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Physics of ion acceleration in the solar flare on 2003 October 28 determines gamma-ray and neutron production

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Abstract: Solar neutrons from the X17.2 flare on 2003 October 28 were observed by the ground-based neutron monitor at Tsumeb in Namibia. The intense emission of γ-rays for this event was observed by the *INTEGRAL* and *RHESSI* satellites. Gamma-ray lines were observed by both detectors, and a $2.2\,\mathrm{MeV}$ γ-ray image was also obtained by *RHESSI*. Based on these γ-ray line observations, we calculate predicted time-dependent neutron spectra arriving at Earth using the solar flare magnetic loop transport and interaction model of Hua et al. [1]. These spectra are then convolved with the response functions of the Earth's atmosphere and the neutron monitor to provide predicted neutron monitor count rates. We compare these predicted and observed rates to determine the accelerated ion spectrum and magnetic-loop transport properties.

Introduction

The Sun is one of the particle accelerators in space, and we sometimes can directly observe these cosmic rays at and near the Earth. In association with solar flares, ions are accelerated and solar neutrons are produced by the interactions with the solar atmosphere. By observing solar neutrons, we can get information on the ion acceleration mechanisms in solar flares.

A few solar neutron events have been observed in solar cycle 23 [2, 3, 4, 5, 6, 7]; one of them is the solar neutron event on 2003 October 28 [2, 6], which occurred in association with an X17.2 flare. In this event, solar neutrons were observed by the neutron monitor at Tsumeb, with a statistical significance of 6.4σ. Not only solar neutrons, but also many phenomena were observed by many detectors in this event, such as a Ground Level Enhancement (GLE) produced by the energetic protons and electromagnetic radiation. The large GLE event was also observed by neutron monitors around the world, but the neutron signal was detected 5 minutes before this GLE event.

The full time history of γ-rays for this event was observed by the *INTEGRAL* satellite, while the *RHESSI* satellite observed γ-rays during the decay phase. The 2.2, 4.4, and $6.1\,\mathrm{MeV}$ γ-ray lines were observed by both detectors, and a $2.2\,\mathrm{MeV}$ γ-ray image was also obtained by *RHESSI* [8].

By using the summed 4.4 and $6.1\,\mathrm{MeV}$ γ-ray line time history as the production time history of solar neutrons, the index of the power law energy spectrum of the solar neutrons at the solar surface was determined to be -2.9 [6]. In that study, the solar neutron spectrum was determined by dividing the observed neutron monitor data by the attenuation ratio and propagation ratio.

In this paper we use the transport model of Hua et al. [1]. By using this program, the neutron spectrum at the Earth's atmosphere can be estimated directly from γ-ray line data.

Simulation by Hua's Model

Hua's model is a simulation program that calculates the time history of the $2.2\,\mathrm{MeV}$ neutron

Table 1: Parameters of the Hua's program for 2003 October 28 event.

Accelerated ion composition (impulsive)	$\alpha/\mathrm{p} = 0.5$ $^3\mathrm{He}/^4\mathrm{He} = 1$
Ambient composition (coronal)	$\mathrm{He}/\mathrm{H} = 0.1$ $\mathrm{Ne}/\mathrm{O} = 0.25$
Atmospheric model	Avrett, 1981 [9]
Photospheric $^3\mathrm{He}/\mathrm{H}$	3.7×10^{-5}
Acceleration release time history	4.4 & $6.1\,\mathrm{MeV}$ γ-ray line profile
Loop length	$85,000\,\mathrm{km}$
Flare heliocentric angle	$23.0\,\mathrm{degree}$

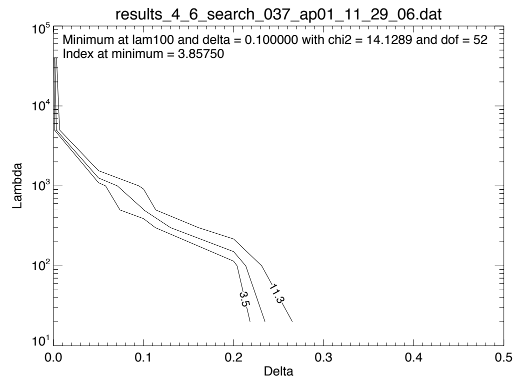

Figure 1: Two-parameter confidence contours for combinations of δ and λ resulting from the time history analysis of the 2003 October 28 flare. The spectral index at minimum χ^2 was -3.86.

