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LONG-LIVED SOLAR NEUTRON EMISSION IN COMPARISON WITH ELECTRON-PRODUCED RADIATION IN THE 2005 SEPTEMBER 7 SOLAR FLARE

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ABSTRACT

Strong signals of neutral emissions were detected in association with a solar flare that occurred on 2005 September 7. They were produced by both relativistic ions and electrons. In particular, relativistic neutrons were observed with the solar neutron telescopes (SNTs) located at Mount Chacaltaya in Bolivia and Mount Sierra Negra in Mexico and with neutron monitors (NMs) at Chacaltaya and Mexico City with high statistical significances. At the same time, hard X-rays and γ-rays, which were predominantly emitted by high-energy electrons, were detected by the *Geotail* and the *INTEGRAL* satellites. We found that a model of the impulsive neutron emission at the time of the X-ray/γ-ray peak can explain the main peaks of all the detected neutron signals, but failed to explain the long tailed decaying phase. An alternative model, in which the neutron emission follows the X-ray/γ-ray profile, also failed to explain the long tail. These results indicate that the acceleration of ions began at the same time as the electrons but that ions were continuously accelerated or trapped longer than the electrons in the emission site. We also demonstrate that the neutron data observed by multienergy channels of SNTs put constraints on the neutron spectrum.

Subject headings: acceleration of particles — cosmic rays — radiation mechanisms: nonthermal — Sun: flares — Sun: particle emission — Sun: X-rays, gamma rays

1. INTRODUCTION

The Sun is the only robust cosmic accelerator of ions to which we have direct access; therefore, it is an important laboratory for studying particle acceleration. It sometimes accelerates ions to the relativistic energies (~1 GeV). The imaging capability of the radiations emitted from electrons enabled detailed studies of electron acceleration (see, e.g., Masuda et al. 1994), but this is not the case for the ion acceleration. Although *RHESSI* has opened a new era of imaging studies of ion accelerations (Hurford et al. 2003), observations are still limited. To bridge the rich information of the electron acceleration to the ion acceleration, comparison of the emission time of electrons and ions, or the secondary particles from them, is still important. Various methods are applied for these studies, and each of them has advantages and drawbacks, as summarized below. As there is a wide variety from event to event, we need to collect more evidence to construct a unified story of the particle acceleration at the Sun.

To avoid the complexity introduced by the magnetic field, observations of secondary neutral particles and/or radiations are suitable. Radiations from electrons (synchrotron radio emission, bremsstrahlung hard X-rays, and γ-rays) are recorded with excellent timing or spatial resolution. On the other hand, observations of nuclear γ-rays, π^0 decay γ-rays, and neutrons emitted from the ion interactions have merits and demerits. Using the excellent time resolution of the nuclear γ-ray observation, Forrest & Chupp (1983) concluded for the flare of 1980 June 7 and 21 that the ions and electrons were simultaneously accelerated within the order of a second. However, Watanabe et al. (2006) demonstrated for the flare of 2003 October 28 that there is a time lag on the order of a minute. Because the parent particles of the nuclear γ-rays have energies below 100 MeV, the observations of the nuclear γ-rays are not sufficient to access relativistic energies; π^0 γ-rays are emitted from ions of relativistic energies. As found in Debrunner et al. (1993) and Kanbach et al. (1993), there are observations that π^0 γ-rays were continuously emitted for a certain duration (20 minutes and 8 hr, respectively). However, as Debrunner et al. (1993) pointed out for the event of 1990 May 24, the discrimination of π^0 γ-rays from bremsstrahlung and neutrons is difficult.

Assuming that the continuous tail is made by π^0 γ-rays and that high-energy (>100 MeV) neutrons were simultaneously emitted, Debrunner et al. (1993) explained the observed profile of a ground-level NM signal. Here solar neutrons are emitted through the interaction between accelerated ions and the solar atmosphere. They can have energies comparable to the parent ions. Ground-level observations of ions and neutrons are only sensitive to energies above 100 MeV and free from the contamination of radiation from electrons. In contrast to the conclusion of Debrunner et al. (1993), Muraki & Shibata (1996) concluded that the neutrons were emitted within a minute for the same event. They have developed a sophisticated Monte Carlo code (Shibata 1994) to simulate the transportation of neutrons in the Earth's atmosphere and found that the delayed signal can be explained by low-energy (~100 MeV), i.e. low-speed, neutrons. Sharp peaks found in X-rays and γ-rays support a simple scenario that both ions and electrons were accelerated simultaneously within a minute.

