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On Possibility of Prolonged Two Step Production of High Energy Neutrons during the Solar Flare on 28 October 2003

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The time profile of the Tsumeb neutron monitor (NM) (Namibia, LAT -19.20; LONG 17.60; ALT 1240 m) during the 28 October 2003 X17.2 solar flare shows an enhancement above background before arrival of solar protons, which was attributed to solar neutrons. Additionally its time profile has the second hump, which coincides in time with anisotropic part of the ground level enhancement observed by the NM network and the solar energetic particle event, but it has been unlikely caused by solar protons due to the large geomagnetic cutoff. Therefore the time profile of Tsumeb NM reminds the famous event of 4 June 1991, when evidence of prolonged two-step injection of solar neutrons has been found basing on the Norikura NM, gamma ray and microwave data. The count rate of ACS SPI from INTEGRAL, which measure both primary and secondary γ-rays, is used for modeling of the first hump of neutron enhancement. For the second hump, when the contamination of secondaries has been large, the prolonged neutron injection corresponding to primary γ-rays with intensity below the ACS count rate is proposed to fit the data. The spectrum of second injection should be considerably softer than during the first. An existence of the neutron injection corresponds to the broken time profile of proton injection deduced from charge particle data.

1. Introduction

High-energy solar protons interacting with solar atmosphere produce primary gamma rays and neutrons, which are an evidence of proton acceleration deep in the Sun. We know few cases of observations of direct solar neutrons by using space borne and ground based instruments. Among them is the 4 June 1991 event, a unique case, when evidence of prolonged two-step injection of solar neutrons has been found from the Norikura NM data basing on the γ-ray and microwave data [1]. Another possible case is the 28 October 2003 event and has not been discussed yet from this point of view. Several talks during numerous conferences in 2004 (see, for instance, [2-4]) presented different aspects of the event on 28 October 2003.

The time profile of Tsumeb neutron monitor (NM) count rates (LAT -19.20; LONG 17.60; ALT 1240 m) during the 28 October 2003 X17.2 solar flare shows an enhancement above background before arrival of solar protons, which might be attributed to solar neutrons [2]. The instruments aboard the CORONAS satellite registered both solar γ-ray and neutron events [3]. The onset of γ-ray emission with energy >60 MeV (indicating the π^0-decay) at 11:03:45 UT shows an appearance of >500 MeV protons in the solar atmosphere. According to the results of INTEGRAL γ-ray observations presented in [4] primary γ-rays start sharply at ~11:02 UT and have practically finished at ~11:20 UT, when secondary γ-rays and particles begin to be detected. The earliest arriving of relativistic solar protons was detected by the Cape Schmidt NM at ~ 11:13 UT [2].

The first numerical analysis of the neutron ground level enhancement (GLE) was done in [5]. The authors of [5] did not have γ-ray intensity profiles at the time of the paper writing and did not use them modeling the neutron event observed by Tsumeb NM. According to their analysis the neutron emission began ~11:04 UT and lasted ~9 min, while proton injection began ~11:11 UT and lasted over an hour. These results do not contradict to the γ-ray observations [3-4].

