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Ion acceleration and neutral emission mechanisms for 2005 September 7 flare

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Abstract: In association with an X17.0 flare on 2005 September 7, intense emissions of hard X-rays and γ-rays were registered by satellites, and relativistic neutrons were observed by ground-based detectors. The neutron signal continued for more than 20 minutes with high statistical significance. The long decay of the signals suggests that ions were continuously accelerated or trapped in the emission site. We also find that γ-rays were emitted over a corresponding extended period. Only when we incorporate the high-energy γ-ray emission time history can we explain the long-lasting neutron emission. However we cannot explain neutron emissions by using Hua's model [3].

Introduction

On 2005 September 7, large and long-lasting enhancements of solar neutrons produced in association with an X17.0 flare were observed by ground-based detectors [4]. In this paper, we analyze the neutron spectrum and time history using the *INTEGRAL* and *RHESSI* satellites γ-ray data. We will use Hua's solar-flare magnetic loop transport and interaction model [3] to determine the best-fitting parameters.

Observations

At 17:17 UT on 2005 September 7, when solar active region 10808 (S06° E89°) appeared at the East limb, the first and most energetic X-class flare occurred with a soft X-ray magnitude of X17.0. During this flare, intense emissions of hard X-rays and γ-rays were observed by *INTEGRAL* and *RHESSI* satellites (Figure 1). Unfortunately, *RHESSI* was both in the South Atlantic Anomaly (SAA) and on the night side of the Earth during most of the event. However, some emission was observed around 17:45 UT between SAA and night: γ-ray lines at 0.511, 2.2, 4.4, and 6.1 MeV were observed and there was evidence for π^0-decay radiation. On the other hand, strong emission of hard X-rays and γ-rays during the whole flare time was observed by the *INTEGRAL* satellite.

As shown the top panel of Figure 2, the 4.4 MeV Carbon γ-ray line was clearly observed by the *IN-*

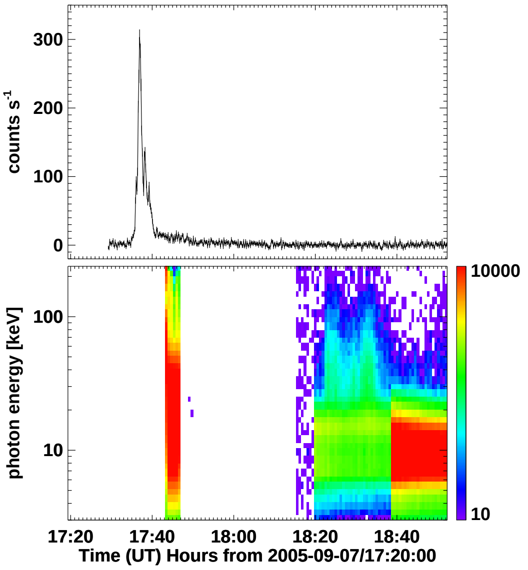

Figure 1: The X-ray data observed by the *INTEGRAL* and *RHESSI* satellites on 2005 September 7. Top panel shows hard X-ray light curve observed by the *INTEGRAL* satellite between 200 and 300 keV. Bottom panel shows spectrogram observed by *RHESSI*. The *RHESSI* was in SAA until 17:43 UT and at the night side of the Earth from 17:47 UT.

TEGRAL. It does not clearly show the 2.2 MeV neutron-capture line, but this is consistent with the limb location of this flare. By fitting spectra, we obtain the time history of 4.4 MeV line γ-rays as shown bottom panel of Figure 2. Since such de-excitation γ-rays are prompt, this time history is a good approximation of the ion acceleration time history. Ions were accelerated not only during the impulsive phase, but also during the decay phase. The 4.4 MeV γ-ray emission does not return to the background level until at least 18:00 UT. During this decay phase, hard X-ray and γ-ray emissions were also observed by *RHESSI*.

The X-ray image obtain with *RHESSI* is shown in Figure 3. A soft X-ray loop is seen above the limb with only one hard X-ray foot-point visible. Although only one image was obtained from *RHESSI* data, we obtained many images from the *GOES*/SXI data and the soft X-ray loop could be seen rising up from the limb. Figure 4 shows the altitude of the soft X-ray emission center from the limb recorded by the *GOES*/SXI and *RHESSI*. The

