Cosmic ray anisotropies during the Oct. 28-31, 2003 Halloween event

R P Kane
Instituto Nacional de Pesquisas Espaciais – INPE, C. P. 515, 12245-970 - São José dos Campos, SP, Brasil
(e-mail: kane@dge.inpe.br)

Received 23 February 2006; revised 29 June 2007; accepted 1 January 2008

Using data from the Nagoya muon directional telescopes during the storm of 29 Oct. 2003, the anisotropies were traced at successive UT times. Some features were very prominent, positive in some directions, negative in others. In each, different directional telescopes indicated different magnitudes, implying large directional anisotropies. By tracing the anisotropies in space, one could conclude that the Earth was engulfed by the interplanetary blob and passed slightly in its northern part (same as North of Sun). These results are approximate, as the simple analysis was carried out assuming straight line paths for cosmic rays, while some bending in magnetic fields and some scattering may be involved. Nevertheless, useful information can be obtained even from one muon set up as shown here. Using more copious data from other sources would, of course, give more detailed information.

Keywords: Muon telescopes, Cosmic rays, Cosmic ray anisotropies; Geomagnetic storms

PACS No.: 95.85.Ry, 91.25.-r

1 Introduction
Cosmic ray intensities show variations on different time scales, e. g., minutes (solar flare effects) to hours, days (FD, Forbush decreases) and years (solar cycle variation). During FDs, measurements at different latitudes, longitudes and altitudes show quantitative as well as qualitative differences, some of which are due to spatial anisotropies. Some anisotropies are dependent on sidereal time, while some are dependent on solar time. A solar time anisotropy for cosmic rays with energy above several GeV was explained by Parker on the basis of the diffusion-convection theory. Swinson reported solar anisotropies due to vector production of density gradient vertical to solar equatorial plane and IMF (Interplanetary Magnetic Field), while Munakata et al. and Kojima et al. reported anisotropies caused by North-South symmetry and North-South asymmetry, dependent on IMF (interplanetary magnetic field). All these anisotropies are small (less than 0.5%).

On the other hand, during FDs or immediately before, larger anisotropies are noticed. Bieber et al. used anisotropy data of one event to deduce that the ejecta passed South of the Earth. Belov et al. determined the isotropic density and 3D-anisotropies of cosmic rays for long periods (years) using the ‘global survey method’. Nagashima et al. reported decreases and increases caused by density gradient flows across the shock. The decreases, which are sometimes visible prior to shock arrival, may have some application in Space Weather forecasting. Cane illustrated a sketch of a large-scale structure of fast ejecta and associated shock, where the upstream solar wind was draped around the ejecta and heated and compressed at the front of the ejecta, and two different paths through the ensemble indicated differing resultant cosmic ray FD profiles. Also, various types of anisotropies could be envisaged, depending on where the Earth was in such a configuration.

The anisotropies are directional, small and short-lived (few hours). Neutron monitors have a broad directional response and hence, anisotropy amplitudes are small (~ 0.5%). Muon telescopes have a better directional response and generally larger anisotropy amplitudes. In recent years, giant muon telescopes have been installed. Two major setups are presently operative, one of which is at Ooty (11°N, 77°E, 2200 m above sea level) in South India, as a part of the present GRAPES (Gamma Ray Astronomy at PeV EnergieS) III project of Indo-Japanese collaboration. Anisotropy studies from this Ooty setup (experimental details in Kawakami et al.) have been reported in the past, for FDs and for short-term variations. Earlier, Nagashima et al. had pointed out that the small angular scale anisotropy near the direction of IMF (interplanetary magnetic field) is due
to “Loss-cone” effects between the turbulent region behind the shock and the observer. Nonaka et al. reported to have located several LCPD (Loss-Cone Precursor decreases), many of these associated with (or observed slightly before) Forbush decreases. Earlier, Nonaka et al. had presented the time profiles of the muon variations observed in nine categorized directions (Vertical, and N, NE, E, SE, S, SW, W, NW) before and during the FD of 11 Apr. 2001, and identified some features as precursor phenomena of the arrival of an interplanetary shock. These data for 11 Apr. 2001 were reexamined recently by Kane who reported that the Earth passed the northern part of the blob. Also, some anisotropies which occurred when the Earth was outside the blob (notably before the FD) could be precursory increases due to reflection from the shock fronts, but some others could not be understood as these appeared in a direction away from the blob.

