Simultaneous Observations of Solar Neutrons in Association with a Large Solar Flare on June 6, 1991

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Abstract

Solar neutrons have been detected simultaneously by the neutron monitor located at Mt. Norikura, in Japan, and Mt. Haleakala, in Hawaii, in association with a large solar flare on June 6, 1991. The statistical significance of the detection is $5.16\,\sigma$ and $4.28\,\sigma$, respectively. In this flare, intense emission of γ-rays and millimeter-waves was observed by the Burst and Transient Source Experiment (BATSE) onboard the *Compton Gamma Ray Observatory (CGRO)* and the Nobeyama Radio Polarimeters (NoRP) at the Nobeyama Radio Observatory, in Japan, respectively. The production time of solar neutrons is better correlated with those of γ-rays and millimeter-waves than with the production time of soft X-rays. Solar neutrons were probably produced continuously during the time γ-rays and millimeter-waves were produced.

1. Introduction

A series of six X-class solar flares which were larger than X10 occurred during June 1 and June 15, 1991 in NOAA region 6659. Among them, during the flares on June 4, 6, 9 and 11, the BATSE detector onboard the CGRO satellite detected γ-rays, and millimeter-waves were observed by the NoRP simultaneously. In association with the flares on June 4 and 6, solar neutrons were observed by the neutron monitor, the 1m^2 neutron telescope and the 36m^2 muon telescope located at Mt. Norikura, Japan. At the June 6 event, solar neutrons were also detected by the neutron monitor at Mt. Haleakala, Hawaii across the Pacific Ocean. In this paper, we report on solar neutron event on June 6, 1991.

2. Observations

An X12.0 class solar flare occurred at 0:54 UT in NOAA region 6659 on June 6, 1991. The location of the active region was N33°E44° and the flare was

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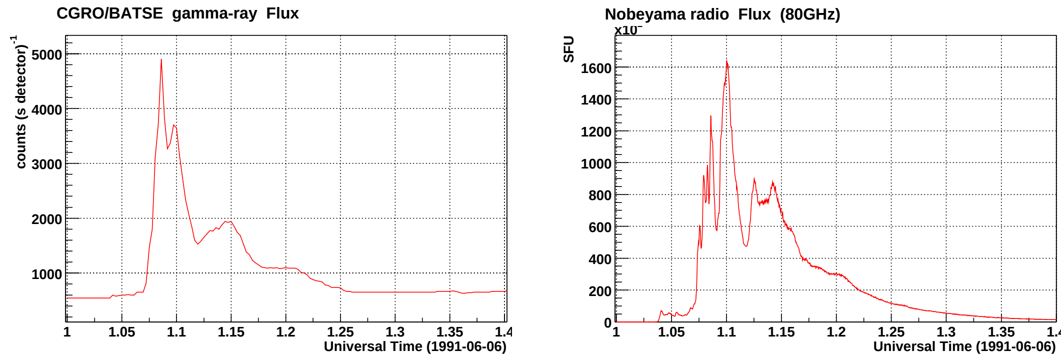

Fig. 1. The time profile of $1-10$MeV γ-rays observed by the *CGRO*/BATSE, and the time profile of 80 GHz millimeter-waves observed by the NoRP on June 6, 1991. The unit of the abscissa is one hour.

a disk flare.

Large fluxes of γ-rays and millimeter-waves were observed in this event. Fig. 1 shows the time profile of $1-10$MeV γ-rays observed by the *CGRO*/BATSE, and the time profile of 80 GHz millimeter-wave observed by the NoRP on June 6, 1991. In the γ-ray data, two large peaks are seen at 1:05 UT and 1:06 UT, and one small peak is seen around 1:09 UT. In the 80 GHz data, several intense emissions are seen, the largest peak is 1:06 UT, which is the same time of γ-ray peak.

At the start time of the X12.0 flare on June 6, 1991, the Sun was over the Pacific Ocean between Hawaii islands and Japan. The station at Mt. Norikura, Japan, was at the most suitable place for observing solar neutrons. And, the station at Mt. Haleakala was also a possible station from which solar neutrons could be observed.

The Mt. Norikura station is located at 36.1°N, 137.5°E, and 2770 m above sea level, where the vertical air mass is 730 g/cm^2. At the flare start time, the zenith angle of the Sun was 26.0° and the air mass along the line of sight to the Sun was 812 g/cm^2. The neutron monitor installed at Mt. Norikura is 12NM64. The counting rate is recorded every 10 seconds.

The Mt. Haleakala station is located at 20.7°N, 203.7°E, and 3030 m above sea level, and the vertical air mass is 707 g/cm^2. At the flare start time, the zenith angle of the Sun was 44.5° and the air mass along the line of sight to the Sun was 991 g/cm^2. The neutron monitor installed at Mt. Haleakala is 18NM64. The counting rate is recorded every 1 minute.

