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# What did the occurrence of relativistic solar neutrons on 28 October 2003 mean?

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**Abstract:** In this paper we make an analysis of when relativistic neutrons escaped from the sun and where the relativistic neutrons in interplanetary space decayed into relativistic protons which were observed by several neutron monitors on the ground. The relativistic neutrons seemly support the conclusion obtained by Miroshnichenko et al. (2005) that relativistic solar protons (RSPs) were accelerated by solar flare and the path length traveled by solar protons with energy greater than 100MeV was about 2.2AU.

## Introduction

It is accepted that impulsive solar energetic particles (SEPs) are accelerated in flares while whether gradual SEPs are only accelerated at coronal mass ejection (CME) driven shock is still an open question. Reames (2002) suggested that mixed events that SEPs accelerated both in the flare and the CME-driven shock don't exit. Cane et al. studied the intense solar energetic particles during the interval form 1997-2001 with the particle energy 20-80MeV/n. They found that there were two peaks in the solar energetic particle intensity in some SEP events. The first peak has a high value of Fe/O and the second peak has a low value of Fe/O suggesting that the solar particles are mainly accelerated by solar flare in the first peak and mainly accelerated by CME-driven shock at the second peak. Cane et al. (2006) extended their study and got the similar conclusion. It is accepted that both flare and CME-Driven can accelerate the solar particles to nonrelastivistic energy. Howerve, there is still intense argument in the acceleration of relativistic solar protons (RSPs). Tylka et al. (2005) suggested that RSPs are accelerated by quasi perpendicular shock. Based on the onset time of metric type bursts earlier than the solar release time of RSPs, Gopalswamy et al (2005) suggested that RSPs are accelerated by CME-driven shock.

Li and Tang et al. (2007) have studied the magnetic reconnection in this event, and maximum induced electric field was estimated to be E $\sim 13.0Vcm^{-1}$. The amplitude evolution of this field correlates in time with the evolution of hard X-ray and -ray emission, indicating that induced electric field may play an important role in acceleration of non-thermal particles. Given the maximum E $\sim 13.0Vcm^{-1}$, an acceleration length $\sim 7.0 \times 10^7$ cm is needed to accelerate protons to $\sim$ GeV energy in the reconnection current sheet by DC electric field. The ratio of the acceleration length to the whole filament length in this event is $10^{-2}$. Therefore, the reconnection electric field probably makes a crucial contribution to the acceleration of relativistic particles and the impulsive component of the large gradual SEP events. It was suggested that the spectral index of electron can be used to identify the source of the electrons (Simnett 2005, 2006) . The spectral index of electrons was lower than 1.5 reveling that the electrons were accelerated in the solar flare (Simnett, 2006) for SEP event on 20 January 2005. The onset time of RSPs observed by South Pole neutron Monitor was 06:48UT±30s which coincided with the gama ray's emission interval 06:38:30-06:42:30 ST with energy 60-100MeV, which was the decay of pion in the SEP event on 20 January 2005 (Kuznetsov et al. 2005, 2006). This means that RSPs were accelerated by the solar flare during the interval from 06:38:30 ST to 06:42:30 ST, during which the high energy gama ray emission was going on.

A very bad space weather occurred after the solar intensive eruption on 28 October 2003, a large flare (X17.2/4B) erupted from the super active region AR10486 accompanied by a earth-directed CME with initial speed 2429km/s. RSPs led to ground level enhancement (GLE), when the CME reached the earth, it caused a very strong geomagnetic storm. Many paper have been devoted the event study (e. g., Bieber et al. 2005, Classen et al. 2005, Cohen et al. 2005,Gopalswamy et al, 2005, Aurass, et al, Kiener et al. 2006, 2006, Le et al. 2007, Mewaldt, et al. 2005, Miroshnichenko et al. 2005, Simnett, 2005).

The release time of RSPs obtained by Bieber et al (2005) was about 11:03ST. Because the coronal shock formed at ∼10:55ST (Klass et al. 2005) and the impulsive flare phase starts with a steep rise of X rays at 10:52ST and peaks at about 11:02Klass et al. 2005so the result obtained by Bieber et al (2005) seemly supported that the RPS was accelerated by the CME-driven shock.

Source location of the flare X17.2 was at S16E08, so the source location of the flare was not at the region of well connected with the earth. Miroshnichenko et al. (2005) studied the GLE event and proposed that RSPs were accelerated by the solar flare, the path length traveled by the protons with energy greater than 100MeV was ∼2.2AU. Why the path length traveled by the protons with energy greater than 100MeV was so long? Miroshnichenko et al. (2005) proposed that the ICME from AR10486 on the 26 October 2003 reached earth with their two legs still connected with the AR10486 and the RPSs injected into the eastern leg of the ICME. Li et al. (2007) also studied the GLE event on 28 October 2003they proposed that the flare magnetic connection, especially the induced electric filed, made a crucial contribution to the prompt RSPs.

