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IMPULSIVE AND EXTENDED ACCELERATION IN THE 1977 NOVEMBER 6 SOLAR FLARE

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ABSTRACT

Yohkoh observed strong gamma-ray emission from a flare (X9.4/2B) on November 6, 1997. The emission was impulsive and lasted for about 4 min (11:52-11:56 UT). The spectrum exhibits gamma-ray lines and extends up to a few tens of MeV. The Oriented Scintillation Spectrometer Experiment (OSSE) on board the *Compton Gamma-Ray Observatory (CGRO)* missed the peak phase of gamma-ray flare but detected significant solar neutrons between 12:08 and 12:28 UT. In order to explain the OSSE neutron time profile, we propose an extended neutron production. We find a continued gamma-ray production after the peak phase from the *Yohkoh* result, supporting our proposal. We discuss the possibility that particle acceleration is associated with a magnetic reconnection and its site moves up with time.

INTRODUCTION

Ions accelerated to high energies in solar flares produce gamma-ray lines and neutrons from nuclear reactions with the solar ambient medium. The gamma-ray lines and neutrons provide direct evidence for high-energy ion production during solar flares. A large number of gamma-ray line flares were observed (Share and Murphy, 1995; Murphy *et al.*, 1997; Vestrand *et al.*, 1999; Ryan *et al.*, 1994; Murphy *et al.*, 1999; Yoshimori *et al.*, 1994, 2000a). Direct solar neutron measurement in space is more difficult than gamma-ray detection because of the complicated detection technique, low count rate and time-spread arrival at the Earth. Several neutron events were reported by Chupp *et al.* (1987, 1990), Ryan *et al.* (1994) and Murphy *et al.*

(1999). Based on gamma-ray line and neutron observations the particle acceleration time, energy spectrum and directivity and elemental abundances of the solar atmosphere have been discussed by Ramaty *et al.* (1987, 1996), Mandzhavidze *et al.* (1997), Murphy *et al.* (1997, 1999) and Share and Murphy (2000).

In this paper we present the results of *Yohkoh* X- and gamma-ray and *CGRO*/OSSE neutron observations of the 1997 November 6 flare. *Yohkoh* observed strong gamma-ray emission between 11:52 and 11:56 UT (peak phase). The preliminary result was reported by Yoshimori *et al.* (1999). The OSSE was in the South Atlantic Anomaly (SAA) between 11:40 and 12:08 UT and had no solar data before 12:08 UT. However, it detected significant solar neutrons after 12:08 UT. In order to explain the OSSE neutron time profile, we require an extended neutron production after 11:56 UT. Detailed *Yohkoh* gamma-ray analysis reveals weak 4-7 MeV emission after the peak phase, supporting the possibility of the extended neutron production. We discuss particle acceleration in both peak and extended phases of the flare.

YOHKOH AND OSSE OBSERVATIONS

Yohkoh observed a large gamma-ray flare at 11:52 UT on 6 November, 1997. Its *GOES* class, Hα importance and location were X9.4, 2B and S18W63, respectively. The flare was most intense gamma-ray event which *Yohkoh* has recorded to date and high-energy gamma rays of more than a few tens of MeV were detected (Yoshimori *et al.*, 2000a). Strong gamma-ray emission lasted for about 4 minutes. The count-rate time profiles at 1.04-1.51 MeV (bremsstrahlung is dominant) and 4-7 MeV (C and O de-excitation lines are dominant) are shown in Figures 1(a) and 1(b), respectively. Both bremsstrahlung and de-excitation lines exhibit similar temporal variations. The gamma-ray emission starts at 11:52:30 UT, reaches a main peak at 11:53:40 UT and falls with a decay constant of about 50 s. The background-subtracted gamma-ray count spectrum in 11:52:48-12:01:52 UT is shown in Figure 2. The 2.22 MeV line, de-excitation C and O lines and a