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In this Letter, we present results of a recent ground-level solar neutron event observed with high statistics. We compared time profiles of hard X-rays and neutrons on 2005 September 7 and concluded that the neutrons were emitted for a longer period than X-rays. Although the observation conditions were similar to the case of 1990 May 24, the relationship between neutron and X-ray production was quite different in the two events. In addition to the high statistics observation, we have detected events with two different kinds of detectors (two SNTs and two NMs) located at three diverse stations. This enabled us to study the neutron spectrum and time profile in more detail. In this Letter we aim to present a prompt analysis report of the event. After the description of the observations, we try to explain the observed neutron profiles with two models: impulsive emission or the same profile of X-rays and γ-rays.

2. OBSERVATIONS

A strong solar flare occurred on 2005 September 7. Soft X-ray emission observed by the *GOES* satellite started to increase at 17:17 UT, reached its maximum at 17:40 UT, and decayed to half-maximum at 18:03 UT. The peak X-ray flux was classified as X17.0. This flare occurred in AR 10808, which was located at S06°, E89° at the time of the flare onset. Thus, the flare is classified as an East limb flare. As expected for such events, no increase of charged particles (<0.1 particles $\mathrm{s^{-1}\ cm^{-2}\ sr^{-1}}$ above 100 MeV) were observed with the *GOES* satellite. (A solar proton event occurred 3–4 hr after the flare onset.) The Mauna Loa data show a coronal mass ejection associated with this flare.[11] We have obtained hard X-ray data of the *Geotail*, which indicate a >50 keV X-ray emission (Terasawa et al. 2005) peaked at 17:36:40 UT, as shown in Figure 1. The *INTEGRAL* SPI detector also recorded >150 keV X-rays and γ-rays covering the energy range of the nuclear emissions, whose profile was almost identical to that of the *Geotail*. Because there was no clear evidence of nuclear lines, high-energy radiation is considered to trace the high-energy electrons. The energy of radiation can reach the energy of the parent electron.

At the *GOES* soft X-ray peak time of the flare (17:40 UT), Mexico and Bolivia were suitable places to observe solar neutrons in the SNT network (Tsuchiya et al. 2001; Valdés-Galicia et al. 2004). At Sierra Negra (E262°.7, N19°.0; 4580 m above sea level [a.s.l.]) in Mexico, where an SNT is installed, the solar zenith angle was 17°.5, and the air mass in the line of sight to the Sun was 603 g $\mathrm{cm^{-2}}$. At Mexico City (E260°.8, N19°.3; 2274 m a.s.l.), where an NM is located, the zenith angle and the air mass were 18°.9 and 825 g $\mathrm{cm^{-2}}$, respectively. At Mount Chacaltaya (E292°.0, S16°.2, 5250 m a.s.l.) in Bolivia, where both an SNT and an NM are located, the zenith angle and the air mass were 28°.0 and 612 g $\mathrm{cm^{-2}}$, respectively.

The Mexico SNT has plastic scintillators of a 4 $\mathrm{m^2}$ area and 30 cm thickness covered by gondolas of proportional counters working as anticounters. To convert γ-rays into electron pairs, the proportional counters are covered by lead and iron of 1 radiation length thickness. A signal from the scintillators without any coincidence with anticounter signal is regarded as generated by neutral particles. The coincident signal between the anticounter and the scintillator is generated by charged particles. Scintillator signals are discriminated by four different energy thresholds, which correspond to energy deposit of >30, >60, >90, and >120 MeV. Below the scintillators, 4 layers of proportional counters are also aligned to measure the direction and energy of the recoil particles. Details of the detector and its performance are described in Valdés-Galicia et al. (2004). The Bolivia SNT is simpler. It consists of a 4 $\mathrm{m^2}$ area and 40 cm–thick plastic scintillators covered by 1 cm–thick plastic scintillators as anticounters (Matsubara et al. 1993, 1995). However, at the time concerned, these anticounters were not working, so we can only consider the central scintillators. Counts with four different energy thresholds corresponding to >40, >80, >160, and >240 MeV are recorded. The Mexico NM is 6NM64, and the Bolivia NM is 12NM64. Because one of the Bolivia counters was not functional at the time of the flare, the effective area was 8% reduced.