The main goals of the this paper are to study what did the occurrence of relativistic neutrons mean in the GLE of 28 October 2003. Section 2 studies when the relativistic neutrons escaped from the sun and where the relativistic neutrons decayed into relativistic protons in interplanetary space and the relativistic protons moved toward the earth and then were detected by the Tsumeb Neutron Monitor (TNM). The summary and discussion are given in section 3.

## Relativistic Solar Neutrons (RSN)

The RSNs were observed by Tsumeb Neutron MonitorTNMon 28 October 2003. TNM recorded a 3-4% increase and persisted for about 9 minutes (Bieber et al. 2005). Bieber et al. (2005) modeled the solar release time of the relativistic solar neutrons and relativistic solar protons, which was about 10:56ST and 11:03ST, respectively. Miroshnichenko et al. (2005) reported that the interval for the occurrence of RSN was 11:05UT∼11:15UT. The ray emission with energy 60-100MeV occurred during the period (11:02UT∼11:13UT) (Kuznetsov et al. 2006). The ray with energy 60-100MeV is the production of pion decay. The occurrence of pion indicates that the protons were accelerated up to energies greater than 200MeV during the flare (Kuznetsov et al. 2006). Comparison of the time information of the gama rays with that of the RSNs, we suggested that the RSNs were produced during the interval form 11:02UT to 11:13UT, the interval of solar release time of RSNs was from (11:02-500s)ST to (11:13-500s)ST. It is reported that solar neutrons were observed by TNM, the cut off ridigity of which is 9.21GVbased on the relationship between the particle's rigidity R and energyLe et al. 2006, we have two useful expressions:

$$E_k = \frac{-2E_0 + \sqrt{4E_0^2 + 4(ZeR)^2}}{2}$$
$$v = \frac{\sqrt{E_k^2 c^2 + 2E_k m_0 c^4}}{E_k + E_0} \qquad (1)$$

Where $E_k$ and $E_0$ are the kinetic energy and rest energy, respectively, and $m_0$ is the particle rest mass, $Z$ is the particle charge number.

Based on the expression (1) we can obtained the RSPs, which decayed form RSNs and were observed by TNM, energy was 8.23GeV, the velocity of RSP was 298219.3km/s. Because the RSPs were the production of RSN's decay, the velocity of RSN should be greater than 298219.3km/s.

Solar neutron was the production of nuclear reaction by solar protons, which were accelerated by solar flare, with heavy ions in solar chromosphere atmosphere. Because the energy of RSN was 8.23GeV, so some solar protons had energy greater than 8.23GeV and they should be produced slightly earlier than RSNs. The hard x-ray with energy 7-20MeV observed by RHESSI began at 10:28UT, peaked at 11:13UT and end at 11:30UT. The hard x-ray was produced by relativistic solar electron (RSE) gyral motion around the local magnetic field, which revealed that the flare not only accelerated the electrons to relativistic energy but also accelerated the protons to relativistic energy. The time of hard x ray with energy 7-20MeV revealed that the early RSEs occurred at 10:20ST, while the early RSPs occurred at ∼10:54ST, which was about 34m later than that of RSE. Solar release time of RSNs was earlier than 10:54ST, the time of RSN observed by TNM was 11:06UT, so the traveling time by RSNs in space was nearly 12m. We assume the velocity of RSPs decayed was almost the same with that RSNs, so the traveling distance by RSNs was $(1 + x)AU$, where x was the distance away from the earth along the sun-earth connection direction, the distance traveled by the protons decayed from the RSNs in the antidirection of sun-earth connection was x, the whole distance was: $(1 + 2x)AU$, $1 + 2x = (12 \times 60) \times 298219.3km/s \approx 1.435AU$, so $x = 0.21AU$.

A method to get the path length and solar release time of a particle traveling form the sun to the earth was proposed (VDA method) (Krucker et al. 1999)

$$t_g = t_s + \frac{l}{c\beta} \tag{2}$$

where $\beta = v/c$. Because $8.33c = 1AU$, so the formula (2) can be written as the expression below,

$$t_g = t_s + \frac{8.33l}{\beta} \tag{3}$$

Using the arrival time for protons at the Earth at the various energies given by Miroshnichenko et al. (2005), we can get the result shown in figure 1. The result in figure 1 is: $l \sim 2.25AU$ SRT<10:54ST. This result is almost consistent with that obtained by Miroshnichenko et al. (2005b), but there is one minute difference between the two results, their RST was 10:55ST.