capture line and the spectra of neutrons escaping from the Sun. A number of parameters must be set to use Hua's program. Many of these parameters can be derived from the observed data. For the acceleration release time history, we used the 4.4 and $6.1\,\mathrm{MeV}$ γ-ray line time profile observed by the *INTEGRAL* and *RHESSI* satellites. The flare heliocentric angle was obtained from the $2.2\,\mathrm{MeV}$ line γ-ray image obtained from *RHESSI* data ($23.0\,\mathrm{degrees}$). The loop length was also obtained with the $2.2\,\mathrm{MeV}$ image: we measured the separation of the two foot-point sources and calculated the loop length assuming it is semicircular, giving $85,000\,\mathrm{km}$. For the accelerated ion composition, ambient composition, atmospheric model and photospheric $^3\mathrm{He}/\mathrm{H}$ ratio, we use typical values estimated from observations of previous flares. These parameters are summarized in Table 1. We derive the remaining parameters (λ, δ and s) by comparing $2.2\,\mathrm{MeV}$ line time histories calculated with Hua's code with the observed time history.

λ is the level of pitch-angle scattering within the loop, δ is the magnetic field convergence index, and s is the index of the power law energy spectrum of the accelerated ios at the solar surface. We vary λ from 20 to 40000, and δ from 0.00 to 0.45. If δ is 0.0, there is no convergence, and if δ is 0.45, there is strong convergence. Two-parameter confidence contours for combinations of λ and δ are shown in Figure 1. When λ is 100, δ is 0.10, and s is -3.86, χ^2 is minimum and the predicted time profile of the $2.2\,\mathrm{MeV}$ line fits the observed data quite well as shown in Figure 2.

By using these parameters, we calculate predicted time-dependent neutron spectra arriving at the top of the Earth's atmosphere as shown in Figure 3. At first, high energy neutrons arrive, followed by lower energy neutrons. We calculate resulting neutron monitor count rates due to these arriving neutron spectra by using the solar neutron atmospheric attenuation ratio calculated by the Shibata program [10] and the neutron monitor efficiency calculated by Clem and Dorman [11]. We compare the predicted count rate with the observed count rate in Figure 4. We see that the calculation significantly underestimates the observed neutron monitor count rate, with a reduced χ^2 of 7.2. For the λ and δ derived from the $2.2\,\mathrm{MeV}$ time history, too many neutrons are going downwards toward the solar atmosphere, and too few are going upwards toward the Earth.

Summary

We have compared observed neutron count rates for the 2003 October 28 solar flare obtained with the Tsumeb neutron monitor with calculated count rates based on γ-ray data obtained with *INTEGRAL* and *RHESSI*. We find that the predicted rate is significantly less than the observed rate when the values of λ, δ and s derived based on the $2.2\,\mathrm{MeV}$ neutron capture line are used. However, these values were derived assuming a loop length of $85,000\,\mathrm{km}$ based on the *RHESSI* image of γ-ray foot-points obtained late in the flare. If the

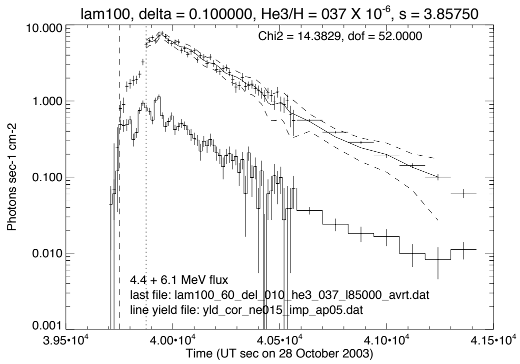

Figure 2: Comparison of the $2.223\,\mathrm{MeV}$ neutron capture line time history measured with *INTEGRAL* and *RHESSI* from the 2003 October 28 flare with a time history calculated by using Hua's program (solid curve). Also shown is the time history of the 4.4 and $6.1\,\mathrm{MeV}$ line flux assumed to represent the accelerated ion release time history. The dashed curves represent the $\pm 1\sigma$ uncertainties for the calculated curves.

foot-point separation increased with time during this flare, as X-ray foot-points are often seen to do, this loop length would represent only an upper limit. If the separation were less (and the loop length thus smaller) during the peak of the flare when most of the neutrons were produced, the derived values of λ and δ would change. The neutron angular distribution would then be less downward directed which would increase the predicted neutron flux at Earth. We are currently studying this possibility.

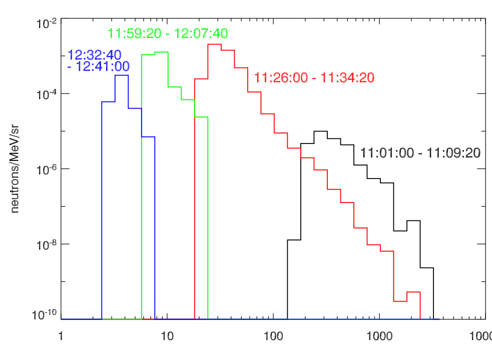

Figure 3: The time dependent neutron spectra at the top of the Earth's atmosphere.