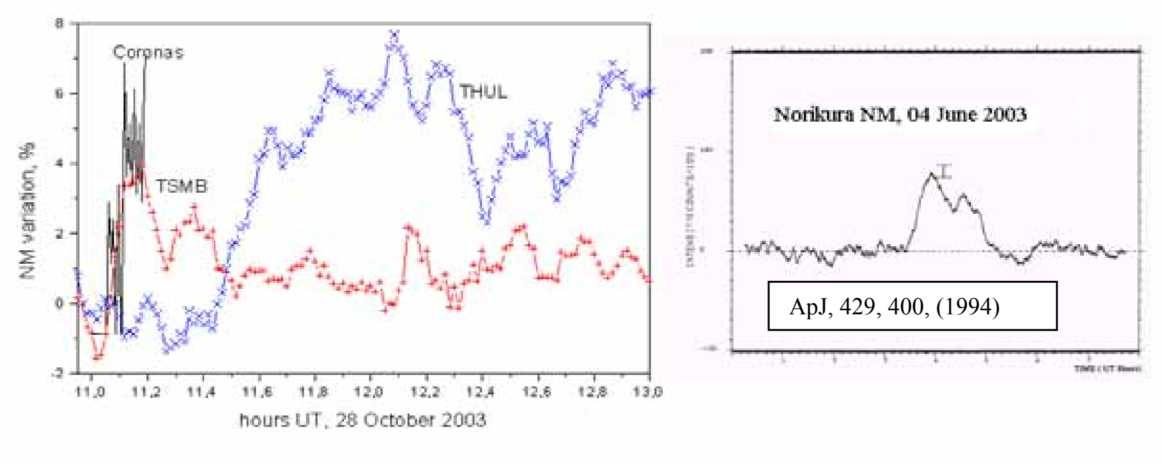

Figure 1. Left panel - comparison of Tsumeb NM variations (red) on 28 October 2003 with those of the Thule NM (blue). The black bars show the possible response of CORONAS to solar neutrons (not in scale). Right panel – the 1810 s running average of the Norikura NM count rate on 4 June 1991.

The purpose of this report is to reanalyze the Tsumeb NM data of the 28 October 2003 data using the available γ-ray data and underline the similarity of this event and the neutron event of 4 June 1991 observed by the Norikura NM.

2. Observations

Figure 1(left panel) shows 20 minute running averages of Tsumeb and Thule NM variations. The two hump structure of the Tsumeb enhancement is clearly seen. The first hump occurred before the GLE onset at 11:13 UT and was identified as a solar neutron event [2]. This enhancement corresponds to arrival of direct solar neutrons registered aboard CORONAS [3]. Nature of the second hump is not so clear. It coincides in time with the anisotropic phase of GLE lasted up to 11:20 UT, but it is unlikely caused by solar protons due to the large geomagnetic cutoff. Note, the solar energetic particle onset was registered aboard satellites near the Earth at ~11:20 UT. Therefore, the time profile of Tsumeb NM reminds the famous event of 4 June 1991, when evidence of prolonged two-step injection of solar neutrons has been found basing on the Norikura NM, gamma ray and microwave data (Fig. 1).

Below we will use the count rate of the Anti-Coincidence System (ACS) of Spectrometer on INTEGRAL (Fig. 2) as a good proxy of time profile of neutron production at the Sun. ACS is sensitive to primary γ-rays above ~100 keV as well as to charge particles and secondary γ-rays from interaction in the telescope and satellite structure. The ACS count rate increased sharply at ~11:02 UT and corresponds to the CORONAS observations of γ-rays within different energy channels [4]. This sharp increase, caused only by primary γ-rays, was ended at ~11:13 UT (the onset of solar protons). Later the ACS count rate was well above background during several hours, when a mixture of primary and secondary particles possibly were detected. At present we do not know the ACS response functions to γ-rays and charged particles and cannot separates their count rates.

We should note that during the second Tsumeb NM hump the ACS count rate was rather quiet, but above background. Its gradual increase started at ~11:20 UT coinciding with arrival of 165-500 MeV protons measured by GOES (Fig. 2, left panel). After that the dynamics of ACS count rate was very similar to that of 165-500 MeV GOES protons during about 40 minutes, i.e. both instruments possibly registered the same population of energetic protons.

