Indian Journal of Radio & Space Physics
Vol 40, April 2011, pp 76-84

Directional muon telescopes not useful for estimating the magnitudes of Forbush decreases and geomagnetic storms

R P Kane
Instituto Nacional de Pesquisas Espaciais, INPE, C P 515, 12245-970, São Jose´ dos Campos, SP, Brazil
E-mail: kane@dge.inpe.br

Received 15 October 2010; revised received and accepted 3 March 2011

When a coronal mass ejection (CME) escapes from the Sun and spreads in interplanetary space as a blob (termed as interplanetary CME, ICME), galactic cosmic rays (CR) passing through the same get modulated and one can detect anisotropies in data of muon directional telescopes located on the Earth. For 15 severe storms (Dst < -200 nT) during solar cycle 23 (1996-2006), the hourly data for Nagoya muon directional telescopes showed that for each one of these storms, there were anisotropies in one or more of the 16 directional telescopes. The maximum magnitudes of the anisotropies were ~1% or less and had reasonably good relationships (correlation +0.75) with the magnitudes of the following Forbush decrease (FD) in the muons in the vertical direction V (muon V) and also in CR neutron monitor (NM) data at Climax, Colorado, USA. But a correlation of ~0.75 implies a variance explained (square of correlation) of only ~55%, leaving ~45% as random component. With geomagnetic Dst(min), the muon anisotropy magnitudes had a still lower correlation (+0.44±0.20), which would imply a variance explained of only ~20%, leaving ~80% as random component, resulting in regression prediction errors exceeding 50%. Thus, the anisotropies were only a rough indicator of there being some anomalous structure out in the interplanetary space, but the magnitudes of the anisotropies could not give any accurate indication of the magnitudes of the Forbush decreases that may follow, much less for the magnitudes of the geomagnetic storm Dst(min) that may follow.

Keywords: Forbush decrease, Coronal mass ejection (CME), Interplanetary coronal mass ejection (ICME), Geomagnetic storms, Cosmic rays (CR), Muon anisotropy

PACS Nos: 96.60.*ph*; 96.50.Bh; 96.50.*sh*

1 Introduction

Cosmic ray (CR) intensities as recorded first by ionization chambers and later by meson telescopes and neutron monitors indicate variations on different time scales: minutes (solar flare effects) to hours, days (Forbush decreases, FD) and years (11-year solar cycle variation). The instruments located at different latitudes, longitudes and altitudes show quantitative as well as qualitative differences, some of which are due to spatial anisotropies[1-3]. Many other researchers have studied relationships of muon anisotropies with interplanetary parameters and reported interplanetary magnetic field (IMF) dependence[4-12]. Some researchers have indicated that these studies may have some application in space weather forecasting[8,10,13-15]. 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 (~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. There are at least three major setups of muon telescopes, one at Southern Space Observatory (SSO) at São Martinho de Serra, South Brazil (29°S, 53°W, 500 m altitude), another at Ooty (11°N, 77°E, 2200 m altitude) in South India, and another at Nagoya, Japan (35°N, 137°E, 77 m altitude; other details on the website http://www.stelab.nagoya-u.ac.jp/omosaic/nagoya/muon1.html). Only the data at Nagoya has been used as it was easily accessible at their website.

For geomagnetic storm index [Dst(min)], the interplanetary parameter with best correlation is the Bz(min) (ref. 16). However, as shown by Kane[17], even for the same high Bz(min) of -25 nT, the Dst(min) magnitude can vary in a large range, -200 to

-500 nT. In the present paper, it is examined if directional muon telescope intensity changes can predict Dst(min) magnitudes more accurately.

2 Data

The hourly data for interplanetary parameters and for cosmic ray neutron monitors were obtained from the NOAA (SPIDR) website. The data for muons at Nagoya were obtained from the document "About Nagoya Multi-Directional Muon Telescope" in the Nagoya website http://www.stelab.nagoya-u.ac.jp/ste-www1/div3/muon/muon3.html. The muon data given there are not in the usual format of hourly counting rate N but are given as logarithms ln(N/No) as per the formulation by Wada[18] as:

$$W = 10^2 \times \ln(N/No) + WL \text{ (in units of \%)} \quad \ldots(1)$$

where, *No,* is the average counting rate; and *WL* (15.0%, i. e. 1500) is artificially added to make the values of W always positive. For pressure correction and the barometer corrected relative intensity (WP), the counting rate (N_P) of the digital barometer is converted into atmospheric pressure (P) by using a conversion formula and a set of calibration coefficients (A, B and C) as

$$P = A + B \cdot N_P + C \cdot N_P^2 \text{ hPa} \quad \ldots(2)$$

Coefficients (β's) for the barometer effect correction were derived by a correlation analysis between *P* and *W*'s. Then using the coefficient, the barometer corrected relative intensity (W_P) is obtained by

$$W_P = 10^2 \times [W - \beta \times (P - PO)] \text{ in units of } 0.01\% \quad \ldots(3)$$

The value of *PO* is set to 1000.0 hPa for simplicity, though the yearly average of the atmospheric pressure is 1010 hPa.

From these, one can obtain simply from the table values *W*p, the factor ln(*N*/*No*) as:

$$\ln(N/No) = (\mathrm{Wp} - 1500)/10000 \quad \ldots(4)$$

and (*N*/*No*) can be obtained as antilog of ln(*N*/*No*), i.e. as

$$(N/No) = \exp[\ln(N/No)] \quad \ldots(5)$$

More simply, since $W = 10^4 \times \ln N$, for *N*i at the start of the FD and *N*j at the end of the FD, the difference

$$Wi - Wj = 10^4 \times (\ln Ni - \ln Nj) = 10^4 \times \ln(Ni/Nj)$$
$$= 10^4 \times \ln[1-(Nj-Ni)/Nj)] = 10^4 \text{ x } (Nj-Ni)/Nj$$

Thus, the percentage change is obtained simply as (*W*i-*W*j)/10000.

For all the data from the Nagoya website, the percentage changes of FD magnitudes have been calculated by the above formulation (Courtesy: Dr. Zenjiro Fujii, Solar-Terrestrial Environment Laboratory, Nagoya University).