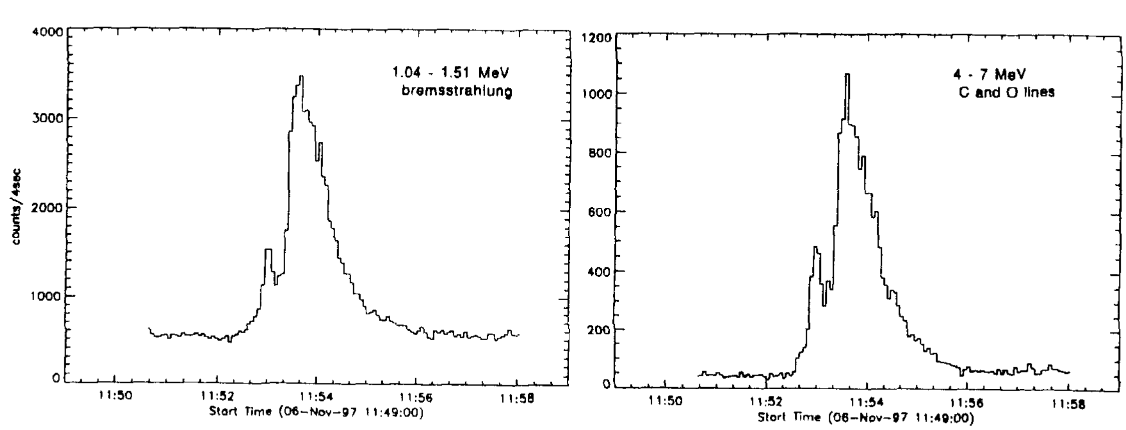

Fig.1 Gamma-ray count-rate time profiles in the peak phase of the flare. 1.04-1.51 MeV (bremsstrahlung is dominated) and 4-7 MeV (C and O lines are dominated).

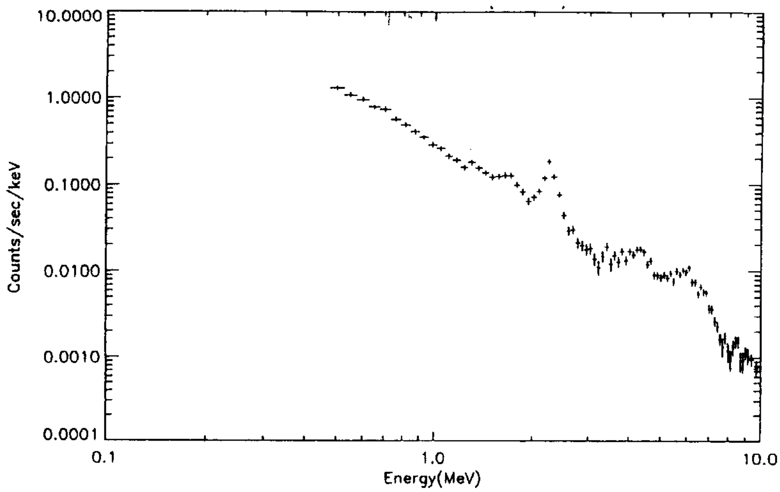

Fig. 2 Flare-averaged gamma-ray count spectrum over 11:52:48-12:01:15 UT.

complex of Ne, Mg, Si and Fe lines in 1-2 MeV are superimposed on the continuum. The *Yohkoh* data suggest that a large number of electrons and ions were efficiently accelerated to more than 10 MeV in the peak phase. A hard X-ray image at 53-93 keV was measured with the hard X-ray telescope aboard *Yohkoh* (Yoshimori *et al.*, 2000b).It shows typical double sources, indicating that accelerated electrons were streamed down to both footpoints of a flaring magnetic loop. The *Yohkoh* hard X-ray image and gamma-ray spectral observations support that the accelerated electrons and ions were almost simultaneously precipitated to the chromosphere.

