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Solar neutron events associated with large solar flares in solar cycle 23

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Five solar neutron events were detected by the ground-based neutron monitors in association with five solar flares with deviations greater than 5σ from the background fluctuations in solar cycle 23. Together with these five solar neutron events and five events detected in former solar cycles, there are a total of ten solar neutron events observed by ground-based detectors. Using these data, we report on some of the properties of the solar neutron events as neutron and proton spectra, flare positions where solar neutron events were produced, and the relation between neutron flux and flare class.

1. Introduction

More than one hundred X class flares have been recorded during solar cycle 23. Among them, five solar neutron events were detected with more than 5σ excesses by ground-based neutron monitors [1]. With the inclusion of five events observed in solar cycle 21 and 22, a total of ten solar neutron events have been observed by the ground-based neutron monitors.

A summary of the characteristics of solar neutron events observed during solar cycles 21, 22, and 23 are given in Tables 1 and 2. The energy spectra at the top of the Earth's atmosphere of solar neutrons observed during solar cycles 21 and 22 have been provided by Shibata [2]. With these data, neutron energy spectra at the solar surface for these solar neutron events can be calculated, as shown in Table 1. The energy spectra of solar neutron events at the solar surface observed during solar cycles 23 were calculated from neutron monitor data, assuming that solar neutrons were produced at the peak times of γ-ray emission as observed by many satellites [1]. Using these events, statistical discussion on the properties of solar neutron events are made.

Table 1. A list of solar neutron events in solar cycles 21 and 22, including information on the flares, observatories and energy spectra of solar neutrons at the solar surface. The neutron fluxes at the solar surface between 50 and 1500 MeV are also provided.

Date	June 3, 1982	May 24, 1990	March 22, 1991	June 4, 1991	June 6, 1991
Start Time [UT]	11:43	20:48	22:44	3:37	0:54
GOES X-ray class	X8.0	X9.3	X9.4	X12.0	X12.0
Sunspot location	S09 E72	N36 W76	S26 E28	N30 E70	N33 E44
Observatory	Jungfraujoch (Switzerland)	Climax (USA)	Haleakala (Hawaii, USA)	Norikura (Japan)	Norikura (Japan)
Height [m]	3475	3400	3030	2770	2770
Detector	12IGY	12IGY	18NM64	12NM64	12NM64
Flux at 100 MeV [$\times 10^{28}$ /MeV/sr]	2.6 ± 0.7	4.3 ± 0.4	0.06 ± 0.01	0.19 ± 0.11	—
Power index	-4.0 ± 0.2	-2.9 ± 0.1	-2.7 ± 0.1	-4.9 ± 1.3	$-4.6^{+0.4}_{-0.3}$
Neutron flux [/sr] at the Sun [erg/sr]	6.9×10^{30} 8.3×10^{26}	8.4×10^{30} 1.4×10^{27}	1.1×10^{29} 2.0×10^{25}	7.3×10^{29} 7.8×10^{25}	1.4×10^{30} 1.6×10^{26}

Table 2. Summary and results of the analysis of the solar neutron events in solar cycle 23, including information on the solar flares and observatories, energy spectrum and flux of solar neutrons.

Date	Nov 24, 2000	Aug 25, 2001	Oct 28, 2003	Nov 2, 2003	Nov 4, 2003
Flare Start Time [UT]	14:51	16:23	9:51	17:03	19:29
GOES X-ray class	X2.3	X5.3	X17.4	X8.3	X28
Sunspot location	N22 W07	S17 E34	S16 E08	S14 W56	S19 W83
Observatory	Chacaltaya (Bolivia)	Chacaltaya (Bolivia)	Tsumeb (Namibia)	Chacaltaya (Bolivia)	Haleakala (Hawaii, USA)
Height [m]	5250	5250	1240	5250	3030
Detector	12NM64	12NM64	18NM64	12NM64	18NM64
Flux at 100 MeV [$\times 10^{28}$ /MeV/sr]	0.04 ± 0.01	0.02 ± 0.01	0.37 ± 0.14	0.03 ± 0.01	1.5 ± 0.6
Power index	-4.2 ± 0.5	-3.1 ± 0.4	-3.8 ± 0.4	-7.0 ± 1.3	-3.9 ± 0.5
Neutron flux [/sr] at the Sun [erg/sr]	8.0×10^{28} 1.0×10^{25}	4.1×10^{28} 6.4×10^{24}	1.2×10^{29} 3.3×10^{25}	2.8×10^{29} 2.6×10^{25}	2.4×10^{30} 3.4×10^{26}

2. Flare Position of Solar Neutron Events

According to some models, solar neutrons are released tangentially to the solar surface [3, 4, 5]. Consequently it has been argued that solar neutrons should be detected most easily from limb flares. This argument cannot necessarily be applied to the results given in Tables 1 and 2. Figure 1 shows the longitudinal distribution of X class solar flares, and that of flares which produced solar neutron events. The positions of flares that produced solar neutron events can be seen to be uniformly distributed over the longitude. Evidently there is no correlation between the longitude of flares and their associated solar neutron events. Thus a solar flare model must account

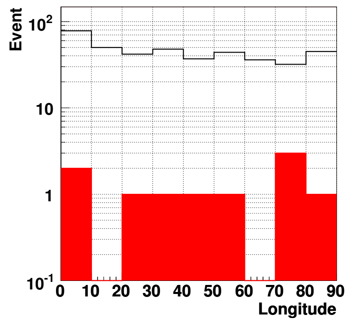

Figure 1. The longitudinal distribution of X class solar flares (upper histogram) and of solar flares that produced solar neutron events (lower histogram) during solar cycles 21, 22, and 23.

