Relativistic solar neutrons and protons on 28 October 2003

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[1] The solar cosmic ray event associated with the X17.2 class flare of 28 October 2003 was unusual in several respects: (1) Several high-latitude neutron monitors observed a large, highly anisotropic spike at event onset. (2) The earliest onset was detected by stations viewing towards the anti-Sunward hemisphere. (3) The event displayed an extremely slow, protracted decay. (4) The near-equatorial monitor in Tsumeb, Africa recorded a small increase consistent with a solar neutron event ≈7 minutes prior to the onset at high latitudes. We analyze these signals and infer that relativistic solar neutrons were emitted over a duration of ≈9 minutes, starting ≈7 minutes before the main injection of relativistic protons. **Citation:** Bieber, J. W., J. Clem, P. Evenson, R. Pyle, D. Ruffolo, and A. Sáiz (2005), Relativistic solar neutrons and protons on 28 October 2003, *Geophys. Res. Lett.*, *32*, L03S02, doi:10.1029/2004GL021492.

1. Introduction

[2] Relativistic solar cosmic rays provide a vital observational basis for understanding acceleration processes near the Sun. When a high flux of solar nucleons with energy greater than a few hundred MeV strikes Earth's atmosphere, the nuclear byproducts cascade to Earth's surface resulting in a "ground level enhancement" (GLE). A distributed network of neutron monitors, such as the *Spaceship Earth* observing network [*Bieber et al.*, 2004], provides an effective means of studying the angular distribution and energy spectrum of these energetic solar particles.

[3] The extreme solar activity of October–November 2003 produced 3 GLEs, with onsets occurring on 28 October, 29 October, and 2 November. This *Letter* concerns the first and largest of these. We present an overview of neutron monitor observations and point out a number of unusual features of this event. We propose that relativistic solar neutrons were emitted at the start of the event. We also model the main phase of the event to determine the solar proton release time and injection function.

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2. An Unusual GLE

[4] Figure 1 presents count rates measured by selected stations of the *Spaceship Earth* neutron monitor network as a function of time on 28 October 2003. This GLE was associated with an X17.2 solar flare located at S16 E08 that reached maximum soft X-ray intensity at 11:10 UT. The time profiles in Figure 1 display several unusual features.

[5] First, a few stations observed a large, narrow spike at event onset. McMurdo observed the largest spike, a 43% increase over the pre-event Galactic background. Most stations did not observe such a spike, or saw a smaller feature, indicating that the particles causing the spike were extremely anisotropic. An expanded view of the spikes appears in Figure 2b. Note that all *Spaceship Earth* neutron monitors are at polar locations and have essentially identical energy responses; any differences in count rates can be attributed to the different viewing directions.

[6] Second, the earliest arriving particles were detected by stations observing the anti-Sunward hemisphere. At high latitudes the earliest onsets were at Norilsk (11:14 UT) and Cape Schmidt (11:13 UT), which were respectively viewing towards GSE longitudes of 127° and 192°, the latter being almost directly anti-Sunward!

[7] Third, the event displayed an unusually slow decay. Intensities remained elevated by several percent over the pre-event background until about 06:00 UT the following day, a total of about 19 hours. In comparison, station intensities in the more typical GLE of Easter 2001 [*Bieber et al.*, 2004] declined to one-tenth their peak value after only 4 hours. The 28 October 2003 GLE persisted until the coronal mass ejection (CME) shock associated with the X17.2 flare arrived at Earth, resulting in the largest Forbush decrease of the present solar cycle. (The decrease continues beyond the time shown in Figure 1, ultimately reaching 27% at South Pole.)