The time profiles of neutrons observed by the two neutron monitors are shown in Fig. 2. A clear excess was found between 1:12 UT and 1:42 UT at Mt. Norikura, and between 1:12 UT and 1:27 UT at Mt. Haleakara. At Mt. Norikura, the statistical significance of the strongest excess is 3.96 σ during 1:12$-$1:17 UT, and the total significance for 30 minutes between 1:12 UT and 1:42 UT, is 5.16 σ. At Mt. Haleakara, the statistical significance of the strongest excess is 3.03 σ during 1:22$-$1:27 UT, and the total significance for 15 minutes

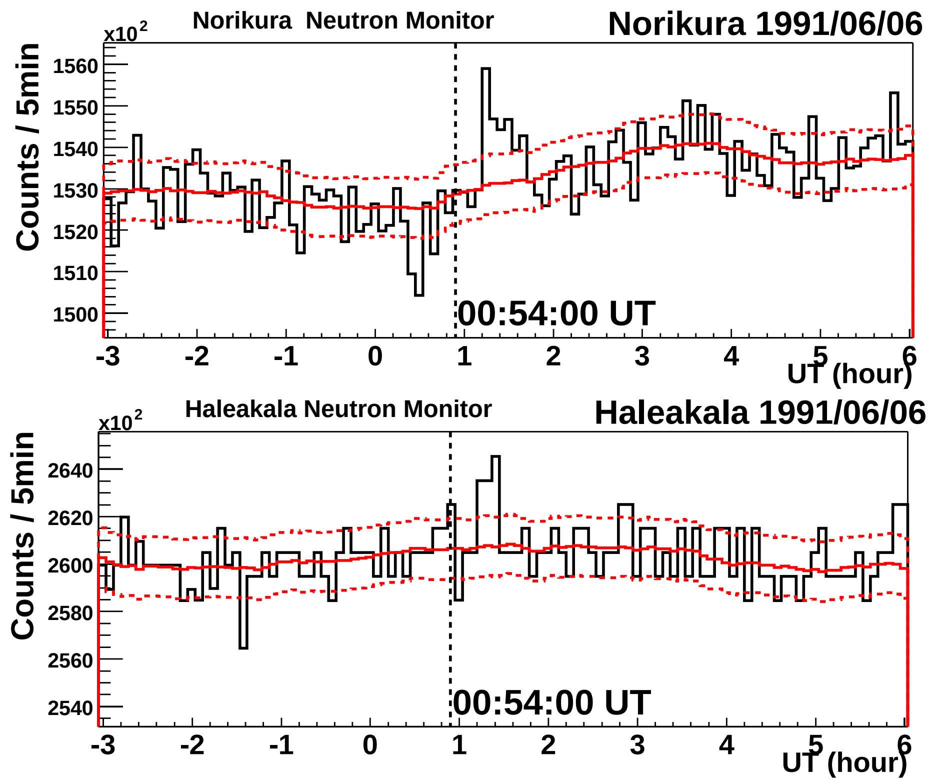

Fig. 2. The time profile of neutrons detected by two neutron monitors on June 6, 1991. The vertical axis is the counting rate per 5 minutes. The solid smooth line is the averaged background, and dashed lines are $\pm 1\,\sigma$ from the background. The upper figure is the data from Norikura neutron monitor, and the lower one is the data from Haleakara.

between 1:12 UT and 1:27 UT, is $4.28\,\sigma$.

There is a possibility that these excesses came from energetic ions because the neutron monitor can also detect energetic ions. But, there is no evidence that the enhancement was produced by energetic ions since the measurements by the other stations in the worldwide network of neutron monitors and the proton channel of *GOES* satellite showed no enhancement. Therefore, these signals must have come from solar neutrons.

3. Analysis result and Discussion

Neutron monitors cannot measure the energy of neutrons. Therefore, we cannot directly derive the energy spectrum of solar neutrons. But, using the time of flight (TOF) method by assuming the emission time of solar neutrons, this can be derived. To this end, we must determine the production time of solar neutrons.

There is a candidate for the neutron production time obtained in Fig. 1, if we use the same method as in Watanabe *et al.* [4]. One of the candidates for the neutron production time is 1:05 UT and 1:06 UT, when a spike-like enhancement of γ-ray and radio was detected by the *CGRO*/BATSE and NoRP, respectively. The other candidate is around 1:09 UT, when shelving peaks were observed by these detector.

If solar neutrons were produced at 1:05 UT or 1:06 UT instantaneously, then the energy of the neutrons detected by the Norikura neutron monitor between 1:12 UT and 1:42 UT is calculated to be $208 - 16$ MeV. The energy of the neutrons detected by the Haleakala neutron monitor between 1:12 UT and 1:27 UT is calculated to be $215 - 40$ MeV. Since neutrons suffer violent attenuation in the Earth's atmosphere, low energy neutrons, less than 50MeV, cannot arrive at the ground (Shibata [3]). Hence, the excesses detected by the Norikura neutron monitor between 1:27 UT and 1:42 UT cannot be explained by this assumption. On the other hand, the assumption that the production time is 1:09 UT gives $423 - 19$ MeV at the Norikura neutron monitor. This assumption also cannot explain the time profile of Norikura neutron monitor as long as it is assumed that neutrons were produced impulsively.

Therefore, for this event, we have to consider the possibility of the extended production of neutrons. Since in Fig. 2, the excess flux at the Norikura neutron monitor continued for 30 minutes, it is fairly probable that solar neutrons were produced continuously during the production of γ-rays and radio emissions. In order to verify this assumption, we need to simulate neutron time profiles detected at the Earth using γ-ray or radio time profiles.

4. Conclusion

We detected solar neutrons in association with the solar flare that occurred on June 6, 1991. The detection was made by the neutron monitors at Mt. Norikura and Mt. Haleakara, which were very suitable sites to observe solar neutrons in this case. In order to investigate the production time of neutrons, we compared the solar neutron data with the γ-ray data obtained by the *CGRO*/BATSE, and radio data by the NoRP. From the data of γ-rays and radio, it is concluded solar neutrons were not produced instantaneously but continuously.

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