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COSMIC RAY ANISOTROPIES AROUND THE FORBUSH DECREASE OF APRIL 11, 2001

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Abstract. During the Forbush decrease of April 11, 2001, the Ooty (11.4°N, 76.7°E, 2200 m altitude, South India) high energy muon detectors showed considerable anisotropies. Some anisotropies and asymmetries indicated that the Earth did not pass the middle of the interplanetary structure (blob), and passed its northern part. Some anisotropies which occurred when the Earth was outside the blob (notably before the Forbush decrease) could be the 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.

1. Introduction

Cosmic ray intensities as recorded by meson telescopes and neutron monitors indicate variations on different time scales: minutes (solar flare effects) to hours, days (Forbush decreases) and years (solar cycle variation). Instruments located at different latitudes, longtitudes, and altitudes show quantitative as well as qualitative differences, some of which are due to spatial anisotropies. Some of these are dependent on sidereal time (Nagashima, Tatsuoka, and Matsuzaki, 1983; Hall *et al.*, 1999; Kojima *et al.*, 2003) while some are dependent on solar time. The diffusion–convection theory of Parker (1958a,b, 1959) explained a solar time anisotropy for cosmic rays with energy above several GeV. Swinson (1969, 1970) reported other types of solar anisotropies due to vector production of density gradient vertical to solar equatorial plane and interplanetary magnetic field (IMF). Munakata *et al.* (1999, 2002) and Kojima *et al.* (2003) reported other types of anisotropies caused by North – South symmetry and North – South asymmetry and having IMF dependence. All these anisotropies are of small amplitudes (less than 0.5%). On the other hand, during Forbush decreases or immediately before, larger anisotropies are noticed. Barnden (1973a,b) interpreted these in terms of the particle flow patterns related to interplanetary ejecta and the accompanying shock. Iucci *et al.* (1989) and Nagashima *et al.* (1990) tried to relate large cosmic ray anisotropies to interplanetary magnetic field conditions. Bieber *et al.* (1999) used anisotropy data of one event to deduce that the ejecta passed South of the Earth. Hofer and Flückiger (2000) studied a large event in March 1991 and found that the cosmic ray anisotropy vectors exhibited a rotational behavior at the onset of the ejecta decrease where the modulation was greatest, but the required magnetic cloud-like structure could not be confirmed as no interplanetary data were available. Belov *et al.* (1995) and Belov, Eroshenko, and Yanke (1997) determined the isotropic density and 3D-anisotropies of cosmic rays for long periods (years) using the 'global survey method'. They illustrated the variability from one Forbush decrease to another, and in some cases, the phase of the in-ecliptic anisotropy showed an anti-sunward flow in the ejecta and then a clear swing back to the normal corotation flow from approximately the East near the rear of the ejecta. Nagashima *et al.* (1992) studied anisotropies related to particle effects at shocks and in particular, 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 (*e.g.*, Belov *et al.*, 1995; Bieber and Evenson, 1998; Bieber *et al.*, 1999; Cane, 2000). Cane (2000, Figure 4, page 63) had illustrated a sketch of a large-scale structure of a 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. Two paths through the ensemble were indicated with differing resultant cosmic ray profiles. Also, various types of anisotropies could be envisaged, depending on where the Earth was in such a configuration.

Since the anisotropies are directional, small and short-lived (few hours), their magnitudes are often within the statistical errors of the data. Neutron monitors have a broad directional response and hence, anisotropy amplitudes are small ($\sim$0.5%), not always above the standard errors. Muon telescopes have a better directional response and generally larger anisotropy amplitudes, but here, the statistical errors are generally larger than those for neutron monitors. However, in recent years, giant muon telescopes have been installed and anisotropy studies have improved. At Ooty (11.4°N, 76.7°E, 2200 m altitude) in South India, the present GRAPES III (Gamma Ray Astronomy at PeV Energies III) setup has as detector element a 6 m long proportional counter with cross section of 10 cm by 10 cm; 58 counters are placed side by side on a concrete platform and covered with 15 cm thick concrete slabs (Kawakami *et al.*, 2001). Four layers of counters are arranged in crossed configuration to obtain the track and angle of the individual muons. On the top of the counter layer, thick concrete is put yielding a total thickness of the detector as 550 g/cm^2. The minimum energy of a penetrating muon is about 1 GeV and corresponds to a primary cosmic ray energy of $\sim$65 GeV. The total number of modules for muon detector is 16. Area of each module is around 35 m^2, the total area is 560 m^2, and the counting rate is $\sim 1.7 \times 10^8$ per hour (statistical error $\sim$0.01%). In principle the angle of an individual muon is recorded every 10 s. There are nine categories of muons in total, North, Northeast, East, Southeast, South, Southwest, West, Northwest, and Vertical. For N – E, S – E, S – W, N – W, the zenith angle is about 40° with vertical. For N, S, E, W, the angle is about 30°. All the successive directions N, NE, E, etc. are 45° apart in azimuth and the statistical error of the hourly counting rates is less than 0.05%. All the raw data (each one minute interval) have been checked up thoroughly. After confirming that there is no misbehavior due to hardware problems, the counting rates of all the modules are summed up.