The OSSE instrument is capable of distinguishing high-energy gamma rays and neutrons by a pulse shape discrimination method. The gamma-ray and neutron energies can be derived from their energy-loss spectra. The pulse shape discrimination method is reliable at low energies (neutrons of 36-100 MeV and gamma rays of 15-65 MeV) but neutrons and gamma rays are not well separated at higher energies. The OSSE was in the SAA during the gamma-ray flare and emerged from it at 12:08 UT. The count-rate time profile of separated >16 MeV neutron events is shown in Figure 3. The neutron count rate decreases with time and reaches a

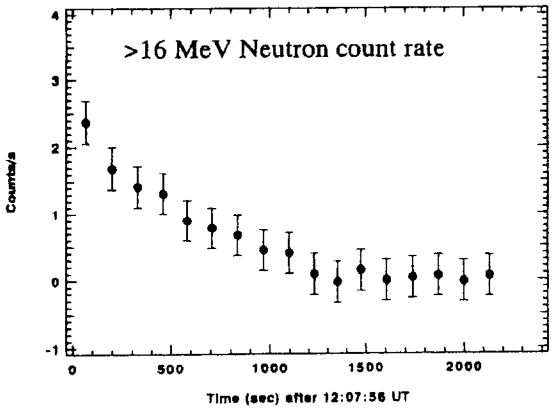

Fig. 3 Count-rate time profile of >16 MeV neutrons in 12:08-12:30 UT.

background level at 12:28 UT. When the OSSE passed the regions of similar background condition in both previous and subsequent orbits, a significant change in the OSSE neutron count rate was not measured. Further, the OSSE did not record separated gamma-ray events in 12:08-12:28 UT. We find that the OSSE events are indeed predominantly due to solar neutrons.

DISCUSSION

Two time profiles of the 4-7 MeV gamma-ray flux and the OSSE neutron count rate are shown in Fig. 4. We try to explain the OSSE neutron count-rate time profile. First we consider that the neutrons were simultaneously produced with the gamma-ray lines in the peak phase. It means that the neutrons were produced between 11:44 and 11:48 UT on the Sun. Since the OSSE observation started at 12:08 UT, the propagation time of the observed neutrons is more than 20 minutes. It indicates that the flare produced a large number of neutrons of less than 80 MeV. Assuming that the neutrons were produced between 11:44 and 11:48 UT on the Sun, we calculate the neutron count-rate time profile at the Earth. It depends on the proton spectral index. Murphy *et al.* (1999) have developed an algorithm to predict the time profile of neutrons at the Earth. A soft proton spectrum is necessary for explanation of the observed neutron time profile. When the proton spectral index is 5, we show the resultant neutron time profile (dotted curve) in Figure 4. It is in agreement with the observed one between 12:08 and 12:17 UT but rapidly falls after 12:17 UT. We need an extended neutron production to explain the observation.

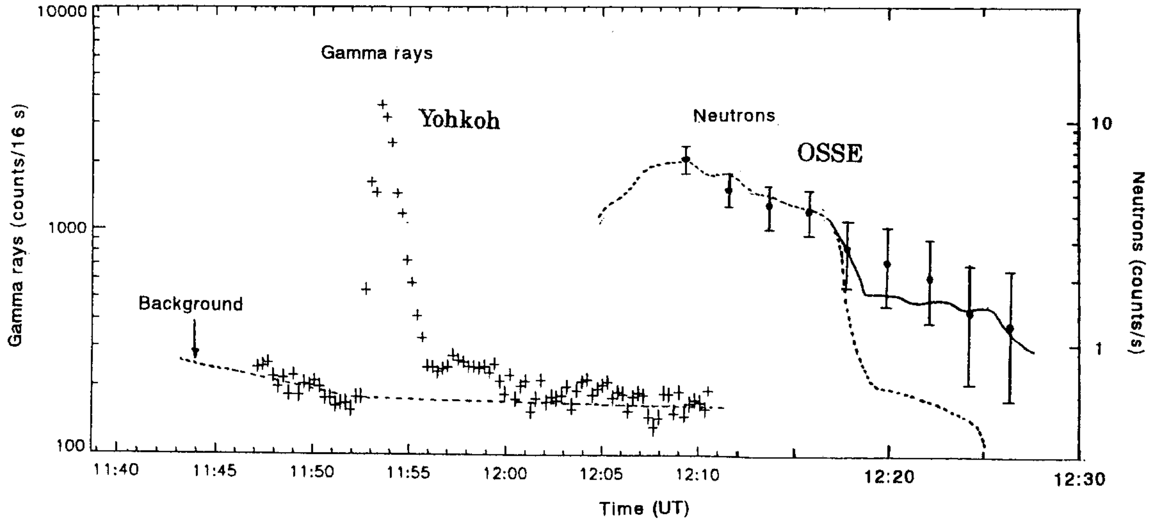

Fig. 4 Count-rate time profiles of Yohkoh gamma rays (4-7 MeV) and OSSE neutrons (>16 MeV).