3 Halloween events of 29-30 October 2003

Figure 1 shows a plot of hourly values during the 5-day interval 27-31 October 2003 which was characterized by the occurrence of several solar flares and major CMEs[19-21]. The first four plots are for the interplanetary parameters, number density (N per cm^3) (some data missing or unreliable); solar wind speed V (km s^{-1}); total magnetic field B (nT); and its Bz (nT) component. Negative Bz values are known to cause geomagnetic storms by the Dungey[22] mechanism, where solar wind particles have a free

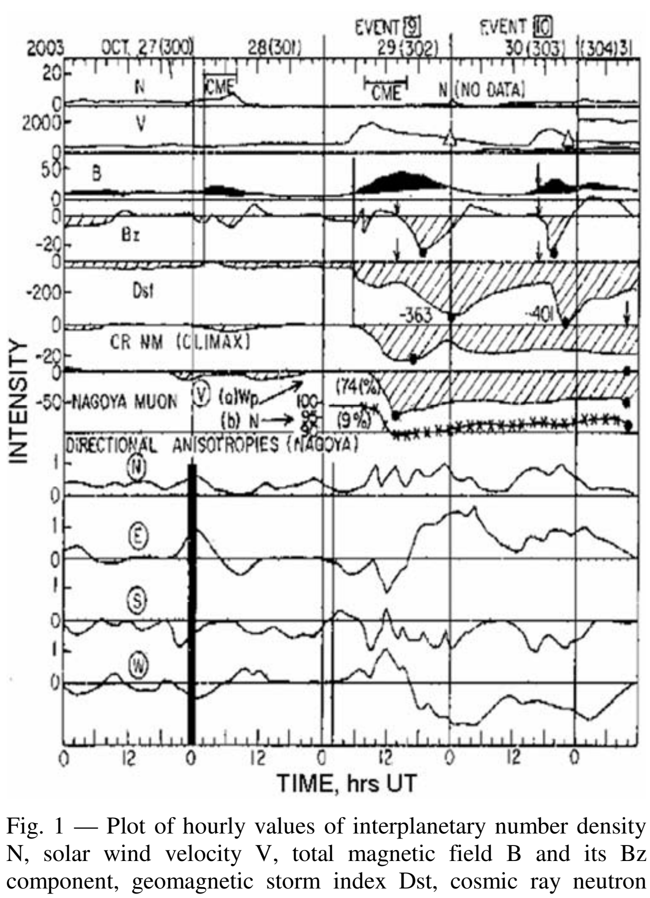

Fig. 1 — Plot of hourly values of interplanetary number density N, solar wind velocity V, total magnetic field B and its Bz component, geomagnetic storm index Dst, cosmic ray neutron monitor CR NM count at Climax, Colorado, cosmic ray vertical muon telescope CR muon V at Nagoya, Japan, and directional anisotropies for Nagoya muon telescopes, averaged over four angles (30°, 39°, 49°, 64°) for the directions N(North), E(East), S(South) and W(West) for the period 27-31 October 2003, which has the Halloween events 9 (Oct 29) and 10 (Oct 30)

entry into the magnetosphere through a neutral point in the magnetotail. The fifth plot is for the geomagnetic disturbance index Dst (ref 23). As can be seen, the Bz values were small negative even on 27-28 October causing small negative Dst values, but the first large Bz(min) of –25 nT occurred at 1900 hrs UT on 29 October resulting into a large Dst(min) of –363 nT, 5 hours later at 2400 hrs UT on 29 October (labeled as Event 9) and the second large Bz(min) of –29 nT occurred at 2000 hrs UT on 30 October resulting into a large Dst(min) of –401 nT, 2 hours later at 2200 hrs UT on 30 October (labeled as Event 10). [About values for these October Halloween events, there are uncertainties. The Bz(min) hourly values of –25 and –29 nT seem to be too small for causing the very large Dst(min) values of –363 and –401 nT. Skoug *et al.*[19] mentioned that for some intervals, the satellite data were missing. They also mentioned that Bz(min) values could have exceeded –50 nT. Hence, two alternatives have been done, some analyses using Bz(min) as –25 nT and –29 nT, and some with Bz(min) –50 nT and - 50 nT]. The next plot is for the CR count rate of the neutron monitor NM operating at Climax, Colorado, USA. It shows a very large FD of ~25% at 1700 hrs UT on 29 October, 7 hours before the Dst(min) at 2400 hrs UT. Later, when Dst(min) had the second minimum at 2200 hrs UT on 30 October, CR intensity did not show a clear minimum, only an extended low level of ~20%, continuing from the earlier CR minimum. Thus, evolutions of FD and Dst were very different in these two successive events.

At Nagoya, 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 rigidity of primary cosmic rays is several tens of GV, with a geomagnetic bending equivalent to a few hours in the east-west direction. The hourly counting rates have standard errors generally of less than 0.5%, but for some, much less (For 39^o, there was no data for N, E, W, S but only for NE, SE, NW, SW but for uniformity, these have been considered as for N, E, W, S). The vertical component V is plotted in Fig. 1 as the seventh plot. There are two plots here for muon V (vertical). The full line plot (a) is for W_P data, It is similar to that of CR neutron monitor at Climax (~25%), but the magnitude in V is much larger (~75%). The second plot (b) (crosses joined by lines) is for the intensity (N/No). This plot also is very similar to that of CR neutron monitor and very similar to the plot (a) of W_P, but the magnitude in V for the intensity (N/No) is much smaller in (b) ~12%, in contrast to ~75% in (a). Thus, whether one uses the standard values N or the logarithm ln (N/No) represented by the Nagoya website table values W_P, does not make much difference qualitatively (FD starts and ends at similar hours in both), but the quantitative value of FD is ~6 times lower for N values. This is encouraging because qualitative features (maxima, minima) would be at the same hours in both (N/No) and ln(N/No). This is understandable, as the functions x and logx increase or decrease similarly, though in different magnitudes.