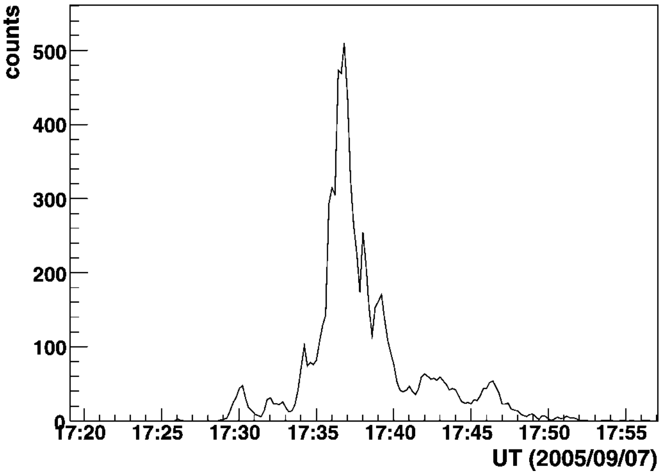

FIG. 1.—Hard X-ray time profile observed by the *Geotail* satellite on 2005 September 7.

The detectors record counting rates with a 10 s interval, except the Mexico NM, which has a 5 minute interval. The absolute time is recorded with GPS antennas with a precision of 1 s. The observed time profiles of all the detectors are shown in Figure 2 (Bolivia NM, Mexico NM, and Bolivia SNT) and Figure 3 (Mexico SNT). Clear excesses are recorded by all the detectors after the hard X-ray peak time (17:36:40 UT) of the *Geotail* satellite. Less significant bumps found in the penetrating particle and charged particle channels in the Mexico SNT are also important to constrain the primary energies.

3. ANALYSIS AND DISCUSSION

Before attributing the observed signals to neutrons, we first investigate the possibility of a proton event. Since the flare occurred at the solar east limb, protons must move across the magnetic field diffusively before arriving at the Earth. Then it is unlikely that the sharp increase seen in Figure 2 is due to protons. The cutoff rigidities of Chacaltaya and Mexico City are 12.5 and 8.6 GV, respectively. On the other hand, at the Apatity station,[12] where the cutoff rigidity is 0.57 GV, no significant excess was found. Because the subsolar point at the time of the flare was between Mexico and Bolivia, it is natural to conclude that the signal was caused by neutrons. Furthermore, when we plot the relative increase of the Bolivia NM (11%) and the Mexico NM (6%) with respect to the line-of-sight air mass in Figure 3 of Shea et al. (1991), the plot comes just between two historical solar neutron events of 1990 May 24 and 1982 June

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[11] The Mauna Loa data on 2005 September 7 is available at http://mlso.hao.ucar.edu/cgi-bin/mlso_datasum.cgi?2005&9&7&ACOS, courtesy of the High Altitude Observatory, National Center for Atmospheric Research.

[12] Apatity neutron monitor data are available at http://pgi.kolasc.net.ru/CosmicRay.

