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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

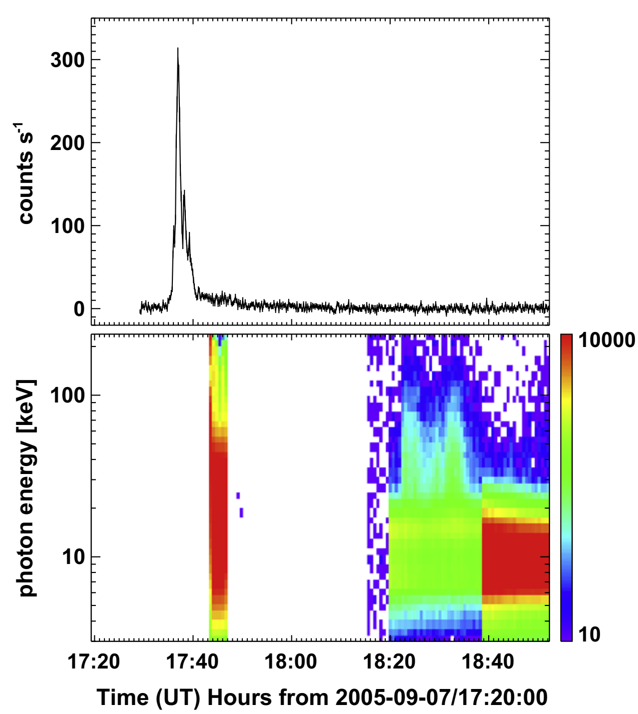

Fig. 1. The X-ray data observed by the *INTEGRAL* and *RHESSI* satellites on 2005 September 7. Top panel shows hard X-ray light curve observed by the *INTEGRAL* satellite between 200 and 300 keV. Bottom panel shows the spectrogram observed by *RHESSI*. Color bar indicate the photon counts per 4 s. *RHESSI* 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.)