For the 16 parameters N, E, S, W of 30^o, 39^o, 49^o, 64^o, detailed plots for 28-31 October 2003 have been shown in the earlier paper[21] and are not shown here. All those showed FDs similar to V, but with varying magnitudes (~5-10%). For obtaining the anisotropies, the N. E. S, W of 30^o were first averaged to give 30^o (average) which showed isotropic FD. Then this was subtracted from each 30^o (N, E, S, W) to yield the four anisotropies 30^{o}N(anis), 30^{o}E(anis), 30^{o}S(anis), 30^{o}W(anis). Similarly, subtracting the 39^o(average), four anisotropies 39^{o}N(anis), 39^{o}E(anis), 39^{o}S(anis), 39^{o}W(anis).were obtained; subtracting the 49^o(average), four anisotropies 49^{o}N(anis), 49^{o}E(anis), 49^{o}S(anis), 49^{o}W(anis) were obtained; and subtracting the 64^o(average), four anisotropies 64^{o}N(anis), 64^{o}E(anis), 64^{o}S(anis), 64^{o}W(anis) were obtained. Thus, there were 16 anomaly parameters. All these have not been shown here but the averages for all angles [N = average of 30^{o}N(anis), 39^{o}N(anis), 49^{o}N(anis), 64^{o}N(anis)], [E = average of 30^{o}E(anis), 39^{o}E(anis), 49^{o}E(anis), 64^{o}E(anis)], [S = average of 30^{o}S(anis), 39^{o}S(anis), 49^{o}S(anis), 64^{o}S(anis)], [W = average of 30^{o}W(anis), 39^{o}W(anis), 49^{o}W(anis), 64^{o}W(anis)] have been shown in bottom part of Fig. 1. As can be seen, these show considerable fluctuations, ~1%, positive or negative, during the storm intervals, but here, main interest has been to know what happened in the pre-storm interval. Here, near the 0000 hrs UT on 28 October, there are anisotropies of ~1%, positive or negative (marked by the solid rectangle). These could be interpreted as precursors, but there is one serious problem. The CME responsible for the 29 October event (number 9) erupted at the Sun only after

0200 hrs UT on 29 October and its ICME blob would be in the interplanetary space only a few hours after 0200 hrs UT on 29 October, when it had shown anisotropies. Thus, the ~1% anisotropies seen at ~0000 hrs UT cannot be due to this ICME, but probably due to some earlier small interplanetary blob. This indicates the hazards of interpretation of anisotropies as precursors. Some studies about the anisotropic features of FD events and short term variations of cosmic rays using the multidirectional muon telescope of GRAPES III at Ooty have been reported[24-27], while Kuwabara *et al.*[28] have reported studies of the geometry of the interplanetary CME on 29 October 2003. Using simple methods, Kane[29] and Kane[21] illustrated how the anisotropies could reveal roughly the geometry of the blobs during 11 April 2001 and 29-30 October 2003, respectively.

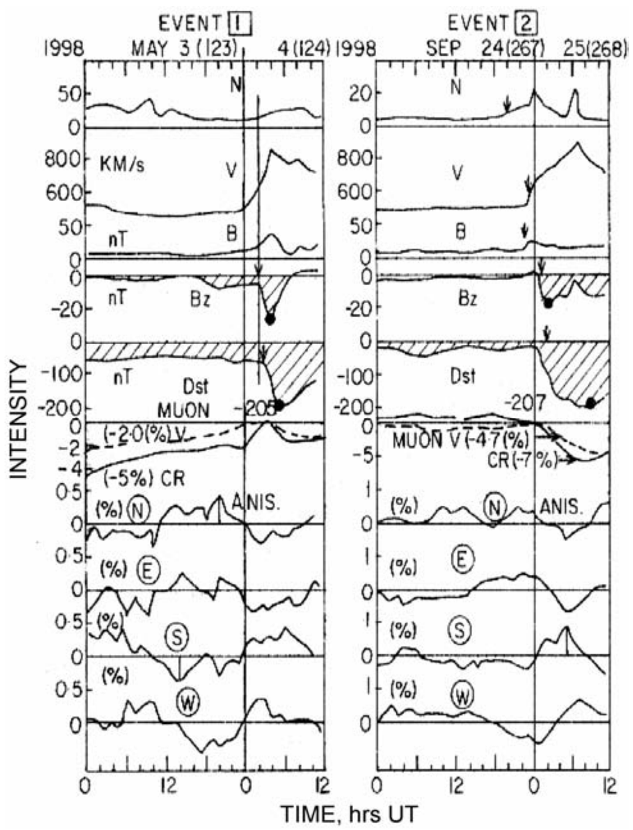

Fig. 2 — Plot of hourly values of interplanetary number density N, solar wind velocity V, total magnetic field B and its Bz component, geomagnetic storm index Dst, cosmic ray neutron monitor CR NM count at Climax, Colorado, cosmic ray vertical muon telescope CR muon V at Nagoya, Japan, and directional anisotropies for Nagoya muon telescopes, averaged over four angles (30°, 39°, 49°, 64°) for the directions N(North), E(East), S(South) and W(West) for event 1 (3-4 May 1998) and event 2 (24-25 Sep 1998)

4 Other events

For cycle 23, hourly interplanetary data could be obtained (at least the magnetic fields B and Bz), CR Climax NM data and the Nagoya muon data for 15 severe storms of [Dst(min) ≤ 200 nT]. Figure 2 shows similar plots for event 1 on 3-4 May 1998 when Dst(min) reached –205 nT and event 2 on 24-25 September 1998 when Dst(min) reached –207 nT. Figure 3 shows similar plots for events 3 and 4. For other events 5-15 (excepting events 9 and 10, which are shown in Fig. 1), diagrams were prepared but are not shown here. However, Table 1 gives details of all the storms 1-15. The following has been noted:

1. Generally, for each event, two consecutive dates are considered and 0000 hrs UT in between is marked by a vertical line.
2. In 29-30 October events, the velocities were very high (~2000 km s^{-1} or more) and the transit

