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Physics of ion acceleration in the solar flare on 2005 September 7 determines γ-ray and neutron production

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Abstract

Relativistic neutrons were observed by the neutron monitors at Mt. Chacaltaya and Mexico City and by the solar neutron telescopes at Chacaltaya and Mt. Sierra Negra in association with an X17.0 flare on 2005 September 7. The neutron signal continued for more than 20 min with high statistical significance. Intense emissions of γ-rays were also registered by *INTEGRAL*, and during the decay phase by *RHESSI*. We analyzed these data using the solar-flare magnetic-loop transport and interaction model of Hua et al. [Hua, X.-M., Kozlovsky, B., Lingenfelter, R.E. et al. Angular and energy-dependent neutron emission from solar flare magnetic loops, Astrophys. J. Suppl. Ser. 140, 563–579, 2002], and found that the model could successfully fit the data with intermediate values of loop magnetic convergence and pitch-angle scattering parameters. These results indicate that solar neutrons were produced at the same time as the γ-ray line emission and that ions were continuously accelerated at the emission site.

Keywords: Solar flare; Solar X-rays and γ-rays; Solar particle event; Cosmic rays

1. Introduction

Ions are accelerated in association with solar flares and interact with the ambient solar atmosphere to produce γ-ray lines and neutrons. Some of the neutrons that escape from the Sun into interplanetary space can reach Earth.

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These neutrons are attenuated by the Earth's atmosphere and observed by ground-based detectors such as neutron monitors and solar neutron telescopes. Because the flux of solar neutrons is reduced by propagation in interplanetary space and attenuation in the Earth's atmosphere, solar neutron observation is difficult. The neutron observability also depends on the locations of detectors. In order not to miss events, detectors should be located at many different longitudes. Detectors are now installed around the world, especially on high mountains, and make up an international network for solar neutron observation (http://www.stelab.nagoya-u.ac.jp/ste-www1/div3/CR/Neutron/).

By using these detectors, a few solar neutron events have been observed in solar cycle 23 (e.g. Watanabe et al., 2003, 2006; Bieber et al., 2005). These events were invariably observed in association with strong γ-ray emissions, and solar neutron emission can be explained by assuming that solar neutrons were emitted at about the same time as the γ-ray emissions (Watanabe et al., 2005). On 2005 September 7, in association with an X17 flare, a large solar neutron event was observed by ground-based detectors. The neutron signals continued for more than 20 min.

A solar neutron event having a similar long decay was observed on May 24, 1990 (Debrunner et al., 1993, 1997). For the May 1990 event, solar neutrons were observed by neutron monitors located around North America, and very significant signals continued for a long time. In association with this flare, strong emission of γ-rays from π^0 decay was observed by the Granat spacecraft. Debrunner et al. (1993) explained the observed neutron time profile assuming that high-energy neutrons were simultaneously emitted with the π^0 γ-rays. However, using the attenuation and propagation simulation code of Shibata (1994) and Muraki and Shibata (1996) explained the long decay of neutron signals for this event by assuming that the neutrons were emitted only within a minute of the peak time of π^0 γ-ray emission.

In this paper, we report on the 2005 September 7 neutron event and describe the analysis results. For this event, we could not explain the long decay of neutron emission by assuming that solar neutrons were produced only at the peak of the γ-ray emission and using the neutron propagation model of Shibata (1994). This is the first neutron event for which the neutron time profile cannot be explained using the Shibata (1994) model with impulsive injection. To explain the long-lasting neutron emission of September 7, we require either continuous injection (that is, continuous acceleration) or strong trapping in the flare loop.

2. Observations of the solar flare on 2005 September 7

On 2005 September 7, a strong neutron signal in association with an X17 flare was observed by ground-based detectors. At the time of this flare, the Sun was located over South America, and detectors located in Mexico and Bolivia were in good locations for observing solar neutrons. Two neutron monitors and two solar neutron telescopes are installed in this region, and all of these detectors observed very clear signals. The largest signal was observed by the neutron monitor located at Mt. Chacaltaya in Bolivia. All neutron signals continued for more than 20 min (Watanabe et al., 2007, Fig. 3).

There is a possibility that these excesses came from energetic ions because the neutron monitor can observe energetic ions. But the cutoff rigidity at Mt. Chacaltaya is high (12.53 GV) so it is difficult for ions to reach ground level. Also, there are many neutron monitor stations located at places where the cutoff rigidity is lower. If these excesses came from energetic ions, some enhancement should have been detected by these other stations but none were. Furthermore, this flare occurred at the East limb (E89) and it is very difficult for ions to arrive at Earth from the East limb. Therefore, these signals must have come from solar neutrons.

For this event, both *INTEGRAL* and *RHESSI* satellites observed hard X-rays and γ-rays (Fig. 1). Unfortunately, *RHESSI* was in the South Atlantic Anomaly (SAA) during the impulsive phase and observed γ-rays only during the decay phase and then went into satellite night. However, *INTEGRAL* observed hard X-rays and γ-rays during the entire flare, and obtained an excellent γ-ray spectrum.

The top panel of Fig. 2 shows the γ-ray spectrum obtained with *INTEGRAL*, showing the prompt 4.4 MeV γ-ray line from de-excitation of ambient carbon. We fitted

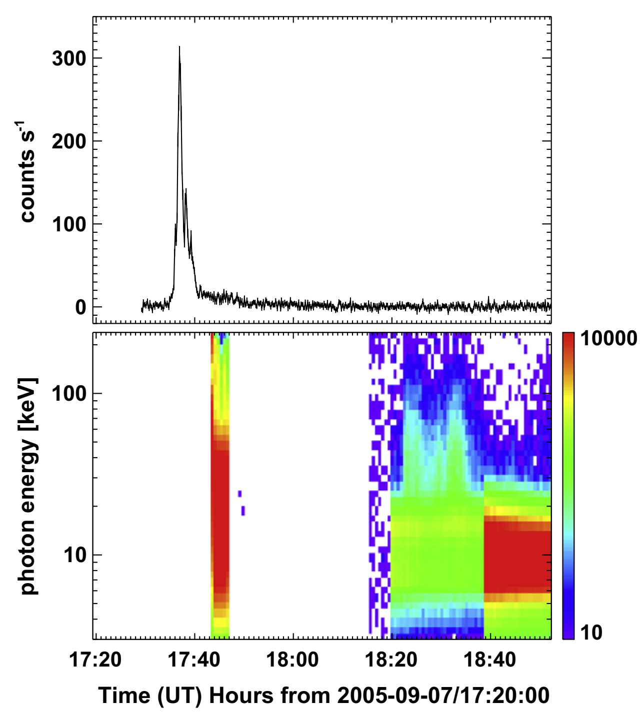

Fig. 1. The X-ray data observed by the *INTEGRAL* and *RHESSI* satellites on 2005 September 7. Top panel shows hard X-ray light curve observed by the *INTEGRAL* satellite between 200 and 300 keV. Bottom panel shows the spectrogram observed by *RHESSI*. Color bar indicate the photon counts per 4 s. *RHESSI* was in the SAA until 17:43 UT and in satellite night after 17:47 UT. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)