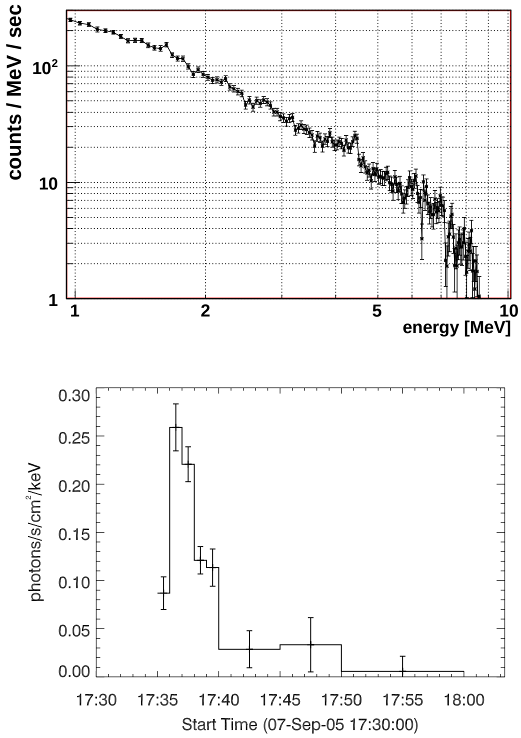

Figure 2: The γ-ray data observed by the *INTEGRAL* satellite on 2005 September 7. Top panel shows the γ-ray spectrum observed from 17:35−18:00 UT, and 4.4 MeV line appear superimposed on the bremsstrahlung component. Bottom panel shows the time profile of line γ-ray components of Carbon nuclei.

difference of the two position is due to the different energies detected by *RHESSI* and *GOES*/SXI.

On the ground, 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 [4]. The statistical significance of all neutron signals was more than 10σ and the detection lasted for more than 20 minutes. This was the largest solar neutron event observed in solar cycle 23.

Energy Spectrum of Solar Neutrons

We analyze the neutron data obtained with the Bolivia neutron monitor since this detector recorded the largest signal. To estimate the energy spectrum of the emitted neutrons, we use the same method as

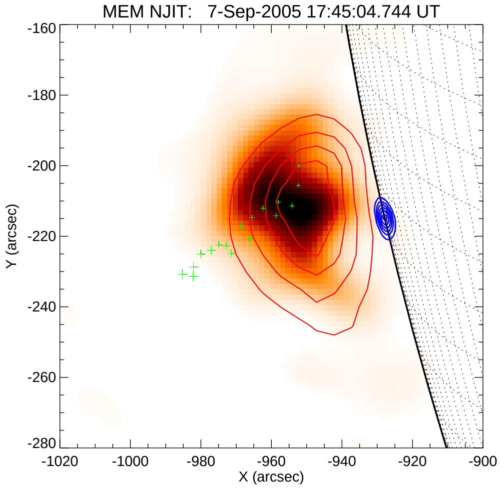

Figure 3: The X-ray image observed by the *RHESSI* and *GOES*/SXI on 2005 September 7. Red image shows $5 - 25\,\mathrm{keV}$ soft X-ray image obtained by *RHESSI*, red contour shows soft X-ray image obtained by *GOES*/SXI, blue contour shows $100 - 150\,\mathrm{keV}$ hard X-ray image obtained by *RHESSI*, and green + marks show the center locations of the soft X-ray emission obtained by the *GOES*/SXI.

Watanabe et al. [6]. This method calculates time-dependent arriving neutron spectra from an emitted neutron spectrum assumed to be a power law. We use the atmospheric attenuation ratio of solar neutrons calculated by the Shibata program [5] and efficiency of the neutron monitor calculated by Clem and Dorman [2] to convert these spectra into count rates and compare with the observed neutron data. We use the time profile of the $4.4\,\mathrm{MeV}$ line γ-rays (Figure 2) as a hypothetical production time profile for the solar neutrons. Good agreement was obtained (reduced $\chi^2 = 1.8$) for a neutron spectral index of -3.1, as shown in Figure 5. The extended presence of high-energy ions implied by the line emission is required to explain the extended neutron emission. Such ions could have been continuously accelerated or trapped in the emission site.

Simulation by Hua's Model

We next use the simulation program of Hua et al. [3] to estimate the spectrum of accelerated ions. By using this program, neutron spectra arriving at the Earth's atmosphere can be estimated from line γ-ray data. These arriving spectra are converted

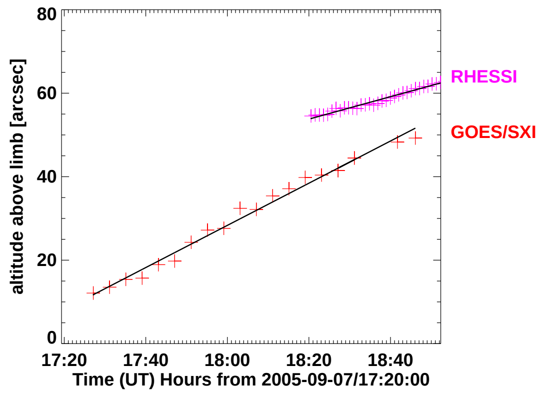

Figure 4: The altitude of the soft X-ray emission center from limb observed by the *GOES*/SXI and *RHESSI* on 2005 September 7.

