SOLAR NEUTRON EVENTS OF JUNE 4TH AND 6TH, 1991
— 20 sec acceleration or 5 min acceleration? —

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Abstract

Solar neutrons observed by a solar neutron telescope, a neutron monitor and a muon telescope on June 6th 1991 indicate that ions are accelerated a few minutes later than electrons. We propose that ions are accelerated by the shock wave which has been induced by the flux of electrons in the solar atmosphere. In other cases such as May 24, 1990, March 22, 1991 and June 4th, 1991, the same features have been seen.

1. Introduction

Early in June 1991, gigantic solar flares were observed at the Sun. Among them, flares of June 4th, 6th, 9th and 11th of 1991 occurred at Japanese local noon and a wealth of valuable scientific data was obtained by Japanese instruments located at ground level as well as by the instruments on board the CGRO satellite. Here we report on these novel phenomena.

The detectors for solar neutrons located at Mt. Norikura Cosmic Ray Observatory of Institute for Cosmic Ray Research, Univ. of Tokyo (2770 m) recorded solar neutrons for the flares which occurred on June 4th and 6th, 1991. Those detectors include a traditional solar neutron monitor and also a newly designed solar neutron telescope developed at Nagoya university. Part of the present results have already been published by us elsewhere [for all related references, see *Astrophys. J.* **400** (1992) L75]. In this short note, we describe experimentally-obtained results on the production mechanism of solar neutrons and compare these with data obtained by the Nobeyama radio-heliograph and the CGRO BATSE and OSSE gamma-ray detectors.

In sections 2 and 3 we briefly survey the June 4th and 6th events, and in section 4 we show the results of fits of particle acceleration time to the data. The results were obtained by comparing our data on neutrons with the Nobeyama radio-heliograph data and the BATSE gamma-ray data.

2. The June 4th event

The June 4th event began at 03:37 UT. Near the East limb (N30E70), a bright small flash was seen and four minutes later at 03:41 UT, the flare area reached maximum size.

The BATSE gamma-ray data for $E_\gamma > 1$ MeV shows very spiky structure which continued for nearly 20 seconds. This gamma-ray emission is produced mainly by electron bremsstrahlung. The time profile observed by the Nobeyama radio-heliograph coincides quite well with the gamma-ray profile. In particular, the time profile at the highest frequency (80 GHz) shows very similar features to the BATSE gamma-ray data.

Measurements of the time profiles of solar neutrons for this event are interesting because, for the first time, solar neutrons were recorded by three different detectors with one of these detectors providing energy measurements. The information obtained by this detector strongly constrains the flight time of high energy solar neutrons (in the region of neutron energy $E_n \approx 100 \sim 500$ MeV).

For the June 4th event, the solar neutron telescope of Nagoya university (NT) recorded an enhancement for three minutes between 03:46 UT and 03:49 UT. The Riken neutron monitor (NM) and the Nagoya muon telescope (MT) recorded enhancements of much longer duration (approximately 11 min.). A possible acceleration time of ions for this event has recently been reported by Struminsky *et al.* (preprint submitted to Astrophysical Journal). According to them, ions were accelerated for as long as 5 minutes in this event.

These measurements are in severe conflict with models which assume a 20 seconds δ-function type neutron production. For a δ-function type production model, the observed enhancement should follow the expectation given by the dotted line in Fig. 1. The expectation depends on the energy spectrum of produced neutrons (γ-factor) and also the time spread. The dotted-dash line indicates another expected curve for a more realistic production time profile, with a rise-time of 9.5 sec. and a fall-time of 14.8 sec. superimposed by a longer tail with a fall-time of 360 sec. similar to the BATSE and OSSE gamma-ray time profiles.

From Fig. 1, the 20 second δ-function type production model is seen to reproduce quite well the Nagoya neutron telescope results, but it clearly contradicts the results obtained by the Neutron monitor. On the other hand, the production time predicted by Struminsky *et al.* (shown by the dashed-two-dotted line) can reproduce their results fairly well.

The interpretation of this event is complicated by the fact that it coincides with a Forbush decrease of cosmic rays which had its origin with a flare which occurred on June 1st. Two of the neutron detectors (NM and MT) are sensitive to cosmic rays as well as neutrons, and the data on neutrons for this event is uncertain for this reason. Accordingly, further analysis of this event was not attempted.

