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EFFECTS OF THE POLARITY STATES OF THE HELIOSPHERIC MAGNETIC FIELD AND PARTICLE DRIFTS IN COSMIC RADIATION

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Abstract. Forbush decrease (FD) events recorded at the ground-based neutron monitors (NMs) during the period 1961 – 1999, have been selected and recovery characteristic of these events have been analyzed. The average profile of FDs observed during different polarity states of the heliosphere is obtained by superposed epoch analysis separately for the periods 1961 – 1969 ($A < 0$), 1971 – 1979 ($A > 0$), 1981 – 1989 ($A < 0$) and 1991 – 1999 ($A > 0$). Hourly count rate of neutron monitors of different cut-off rigidities have been utilized. The results are compared with model predictions including drifts. No marked difference is observed in the amplitudes of FDs during $A < 0$ and $A > 0$. Rigidity spectrum fitted with a power law yields the values of spectral exponent that are closer to values predicted by two-dimensional models including drifts. The recovery rate of FDs varies with the polarity of HMF and the rate is higher (recovery time smaller) during $A > 0$ than during $A < 0$ epoch, consistent with the model predictions including the drift effects in the HMF. This difference in recovery time of FDs during $A > 0$ and $A < 0$ polarity conditions provides experimental evidence that drift plays an important role in cosmic ray modulation.

1. Introduction

Intensity of galactic cosmic rays entering the heliosphere is modified as they travel through the Heliospheric Magnetic Field (HMF) embedded in the solar wind. The large-scale HMF consists of a Parker spiral, the opposite magnetic hemispheres are divided by a thin current sheet. In the decades 1970s and 1990s, the field is directed outward in the northern and inward in the southern magnetic hemisphere. In this configuration, referred to as $A > 0$, positively charged particles drift inward at the poles and then downward from the poles toward the current sheet (near the equator). In the opposite polarity configuration *i.e.* in 1960s and 1980s, referred to as $A < 0$, particles drift inward along the current sheet (near the equator) and then upward toward the poles. Thus, it might be expected that incoming cosmic rays will be affected differently by drift effects during the two magnetic configuration $A > 0$ and $A < 0$.

The cosmic ray modulation has been known to have various time scales. A Forbush decrease (FD) is a short term modulation occurring in $\sim$1 day and recovering over a few days. Since their discovery (Forbush, 1937), FDs have been studied extensively and, in general, these decreases were attributed to solar flares (*e.g.* Lockwood, 1971; Iucci *et al.*, 1979). However, Duggal and Pomerantz (1977) suggested that the majority of cosmic ray decreases are related to the passage of active centers and cannot be uniquely assigned to specific solar flares. Later analysis, utilizing coronograph observations of CMEs and their association with interplanetary shocks, have found that FDs and major geomagnetic storms are well associated (see, Kane, 1977; Kudela and Brenkus, 2004) as noted first by Forbush (1938), and largest geomagnetic storms are caused by CMEs and associated shocks (Gosling, 1993). Forbush decreases result from shocks/CMEs (Badruddin, Yadav, and Yadav 1986; Venkatesan and Badruddin, 1990; Cane, 1993, 2000; Badruddin, 2002; Badruddin and Singh, 2003a). Though the time scales of various modulation effects differ from each other, the basic process must be common *i.e.* interaction between cosmic ray particles and HMF irregularities. Thus, investigation of the FDs would also lead to the understanding of modulation with other time scales (Kadokura and Nishida, 1986).

The aim of this work is to study the effect of large-scale HMF polarity and drift on the amplitude and recovery characteristics, and rigidity spectrum of FDs. The obtained results are discussed in the light of simulation of FDs including drift effects.

2. Analysis

Isolated FDs during the periods, 1961 – 1969, 1971 – 1979, 1981 – 1989 and 1991 – 1999, excluding the periods of polarity reversal, are selected by visual inspection of hourly cosmic ray intensity graphs of neutron monitors at Thule ($R_c = 0.0$ GV), Calgary ($R_c = 1.09$ GV), Climax ($R_c = 2.97$ GV), Rome ($R_c = 6.24$ GV) on the basis of the following criteria.