Another setup is the Multi-Directional Cosmic-Ray Muon Telescope at Nagoya (35°N, 137°E, Altitude; 77 m above sea level, other details on the website http://www.stelab.nagoya-u.ac.jp/omosaic/nagoya/muon1.html). Muon intensities are obtained for specific directions and zenith angles, namely, Vertical (V), 30°N, 39°NE, 49°N, 64°N; 30°E, 39°SE, 49°E, 64°E; 30°S, 39°SW, 49°S, 64°S; 30°W, 39°NW, 49°W, 64°W. These telescopes record muons of more than one GeV and the corresponding median rigidities of primary cosmic rays is several tens of GeV, with a geomagnetic bending equivalent to a few hours in the east-west directions. The hourly counting rates have standard errors of less than 0.5%, and for some, even less.

During 28-31 Oct. 2003 there occurred a giant event, which has been a subject of study by many workers. Kuwabara et al. used a simple inclined cylinder model and used the anisotropy data from three multi-directional muon detectors at Nagoya (Japan), Hobart (Australia) and Săo Martino (Brazil) to derive the three-dimensional geometry of the cosmic ray depleted region formed behind the shock that occurred on 29 Oct. 2003, when solar wind velocity was very high (~ 2000 km/s), maximum negative geomagnetic $D_{st}$ was ~ 400 nT, and cosmic ray neutron monitors had FDs of ~ 30%. In the present communication, the intensity variations for the same event are studied in a simple way by examining multi-directional data at only one location (Nagoya, 35°N, 137°E), but minutely.

2 Data and plots

Hourly data for interplanetary parameters and for cosmic ray neutron monitors were obtained from the NOAA (SPIDR) website. Data for muons at Nagoya were obtained from the website http://www.stelab.nagoya-u.ac.jp/ste-www1/div3/muon/muon3.html. Figure 1 shows the plots of hourly values for 28-31 Oct. 2003. Long vertical lines mark 0000 hrs UT of the successive dates. The top part shows the interplanetary parameters $N$ (ion density, data intermittent and not quite reliable, Skoug et al.), $V$ (solar wind speed), $B$ (total magnetic field), $B_{z}$ (the North-South component of $B$), and the geomagnetic disturbance index $D_{st}$. As can be seen, a major storm (henceforth called Storm 1, marked by small vertical lines) seems to have started at ~ 0500-0600 hrs UT of 29 Oct. 2003 ($V$~ 2000 km/s; $B$~ 50 nT; $B_{z}$~ 25 nT), though 28 Oct. 2003 was not absolutely quiet. There was another storm (henceforth called Storm 2, marked by small vertical lines) which started next day (30 Oct. 2003) at ~ 1200 hrs UT, for $V$ and $B$, but 6 hours later at ~ 1800 hrs UT for $B_{z}$ and $D_{st}$.

For cosmic rays, plots were made (not shown here) for cosmic ray neutron monitor percentage intensities recorded at several locations: During Storm 1, there were severe FDs with magnitudes in the range 18-30%. For their average, the isotropic FD magnitude was 23%. To detect anisotropies, the isotropic average was subtracted from the data of each location. A plot of the residues (not shown here) indicated that deviations occurred during Storm 1, positive at some locations and negative at others, not all starting at ~ 0600 hrs UT, indicating that cosmic rays entering the blob from different directions encountered different paths, leading to different modulations. However, the anisotropies in neutron monitor data were not very striking or consistent. Therefore, more attention is paid to muon intensities.

In Fig. 1, plots are shown for muon intensities during 28-31 Oct. 2003. Long vertical lines mark 0000 hrs UT of the successive dates. Plots UPP and LOW are for the upper and lower counter trays, recording omni-directional intensities. The next plot is for the vertical intensity, and the others are for the directional intensities. The FDs are seen in all of these (starting at ~ hrs UT, marked by a long vertical line) and the magnitudes are very much larger (exceeding 45%) than those for the neutron monitor intensities (32% or less, not shown here). The omnidirectional UPP and LOW have FD magnitudes of 54 and 52%.
respectively, while Vertical V and zenith angles of 30°, 39°, 49°, 64° have magnitudes of 66-75%, 59-68%, 54-58% and 43-47%, respectively. Thus, larger zenith angles have smaller FD magnitudes (43-58%), almost comparable to those of the omni-directional UPP and LOW (52-54%).