The large muon telescope (shower array) of GRAPES III at Ooty is a project of Indo-Japanese collaboration and so far, many aspects (energy spectra, sidereal variations, etc.) have been studied and reported on. Kawakami *et al.* (2001) presented the 3-D features of Forbush decreases, while Nonaka *et al.* (2003, 2005) studied short-term variations. Earlier, Nagashima *et al.* (1992) had pointed out that the small angular scale anisotropy near the direction of interplanetary magnetic field (IMF) is due to "Loss-cone" effects between the turbulent region behind the shock and the observer. Since the angular resolution in GRAPES III is $\sim 10^\circ$ or less, Nonaka *et al.* (2005) 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.* (2003) 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 Forbush decrease of April 11, 2001, and identified some features as precursor phenomena of the arrival of an interplanetary shock.

In the present communication, the GRAPES III muon variations in the nine categorized directions during April 10 – 13, 2001 are examined in greater detail.

2. Plots

Figure 1 shows the plots of hourly values during April 10 – 13, 2001. The main vertical lines separate the dates April 10, 11, 12, and 13. The first six plots are for interplanetary parameters, for which data from the ACE satellite were obtained from NOAA websites. The seventh plot is of geomagnetic disturbance index D_{st} (mostly negative values, shown hatched) and the corresponding auroral AE index (mostly positive values, shown black, data from NOAA website and website of WDC for Geomagnetism, Kyoto). The interplanetary abnormalities (including B_z) seem to have started at about 13 UT on April 11 (vertical line), while abnormalities of geomagnetic D_{st} and AE seem to have started a few (about 3 h) later, at about 16 UT. We have noticed such delays in many other storms, and these probably indicate that even though D_{st} and AE changes are intimately related to negative B_z (magnetotail neutral point entry mechanism for solar wind, suggested by Dungey, 1961), some threshold value of negative B_z is needed for D_{st} to respond. Gonzalez and Tsurutani (1987) have shown empirically that intense storms with peak $D_{\mathrm{st}} < -100$ nT are primarily caused by large negative B_z exceeding about 10 nT.

The succeeding plots are for the percentage deviations from means of the nine categorized muon directional intensities: V (Vertical), and N, NE, E, SE, S, SW, W, NW. These show mostly large positive values (exceeding 1%, painted black) in the interval 00:12 UT of April 11, before the Forbush decrease, *i.e.*, the precursor increases, not decreases. After this interval, a strong Forbush decrease is observed,