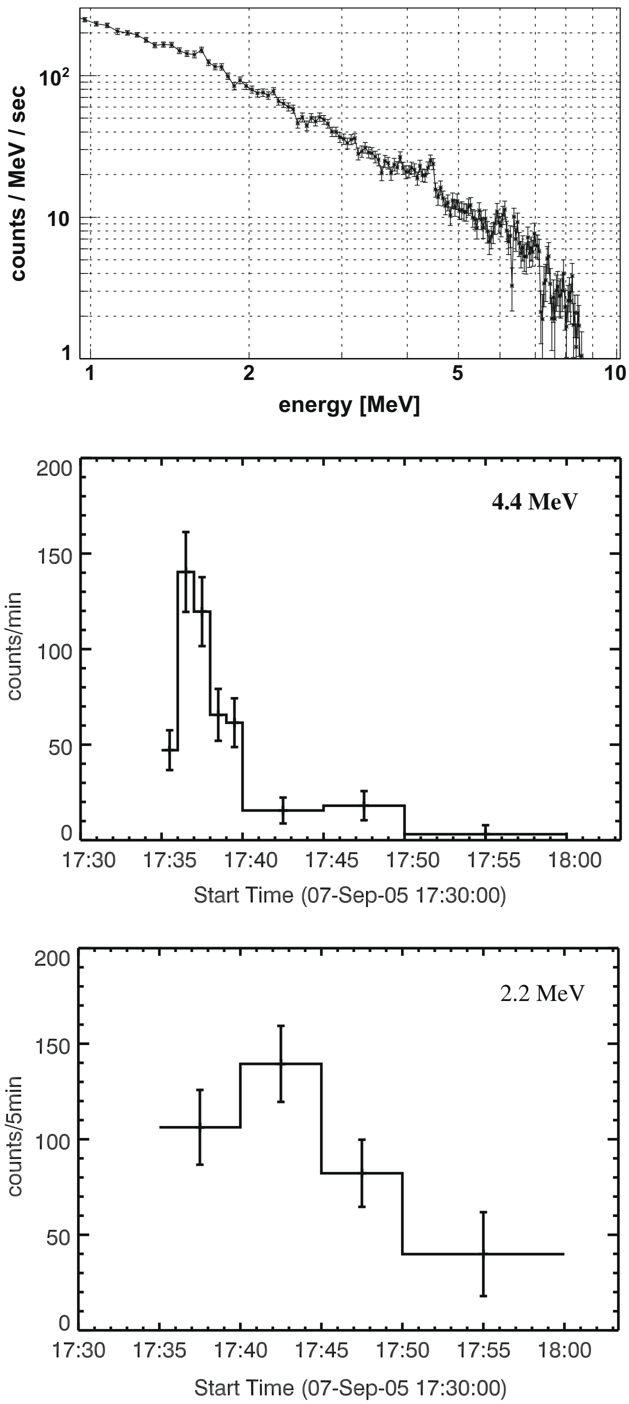

Fig. 2. The γ-ray data observed by the *INTEGRAL* satellite on 2005 September 7. Top panel shows the γ-ray spectrum observed from 17:35 to 18:00 UT. The 4.4 MeV line can be seen superimposed on the bremsstrahlung component. Middle panel shows the time profile of the prompt γ-ray de-excitation line of carbon (4.4 MeV). Bottom panel shows the time profile of the 2.2 MeV neutron-capture γ-ray line. Error bars indicate $\pm 1\sigma$.

1, 5 or 10 min integrated γ-ray spectra by using power-law and single Gaussian for bremsstrahlung and line component, respectively, and obtained 4.4 MeV line time history as shown in the middle panel of Fig. 2. The time history of the delayed 2.2 MeV neutron-capture line was also obtained using the same method (bottom panel of Fig. 2). We found that the prompt γ-ray emission continued after the impulsive phase until about 17:50 UT. From these data we see that ions were either continuously accelerated or trapped in the flare loop, but cannot tell which process is dominant.

3. Loop transport and interaction model by Hua et al. (2002)

Hua et al. (2002) developed a magnetic-loop transport and interaction model in which a Monte Carlo simulation follows an individual accelerated ion through a flare loop until it either undergoes a nuclear reaction or its energy falls below nuclear reaction thresholds. The most important aspects of ion transport are included in the model: energy losses due to Coulomb collisions, removal by nuclear reactions, magnetic mirroring in the convergent flux tube, and MHD pitch-angle scattering. Using this model, the emission profiles of γ-rays and neutrons can be predicted, along with the neutron spectrum arriving at the top of the Earth's atmosphere.

We use Hua's model to analyze the neutron data from the September 7 flare. To use this program, several parameter values must be set, as shown in Table 1. The "acceleration release time history" means injection time history of accelerated ions, and the "pitch-angle scattering mean free path" and "magnetic convergence index" are parameters related to trapping in the flare loop. For the other parameters, we use both observed data and assumed typical values estimated from previous observations. For the accelerated ions, we assume an impulsive-flare composition (Ramaty et al., 1996) with $\alpha/p = 0.5$, and $^3He/^4He = 1$. For the ambient material we use the coronal composition of Reames (1995) with $He/H = 0.1$, and $Ne/O = 0.25$, the atmospheric model of Avrett (1981), and photospheric $^3He/H = 3.7 \times 10^{-5}$. The flare loop length is obtained from *RHESSI* and *GOES* data and is 36,800 km. Since the flare occurred just at the limb, the heliocentric angle is 89 deg.

λ is related to the pitch-angle scattering mean free path, and δ is related to the magnetic field convergence. These parameters control the amount of trapping in the flare loop. If δ is 0.0 and λ is 20, there is no trapping. If δ is 0.45 and λ is 40,000, ions are strongly trapped. We varied the ion spectral index, δ and λ to determine the combina-

Table 1
Loop model parameters for 2005 September 7 event.