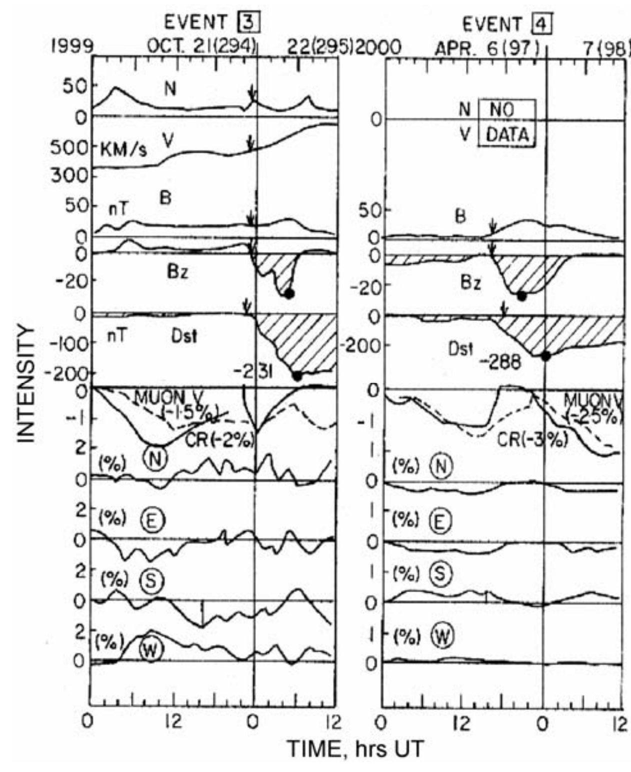

Fig. 3 — Plot of hourly values of interplanetary number density N, solar wind velocity V, total magnetic field B and its Bz component, geomagnetic storm index Dst, cosmic ray neutron monitor CR NM count at Climax, Colorado, cosmic ray vertical muon telescope CR muon V at Nagoya, Japan, and directional anisotropies for Nagoya muon telescopes, averaged over four angles (30°, 39°, 49°, 64°) for the directions N(North), E(East), S(South) and W(West) for event 3 (21-22 Oct 1999) and event 4 (6-7 Apr 2000)

time was ~20 hours. In all other events, the interplanetary velocities were much smaller and the transit time had been more than 24 hours. So, the anisotropies in the 24 hours before the storm would be able to respond to an interplanetary blob. Therefore, the anisotropies in all these events in the 24 hours preceding the storm can be considered as genuine.

3. In almost every storm, there were pre-storm anisotropies. Ignoring the direction, the maximum magnitudes (in any one of the directions N, E, S, W) was ~1% (positive or negative) or less. So, anisotropies of this order were detected and could be considered as legitimate precursors. However, since the magnitudes were not the same for all storms, a quantitative comparison is necessary to see whether the precursors had any quantitative potential to predict whether the storms would be small or big.

5 Quantitative comparisons - Correlations

In Table 1(a), details of the 15 storms given include: event number (1-15), year-month-day, magnitudes of negative Bz(min) and Dst(min), magnitude of interplanetary magnetic field B, the Forbush decrease FD magnitudes for CR NM (neutron monitor) at Climax and the vertical (V) muon telescope at Nagoya, the muon anisotropy maximum magnitudes in any of the 16 parameters (4 angles in 4 directions, positive or negative), and the interplanetary values of V and N at the hour of Dst(min). In Table 1(b), data for each event include: the UT hour at which Bz started becoming negative, lag of Bz(min) in hours with respect to the hour of Bz, lags of negative Dst start and Dst(min) with respect to the Bz start, the time interval between Dst start and Dst(min), time interval between Bz(min) and Dst(min), and lags of CR NM and muon V Forbush decreases FD, with respect to the Bz start.

Table 1(a) — Magnitudes of -Bz start

S No	Event	-Bz(min), nT	-Dst(min), nT	B, nT	CR NM FD, %	Muon V FD, %	Anisotropy any angle	V, km s^{-1}	N, cm^{-2}
1	04 May 1998	30	205	20	5	2.0	0.81	806	20
2	25 Sep 1998	18	207	20	7	4.7	1.02	798	2
3	21 Oct 1999	31	231	35	2	1.5	0.36	546	20
4	06 Apr 2000	28	288	20	3	2,5	0.42	-	-
5	12 Aug 2000	29	235	25	5	1.4	0.27	-	-
6	17 Sep 2000	25	201	30	8	3.5	0.25	-	-
7	31 Mar 2001	45	358	45	3	1.4	0.39	645	20
8	11 Apr 2001	21	256	20	12	3.1	0.37	730	12
9	29 Oct 2003	25, 50	363	50	25	12,3	1.41	2000	-
10	30 Oct 2003	29, 50	401	50	20	10.0	1.41	2000	-
11	20 Nov 2003	46	472	50	5	2.0	0.90	553	20
12	07 Nov 2004	44	373	45	6	2,4	0.78	715	4
13	10 Nov 2004	28	289	30	12	2.8	1.13	697	5
14	15 May 2005	37	263	50	10	4.4	0.99	895	6
15	24 Aug 2005	39	216	50	7	3.0	0.66	621	19

Table 1(b) — Time (hrs UT) of -Bz start and time lag (hours) with respect to hour of -Bz start

S No	Event	-Bz start, hrs UT	Bz(min) lag, h	-Dst start lag, h	Dst(min) lag, h	Dst start to Dst(min), h	Bz(min)to Dst(min), h	CR NM FD lag, h	Muon V FD lag, h
1	05 May 1998	0200	2	1	3	2	1	8	8
2	25 Sep 1998	0100	1	1	8	7	7	9	9
3	21 Oct 1999	2300	6	1	7	6	1	-13	-9
4	06 Apr 2000	1600	5	2	8	6	3	19	19
5	12 Aug 2000	0200	6	1	7	6	1	13	13
6	17 Sep 2000	2000	1	1	3	2	2	6	6
7	31 Mar 2001	0300	3	1	5	4	2	7	7
8	11 Apr 2001	1500	8	2	8	6	0	18	18
9	29 Oct 2003	1400	5	0	10	10	5	3	0
10	30 Oct 2003	1700	3	0	5	5	2	22	22
11	20 Nov 2003	0900	6	0	10	10	4	19	19
12	07 Nov 2004	2000	6	1	10	9	4	4	0
13	10 Nov 2004	0100	3	0	8	8	5	2	4
14	15 May 2005	0500	1	1	3	2	2	2	6
15	24 Aug 2005	0900	0	0	2	2	2	8	8

The following relationships are observed (intercorrelations are given in Table 2).