1. There should be a rapid decrease (within ≤ 24 h) followed by slow recovery, at least up to $\geq 70\%$ of the magnitude of decrease within $\sim$10 days.
2. The amplitude of decrease (at Calgary) should be $>1.5\%$ and $<9.5\%$.
3. There should be no sudden decrease/GLE 3 days before or 10 days after the onset of FD under consideration.
4. There should not be any data gap around the time of intensity minimum and/or any other data gap of $\geq$1 day.

The period of analysis covered two $A > 0$ epoch when the polarity of the solar magnetic field is outward in the northern hemisphere such as 1971 – 1979 and 1991 – 1999, and two $A < 0$ epoch of opposite polarity (1961 – 1969 and 1981 – 1989).

We could identify about 20 events each in 1960s, 1970s, 1980s and 1990s, within the criteria mentioned above. After selecting FDs satisfying the above criteria, we studied the amplitude and recovery characteristics statistically. We also applied the superposed epoch (Chree) analysis on the pressure corrected hourly cosmic ray intensity recorded at a number of neutron monitors located at various locations on the Earth well distributed in latitude from pole to equator, by taking the onset time (hour) of each FD as 0 h. The analysis is carried out separately for periods 1961 – 1969, 1971 – 1979, 1981 – 1989 and 1991 – 1999. The data for recovery has been fitted by assuming an exponential recovery.

3. Results and Discussion

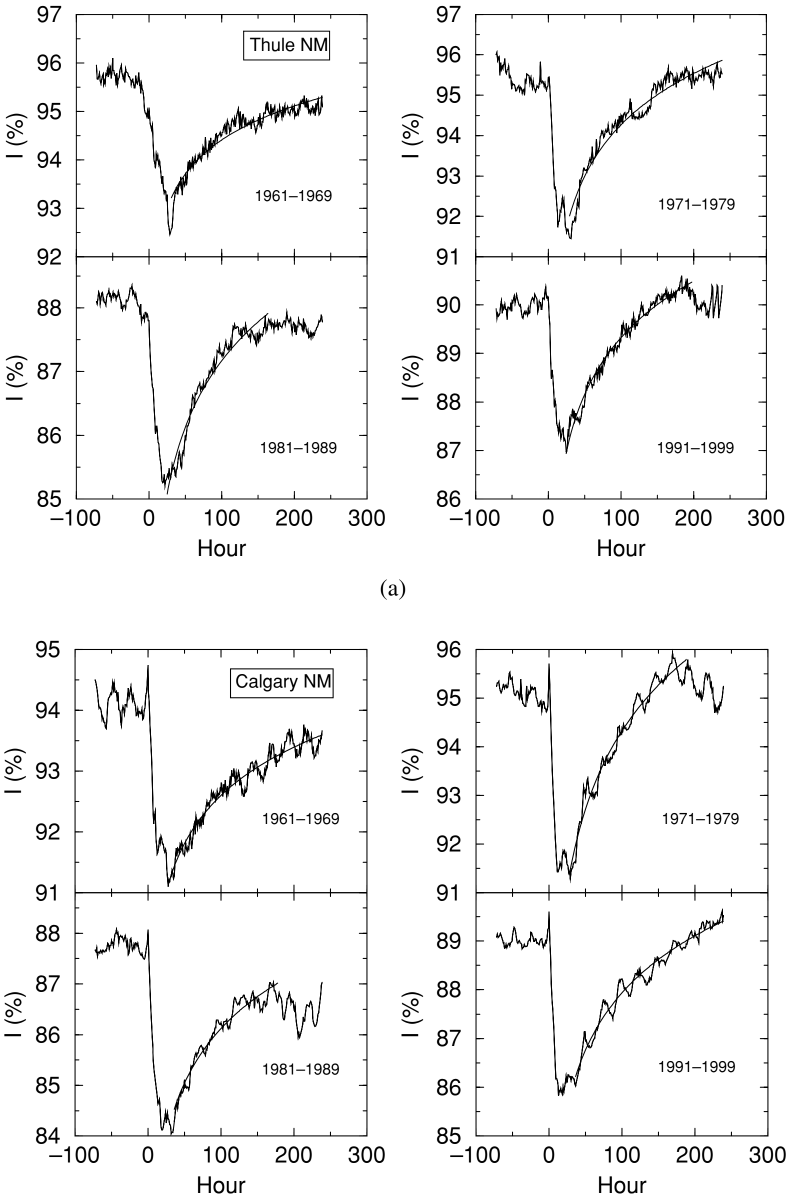
The average time profiles of Forbush decreases recorded at four neutron monitors during 1960s, 1970s, 1980s and 1990s are shown in Figure 1a (Thule NM), Figure 1b (Calgary NM), Figure 1c (Climax NM) and Figure 1d (Rome NM). The data for the recovery were fitted to an equation