We look for the possibility of the extended neutron production. Here we plot *Yohkoh* time profiles of hard X-ray (128–826 keV) and gamma–ray (4–7 MeV) emissions in the extended phase in Figures 5(a) and 5(b). Figure 5(b) is a replot of the gamma-ray time profile in Fig. 4 with a different count-rate scale to emphasize the extended phase. *Yohkoh* measured three peaks of hard X–ray emission and two peaks of gamma–ray emission in the extended phase (11:56-12:06 UT). In these two time profiles the background levels are given by the dotted curves for comparison. Figure 5(b) indicates the possibility that a small flux of gamma-ray lines were emitted in the extended phase. The *Yohkoh* result shows that the electrons and ions were simultaneously accelerated in both peak and extended phases. If it is the case, neutrons also could be produced in both phases. Assuming the proton-acceleration during both phases and the proton power-law spectral index of 5, we calculate the neutron time profile at the Earth using the Murphy *et al*' s algorithm. It is shown by the solid curve in Figure 4. The calculated neutron time profile is in agreement with the observed one within the errors. The present calculation suggests that the extended neutron production occurs after the gamma-ray peak phase. However, the assumed proton spectral index of 5 seems to be too soft for strong gamma-ray flare. If we take into account the temporal variation in the proton spectrum, the OSSE neutron time profile may be explained from a hard proton spectrum. A similar neutron observation was reported from the OSEE observation of the 1991 June 1 flare (Murphy *et al.*, 1999).

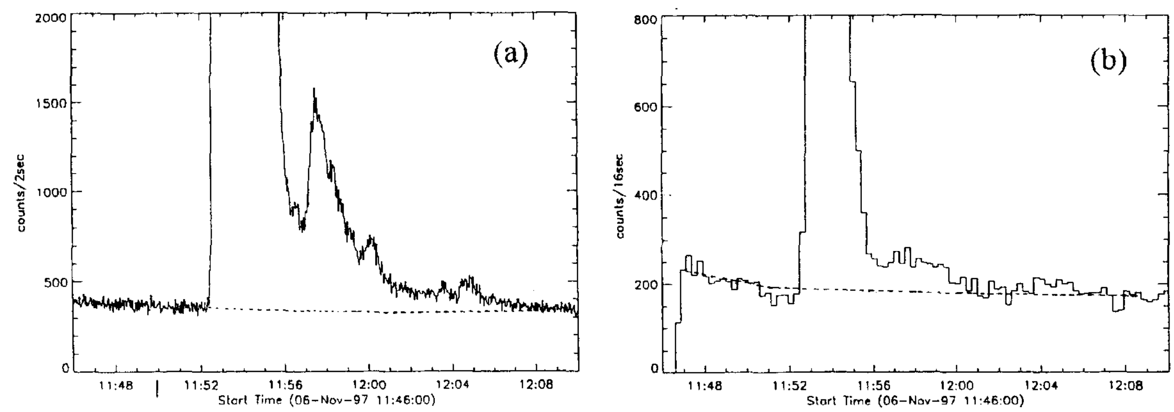

Fig. 5 (a) Hard X-ray (128-826 keV) and (b) gamma-ray (4-7 MeV) count-rate time profiles in the extended phases. The dotted curves are the background levels. The right figure is a replot of the gamma-ray (4-7 MeV) time profile in Fig. 4 with a different count-rate scale to emphasize the extended phase.

We discuss particle acceleration in the peak and extended phases. The *Yohkoh* hard X-ray images reveal that a distance between two hard X-ray sources is almost constant in the peak phase (~10,000 km) but gradually increases after that (up to ~18,000 km). It suggests the possibility that a magnetic reconnection site gradually moved up to the higher corona (Sakao *et al.*, 1998). According to this scenario, strong acceleration impulsively starts associated with a first magnetic reconnection and the acceleration site gradually moves up in the extended phase. Neutrons are produced in both impulsive and extended phases.

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