1. Figure 4(a) shows a plot of muon maximum anisotropy (any angle) percentage magnitudes versus CR Climax neutron monitor FD magnitudes. The scatter is large. The correlation is moderately high (+0.73±0.12), but this is largely contributed by the two Halloween events on 29-30 October, 2003 (two full squares). Without these two events, the correlation for the rest of the 13 pairs is low (+0.39±0.21). Thus, given a magnitude of muon anisotropy, not much can be said about the magnitudes of the CR neutron monitor FDs that follow. It may be noted that even a correlation of 0.70 implies a variance explained of about 50% (square of the correlation) and thus, 50% remains unexplained (random). Thus, no meaningful predictions are possible unless correlations exceed 0.90 (80% variance explained).
2. Figure 4(b) shows a plot of muon maximum anisotropy (any angle) percentage magnitudes versus muon V magnitudes. The scatter is large. The correlation is moderately high (+0.75±0.11), but this is largely contributed by the two Halloween events on 29-30 October 2003 (two full squares). Without these two events, the correlation for the rest of the 13 pairs is low (+0.49±0.195). Thus, given a magnitude of muon anisotropy, not much can be said with any certainty about the magnitudes of the muon V FDs that follow.
3. Figure 4(c) shows a plot of muon maximum anisotropy (any angle) percentage magnitudes versus Dst(min). The scatter is large and the correlation is moderately low (+0.44±0.20) Even this is largely contributed by the two Halloween events on 29-30 October 2003 (two full squares). Without these two events, the correlation for the rest of the 13 pairs is very low (+0.22±0.24), almost zero. Thus, given a magnitude of muon anisotropy, nothing can be said with any certainty about the magnitudes of the Dst(min) geomagnetic storm that follow. If a regression equation is evaluated with these low correlations, the predictions can have an error exceeding 50% (for example, a prediction of Dst = 300 nT, would have an error exceeding ±150 nT, and the prediction could turn out to be anything between ~150 nT and ~450 nT, not able to tell even whether it will be a moderate storm or a very severe storm).
4. Figure 5(a) shows a plot of CR NM FD magnitudes versus the muon vertical FD. The correlation is very good (+0.93±0.04), but largely because of the two giant events 9 and 10 on 29-30 October (big full squares). If these two are omitted, the correlation is only +0.68±0.13 (values in the rectangle in the left bottom). But on the whole, the muon V component seems to show FD characteristics similar to those of CR NM at Climax, with muon V FD magnitudes almost half of those of CR NM. However, this information has no prediction value as all FDs occur simultaneously.
5. Figure 5(b) shows a plot of CR NM FD magnitudes versus Dst(min). The correlation is very poor (0.30±0.24), indicating poor relationship between the evolutions of CR and geomagnetic storms.
6. Figure 5(c) shows a plot of CR NM FD magnitudes versus interplanetary total magnetic field B. The correlation is poor, +0.35±0.26, which is surprising because CR were supposed to be modulated by the total B in an interplanetary blob. Obviously, these snapshot values of B as seen by the ACE satellite do not represent adequately the magnetic structure of the wide region where CR get modulated.
7. Figure 5(d) shows a plot of Bz(min) versus Dst(min). A very good correlation is generally reported, but the correlation here is moderate, +0.46±0.18, if for the 29-30 October events, the Bz(min) values –25 and –29 nT (big full dots) are used. If the values used are –50 nT (the two full dots shifted to the two open circles), the correlation increases to +0.79±0.12. Thus, the low values –25

Table 2 — Inter-correlations

	Bz(min), nT	Dst(min), nT	B, nT	CR NM FD, %	Muon V FD, %	Muon anisotropy, any angle
Bz(min), nT	1.00					
Dst(min), nT	0.79	1.00				
B, nT	0.89	0.63	1.00			
CR NM FD, %	0.38	0.30	0.35	1.00		
Muon V FD, %	0.45	0.31	0.39	0.93	1.00	
Muon anisotropy, any angle	0.48	0.44	0.45	0.73	0.75	1,00

and –29 nT of Bz(min) reported in the NOAA website for the Halloween events seem to be erroneous underestimates, not commensurate with the large Dst(min) –363 nT and –401 nT that were caused by them.

8. Figure 5(e) shows a plot of Bz(min) versus the time of evolution of negative Bz from start to the hour of Bz(min). The correlation is very low, -0.08±0.26. If the Bz(min) values for events 9 and 10 are boosted up from 25 and 29 nT to 50 nT, the correlation is still low, 0.18±0.26. Thus, after the start of negative Bz values, the Bz(min) may occur any time and of any magnitude, both unpredictable.