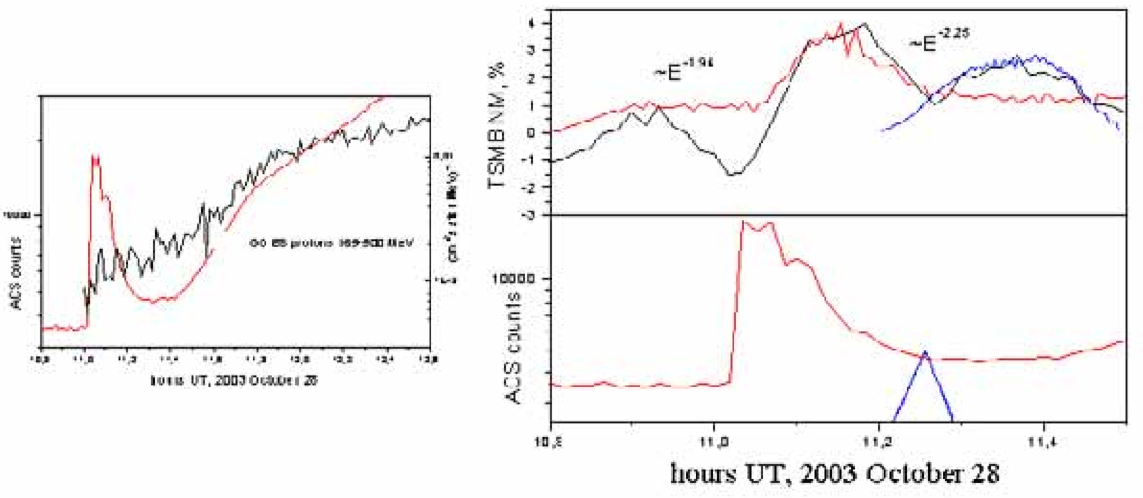

Figure 2. Left panel - the ACS SPI count rate (red curve) and the GOES proton intensity within 165-500 MeV energy range (black curve), one minute averages. Right upper panel – the running average variations of the Tsumeb NM (black curve) and their modeling using the proposed time profiles of neutron production. Right bottom panel – the time profiles of neutron production at the Sun (red – the ACS count rate, blue – as proposed for the second hump).

3. Model Calculations and Discussion

The NM count rate due to primary solar neutrons can be calculated using the expression [1]:

$$N(t_1,t_2)=\int_{t_1}^{t_2}\int_{E_1}^{E_2} S\left[E,T-D/c/(\beta^{-1}-1)\right]P(E)Y(E)dEdT/D^2\,, \qquad (1)$$

where S(E,T) – the neutron production on the Sun as a function of neutron energy E, and a Sunlight delayed time at Earth orbit T, P(E) is the neutron survival probability, Y(E) is the detector sensitivity, and D is the Sun-Earth distance. We express the neutron production on the Sun as a function of E and T by

$$S(E,T)=N_0F(T)E^{-\alpha}\quad ,$$

where N_0 is the normalization coefficient, $E^{-\alpha}$ - is a power law spectrum of primary neutrons and F(T) is a time profile of γ-ray emission.

The right bottom panel of Fig. 2 shows the time profiles used in our model calculations, i.e. the ACS count rate for the first hump and the rising and decaying exponent with characteristic time of 200 for the second. The second neutron production starts at 11:12 UT and has a maximum after 200 s. In these model calculations we do not separate the detector sensitivity and spectrum of primary solar neutrons assuming that a power law express a product of them. Such power laws for the first and second episodes of neutron production are shown in Fig. 2 (right upper panel). The spectrum of solar neutrons at the Sun should be softer and N_0 larger during the second episode.

The proposed model fits rather well variations observed by the Tsumeb NM Since the second neutron production has a different relation between the solar γ-ray and neutron intensities the physical conditions in the interaction region also should be different. Temporal variations of the primary γ-ray spectrum between 11:12 and 11:20 UT should be studied very carefully to justify this conclusion.

4. Conclusions

- The ACS SPI is sensitive to primary γ-rays above ~100 keV as well as to particles and secondary γ-rays from interaction in the telescope and satellite structure, before arrival of first solar protons the SPI count rate can be used as a good proxy of time profile of neutron production at the Sun.
- The ACS count rate observed before the charged particle onset at 11:13 UT on 28 October 2003may explain the first hump observed by the Tsumeb NM.
- The ACS count rate was well above background during several hours after the X-ray onset, but it could not be used directly for fitting of time profiles of solar neutrons after the onset of charged particles due to the large contamination of secondary γ-rays.
- Therefore, an existence of the second maximum of the γ-ray emission at the Sun do not contradict to the ACS SPI data and may explain the second hump observed by the Tsumeb NM. Solar neutrons should have a softer spectrum. For the second neutron production one needs assuming a different relation between the γ-ray intensity and number of solar neutrons, i.e. different conditions in the interaction region.
- Therefore, two episodes of the prolonged neutron production might occur in the solar atmosphere on 28 October 2003. The source of solar energetic particles should be extended in space and time and possibly corresponds to different acceleration episodes.
- In this case the first episode of neutron production corresponds to the proton injection at ~11:03 UT and their anisotropic arrival to the Earth at ~11:13 UT. The second episode occurred at ~11:12 UT and corresponds to arrival of solar protons after ~11:20 UT. We need look very carefully on temporal variations of the primary γ-ray spectrum between 11:12 and 11:20 UT to justify this conclusion.

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