$$I = I_0 - \beta \exp(-t/t_0),$$

where I is the normalized intensity in percent of May 1965 minimum modulation level at time t, I_0, also in percent, is the pre-decrease intensity level taken as the mean of the 72-hour intensities before the event and β is the amplitude of decrease. The characteristic recovery time t_0 corresponds to the time for the decrease to decay to e^{-1} times its amplitude. From an examination of these figures, qualitative inferences about a few features of the time profiles, during $A < 0$ (1960s, 1980s) and $A > 0$ (1970s, 1990s) relevant to simulation of Forbush decreases, are as follows: The amplitude of decreases during $A < 0$ and $A > 0$ is not significantly different in two cases and recovery rate is slower during periods 1960s and 1980s ($A < 0$) than 1970s and 1990s ($A > 0$). Qualitative values of amplitude and characteristic recovery time during different periods at four stations are given respectively, in Tables I and II.

We fitted the exponential to individual events selected on the basis of criteria outlined earlier, and obtained the statistics for amplitude and characteristic recovery time, separately, for the periods 1961 – 1969 ($A < 0$), 1971 – 1979 ($A > 0$), 1981 – 1989 ($A < 0$) and 1991 – 1999 ($A > 0$). For the study of statistical distribution of FDs, we have plotted histogram for amplitude by dividing them into four arbitrary groups, depending upon the amplitude of decrease, namely, small amplitude FDs (1.5 – 3.5%), medium amplitude FDs (3.6 – 5.5%), large amplitude FDs (5.6 – 7.5%) and very large amplitude FDs (7.6 – 9.5%). These histograms for 1960s, 1970s, 1980s and 1990s are shown in Figure 2. It is clear from these diagrams that essentially, there is no difference in the frequency distribution during $A < 0$ and $A > 0$ epochs.

In order to study the statistical distribution of characteristic recovery time of FDs, we have categorized them, depending on the range of characteristic recovery time, into quick ($t_0 \leq 35$ h), fast (35 h $< t_0 \leq$ 55 h), normal (55 h $< t_0 \leq$ 75 h) and slow ($t_0 >$ 75 h) FDs. Frequency distribution on the basis of these different groups of FDs are shown in Figure 3. It is seen from these plots that peaks in the histogram



(a)

(b)

Figure 1. Average superposed time profile of Forbush decreases during different polarity states of the heliosphere along with fitted exponential curve during recovery time. (a) Thule Neutron Monitor ($R_c = 0.00$ GV); (b) Calgary Neutron Monitor ($R_c = 1.09$ GV); (c) Climax Neutron Monitor ($R_c = 2.97$ GV); (d) Rome Neutron Monitor ($R_c = 6.24$ GV).

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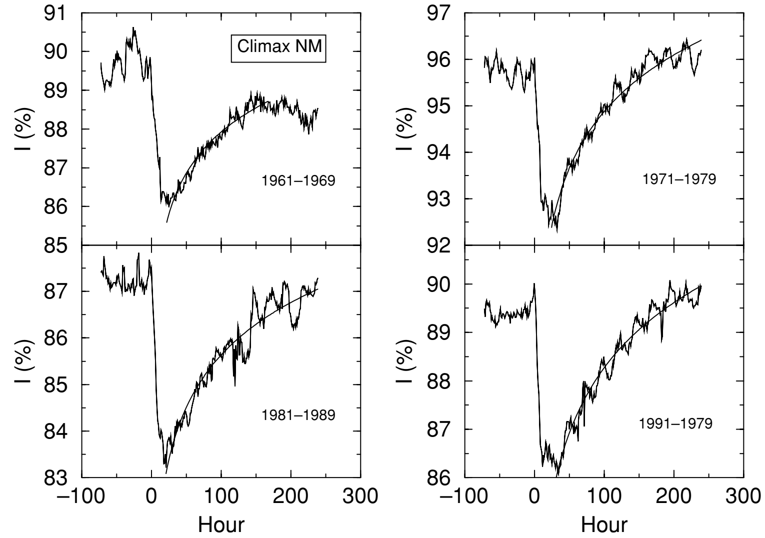
(b)