[8] Fourth, as shown in Figures 1b and 2a, the near-equatorial neutron monitor in Tsumeb, Namibia observed a small but clear increase in count rate beginning at 11:06 UT and lasting for ∼9 minutes. (Note that the ordinate in these panels is excess count rate; the increase at Tsumeb amounts to 3–4% above the pre-event background.) This precursor increase seen at a high-altitude (1240 m) station near the subsolar point (zenith angle 8.4°) is reminiscent of earlier solar neutron events detected by neutron monitors [*Chupp et al.*, 1987; *Shea et al.*, 1991b]. The presence of direct

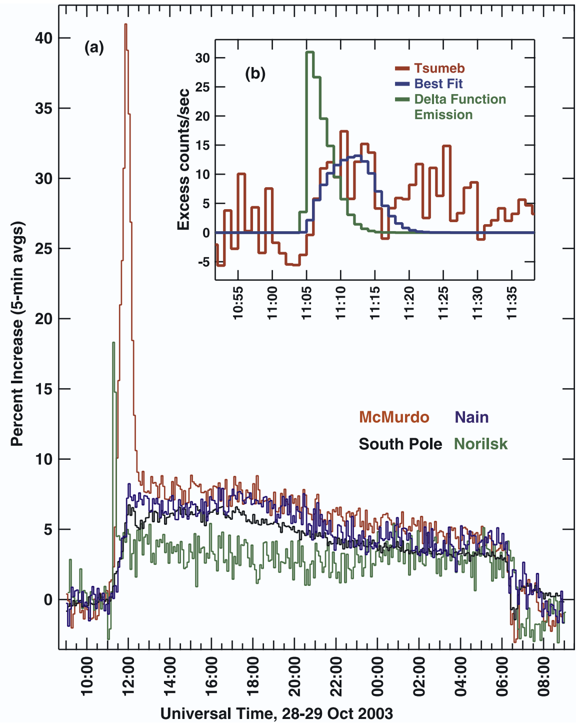

Figure 1. (a) Overview of the 28 October 2003 ground level enhancement (GLE), as observed by four selected stations of *Spaceship Earth*. Count rates are expressed as a percent increase over the pre-event Galactic background. All data are 5-minute averages corrected to standard pressure (760 mm Hg) using an assumed solar particle absorption length of 100 g cm^{-2}. (b) Excess count rate observed by the neutron monitor in Tsumeb, Africa (red), compared with our best fit for extended neutron emission at the Sun (blue) and expectation for δ-function emission at the Sun (green).

neutrons at Tsumeb in this event was previously noted by *Plainaki et al.* [2004].

3. Modeling of the Neutron Event

[9] During intense solar events, accelerated protons and nuclei produce high energy neutrons through inelastic collisions in the solar atmosphere. These (uncharged) neutrons follow a straight line path from the emission point to Earth undisturbed by magnetic fields, arriving before direct protons from the same event. If the neutron emission time is very short compared to the propagation time to Earth, the observed time profile of the neutron monitor allows a direct time-of-flight measurement of the energy spectrum. However, there have been reported cases of extended emission lasting hours, while others may be as brief as a minute [*Chupp*, 1995; *Muraki and Shibata*, 1995, and references therein].

[10] The nuclear processes responsible for solar neutron emission also generate high energy gamma rays [*Lingenfelter and Ramaty*, 1967], which can provide a key proxy for the neutron emission profile. Unfortunately, we have not obtained such measurements at the time of writing.

[11] On 28 October 2003 at 11:06 UT the Tsumeb neutron monitor recorded a 3–4 percent increase that began 7 minutes before the onset of charged particle GLE signals and persisted for roughly 9 minutes. The Tsumeb monitor is an 18-NM-64 instrument located in Namibia at 17.58°E, 19.2°S (9.12 GV vertical cutoff rigidity), with 1240 m elevation resulting in average atmospheric pressure of 660 mm Hg. Using a Monte Carlo code [*Clem and Dorman*, 2000; *Fasso et al.*, 2001] to simulate high energy and nuclear transport through the atmosphere and through an 18-NM-64 neutron monitor, the Tsumeb yield function for solar neutrons was calculated. The resulting Tsumeb yield function is shown in Figure 3 (red squares) along with related quantities.