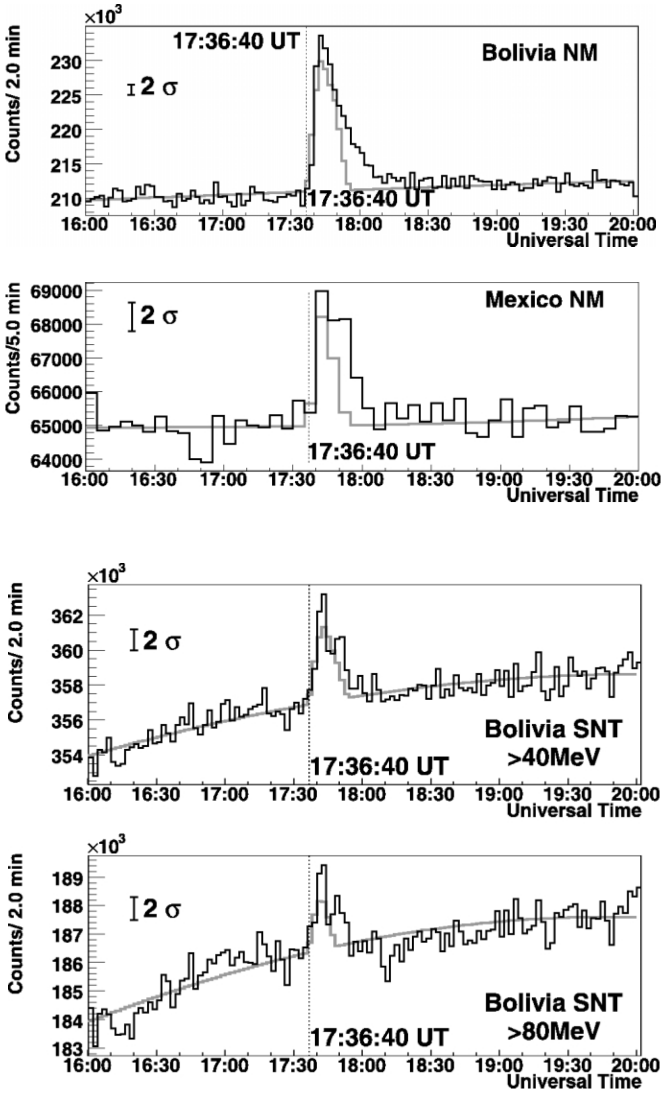

FIG. 2.—From top to bottom, 2 minute counting rate of the Bolivia NM (*first panel*), the 5 minute counting rate of the Mexico City NM (*second panel*), and the 2 minute counting rates of different channels of the Bolivia SNT (>40 MeV, *third panel*; >80 MeV, *bottom*). The 2 σ background fluctuation is indicated in the top left of each panel. The *Geotail* hard X-ray peak time is 17:36:40 UT. Gray curves show expected counts assuming a neutron flux derived from the Bolivia NM data. Background is estimated by a third-order polynomial fit excluding 17:30–18:30 UT.