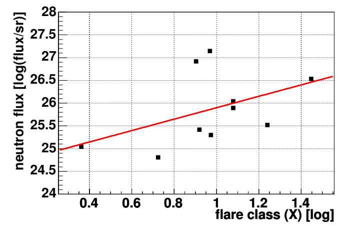

Figure 2. The relation between the flux of solar neutrons at the solar surface and the soft X-ray flux of solar flares. This is a double logarithmic graph. The correlation coefficient is 0.46.

for the acceleration of ions away from the solar surface, or produce neutrons which move away from the solar surface.

3. Flare Class of Solar Neutron Events

The relation between the flux of solar neutrons at the solar surface and the soft X-ray flux of solar flares is shown in Figure 2. The correlation coefficient is 0.46. No convincing correlation is found between soft X-ray classes and solar neutron events, and no flare class threshold for the occurrence of solar neutron events. There is a weak correlation between the solar neutron flux and flare class.

4. Neutron and Proton Spectra of Solar Neutron Events

The energy spectra of solar neutrons at the surface of the Sun for the solar neutron events are shown in Tables 1 and 2. The power law index for most solar neutron events lie between -3 and -4.

The spectrum of ions accelerated in a flare can be calculated from the neutron spectrum by using the calculated escaping neutron spectrum produced by accelerated ions [3, 4, 5]. From the simulation code of Hua et al. [5], we can obtain the neutron spectrum corresponding to an assumed proton spectrum. Note that the energy spectrum of the neutrons differs from that of the protons. The spectral index of escaping neutrons between 100 and 1500 MeV becomes harder (by one) than the energy spectrum of the ions, because low energy protons, although there are many of them, produce less neutrons in comparison to higher energy protons. Figure 3 shows the relation between the spectral index of accelerated protons (α_p) and that of escape neutrons (α_n), which can be expressed as;

$$\alpha_n = (0.89 \pm 0.17) \times \alpha_p + (0.44 \pm 0.47). \qquad (1)$$

Thus the ion spectrum is softer than the spectrum of neutrons as shown in Tables 1 and 2. Using Equation (1), the proton indices of the solar neutron events listed are calculated as shown in Table 3.

From the neutron spectra shown in Tables 1 and 2, we can calculate the number of protons above 30 MeV [3, 4, 5]. For this calculation the ion spectrum has been assumed to be of the form $N(E) \approx E^{-S}$, as expected from shock acceleration. With these values, we can determine the number of protons above 30 MeV. Results

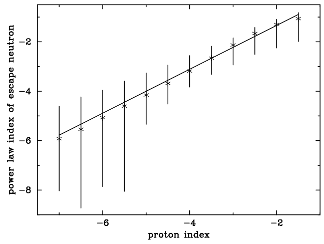

Figure 3. The relation between the power index of accelerated protons and escape neutrons.

Table 3. The number of protons N_p above 30 MeV for the solar neutron events in the solar cycle 23.

Date	Neutron index	Proton index	Proton flux [/sr]
1982 Jun 3	-4.0	-5.0	$\sim 10^{33}$
1990 May 24	-2.9	-3.8	$\sim 10^{33}$
1991 Mar 22	-2.7	-3.5	$\sim 10^{31}$
1991 Jun 4	-4.9	-6.0	$\sim 10^{32}$
1991 Jun 6	-4.6	-5.7	$10^{31} \sim 10^{32}$
2000 Nov 24	-4.2	-5.2	$10^{31} \sim 10^{32}$
2001 Aug 25	-3.1	-4.0	$\sim 10^{31}$
2003 Oct 28	-3.8	-4.8	$10^{31} \sim 10^{32}$
2003 Nov 2	-7.0	-8.4	$10^{30} \sim 10^{31}$
2003 Nov 4	-3.9	-4.9	$\sim 10^{33}$

are shown in Table 3. The spectral index of the accelerated ions is softer by about -1.0 and the numbers of accelerated protons are $10^{30} \sim 10^{33}$, that is a factor of 100 to 1000 more than the neutron flux.

5. Conclusions

Using ten solar neutron events observed in solar cycles 21, 22 and 23, an extensive statistical discussion on the properties of solar neutron events was made. The results of this work can be summarized as follows; (1) The spectral indices of solar neutrons range between -3 and -4, the corresponding proton index is softer by about -1.0 and the numbers of accelerated protons are $10^{30} \sim 10^{33}$, that is 100 to 1000 times more than the neutron flux. (2) There is no correlation between the longitude of solar flares and solar neutron events. Hence a solar flare model must account for the acceleration of ions away from the solar surface, or produce neutrons moving away from the solar surface. (3) The class of solar flares is not the main indicator of the magnitude of the ion acceleration.

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