[12] The black curve in Figure 3 is *Chupp*'s [1990] spectrum derived for the 2 June 1982 event

$$Q = 1.293 \times 10^{30} E_n^{3/8} \exp\left[-(E_n/0.016)^{1/4}\right], \qquad (1)$$

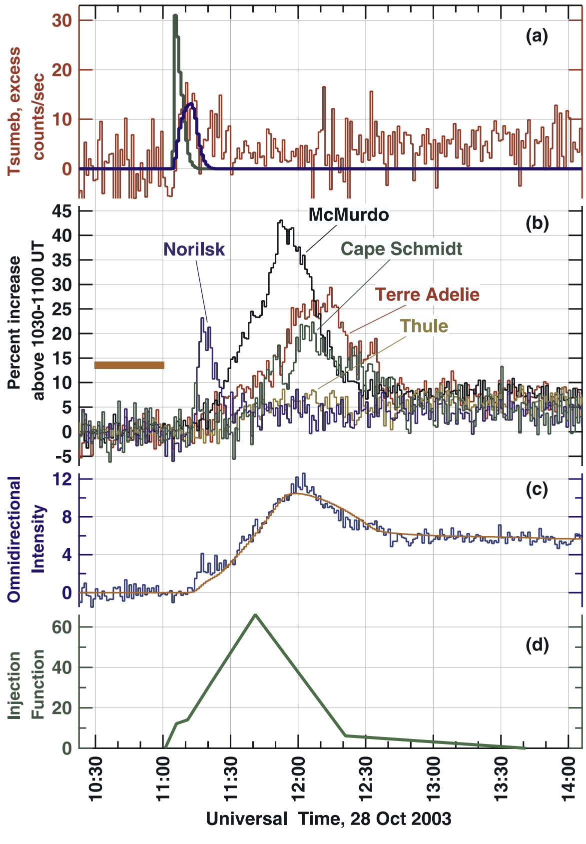

Figure 2. (a) Excess count rate at Tsumeb neutron monitor with fits as in Figure 1b. (b) Expanded view of the spikes observed by several stations at the beginning of the GLE. Station intensities are expressed as a "percent increase" over the pre-event Galactic background during a normalization interval 10:30–11:00 UT indicated by the horizontal bar. These are 1-minute data corrected to standard pressure. (c) Directionally averaged intensity (blue) at polar neutron monitors and model fit (red) to main peak. (d) Model injection function (solar time) of relativistic solar protons, optimized to fit intensity and weighted anisotropy during and after the main peak, for a closed magnetic loop of length 4.2 AU.

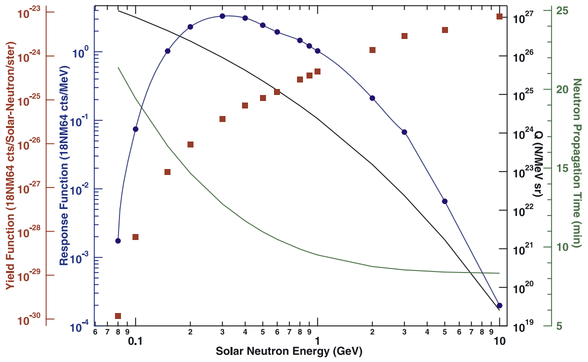

Figure 3. Tsumeb 18-NM-64 yield function versus energy for neutrons arriving 8.4° from zenith (red squares), *Chupp*'s [1990] exponential spectrum (black curve), Tsumeb response function (blue), and propagation time of a neutron from the Sun to 1 AU (green).

where Q is the spectrum in units of (sr MeV)$^{-1}$, and E_n is neutron energy in MeV. We found that simple linear scaling of this spectrum provides a good description of the 28 October 2003 event. The blue curve in Figure 3 is the Tsumeb response function (product of yield function and spectrum), and the green curve shows the propagation time of a neutron from the Sun to 1 AU. For a given emission time profile, we can derive the expected count rate profile by integrating the response function in time delayed segments based on propagation time to Earth.