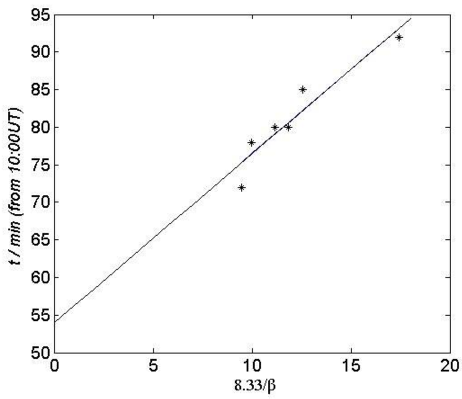


Figure 1: onset time vs. $8.33\beta^{-1}$

## Summary and discussion

SRT of solar proton with energy greater than 100MeV was slightly earlier than 10:54ST. The RSNs decayed into RSPs at 1.21AU away from the sun in the direction of sun-earth connection and then moved back towards the earth, which led to they were captured by geomagnetic field and were observed by TNM on the ground. The occurrence of RSNs seemly supports the results obtained by Miroshnichenko, et al. (2005) that the RSPs were accelerated by solar flare. The solar release time of RSNs was slightly earlier than 10:54ST. The path length traveled by the protons with energy greater than 100MeV from the sun to the earth was ∼2.25AU.

Because the RSNs were the production of the nuclear interaction between the protons, which were accelerated by solar flare, and heavy ions in the solar chromosphere atmosphere, so, some of the protons accelerated by the solar flare had energy greater than 8.23GeV at the time earlier than 10:54ST. The SRT of SEP with energy greater than 100MeV computed by VDA method was also slightly earlier than 10:54ST, so the earliest arriving RSPs were accelerated by solar flare and once the solar protons reached relativistic energy, they immediately injected into interplanetary space and the path length of solar proton with energy greater than 100MeV was about 2.25AU. The occurrence of RSNs prove that the results obtained by Miroshnichenko et al. (2005b), i.e. the CME, which erupted from AR10486 on 26 October 2003, reached the earth with its root still on the AR10486 on 28 October 2003solar protons with energy greater than 100MeV injected into the eastern leg of the ICME loop rooted in the active region on 28 October 2003 and reached the earth along the magnetic field line. It is accepted that the type III bursts are produced by electrons escaping the solar corona into interplanetary space. The onset of type III bursts was ∼10:54ST which means that the magnetic field line of the AR10486 was opened and connected with the magnetic field line in interplanetary space at 10:54ST, so the RSPs almost immediately injected into interplanetary space when they got the relativistic energy. Though the suggestion that SRT of RSNs was in the interval form 11:02UT to 11:13UT should be checked, the results of the paper is seemly reasonable.

## References

[1] Aurass, *et al.* 2006, A&A, 457, 681
[2] Bieber J W, J. Clem, P. Evenson, *et al.* 2005, Goophys. Res. Lett, 32, L03s02
[3] Cane H. V. *et al.*, 2003, Goophys. Res. Lett, 30, 8017
[4] Cane H. V. *et al.*, 2006, J. Geophys. Res., 111, A06S90
[5] Cohen, C. M., *et al.* 2005, J. Geophys. Res., 110, A09S18
[6] Gopalswamy N, *et al.* J. Geophys. Res., 110, A09S15
[7] Gopalswamy N, *et al.* Proc. 29th Int. Cosmic Ray Conf., 2005, 1,169
[8] Kiener, *et al.* 2006, A&A, 445, 725
[9] Klass A, Krucker S, Kunow H, *et al.* (2005), J. Geophys. Res., I10, A09S04
[10] Krucker S, Larson D E, Lin R P, *et al.* ApJ, 1999, 519:864
[11] Kuznetsov S N, *et al.* Solar System Research, 2006, 40(2): 104-110
[12] Kuznetsov S N, *et al.* Contrin. Astron. Obs., Skalnat Pleso, 36-85-92, 2006
[13] Li C. *et al.*, Astronomy and Astrophysics, 461, 1115 (2007)
[14] Le G. M. *et al.*, Chin. J. Astron. Astrophys., 6, 751 (2006)
[15] Le G. M. *et al.*, Chinese Science bulletin, 2007, 52(1):47-52
[16] Li C, *et al.*, A&A ( to be published)
[17] Li C, *et al.*, A&A,2007
[18] Mewaldt, R. A., *et al.* 2005, J. Geophys. Res., 110, A09S18
[19] Miroshnichenko L I, *et al.*,(2005), J. Geophys. Res., I110, A09S08
[20] Reames D. V., Astrophys. J., 571, L63 (2002)
[21] Simnett G. M., Asronomy and Astrophysics, 445, 715 (2006)
[22] Simnett G. M., J. Geophys. Res., 110, A09S01 (2005)
[23] Simnett G. M., Solar Physics, 229, 231 (2005)
[24] Tylka A J, Cohen C M S, Dietrich W F, *et al.* (2005), ApJ, 625: 474

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