Release time history	4.4 MeV line history, impulsive, etc.
Accelerated-ion composition (impulsive)	$\alpha/p = 0.5$, $^3He/^4He = 1$
Power-law spectral index	$s = -2.0$ to -6.0
Pitch-angle scattering mean free path	$\lambda = 20$(saturated)–40,000(none)
Magnetic convergence index	$\delta = 0.0$(no)–0.45(strong)
Ambient composition (coronal)	$He/H = 0.1$, $Ne/O = 0.25$
Atmospheric model	Avrett (1981)
Photospheric $^3He/H$	3.7×10^{-5}
Flare loop length	36,800 km
Flare heliocentric angle	89.0 deg (S06 E89)

Table 2
Best fit results for neutron profiles of 2005 September 7 event.

Injection	λ	δ	Index	Reduced χ^2 for neutron	Reduced χ^2 for 2.2 MeV
Delta	9000	0.24	−4.11	2.01	11.33
τ = 60 s	9000	0.24	−4.19	2.36	9.10
τ = 120 s	4000	0.28	−4.28	3.85	3.50
τ = 180 s	500	0.32	−4.25	5.20	4.60
τ = 240 s	300	0.34	−4.28	4.03	7.00
τ = 300 s	100	0.32	−4.31	3.37	15.82
τ = 360 s	100	0.32	−4.35	3.37	20.23
τ = 420 s	100	0.16	−4.29	3.88	47.55
τ = 480 s	100	0.16	−4.31	4.99	59.02
τ = 540 s	100	0.16	−4.34	6.53	68.80
τ = 600 s	100	0.16	−4.36	8.27	80.50
4.4 MeV	300	0.34	−4.23	1.50	5.58

tion of these parameters that best fit the observed neutron and 2.2 MeV line data.

We also varied the ion-release time history. Because strong trapping of ions can extend the emission of neutrons, we tried a delta-function injection of ions (at the peak of the 4.4 MeV line emission). We also tried profiles exhibiting a sudden onset (at the peak of the 4.4 MeV line emission) with 1- and 10-min exponential decay times (τ). Finally, we used the 4.4 MeV line history itself as the ion-release time profile.

By using loop model of Hua et al. (2002) with these parameters, we predicted the emission profiles of 2.2 MeV γ-rays and neutrons. For 2.2 MeV γ-rays, we directly compared predicted profiles with observed data as shown in Fig. 2. For neutrons, we compare predicted neutron count rates with the observations using the neutron attenuation ratio in the Earth's atmosphere given by the Shibata model (Shibata, 1994) and the detection efficiency of the neutron monitor as calculated by Clem and Dorman (2000). The decay of neutrons between the Sun and the Earth is taken into account. We use the data of the Bolivia neutron monitor since the largest signal was observed there.

Fitting results which gives minimum χ^2 for neutron profile were shown in Table 2. Minimum χ^2 was obtained when we use 4.4 MeV γ-ray profile as injection, however, we could not fit to 2.2 MeV profile by using same parameters. Delta injection also could not fit to 2.2 MeV profile, χ^2 of 2.2 MeV profile was getting smaller until 2-min exponential decay time injection, and after that, χ^2 of 2.2 MeV profile was getting larger followed by the length of decay time getting longer.

Table 3
Best fit results for neutron and 2.2 MeV γ-ray profiles of 2005 September 7 event.