[13] In order to derive start time and emission duration, a least squares fit was performed assuming the emission time profile can be represented by a boxcar function. The fit has three free parameters: the normalization, onset time, and duration. The result of this fit is shown in Figures 1b and 2a. The blue line represents the best fit with emission onset at the Sun at 10:56:30 ST ±1 minute ("ST" is Solar Time, and refers to the Universal Time of an event at the Sun) and an emission duration of 8.7 minutes. The scaling factor (relative to *Chupp*'s [1990] spectrum) is 0.93. The model represents the data well.

[14] The green curve in Figures 1b and 2a illustrates the count rate profile expected for an instantaneous emission with the same normalization and start time determined from the three parameter fit. This is clearly inconsistent with the data. We tried other neutron spectral shapes (power law variations) and found that the emission duration time did not vary by more than ~1 minute.

4. Why Did the First Particles Arrive From Anti-Sunward?

[15] Given strong indications that relativistic solar neutrons were detected in the 28 October GLE, we considered the possibility that neutron decay protons (NDP) [*Ruffolo*, 1991; *Shea et al.*, 1991a] might account for the early onset and anomalous arrival directions observed at Norilsk and Cape Schmidt. Neutrons decaying locally onto a (hypothetical) near azimuthal field will have an initial pitch angle near 90°. One-half gyroperiod after they decay, they will be moving back toward the Sun and could in principal be detected by stations viewing anti-Sunward.

[16] However the NDP hypothesis encounters difficulties on two grounds. First, one would expect NDPs to onset at the same time as direct neutrons, but the Cape Schmidt (proton) onset followed the Tsumeb (neutron) onset by 7 minutes. Second, we modeled NDP intensity using the neutron spectrum derived above, and we obtained a sea level NDP signal less than 1%, more than 20 times smaller than the increase observed at Norilsk.

[17] A second hypothesis for the anomalous arrival direction of the first particles is that Earth was located inside a closed magnetic loop at event onset. If the first injection of particles was on the far leg (relative to Earth) of the loop, then the far-leg particles would move past 1 AU, loop back, and be observed at Earth coming from anti-Sunward. Indeed, even without the anti-Sunward spike, trapping of particles in a magnetic loop might be hypothesized to account for the unusually slow decay of the event. Anti-Sunward streaming in a loop geometry explains various unusual features of the 22 October 1989 GLE [*Ruffolo et al.*, 2004] and is observed rather commonly in lower energy ions [*Richardson and Cane*, 1996]. The problem with this scenario is a lack of independent evidence that Earth was in a closed magnetic loop at event onset. Further analysis is needed to answer the question posed in the title of this section.

5. Modeling Relativistic Solar Protons

[18] While the excess counts of the Tsumeb neutron monitor can be attributed to solar neutrons, the GLE at high latitude stations is attributed to relativistic solar protons. Given the uncertain origin of the initial spike from the anti-Sunward hemisphere, we do not attempt quantitative modeling of those data at present. Instead, we concentrate on the later anisotropic spike observed at McMurdo, Cape Schmidt, and Terre Adelie (Figure 2b).

[19] We first fit data from 13 neutron monitors (11 stations of the *Spaceship Earth* network supplemented by Terre Adelie and Barentsburg) to a second-order Legendre expansion about an optimal axis of symmetry taking into account bending of particle trajectories in Earth's magnetic field. The omnidirectional intensity and weighted anisotropy (standard anisotropy multiplied by intensity) are extracted as quantities to be fit by the transport model. Then we numerically solve a transport equation that takes into account pitch angle scattering and adiabatic focusing [*Ruffolo*, 1991; *Nutaro et al.*, 2001].

[20] In this analysis, we consider two types of magnetic field configurations: (1) a standard Archimedean spiral for the measured solar wind speed of approximately 800 km/s [Source: http://www.srl.caltech.edu/ACE/ASC/level2/lvl2DATA_SWEPAM.html.], and (2) a closed magnetic loop of total length $\ell = 4.2$ AU. In both models, Sun-Earth distance along the magnetic field is taken to be 1.03 AU. For the focusing length $L \equiv -B/(dB/dz)$, where B is magnetic field strength and z is distance along the magnetic field, the loop model uses the functional form

$$\frac{1}{L} = \frac{2\pi}{\ell} \cot\left(\frac{\pi z}{\ell}\right) \tag{2}$$

which is chosen so that $1/L \approx 2/z$ as $z \rightarrow 0$ and $1/L \approx -2/(\ell - z)$ as $z \rightarrow \ell$, consistent with a nearly radial field near the Sun, and $dB/dz = 0$ and $1/L = 0$ at $z = \ell/2$.