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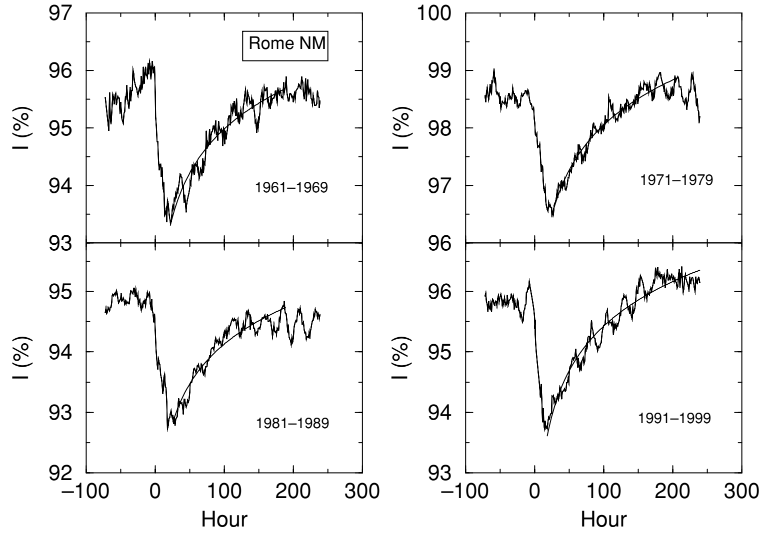


(d)

Figure 1. (*Continued*)

are shifted towards higher t_0 during $A < 0$ (1960s and 1980s) as compared to $A > 0$ (1970s and 1990s) where the peaks are shifted towards lower t_0 values.

As regards the recovery time of FDs in different polarity states of the heliosphere ($A < 0$ and $A > 0$) the following is the consequence of the drift-dominated models.

TABLE I

Amplitude of depression (percent) obtained from average time profile during different epochs.

Period/station	Calgary NM	Climax NM	Rome NM	Thule NM
1961 – 1969	3.15	3.68	2.55	3.24
1971 – 1979	3.85	3.44	2.16	3.81
1981 – 1989	3.71	4.00	2.16	2.72
1991 – 1999	3.13	3.44	2.10	2.96