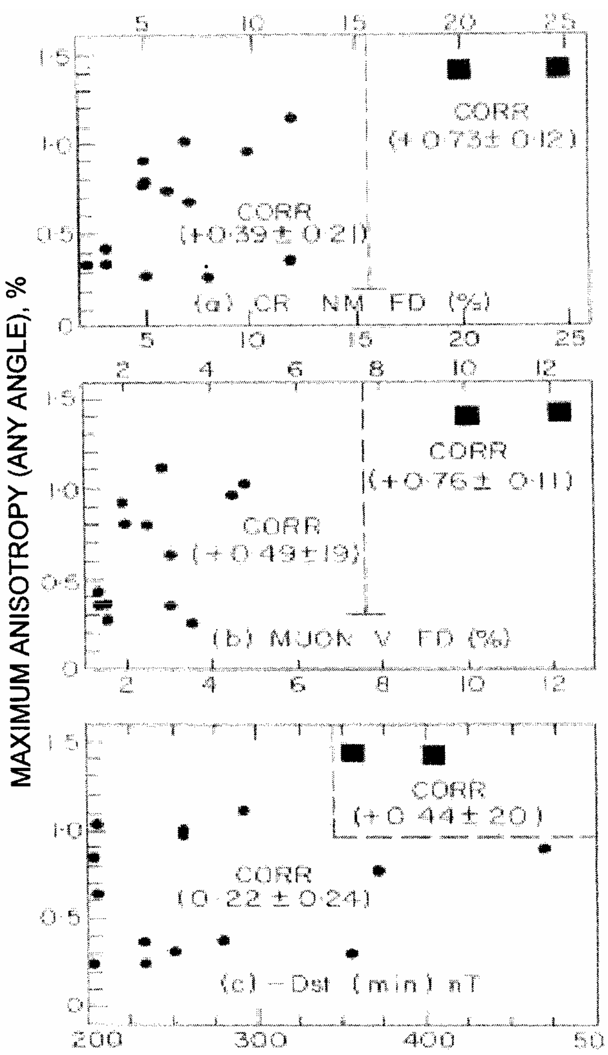

Fig. 4 — A plot of muon maximum percentage anisotropies (any angle) versus: (a) percentage magnitudes of cosmic ray neutron monitor (CR NM) Forbush decreases FD; (b) muon vertical telescope FD; and (c) Dst(min) for the fifteen storm events. Correlations are indicated

9. The –Dst start is within an hour or two of –Bz start. (It may be noted that Bz start is detected by ACE satellite which is near to but away from the Earth towards the Sun. For solar wind, the transit time from ACE to Earth is about half an hour. So, this much delay is normal). Hence, the –Dst storm starts almost simultaneously with the –Bz storm.

10. Figure 5(f) shows a plot of the magnitude Dst(min) versus the time of evolution (obtained as O-N) of negative Dst, from start to the hour of Dst(min). The correlation is 0.61±0.17. Thus, after the start of negative Dst values, longer the evolution time, larger may be the magnitude of Dst(min) in a rough way.

11. The spacing between Bz(min) and Dst(min) is in a very wide range, 0-7 hours (ref. 30 and references therein). The correlations of Dst(min) and Bz(min) with this spacing were very low, –0.26±0.25 and +0.10±0.26, indicating that even if large Bz(min)

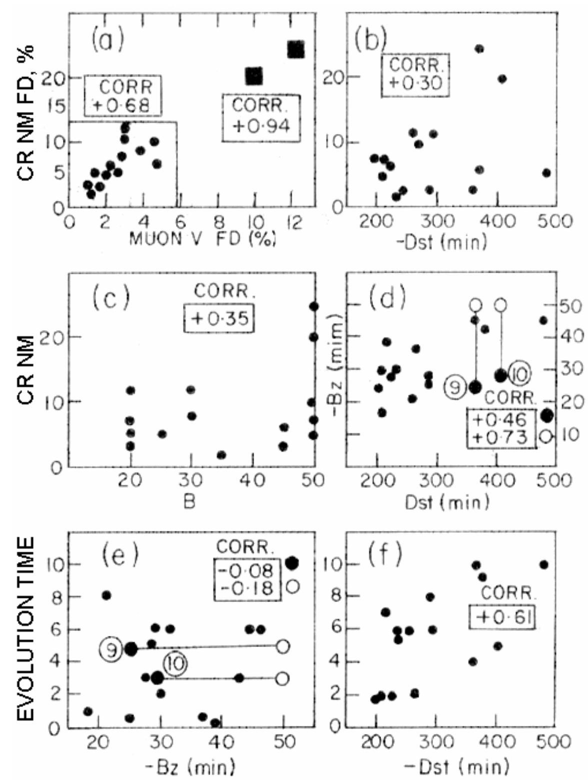

Fig. 5 — Plots of CR NM Forbush decrease magnitudes versus: (a) muon vertical; (b) Dst(min); and (c) interplanetary B. Further plots are: (d) Bz(min) versus Dst(min); (e) evolution times of Bz(min) versus magnitude of Bz(min); and (f) evolution times of Dst(min) versus magnitude of Dst(min). Correlations are indicated. In (d) and (e) where Bz(min) is involved, two correlations are indicated, one for the values –25nT, –29 nT (big dots) and the other for values –50, -50nT (open circles, joined by straight lines to the big dots) for the Halloween events 9, 10 of 29-30 October 2003

occurs and its value becomes known, one cannot tell anything about the time of occurrence and magnitude of the Dst(min) that would follow.

12. The hours of CR NM FD and muon V FD are very similar to each other (expected, as both are cosmic rays) but their lags with respect to hours of Bz(min) or Dst(min) changed very much from event to event, again indicating that in any storm, the geomagnetic Dst storms and CR FDs evolved very differently from each other.

Thus, in almost all cases, the correlations are low and hence, prediction potentials are poor. Kudela *et al.*[31] and Kudela & Storini[32,33] have explored the variations of cosmic rays *vis-a-vis* geomagnetic activity and space weather but quantitative predictions with any antecedence have not been possible.

6 Discussions and Conclusion

For 15 severe storms (Dst ≤ -200 nT), which occurred during solar cycle 23 (1996-2006), the hourly data for Nagoya muon directional telescopes were examined to see whether any anisotropies could be detected during ~24 hours preceding the main storm period of Dst(min). It was observed that for each one of these storms, there were anisotropies in one or more of the 16 directional telescopes (angles with vertical, 30^{o}, 39^{o}, 49^{o}, and 64^{o}, in each of the directions North, East, South and West). The maximum magnitudes were ~1% or less, different in different events. These anisotropy magnitudes had reasonably good relationships (correlation +0.75) with the magnitudes of the following Forbush decrease (FD) in the muons in the vertical direction V (muon V) and also in CR neutron monitor (NM) data at Climax, Colorado USA. But a correlation of ~0.75 implies a variance explained (square of correlation) of only ~55%, leaving ~45% as random component. With geomagnetic Dst(min), the muon anisotropy magnitudes had a still lower correlation (+0.44±0.20), which would imply a variance explained of only ~20%, leaving ~80% as random component. If a regression equation is tried with such a low correlation, the predicted values of Dst(min) of say, 300 nT would have an uncertainty exceeding 50%. Thus, at least for the events studied in this investigation, given a magnitude of muon anisotropy, nothing can be said with any certainty about the magnitudes of the Dst(min) geomagnetic storm that follows, and one will not able to tell even whether it will be a moderate storm or a very severe storm. Manoharan[34] has described a study of the evolution of coronal mass ejections (CMEs) in the inner heliosphere (heliocentric distance <30 solar radii), using white-light and scintillation images. Many aspects of the speed evolution of CMEs during their transit in the interplanetary space are given. However, even when the speed and arrival times at 1 AU could be correlated for 30 CME events, there was nothing to indicate when exactly and how strong the following geomagnetic storms would be.