To isolate the anisotropies, the isotropic FD effect has to be eliminated. However, this isotropic effect cannot be estimated as average of all the plots, because the FD magnitudes have a large range of 43-75%. Hence, the averages were obtained for each zenith angle separately and used for subtraction for that zenith angle only. Thus, the average of 49°N, 49°E, 49°S, 49°W was subtracted from each of these four only, and so on for other zenith angles 30°, 39°, 64°. (Vertical V was included in the 30° zenith angle group.) The residuals are plotted in the lower part of Fig. 1. Plots for different zenith angles for the same direction are plotted in succession. For 39°, there are no data for N, E, S, W, but only for in-between directions NE, SE, SW, NW. These are considered in succession of 30° N, E, S, W, respectively. Positive deviations are painted black and negative deviations are shown hatched. The following may be noted:

(i) The plot for Vertical V shows small anisotropies (2% or less) as compared with other directions (exceeding 5%) and hence, will not be discussed any more.

(ii) For other specific directions N, E, S, W, plots for all zenith angles in each (30°, 39°, 49°, 64°) are similar, indicating that these anisotropies are genuinely directional.

(iii) On 28 Oct. 2003, there are some anisotropies, but the magnitudes are small (~ 2%). These could be precursors, but will be ignored and more attention will be paid to the larger anisotropies in the main intervals of Storm 1 as well as Storm 2. (Incidentally, Munakata et al. analyzed a loss cone anisotropy observed by a ground-based muon hodoscope at Mt. Norikura, Japan for 7 hours preceding the arrival of an interplanetary shock at the Earth on 28 Oct. 2003 and concluded that the loss cone had a broad pitch-angle distribution with a half-width of ~ 50° from the IMF).

(iv) The deviations have large fluctuations, not necessarily starting at 0800 hrs UT. Some started earlier, some later. Some features are very prominent, positive in some directions, negative in others. These are designated as
Events, A, B, C and D roughly at time intervals: A, ~1200 hrs UT of 29 Oct.; B, ~0000 hrs UT of 30 Oct.; C, ~2200 hrs UT of 30 Oct.; and D, ~1600 hrs UT of 31 Oct. 2003. In A, North N and West W show positive deviations, while East E and South S show negative deviations. In B, C, D, North N and East E show predominantly positive deviations while, South S and West W show predominantly negative deviations. Since the Earth is not only moving through the blob but is also rotating on its axis, the directions in space where the different telescopes would be pointing change with time.

Nagoya is at 35°N, 137°E. So, the local time LT is ~9 hours ahead of UT. In addition, geomagnetic bending pushes the LT by another ~5 hours (Nokata et al. for Ooty telescope). Hence, the effective LT for the muon telescopes is ~14 hours ahead of UT. Therefore, for Nagoya muons, pre-storm is at 0000 hrs UT, asymptotic = 1400 hrs LT; Event A at 1200 hrs UT, asymptotic = 0200 hrs LT; Event B at 0000 hrs UT, asymptotic = 1400 hrs LT; Event C at 2200 hrs UT, asymptotic = 1200 hrs LT; and Event D at 1600 hrs UT, asymptotic = 0600 hrs LT.

Figure 2 illustrates the anisotropies (positive variations, full circles; negative variations, open circles), left half, in the ecliptic plane (the paper plane roughly equatorial for the Sun as well as Earth, the North of both Sun and Earth perpendicular from the paper plane upwards) and right half in a perpendicular plane (the North-South of both Sun and Earth in the plane of the paper). The top plot is for the pre-storm interval ~0000 hrs UT of 29 Oct. 2003. The other four plots are for successive Events A, B, C, D (see text). The sketches are approximate, certainly not to scale. Here T indicates approximately where the Nagoya telescope was on the Earth (EA), and E and W in the left half and N and S in the right half, emerging from T, indicate where these directions pointed in space.

The following may be noted:

(i) In the pre-storm stage at 0000 hrs UT when the telescope T was responding to 1400 hrs LT (almost sunward), the E, W directions in the left half and the N, S directions in the right half at T on the Earth, are pointed away from the blob, and no anisotropies are expected. There might be some reflection effects from the core of the blob (shock front) to regions outside the blob towards the Earth, but these effects seem to be small and will be ignored. Since the anisotropies are superposed on a general isotropic FD pattern, a negative deviation (open circle) in a given direction E, W, N or S, will be interpreted as an extra (enhanced) FD effect, implying a larger modulation and a longer path (distance of the Earth from the blob boundary) traversed by the cosmic rays. Contrarily, a positive deviation (full circle) in a given direction E, W, N or S, will be interpreted as a reduced FD effect, implying a smaller modulation and a shorter path (distance of the Earth from the blob boundary) traversed by the cosmic rays.