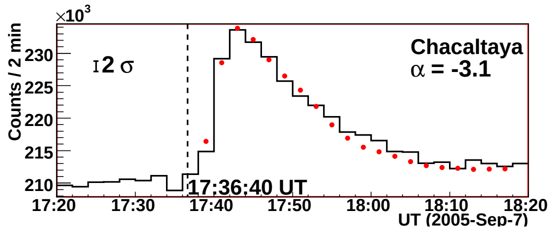

Figure 5: The observed and simulated time profiles of neutrons on 2005 September 7. The black solid line is the observed two-minute counting rates from the Bolivia neutron monitor. The red points represent the simulated time profiles for solar neutrons assumed to have been produced with the same time profile as the $4.4\,\mathrm{MeV}$ γ-rays with spectral index -3.1. The high-energy cutoff of the solar neutron energy is assumed to be $500\,\mathrm{MeV}$.

into neutron monitor count rates using the atmospheric attenuation and neutron monitor efficiency as above. By comparing these rates with the observed rate, we can determine the accelerated ion spectrum.

A number of parameters must be set to use Hua's program. For the accelerate ion composition ($\alpha/\mathrm{p} = 0.5$, ${}^3\mathrm{He}/{}^4\mathrm{He} = 1$), ambient composition ($\mathrm{He/H} = 0.1$, $\mathrm{Ne/O} = 0.25$) and atmospheric model (Avrett [1]), we use typical values estimated from observations of previous flares. For the acceleration release time history, we use the $4.4\,\mathrm{MeV}$ line γ-ray time history observed by *INTEGRAL* and *RHESSI* (Figure 2). The loop length was cal-

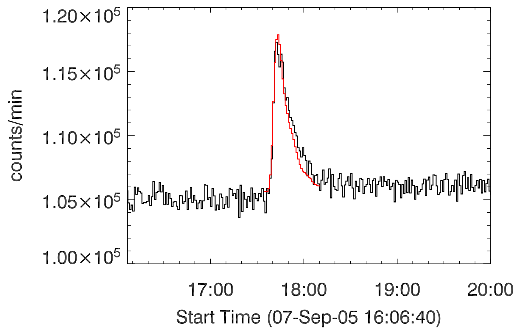

Figure 6: The observed and simulated time profiles of neutrons on 2005 September 7. The black line is the observed two-minute counting rates from the Bolivia neutron monitor. The red line represent the simulated result of Hua's program with spectral index -3.4. The high-energy cutoff of the solar neutron energy is assumed to be $400\,\mathrm{MeV}$.

culated from Figures 3 and 4. At 17:37:30 UT (the peak time of γ-ray emission), the altitude of the soft X-ray emission center was about 16.7 arcsec $(11,700\,\mathrm{km})$ from the limb. Using this altitude as the radius of a semicircular flare loop, the loop length is $36,800\,\mathrm{km}$. The flare heliocentric angle is also determined from the images as $89.0\,\mathrm{degree}$. We derive the remaining parameters (λ, δ and s) by systematically varying them and comparing the predicted count rates with the observed count rate.

Figure 6 shows the best fit to the observed data obtained with λ (level of pitch-angle scattering within the loop) of 1000, δ (magnetic field convergence index) of 0.35, and an accelerated ion power-law index of -3.4. χ^2 is still large however (reduced $\chi^2 = 2.6$) as there are some discrepancies at the peak and decay phase between the observed and predicted data.

Summary

The long-lasting neutron emission observed by neutron monitors from the 2005 September 7 flare could be explained by the long-lasting presence of energetic ions implied by the extended γ-ray line emission. We could not achieve an adequate fit to the neutron data when we used the transport and interaction loop model of Hua et al. [3]. An important parameter of the loop model is the loop length which is not well-determined for this flare. We will continue to analyze these data and explore the effect of changing the loop length and other parameters.

Acknowledgments

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References

[1] E. H. Avrett. In *The physics of sunspots and Proceedings of the Conference, Sunspot, NM, Sacramento Peak Obs.*, pages 235–255, 1981.

[2] J. M. Clem and L. I. Dorman. *Space Science Reviews*, 93:335–359, 2000.

[3] X.-M. Hua, B. Kozlovsky, R. E. Lingenfelter, R. Ramaty, and A. Stupp. *ApJS*, 140:563–579, 2002.

[4] T. Sako, K. Watanabe, Y. Muraki, Y. Matsubara, H. Tsujihara, M. Yamashita, T. Sakai, S. Shibata, J. F. Valdes-Galicia, L. X. Gonzalez, A. Hurtado, O. Musalem, P. Miranda, N. Martinic, R. Ticona, A. Velarde, F. Kakimoto, S. Ogio, Y. Tsunesada, H. Tokuno, Y. T. Tanaka, I. Yoshikawa, T. Terasawa, Y. Saito, T. Mukai, and M. Gros. *ApJ*, 651:L69–L72, 2006.

[5] S. Shibata. *JGR*, 99:6651–6665, 1994.

[6] K. Watanabe, M. Gros, P. H. Stoker, K. Kudela, C. Lopate, J. F. Valdes-Galicia, A. Hurtado, O. Musalem, R. Ogasawara, Y. Mizumoto, M. Nakagiri, A. Miyashita, Y. Matsubara, T. Sako, Y. Muraki, T. Sakai, and S. Shibata. *ApJ*, 636:1135–1144, 2006.