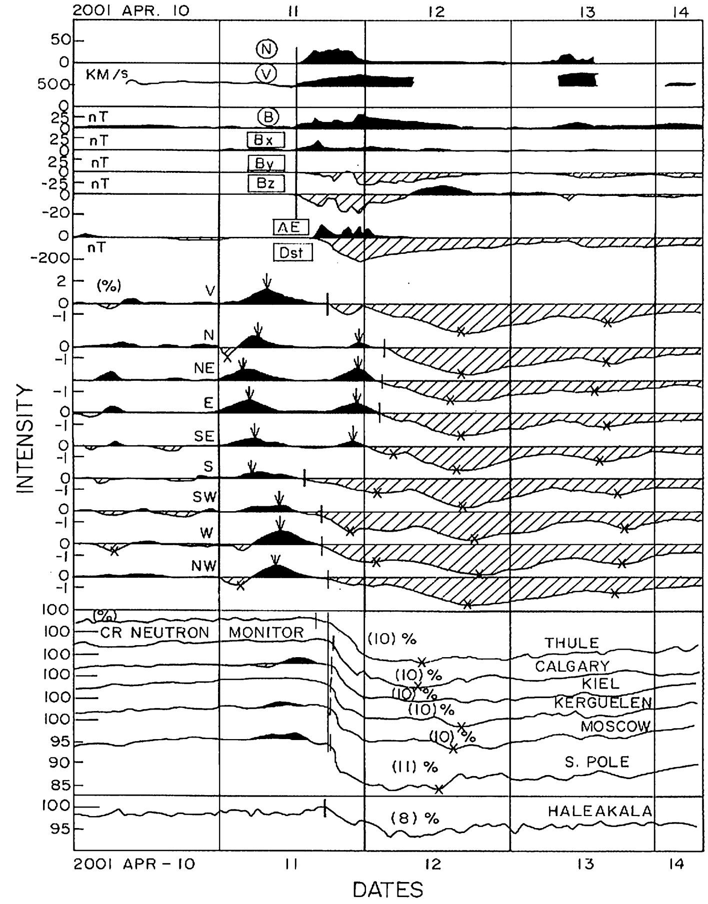

Figure 1. Plots of hourly values during April 10 – 13, 2001. *Vertical lines* separate the dates April 10, 11, 12, and 13. Top six plots, N (interplanetary ion density), V (solar wind speed), B (interplanetary total magnetic field), and B_x, B_y, B_z (the three components of B). Positive values are painted *black* and negative values are shown *hatched*. The seventh plot, geomagnetic disturbance index D_{st} (negative values, shown *hatched*) and the corresponding auroral AE index (positive values, shown *black*). Succeeding plots, percentage deviations from means of the nine categorized muon directional intensities: V (Vertical), and N, NE, E, SE, S, SW, W, NW. Lower part, cosmic ray neutron monitor intensities at seven locations.

but not simultaneously in all directions. Thus, severe directional anisotropies are indicated.

Interplanetary structures are not necessarily single. Wang, Ye, and Wang (2003) mentioned multiple magnetic clouds (Multi-MC) and gave several examples of these during March – April, 2001. For the interval April 11 – 13, 2001, using ACE plasma data, they found that not only a single blob was observed, but complex multiple shock structures went past the Earth, which were related to four consecutive halo CMEs. They found that the first magnetic cloud crossed the observation point between 22:15 UT of April 11 and 03:55 UT of April 12, followed by a second and a third MC on April 12 and 13, respectively. In our plots of Figure 1, interplanetary parameters show strong variations only during the second half of April 11 and the first half of April 12. This corresponds to the first MC (magnetic cloud) mentioned by Wang, Ye, and Wang (2003). The second MC mentioned by them as of April 12 seems to be very weak and lost in the tail end of the first MC. The directional intensities had significant decreases starting from the beginning of April 12 and had maximum troughs (marked by crosses $\times$) in the middle of April 12 and a slow recovery thereafter. So, the second MC does not seem to have had any significant extra effect. In the middle of April 13, the interplanetary parameters had small variations, and the directional intensitites had a second trough (marked by crosses $\times$). So, the third MC did have an effect, but much smaller than the effect of the first MC.

The lower part of Figure 1 shows plots for cosmic ray neutron monitor intensities at Thule (76°N, 69°W), Calgary (51°N, 114°W), Kiel (54°N, 10°E), Port–au-Francais (49°S, 70°E), Moscow (55°N, 37°E), South Pole (90°S) and Haleakala (20°N, 56°W). There are some positive anisotropies (shown black) of $1-2\%$ at some locations, and the Forbush decrease seems to have started at about the same time (17 UT) at all locations, though the longitudes are widely different, in contrast to the large directional differences in the muon components. The magnitudes of neutron monitor changes could have been used in conjunction with the magnitudes of the high energy anisotropies for estimating the cosmic ray energy spectrum. However, the neutron monitors do not have directional resolution and seem to respond to only overall isotropic variations (instruments at widely different longitudes showing similar Forbush decrease magnitudes). Hence, the neutron monitor magnitudes are not of the same category as the directional amplitudes of the muon telescopes, and these two cannot be used for joint spectral studies.

To remove any common factor and bring out the directional differences more clearly, an average pattern was calculated in two ways, firstly by averaging over all the eight directions (N, NE, E, SE, S, SW, W, NW) and secondly, by assuming that the vertical V could represent the average. In Figure 2, the top plot (full line) shows the average of N, NE, etc., while the crosses represent V (same as the 8th plot in Figure 1). The results of the two are almost the same. After this average was subtracted from the individual direction data, the residuals (deviations) were plotted in the successive plots in Figure 2. The major Forbush decrease is now eliminated in N, NE, E, SE, but in S, SW, W, and NW, there is considerable Forbush decrease, indicating that even in the main Forbush decrease, high-energy particles are highly anisotropic. Further plots show asymmetries (N – S, *i.e.*, North minus South, NE – SW, E – W, SE – NW). These show very large asymmetries during, as well as before, the main phase of the Forbush decrease.