3. The June 6th event

The June 6th event has a different time profile from June 4th event. The major differences are seen in the 80 GHz radio data and in the 1 MeV gamma-ray data. For the June 4th event, the time profile consisted of only one sharp increase, a δ-function type profile, while for the June 6th event, the time profile consists of several well-defined increases and decreases in all data taken at different wave lengths (17, 35 and 80 GHz) and also in the gamma-ray data ($>$1 MeV). Two large peaks are seen at 01:05 UT and 01:06 UT.

For the June 6th event we could not unambiguously determine the production time of ions. One possibility is to assume that the complex time profile resulting from the radio and gamma-ray observations is exactly the same as for ions, and try to obtain the expected time profile for solar neutrons from this, taking account of the attenuation of solar neutrons in the atmosphere and the detection efficiency of the detectors, which is of course a function of incident neutron energy.

The other possibility is to set either 01:05 UT or 01:06 UT as the start time of solar neutron production and compare the results. In Fig. 2 we present some of the results of our calculations. The best fit to the solar neutron start time is at 01:05 UT using Struminsky's production model, while for a δ-function type model the best time is 01:08 UT (dotted line). The Nagoya muon telescope also shows an excess between 01:13 UT and 01:24 UT. The time profile was similar to that measured by the neutron monitor, but the start time was 2 minutes delayed in comparison to the Riken data (which showed an increase between 01:11 UT and 01:21 UT).

Careful inspection of the data from the neutron telescope indicate that the flux was enhanced between 01:14:00 UT and 01:15:30 UT. The enhancement was observed mainly in the channel of highest energy ($>$490MeV) at a level of 4.6σ. At that time the inclination of the Sun from the vertical was $\sim 30°$ and low energy neutrons would have been greatly attenuated. We note also that solar neutrons with energy greater than 490 MeV must arrive no more than 3 minutes later than the light.

Can one reconcile the data taken by the solar neutron telescope with that of the neutron monitor? We believe it is possible. It is difficult to explain the solar neutron telescope data with a 20-second δ-function type production spectrum. Therefore we introduce a larger duration, a 90-second rectangular continuous acceleration model. Then the production of solar neutrons at the Sun occurs from 01:02:30 UT to 01:04:00 UT. With this injection profile, we can account for the time profiles of the NM, NT, and MT consistently, as shown in Fig. 2. We assume that the variable structure observed by the NM before 01:11 UT was likely induced by a fluctuation of cosmic rays. This appears to us to be the most natural interpretation for the observations of June 6th.

4. Events of Mar. 22nd, 1991 and May 24th, 1990

It is a surprising experimental result that the particle acceleration times for electrons and ions may be different from each other. In the case of June 4th event, the delay of ion acceleration is only one minute (03:41 UT for electrons and 03:42 UT for ions) and hard to confirm, but in the case of June 6th, the delay is much large (time for ion acceleration is $3\sim6$ minutes later than that for electrons (electron peak flux time)).

We must consider the possibility that the acceleration mechanisms for ions and electrons may be different: the acceleration of ions may occur by shock acceleration, while for electrons a more impulsive mechanism may be involved. An enormous flux of electrons is accelerated and impacts with the solar surface, creating a shock wave at the solar surface which may accelerate ions.

In order to explore this possibility further, we examined two other events which were recorded with the neutron monitors located at Mt. Haleakala, Hawaii and Climax, Colorado. As shown in Fig. 3, in comparison with the peaks observed in the radio signals, the delay time is 0 min. and 1 min. respectively for the Mar. 22, 1991 and May 24, 1990 events. It may be instructive to learn that for all four large flares, ions were accelerated a few minutes later than electrons. The following empirical relation seems to work : T(delay time for ions) = $2 \times \Gamma$(electron acceleration time), where T is the delay time of ion acceleration with respect to the peak of either gamma-ray ($>$1 MeV) or radio (80 GHz) emission, and Γ denotes the width of the electron acceleration time in seconds.

