.29	09:57	10:15	N20W19	X1.7	Swiss (Armenia, Tibet)
2001. 4. 2	10:04	10:14	N17W60	X1.4	Armenia (Swiss)
2001. 4.10	05:06	05:26	S23W09	X2.3	Armenia, Tibet, Norikura
2001. 8.25	16:23	16:45	S17E34	X5.3	Bolivia (Swiss)
2001. 9.24	09:32	10:38	S16E23	X2.6	Tibet
2002. 4.21	00:59	01:31	S14W84	X1.5	Mauna Kea, Norikura
2002. 7.20	21:04	21:30	?	X3.3	Mauna Kea, Haleakala
2003. 5.28	00:17	00:27	?	X3.6	Mauna Kea, Norikura
2003. 6.11	20:01	20:14	N14W57	X1.6	Mauna Kea
2003.10.28	09:51	11:21	S16E08	X17.2	Tsumeb (Swiss, Armenia, Tibet)
2003.11. 2	17:03	17:25	S14W56	X8.3	Bolivia
2003.11. 3	01:09	01:30	N10W83	X2.7	Mauna Kea, Haleakala
2003.11. 4	19:29	19:53	S19W83	X17.4	Mauna Kea, Haleakala

with energy less than this energy are strongly attenuated in the atmosphere or decay in the interplanetary space, so that the detection of solar neutrons becomes impossible by the ground level detectors.[2]

Let us discuss about the possibility to misidentify the fluctuation of the background as a real neutron event for time intervals of 1 min and 3 min. The probability is calculated to be $1/600$ and $1/1800$ respectively. For time intervals of 20 sec, the probability increases to 1 every 200 events, but for such a short time enhancements, we required the further condition that the increase must continue for more than 3 bins of 20 seconds. In case the spectrum is hard like $E^{-2.5}$, high energy neutrons are coming within one minute and piled up in a bin. So search of events not only with 3 min but also with 10 sec binning would be important. The time profile of events is completely dependent on the shape of the neutron production spectrum.

The time difference between rise-up time of neutron channel and soft X-rays, hard X-rays or soft gamma-rays, is within $0-5$ minutes. This implies the important fact that ions are accelerated at the same time of electrons on the solar surface. We found two exceptional events on April 2nd 2001 and June 11th 2003. During the event of April 2nd 2001, the excess was found at 10 minutes before the GOES start time. There was no Yohkoh hard X-ray data on this event. In the event of June 11th 2003, the neutron production started 4 minutes before the GOES start time, but also no detection of soft gamma-rays by RHESSI was found, due to the night of the satellite.

4. Interesting events, Discussions and Summary

We would like to introduce here three events from Table 1 and describe their interesting features.

(1) The event detected at Tibet on November 23rd 1998. The time profiles between the channels of the energy > 120 MeV and > 160 MeV show quite different shape in comparison with the channels > 40 MeV and > 80 MeV. The long lasting time profile of the higher energy channels may be explained by proton effect.

(2) The event detected at Tibet on November 28th 1998. This is the first event when the excess of neutrons[5] was detected with use of a telescope. The event confirmed the prediction of the neutron deflection effect in the atmosphere.[6,7] The most remarkable thing of this event is that a correspondence with the pictures of the Yohkoh soft X-ray telescope has been obtained. The photo strongly suggests that the flare started during the collision between two loops; the rising loop collides with an existing loop at 05:31:28 UT over the solar surface. This is a typical example of the goal of our experiment. During the next solar cycle 24, many of such events will be collected in collaboration with the Solar-B group.

(3) The event detected at Tsumeb, Namibia, on October 28th 2003, by the neutron monitor. Clear data of the Integral satellite are obtained for this event. The position of the Sun was just above Namibia. The neutron telescopes located at the northern hemisphere did not see any excess at 11:03 UT, but on the contrary at the GOES start time of this flare, 09:51 UT, the Gornergrat detector and the Armenian detector have found an excess of events with 30 sec binning (the enhancement continued for 2 minutes). The Coronas-F (SONG) detector also shows a small enhancement of photons at 09:51 UT. Furthermore it is worthwhile to note that the Mt. Norikura 64 m^2 neutron telescope detected a long lasting excess of events just before 11:03 UT.

The study of solar neutrons will be very fruitful to understand the acceleration mechanism of ions at the solar surface. During the solar cycle 24, more fruitful results will be accumulated. During the solar cycle 23, we have developed a new type of solar neutron detector on the ground and understood quite well their behaviors. For the next solar cycle, the improvement of those detectors is also strongly recommended.

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