Figure 3 shows sketches of the location of the Earth and the interplanetary structure at different times. The time intervals corresponding to prominent anisotropies are roughly:

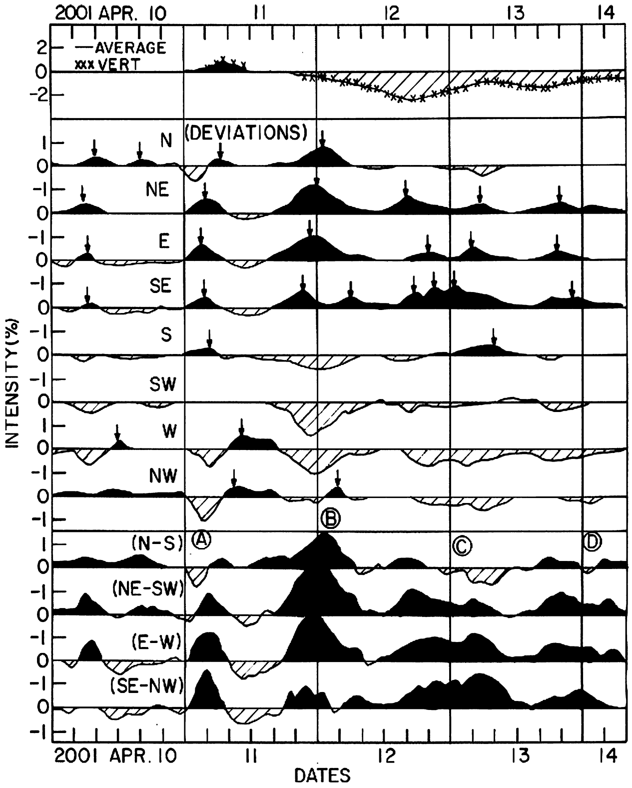

Figure 2. Plots of hourly values during April 10 – 13, 2001. Top plot, avearge of fluxes of eight directions (N, NE, E, SE, S, SW, W, NW) (*full lines*) and the vertical flux V (*superposed crosses*). *Hatched part* shows the main Forbush decrease on April 12 – 13. Succeeding eight plots: deviations obtained by subtracting the average pattern from each one of N, NE, E, SE, S, SW, W, NW. Positive values are painted *black* and negative values are shown *hatched*. Last four plots show the asymmetries (N – S), (NE – SW), (E – W), (SE – NW). A, B, C, and D mark the four events of prominent anisotropies, respectively.

(A) 2001, April 11, 02:00 – 04:00 UT (precursor of Forbush decrease)
(B) 2001, April 11, 23:00 – 24:00 UT (during, as well as before, the start of Forbush decrease)
(C) 2001, April 12, 22:00 UT – April 13, 04:00 UT
(D) 2001, April 13, 24:00 UT

The location of Ooty (11.4°N, 76.7°E) implies LT about 5 h ahead of UT. However, cosmic rays get deviated by the geomagnetic field. Nonaka *et al.* (2003) calculated the asymptotic direction for the high enery muons at Ooty and found an average longitude of ~120°E. Thus effectively, Ooty cosmic ray muons arrived at a LT about 8 h ahead of UT. Hence all the four events A, B, C, and D occurred at ~06:00 – 12:00 LT at Ooty. In Figure 3, the following may be noted:

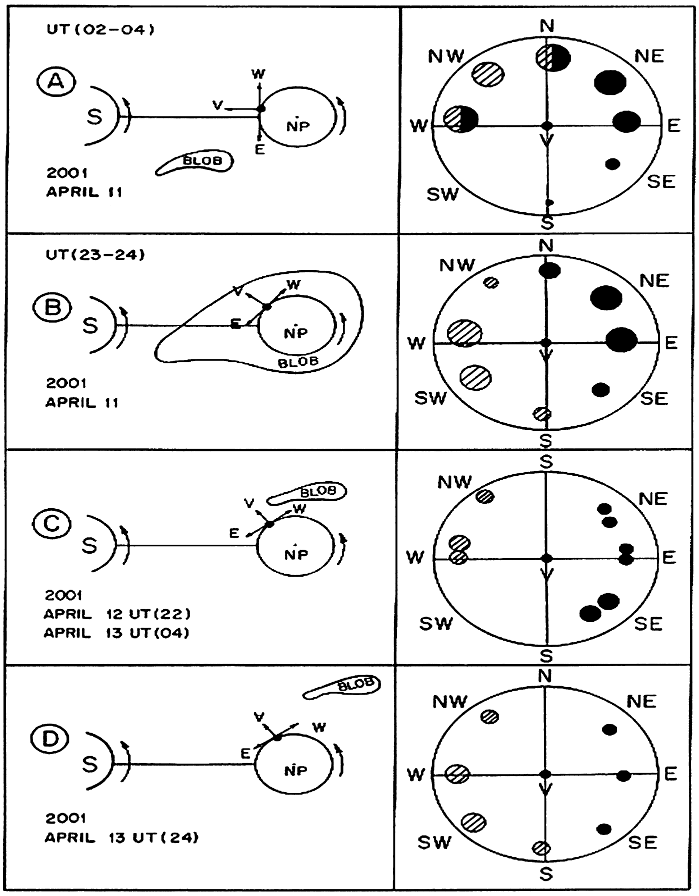

Figure 3. Sketches for the four events of prominent anisotropies.

1. In (A), the left half shows the Sun (S) and the Earth (circle) (not to scale) in their equatorial plane, with Ooty (dot) almost on the rim, and North Pole (NP) in the center. The vertical direction is almost pointing towards the Sun (at ~10 LT). The interplanetary blob (BLOB) has not yet engulfed the Earth. The right half of (A) shows the muon anisotropies at Ooty, looked from above, so that the center upwards (out of the plane of the paper) is the vertical direction V, and the anisotropies in eight different directions (N, NE, E, SE, S, SW, W, NW) are shown by circles of sizes roughly proportional to the amplitudes of the anisotropies, full circles representing positive anisotropies, and hatched circles representing negative anisotropies. There are prominent positive anisotropies on the East – Northeast side and prominent negative anisotropies on the West – Northwest side. Cane (2000) mentioned and discussed precursory increases before Forbush decreases, attributing these to reflection of particles from the shock or acceleration at the shock. In that case,

positive anisotropies would be in the direction of the interplanetary blob, *i.e.* near the East (E) direction. This is seen, but the negative anisotropies in the West and Northwest direction are not understandable, as these directions are opposite to the blob direction. The North and South direction telescopes are also pointing outside the blob. Hence, the N – S asymmetry illustrated in Figure 3 (bottom part) is also not understandable.

2. In (B), the blob has engulfed the Earth. Hence, a general decrease in all directions would be expected. But, as seen in the right half of (B), directions near East show positive anisotropies (full circles) while directions near West show negative anisotropies (hatched citcles). This could be because the Earth may not be yet completely inside the ejecta, and effects of reflected particles and/or general decrease may be different in different directions.
3. In (C), the Earth has come out of the blob, so no effect in the East direction (opposite to the direction of the blob) and reflected particles from the West would be expected. As seen in the right half of (C), this has not occurred. Instead, there are positive anisotropies in the East and negative anisotropies in the West.
4. In (D), the blob is far away from the Earth. Still, as seen in the right half, negative anisotropies are seen in the West. Incidentally, after the major storm in the end part of April 11 (the first MC of Wang, Ye, and Wang 2003), there was a minor storm in the middle of April 13 (the third MC of Wang, Ye, and Wang, 2003). So, some of these anisotropies on April 13 may be related to this minor storm.
5. The N − S and other asymmetries are very large in all events A, B, C, and D, but much more so in event C (strong Forbush decrease). Thus, the Earth seems to have passed not the middle but the northern part of the blob. Only thus, the southern directions would have stronger Forbush decreases.

3. Conclusions

During the Forbush decrease of April 11, 2001, the hourly values of the fluxes of high energy muon detectors operated at Ooty (11.4°N, 76.7°E, 2200 m altitude, South India) and pointing in different directions (Vertical, N, NE, E, SE, S, SW, W, NW), showed considerable anisotropies, different in different directions, before, during and after the Forbush decrease. Some anisotropies and asymmetries indicated that the Earth did not pass the middle of the interplanetary structure (blob), but passed its northern part. Some anisotropies which occurred when the Earth was outside the blob (notably before the Forbush decrease) could be the precursory increases due to a reflection from the shock fronts, but some others could not be understood as these appeared in a direction away from the blob. Nagashima *et al.* (1992) had pointed out that small angular scale anisotropies near the direction of IMF are due to “Loss-cone” effects between the turbulent region behind the shock and the observer.

Since the angular resolution in GRAPES III is ∼10° or less, Nonaka *et al.* (2005) reported to have located several LCPD (Loss-Cone Precursor decreases), many of these being associated with (or observed slightly before) Forbush decreases. Earlier, Nonaka *et al.* (2003) 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 Forbush decrease of April 11, 2001, and identified some features as precursor decreases. However, the present detailed analysis of the same event did not show the precursor decreases and showed instead, precursor increases.

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