Fig. 2—Illustration of the anisotropies (positive variations, full circles; negative variations, open circles), left half, in the ecliptic plane (the paper plane roughly equatorial for the Sun as well as Earth, the North of both Sun and Earth perpendicular from the paper plane upwards) and right half in a perpendicular plane (the North-South of both Sun and Earth in the plane of the paper) [The top plot is for the pre-storm interval ~0000 hrs UT of 29 Oct. 2003. The other four plots are for successive Events A, B, C, D (see text). The sketches are approximate, certainly not to scale. Here T indicates approximately where the Nagoya telescope was on the Earth (EA), and E and W in the left half and N and S in the right half, emerging from T, indicate where these directions pointed in space.]
(ii) In Event A of 1200 hrs UT when the telescope T was responding to 0200 hrs UT (almost midnight, anti-sunward), in the left half, the blob has engulfed the Earth and direction E shows a negative deviation and direction W shows a positive deviation. So, the Earth must be more on one side of the blob than on the other. In the perpendicular plane (right half), S shows a negative deviation and direction N shows a positive deviation. So, the Earth must be nearer to the northward boundary of the blob. Thus, the Earth was in the upper right part of the blob as seen from the Sun.

(iii) In Event B of 0000 hrs UT when the telescope T was responding to 1400 hrs LT (almost sunward, same as in the pre-storm sketch), in the left half, the blob has engulfed the Earth and direction W shows a negative deviation and direction E shows a positive deviation. This is opposite to that in Event A, but the LT situation for T is almost 12 hours away. So, the Earth must be more on one side of the blob than on the other, same as in Event A. In the perpendicular plane (right half), direction S shows a negative deviation and direction N shows a positive deviation (same as in Event A). So, the Earth must be nearer to the northward boundary of the blob. Thus, the Earth was in the upper right part of the blob as seen from the Sun (same as in Event A).

(iv) In Event C of 2200 hrs UT when the telescope T was responding to 1200 hrs LT (sunward, almost the same as in Event B), in the left half, the blob has still engulfed the Earth and direction W shows a negative deviation and direction E shows a positive deviation. So, the Earth must be more on one side of the blob than on the other, same as in Events A and B. In the perpendicular plane (right half), direction S shows a negative deviation and direction N shows a positive deviation (same as in Events A and B). So, the Earth must be nearer to the northward boundary of the blob. Thus, the Earth was in the upper right part of the blob as seen from the Sun (same as in Events A and B).

(v) In Event D 1600 hrs UT when the telescope T was responding to 0600 hrs LT (early morning), in the left half, the blob has still engulfed the Earth, but direction W (anti-sunward) shows a negative deviation and direction E (sunward) shows a positive deviation. So, the Earth must be more on one side of the blob than on the other, more sunward, indicating that the blob is moving outward from the Sun, leaving the Earth behind. In the perpendicular plane (right half), direction S shows a negative deviation and direction N shows a positive deviation (same as in Events A, B and C). So, the Earth must be nearer to the northward boundary of the blob. Thus, the Earth was still in the upper part of the blob as seen from the Sun (same as in Events A, B and C).

3 Conclusions

Using data from the Nagoya muon directional telescopes during the storm of 29 Oct. 2003, the anisotropies were traced at successive UT times. Some features were very prominent, positive in some directions, negative in others. These are designated as Events, A, B, C and D roughly at time intervals: A, ~1200 hrs UT of 29 Oct.; B, ~0000 hrs UT of 30 Oct.; C, ~2200 hrs UT of 30 Oct.; and D, ~1600 hrs UT of 31 Oct. 2003. In each, different directional telescopes indicated different magnitudes, implying large directional anisotropies. From the tracing of the anisotropies in space, one can conclude that the Earth was engulfed by the interplanetary blob and passed slightly in its northern (same as North of Sun) part. Though these results are approximate, the present analysis shows how qualitative information about abnormal interplanetary structures can be obtained by a simple look at directional telescope data even at one location.

Kuwabara et al.\textsuperscript{25} have made a detailed analysis of this event, using data from other muon setups and mention that the center of their cylinder approached closest to the Earth and passed ~ 0.035 AU north of Earth, i.e., the Earth was slightly in the southern part while the author finds that the Earth passed slightly in the northern part. This slight disagreement could be because the present simple analysis assumes straight line paths for cosmic rays, while some bending in magnetic fields and some scattering may be involved. Nevertheless, useful information can be obtained even from one muon set up as shown here. Using more copious data from other sources would, of course, give more detailed information.

Acknowledgements

Thanks are due to the workers of the Cosmic Ray Section, Solar-Terrestrial Environment Laboratory, Nagoya University, Japan, for collecting the data, examining meticulously and putting on their website
for public use. The present work was partially supported by FNDCT, Brazil, under contract FINEP-537/CT.

References
6 Parker E N, Extension of the solar corona into interplanetary space, *J Geophys Res (USA)*, 64 (1959) 1675.