Some recent studies[35-39] have reported muon telescope set-ups at different locations and relationships of their data with interplanetary parameters.

Acknowledgements

The author gratefully acknowledges the partial support by FNDCT, Brazil, under contract FINEP-537/CT for this work.

References

1. Nagashima K, Tatsuoka R & Matsuzaki S, Spurious sidereal daily variation of cosmic rays produced from stationary anisotropy of solar origin, *Nuovo Cimento (Italy),* 6C (1983) 550.
2. Hall D L, Munakata K, Yasue S, Mori S, Kato C, Koyama M, Akahane S, Fujii Z, Fujimoto K, Humble J E, Fenton A G, Fenton K B & Duldig M L, Gaussian analysis of two hemisphere observations of galactic cosmic ray sidereal anisotropies, *J Geophys Res (USA),* 104 (1999) 6737.
3. Kojima H, Fujimoto K, Gupta S K, Hayashi Y, Ishida Y, Ito N, Jain A, Kawakami S, Nonaka T, Oshima A, Sivaprasad K, Tamaki S, Tanaka H, Tonwar S C & Hikoshi T, Observations of anisotropy of cosmic rays with solar time using the multidirectional muon telescope of GRAPES-3 shower array, *Proc 28th International Cosmic Ray Conference* (Tsukuba, Japan), 7 (2003) 3913.
4. Munakata K, Miyasaka H, Sakurai I, Yasue S, Kato C, Akahane S, Koyama M, Hall D L, Fujii Z, Fujimoto K, Sakurazawa S, Humble J E & Duldig M L, Solar cycle variations of modulation parameters of galactic cosmic rays in the heliosphere, *Adv Space Res (UK),* 29 (2002) 1527.
5. Barnden L R, The large-scale magnetic field configurations associated with Forbush decreases, *Proc 13th International Cosmic Ray Conference* (Denver, USA), 2 (1973) 1277.
6. Iucci N, Parisi M, Signorini C, Storini M & Villoresi G, Short-term cosmic-ray increases and magnetic cloud-like structures during Forbush decreases, *Astron Astrophys Suppl Ser (France),* 81 (1989) 367.
7. Nagashima K, Sakakibara S, Fujimoto K, Tatsuoka R & Morishita I, Localized pits and peaks in Forbush decrease associated with stratified structure of disturbed and undisturbed magnetic fields, *Nuovo Cimento (Italy),* 13C (1990) 551.
8. Bieber J W, Cane H, Evenson P, Pyle R & Richardson I, Energetic particle flows near CME shocks and ejecta, *Sol Wind Nine*, (*Italy),* 471 (1999) 137.
9. Hofer M & Fluckiger E O, Cosmic ray spectral variations and anisotropy near Earth during the March 24, 1991 Forbush decrease, *J Geophys Res (USA),* 105 (2000) 23085.