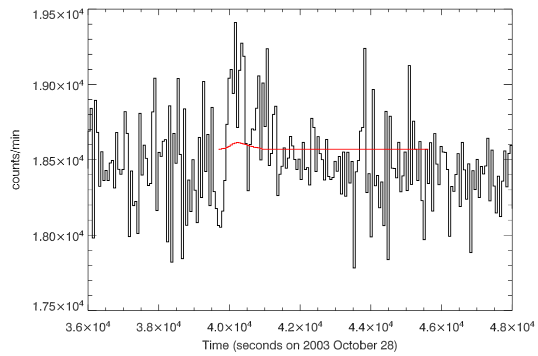

Figure 4: Observed and predicted neutron monitor count rates on 2003 October 28. The black line is the observed three-minute count rate from the Tsumeb neutron monitor. The red line represent the predicted count rate.

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References

[1] X.-M. Hua, B. Kozlovsky, R. E. Lingenfelter, R. Ramaty, A. Stupp, Angular and Energy-dependent Neutron Emission from Solar Flare Magnetic Loops, Astrophys. J. Suppl. 140 (2002) 563–579.

[2] J. W. Bieber, J. Clem, P. Evenson, R. Pyle, D. Ruffolo, A. Sáiz, Relativistic solar neutrons and protons on 28 October 2003, Geophys. Res. Lett. 32 (2005) 3–+.

[3] E. O. Flückiger, R. Bütikofer, A. Chilingarian, G. Hovsepyan, Y. H. Tan, T. Yuda, H. Tsuchiya, M. Ohnishi, Y. Katayose, Y. Muraki, Y. Matsubara, T. Sako, K. Watanabe, S. Masuda, T. Sakai, S. Shibata, R. Ogasawara, Y. Mizumoto, M. Nakagiri, A. Miyashita, P. H. Stoker, C. Lopate, K. Kudela, M. Gros, Solar Neutron Events that have been Found in Solar Cycle 23, In-

ternational Journal of Modern Physics A 20 (2005) 6646–6649.

[4] T. Sako, K. Watanabe, Y. Muraki, Y. Matsubara, H. Tsujihara, M. Yamashita, T. Sakai, S. Shibata, J. F. Valdés-Galicia, L. X. González, 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, M. Gros, Long-lived Solar Neutron Emission in Comparison with Electron-produced Radiation in the 2005 September 7 Solar Flare, Astrophys. J. Lett. 651 (2006) L69–L72.

[5] K. Watanabe, Y. Muraki, Y. Matsubara, K. Murakami, T. Sako, H. Tsuchiya, S. Masuda, M. Yoshimori, N. Ohmori, P. Miranda, N. Martinic, R. Ticona, A. Velarde, F. Kakimoto, S. Ogio, Y. Tsunesada, H. Tokuno, Y. Shirasaki, Solar Neutron Event in Association with a Large Solar Flare on 2000 November 24, Astrophys. J. 592 (2003) 590–596.

[6] K. Watanabe, M. Gros, P. H. Stoker, K. Kudela, C. Lopate, J. F. Valdés-Galicia, A. Hurtado, O. Musalem, R. Ogasawara, Y. Mizumoto, M. Nakagiri, A. Miyashita, Y. Matsubara, T. Sako, Y. Muraki, T. Sakai, S. Shibata, Solar Neutron Events of 2003 October-November, Astrophys. J. 636 (2006) 1135–1144.

[7] K. Watanabe, Y. Muraki, Y. Matsubara, K. Murakami, T. Sako, P. Miranda, R. Ticona, A. Velarde, F. Kakimoto, S. Ogio, H. Tokuno, H. Tsuchiya, S. Shibata, T. Sakai, Y. Mizumoto, R. Ogasawara, M. Nakagiri, A. Miyashita, C. Lopate, Solar neutron events in association with large solar flares in November 2003, Advances in Space Research 38 (2006) 425–430.

[8] G. J. Hurford, S. Krucker, R. P. Lin, R. A. Schwartz, G. H. Share, D. M. Smith, Gamma-Ray Imaging of the 2003 October/November Solar Flares, Astrophys. J. Lett. 644 (2006) L93–L96.

[9] E. H. Avrett, Reference model atmosphere calculation - The Sunspot sunspot model, in: L. E. Cram, J. H. Thomas (Eds.), The Physics of Sunspots, 1981, pp. 235–255.

[10] S. Shibata, Propagation of solar neutrons through the atmosphere of the Earth, J. Geophys. Res. 99 (1994) 6651–6665.

[11] J. M. Clem, L. I. Dorman, Neutron Monitor Response Functions, Space Science Reviews 93 (2000) 335–359.