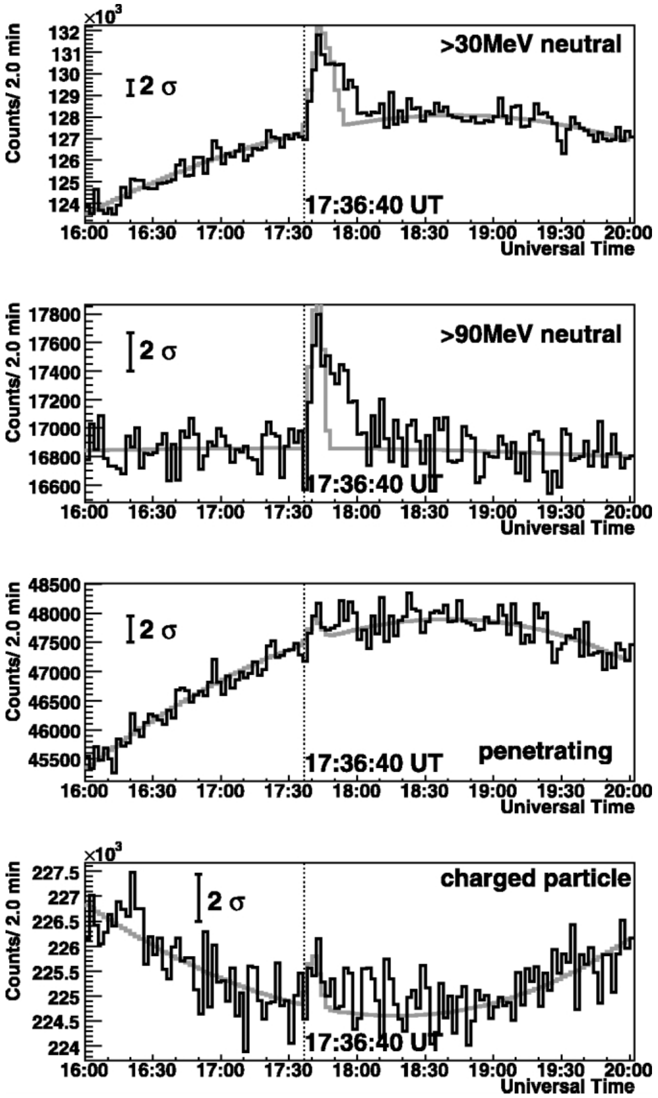

FIG. 3.—The 2 minute counting rates of different channels of the Mexico SNT (>30 MeV neutral, >90 MeV neutral, penetrating neutral, and charged particles). The 2 σ background fluctuation is indicated in the top left of each panel. 17:36:40 UT is the *Geotail* hard X-ray peak time. Gray curves show expected counts assuming a neutron flux derived from the Bolivia NM data with background. Background is estimated by a third-order polynomial fit excluding 17:30–18:30 UT.

3. All these results support the observed signal being made by solar neutrons. The statistical significances of the excess in the 17:40–17:45 UT interval were calculated for each detector. They are defined in units of standard deviation from the running average of the data between 4:30 and 17:30 UT. The results for the Bolivia NM, the Mexico NM, the Bolivia SNT (>40 MeV), and the Mexico SNT (>30 MeV neutral) are 40 σ, 9 σ, 12 σ, and 16 σ, respectively.

The neutron flux is calculated by using the Monte Carlo method. In the calculation, we used data of the Bolivia NM, as it is the most significant signal. Because the NM is sensitive to a broad range of neutron energies, the emission profile is convoluted with a broad time-of-flight distribution and is not measured directly. We therefore hypothesize two models of the emission time. The first one is that the neutrons were emitted impulsively when the hard X-ray emission peaked. Considering the 500 s of X-ray flight time from the Sun to the Earth, the peak emission time is about 17:28:20 UT. With this assumption, the neutron energy corresponding to the sharp increase at about 17:40:00 UT in the Bolivia NM data is 400 MeV. From the time profile of the neutrons, we have calculated the energy spectrum of solar neutrons at the solar surface using the Shibata program for atmospheric attenuation (Shibata 1994) and the efficiency of the NM calculated by Clem & Dorman (2000). By using the method described in Watanabe et al. (2003, 2006), the energy spectrum of neutrons at the Sun is fitted by a power law as $6.1 \times 10^{27}(E/100\ \mathrm{MeV})^{-3.8}\ \mathrm{MeV}^{-1}\ \mathrm{sr}^{-1}$. Because all of the data could not be fitted with a single power law, we fitted only the data between 17:40 and 17:47 UT, which is the interval corresponding to 100 MeV–400 MeV neutrons. Interestingly, in an independent analysis using a different attenuation model (Dorman et al. 1999) and efficiency calculation (Valdés-Galicia et al. 2004), the Mexico SNT data give a quite consistent result of $5.3 \times 10^{27}(E/100\ \mathrm{MeV})^{-4.0}\ \mathrm{MeV}^{-1}\ \mathrm{sr}^{-1}$. This difference is a good estimate of the systematic uncertainty of the analysis method because in this case, the statistical error is almost negligible.