10. Belov A V, Dorman L I, Eroshenko E A, Iucci N, Villoresi G & Yanke V G, Anisotropy of cosmic rays and Forbush decreases in 1991, *Proc 24th International Cosmic Ray Conference* (Rome, Italy), 4 (1995) 912.
11. Belov A V, Eroshenko E A & Yanke V G, Modulation effects in 1991-1992 years, *The 31st ESLAB Symposium on Correlated Phenomena at the Sun, in the Heliosphere, and in Geospace* SP-415 (ESTEC, Noordwijk, Holland), 1997, 463.
12. Nagashima K, Fujimoto K, Sakakibara S, Morishita I & Tatsuoka R, Local-time-dependent pre-IMF-shock decrease of cosmic rays produced respectively by their IMF-collimated outward and inward flows across the shock responsible for Forbush decreases, *Planet Space Sci (UK)*, 40 (1992) 1109.
13. Bieber J W & Evenson P A, CME geometry in relation to cosmic ray anisotropy, *Geophys Res Lett (USA),* 25 (1998) 2955.
14. Cane H V, Coronal mass ejections and Forbush decreases, *Space Sci Rev (Netherlands),* 93 (2000) 55.
15. Leerungnavarat K, Ruffalo D & Bieber J W, Loss cone precursors to Forbush Decreases and advance warning of space weather effects, *Astrophys J (USA),* 593 (2003) 587.
16. Echer E, Gonzalez W D & Tsurutani B T, Interplanetary conditions leading to superintense geomagnetic storms (Dst <-250 nT) during solar cycle 23, *Geophys Res Lett (USA)*, 35 (2008), L06S03, doi: 10.1029/2007GL031755.
17. Kane R P, Scatter in the plots of Dst(min) versus Bz(min), *Planet Space Sci (UK),* 58 (2010) 1792.
18. Wada M, Logarithmic representation of cosmic–ray intensity, *J Sci Res Inst (Japan),* 51 (1957) 201.
19. Skoug R M, Gosling J, Steinberg J, McComas D J, Smith C W, Ness N F, Hu Q & Burlaga L F, Extremely high speed solar wind: October 29–30, 2003, *J Geophys Res (USA),* 109 (2004), A09102, doi: 10.1029/2004JA010494.
20. Kane R P, Limitations of the utility of CMEs for forecasting timings and magnitudes of geomagnetic Dst storms, *Indian J Radio Space Phys,* 37 (2008) 303.
21. Kane R P, Cosmic ray anisotropies during the Oct 28-31, 2003 Halloween events, *Indian J Radio Space Phys*, 37 (2008) 28.
22. Dungey J W, Interplanetary magnetic field and the auroral zones, *Phys Rev Lett (USA),* 6 (1961) 47.
23. Sugiura M, Hourly values of the equatorial Dst for IGY, *Ann Int Geophys Year (USA),* 35 (1964), pp. 945-948.
24. Kawakami S, Fujimoto K, Gupta S K, Hayashi Y, Ito N, Jain A, Kojima H, Mohanty D K, Nonaka T, Noto S, Ravindran K C, Satomi K, Sivaprasad K, Tanaka H, Tonwar S C, Toyofuku T, Viswanathan K & Yoshikoshi T, The first outcome on the 3-D feature of Forbush decrease events from large muon telescope of GRAPES III at Ooty, *Proc 27th International Cosmic Ray Conference* (Humberg, Germany), 9 (2001) 3473.
25. Mohanty P K, Gupta S K, Aikawa Y, Gopalakrishnan N V, Hayashi Y, Ito N, Iyer A, Jain A, Jagadeesan P, John A V, Karthikeyan S, Kawakami S, Matsuyama T, Mohanty D K, Morris S D, Nonaka T, Oshima A, Rao B S, Ravindran K C, Sivaprasad K, Sreekantan B V, Tanaka H, Tonwar S C, Viswanathan K & Yoshikoshi T, Angular resolution of the GRAPES-3 EAS array for UHE gamma-ray astronomy, *Proc 29th International Cosmic Ray Conference* (Pune, India), 6 (2005,) 21.
26. Nonaka T, Hayashi Y, Ishida Y, Ito N, Kawakami S, Oshima A, Tamaki S, Tanaka H, Yoshikoshi T, Fujimoto K, Kojima H, Gupta S K, Jain A, John A V, Mohanty D K, Mohanty P K, Morris S D, Ravindran K C, Sivaprasad K, Sreekantan B V, Tonwar S C & Viswanathan K, 2003, Study of cosmic ray short term variations using GRAPES-3 muon telescopes, *Proc 28th International Cosmic Ray Conference* (Tsukuba, Japan), 6 (2003) 3569.
27. Nonaka T, Gupta S K, Hayashi Y, Ito N, Jain A, John A V, Karthikeyan S, Kawakami S, Kojima H, Matsumoto K, Matsumoto Y, Matsuyama T, Mohanty D K, Mohanty P K, Morris S D, Okuda T, Oshima A, Rao B S, Ravindran K C, Sasano M, Sivaprasad K, Sreekantan B V, Tanaka H, Tonwar S C, Viswanathan K & Yoshikoshi T, Short-term variations of galactic cosmic rays observed with GRAPES-3 muon telescopes, *Proc 29th International Cosmic Ray Conference* (Pune, India), 1 (2005) 359.
28. Kuwabara T, Munakata K, Yasue S, Kato C, Akahane S, Koyama M, Bieber J W, Evenson P, Pyle R, Fujii Z, Tokumaru M, Kojima M, Marubashi K, Duldig M L, Humble J E, Silva M R, Trivedi N B, Gonzalez W D & Schuch N J, Geometry of an interplanetary CME on October 29, 2003 deduced from cosmic rays, *Geophys Res Lett (USA),* 31 (2004), L19803, doi: 10.1029/2004GL020803.
29. Kane R P, Cosmic ray anisotropies around the Forbush Decrease of April 11, 2001, *Sol Phys (Netherlands),* 234 (2006) 353.
30. Kane R P, A comparative study of geomagnetic, interplanetary and cosmic ray storms, *J Geophys Res (USA),* 82 (1977) 561.
31. Kudela K, Venkatesan D, Flueckiger E O, Langer R. Martin I M, Slivka M & Graumann H, Cosmic ray variations: periodicities at T<24 hours, *Proc 24th International Cosmic Ray Conference* (Rome, Italy), 4 (1995) 928.
32. Kudela K & Storini M, Cosmic ray variability and geomagnetic activity: a statistical study, *J Atmos Sol-Terr Phys (UK),* 67 (2005) 907.
33. Kudela K & Storini M, Possible tools for space weather issues from cosmic ray continuous records, *Adv Space Res (UK)*, 8 (2006) 1443.
34. Manoharan P K, Evolution of coronal mass ejections in the inner heliosphere: A study using white-light and scintillation images, *Sol Phys (Netherlands),* 235 (2006) 345.
35. Duldig M L, Muon observations, *Space Sci Rev (Netherlands),* 93 (2000), 207.
36. Chilingarian A, Arakelyan K, Avakyan K, Babayan V, Bostanjyan N, Chilingarian S, Danielyan V, Daryan A, Egikyan A, Eganov V, Gharagyozyan G, Ghazaryan S, Hairapetyan T, Hovhanissyan A, Hovhannisyan T, Ivanov V, Karapetyan G, Kostanyan Kozliner G L, Gevorgyan N, Martirosian H, Melkumyan, Nazaryan L M, Reimers A, Rostomyan G, Tserunyan & Zazyan S M, Correlated measurements of secondary cosmic ray fluxes by the Aragats Space - Environmental Center monitors, *Nucl Instrum Methods Phys Res A (Netherlands),* 543 (2005) 483.
37. Dorman L I, Applbaum D S, Pustilnik L A, Sternlieb, A, Zukerman I G & Yanke V G, New multidirectional muon telescope and EAS installation on Mt. Hermon (Israel) in combination with NM-IQSY, *Proc 29th International Cosmic Ray Conference* (Pune, India), 2 (2005) 469.
38. Angelov, I, Malamova E & Stamenov J, The Forbush decrease after the GLE on 13 December 2006 detected by the muon telescope at BEO – Moussala, *Adv Space Res (UK),* 43 (2009) 504.
39. Savian J F, da Silva M R, Dal Lago AD, Echer E, Vieira A E D, Munakata K, Gonzalez W D & Schuch N J, Forbush decrease on November 6-12, 2004 observed by the muon detector network, *Rev Bras Geofis (Brazil)*, 25 (2007) 169.