Injection	λ	δ	Index	Reduced χ^2 for neutron	Reduced χ^2 for 2.2 MeV
Delta	700	0.48	−3.93	3.53	6.45
τ = 120 s	4000	0.28	−4.28	3.85	3.50
τ = 180 s	5000	0.18	−4.42	5.86	1.31
4.4 MeV	2000	0.12	−4.43	1.99	2.08

Next, we search for the acceptable fit to both the neutron and 2.2 MeV neutron-capture line measured time profiles. For this calculation, we use a delta function,

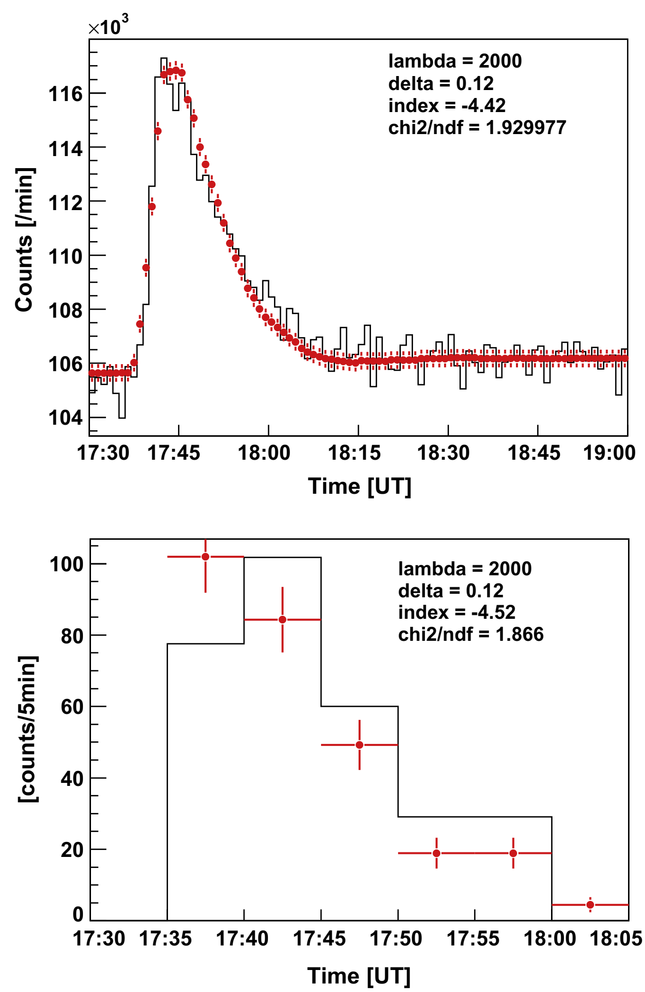

Fig. 3. (Top) Time profiles of neutrons on 2005 September 7. The black line is the observed counting rates from the Bolivia neutron monitor. The red dots represent the calculated result of Hua's transport and interaction model with $\lambda = 2000$, $\delta = 0.12$, and $s = -4.42$. Background of galactic cosmic rays added to this result. (Bottom) The observed (black) and best fitting calculated (red) 2.2 MeV time profile with the same values of λ, δ, and s. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

exponential decay with $\tau = 2$ and 3 min, and the 4.4 MeV line γ-ray profile as ion-release time histories. Fitting results were shown in Table 3. An acceptable fit to both the neutron and 2.2 MeV neutron-capture line measured time profiles was only obtained when the 4.4 MeV history was used as the injection time profile. We show the measurements and the fits to both time profiles in Fig. 3. Both fits were obtained with $\lambda = 2000$ and $\delta = 0.12$, and an ion spectral index of ~ 4.5. Thus, intermediate values of magnetic convergence, and pitch-angle scattering provide good fits to the observed data.

4. Summary

A significant solar neutron event was observed on September 7, 2005 in association with an X17 flare. We estimated the time profiles of the solar neutron spectra arriving at the Earth and the 2.2 MeV neutron-capture γ-ray line using the loop transport and interaction model of Hua et al. (2002). We could not obtain an acceptable fit to these time profiles using a delta-function ion release. An acceptable fit was only obtained using the 4.4 MeV line time profile. The best-fitting values of λ and δ were 2000 and 0.12, respectively, with an accelerated-ion spectral index of ~ 4.5. The observations are consistent with a model in which ions are accelerated over an interval of γ-ray emission, a portion then being trapped in the flare loop.

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