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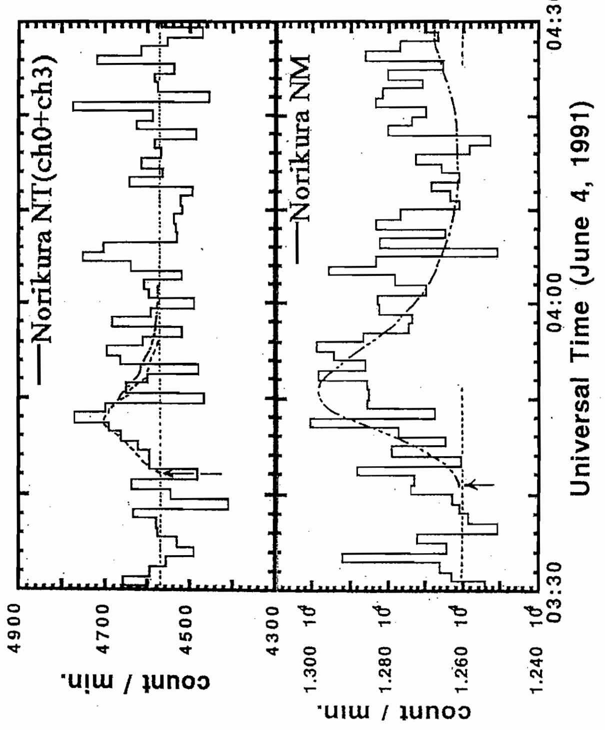

Fig. 1. The June 4, 1991 event observed at Mt. Norikura.

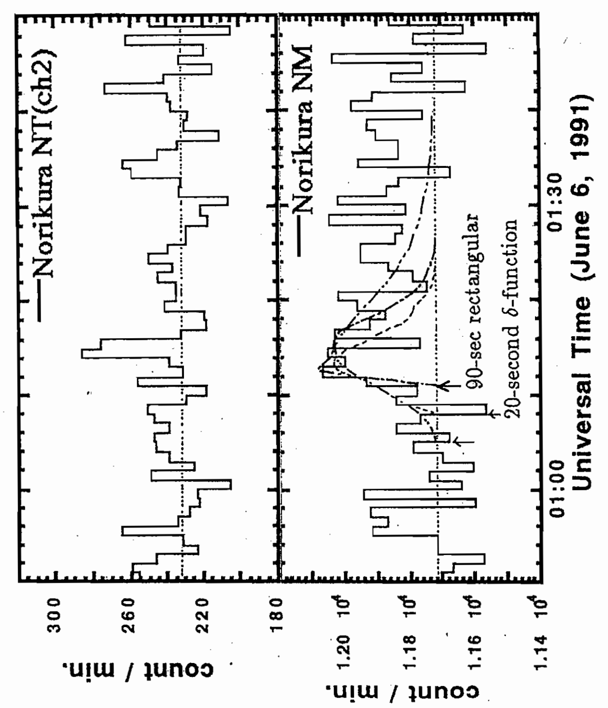

Fig. 2. The June 6, 1991 event observed at Mt. Norikura.

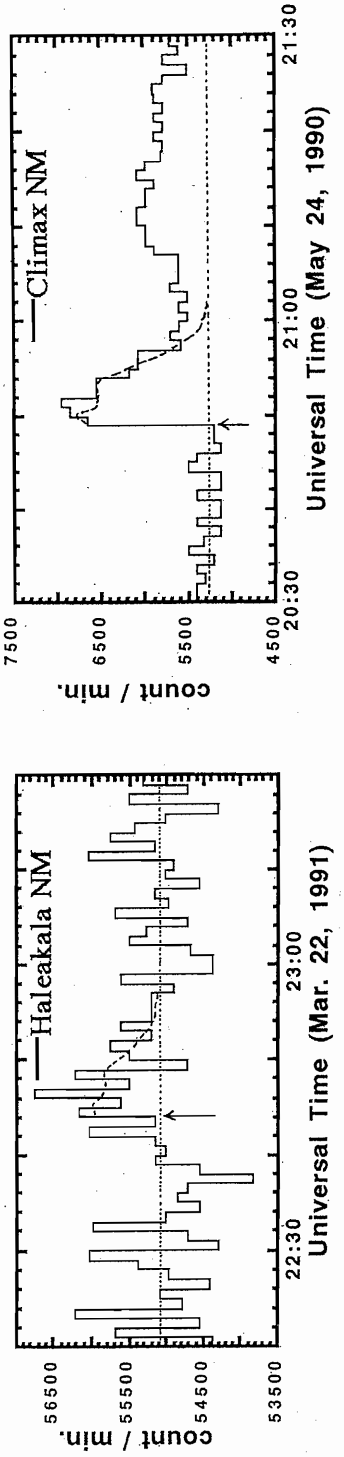

Fig. 3. The March 22, 1991 event observed at Mt. Haleakala and the May 24, 1990 event observed at Climax.