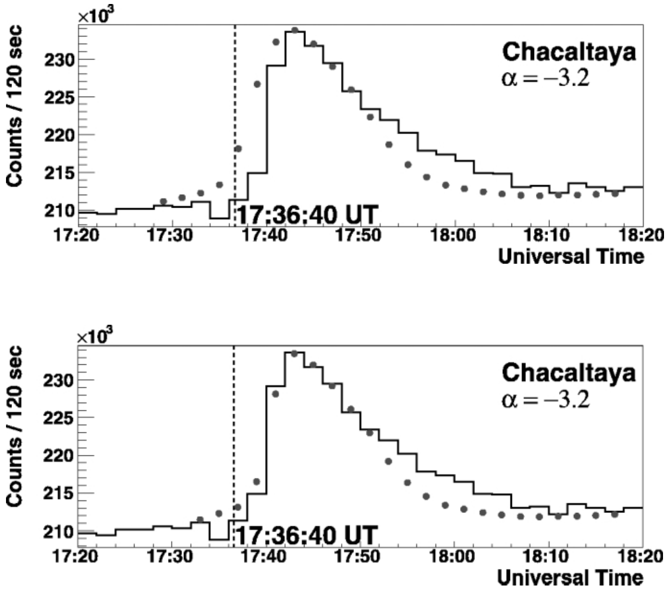

FIG. 4.—Simulated (*dots*) and observed (*histogram*) time profiles of the Bolivia NM. In these calculations, we assumed the neutron emission follows the hard X-ray profile. *Top:* Case in which no cutoff energy is included. The best power index is found to be −3.2, but apparent discrepancies in the rising and decaying phases are seen. *Bottom:* Same spectrum, but a sharp cutoff at 400 MeV is assumed. Rising part is well explained, however a large difference is still found in the decaying phase.

Starting from this intensity, we calculated the response of all the detectors and channels by using the Monte Carlo method. For the calculation of the response of the SNTs, we used the GEANT3 package. Simulated profiles are overlaid with gray curves in Figures 2 and 3. We can find a reasonable agreement in the observed amplitude. (Here we must note that there still remains a systematic uncertainty of the detector response at the level of ±10% that can change the normalization of each detector.) However, it is clear that the long tails of the observed profiles are not well fitted. We tried various power-law indexes and emission times but could not find any parameter to satisfactorily fit the observed profile. To keep the model of an impulsive emission, we need to assume a softening of the spectrum below 60 MeV. Lower energy neutrons, which have smaller speed, can explain the delayed signal. But this is inconsistent with the results of SNTs that both the >80 and >90 MeV profiles have long tails. Such a constraint was impossible only from the data of NMs.

As a second model of the emission profile, we assumed that the neutrons were emitted with the same profile as the hard X-rays and γ-rays. The best-fit result with a single–power-law spectrum with an index of -3.2 is plotted in the top panel of Figure 4. There is an obvious discrepancy between the data and the Monte Carlo simulations. To compensate for the difference at the rising phase, we tried the same spectrum but with a sharp cutoff at 400 MeV. The result is shown in the bottom panel of Figure 4. In this case, the profile up to just after the peak is well fitted. This indicates that the acceleration of ions began at the same time as the electrons. However, the discrepancy of the tails, which we could not fit with any set of parameters, suggests that the ions were continuously accelerated or trapped for a longer period than the electrons.

In the observations of the 1990 May 24 flare, relativistic ions were thought to be accelerated within a minute simultaneously with electrons. Results published for an analysis done of the 1980 June 21 and 2002 July 23 events also suggest an almost simultaneous acceleration of electrons and ions (Chupp 1990; Lin et al. 2003; Hurford et al. 2003). On the other hand, a long lifetime of the relativistic ions was reported in the flare of 1991 June 11 (Kanbach et al. 1993). They also observed different lifetimes of ions and electrons, but could not tell anything about the beginning of the acceleration due to saturation. Chupp (1990) also found extended proton (but not electron) emissions for the flares on 1982 June 3 and 1984 April 24. The new observations of the 2005 September 7 flare presented here are situated between these two extremes. They covered all the history of the flare and found similarities and differences in the behavior of high-energy ions and electrons with high statistics. Furthermore, the ground-based observations are free from the contamination of electron-produced radiations. These high-quality ground-based observations constrain the environment of the acceleration and emission site of the relativistic particles. The other shapes of the energy spectrum and the extended emission profiles independent from X-rays or γ-rays should be tested to consistently explain all the results obtained for the event.

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