[21] The intensity and weighted anisotropy data versus time to 15:00 UT were fit to an optimal piecewise-linear injection function by least squares fitting [*Ruffolo et al.*, 1998]. The parallel mean free path of interplanetary scattering, assumed to be uniform along the loop, was also optimized. Because we are not certain what particle population comprises the fast peak, the data during 11:14 to 11:25 UT were replaced by a linear interpolation.

[22] The spiral and loop field models yield similar fits and injection functions, with the exception that the spiral model is unable to explain the very slow decay of intensity at late times, and therefore compensates with a strong tail of fresh injection at late times. Thus we consider the loop model to be more accurate. Nevertheless, when fitting data only to 13:20 UT the two models yield similar onset and peak times. For the loop model, we found the injection function to be quite robust when fitting the data over different time periods. Figure 2c shows the optimal fit corresponding to the injection function shown in Figure 2d. (However the tail of late injection may be an artifact of an imperfect magnetic field model.) The optimal parallel mean free path is 0.8 AU. This fit to intensity and weighted anisotropy has $\chi^2 = 719$ for 592 degrees of freedom.

[23] Taking into account systematic error due to the choice of magnetic field model and fit duration, for relativistic solar protons in the main peak the injection onset time is estimated as 11:03 ST ±2 minutes, and the injection peak time is 11:41 ST ±2 minutes. A sudden intensification of soft X-ray emission began at roughly 10:52 ST, peaked at 11:02 ST, and ended at 11:16 ST. Hα emission from a flare located at S16 E08 began before 09:53 ST, peaked at approximately 11:57 ST, and ended after 14:12 ST (times are uncertain due to incomplete coverage and differing observations). Radio bursts commonly believed to indicate the presence of a shock were observed from 10:25 to 15:23 ST (type IV) and 10:54 to 11:03 ST (type II). [Source: Space Environment Center. See http://solar.sec.noaa.gov/ftpdir/indices/2003_events/20031028events.txt] We estimate CME lift off to have occurred (extrapolating the halo CME to disk center) between 10:53 ST (linear fit) and 10:58 ST (quadratic fit). [Data source: CME catalog maintained by NASA and The Catholic University of America in cooperation with the Naval Research Laboratory. See http://cdaw.gsfc.nasa.gov/CME_list] Therefore, the injection onset time we infer for relativistic solar protons is contemporaneous with all electromagnetic emissions from the event. In particular, onset of relativistic proton emission coincided with the soft X-ray peak, as also observed for the GLE of 15 April 2001 [*Bieber et al.*, 2004].

6. Summary

[24] The GLE of 28 October 2003 presents many puzzling features, and we are far from explaining all of them. However, it is clear that the observed signals result mainly from relativistic solar neutrons and protons. The protons are likely not the decay products of the neutrons. We modeled both the neutron and proton data, and we conclude that proton injection began later and lasted longer than the neutron emission. Specifically, neutron emission began ≈10:56 ST and lasted ≈9 min, while proton injection began ≈11:03 ST and lasted over an hour.

[25] The timing information permits the usual alternate conclusions. It is consistent with the view that interacting (neutron-producing) particles are accelerated along with the primary energy release, whereas a distinct population of escaping particles is accelerated somewhat later as the CME shock develops and propagates out of the corona. It is also consistent with the view that interplanetary charged particles were accelerated at the same time the neutrons were produced, but were delayed by transport processes in the corona.

[26] Future work will address the details of the directional distribution provided by the *Spaceship Earth* network of neutron monitors, especially the mysterious spike from the anti-Sunward direction. It will also make connections with additional solar observations of this remarkable event and with spacecraft data for lower energy nucleons, ions, and electrons.

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