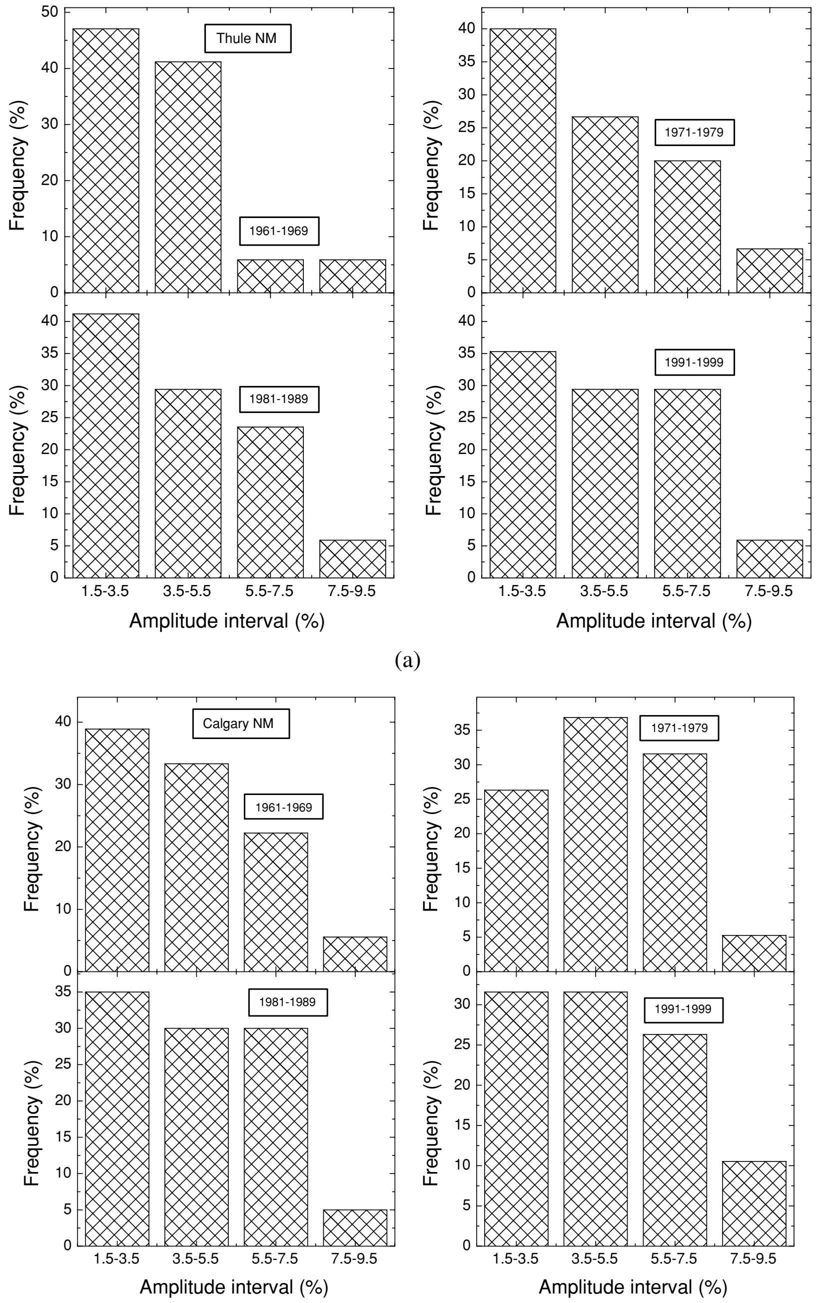
TABLE II

Characteristic recovery time (hours) obtained from average time profile during different epochs.

Period/station	Calgary NM	Climax NM	Rome NM	Thule NM
1961 – 1969	99	92	84	70
1971 – 1979	48	50	57	46
1981 – 1989	80	91	68	60
1991 – 1999	58	65	55	52

In $A > 0$ polarity state when the HMF above the current sheet pointed away from the Sun, cosmic ray particles drift towards the earth from over the solar poles, and under such circumstances, the cavity left behind by propagating disturbance (responsible for FDs) in the equatorial region is expected to be filled at a faster rate and consequently the recovery time will be smaller. This recovery time will be larger when the solar polarity and consequently HMF polarity reverses ($A < 0$), under such condition cosmic ray particles drift towards Earth from the equatorial region and drifting particles will primarily encounter the disturbance (responsible for FDs) head on and the filling process is slower and recovery time is longer in this situation.

The role of gradient and curvature drift on long term modulation has been studied by a number of workers (*e.g.* see Jokipii, 1989; Venkatesan and Badruddin, 1990; Kota, 1991; Potgieter, 1998; Van Allen, 2000; Cliver and Ling, 2001; Boella *et al.*, 2001; Badruddin and Ananth, 2003 and references therein) and many of them emphasized the dominant role of gradient and curvature drifts. On the other hand, the role of drift in the phenomenon of Forbush decrease has been studied by a limited number of workers (*e.g.*, Lockwood, Webber, and Jokipii, 1986; Mulder and Moraal, 1986; Rana, Sharma, and Yadav, 1996; Singh and Badruddin, 2003; Badruddin and Singh, 2003b) and experimental evidences are inconclusive as regards the role of drift during FDs.



(a)

(b)

Figure 2. Frequency distribution of amplitude of FDs during two $A < 0$ and two $A > 0$ epochs as observed at (a) Thule Neutron Monitor ($R_c = 0.00$ GV); (b) Calgary Neutron Monitor ($R_c = 1.09$ GV); (c) Climax Neutron Monitor ($R_c = 2.97$ GV); (d) Rome Neutron Monitor ($R_c = 6.24$ GV)

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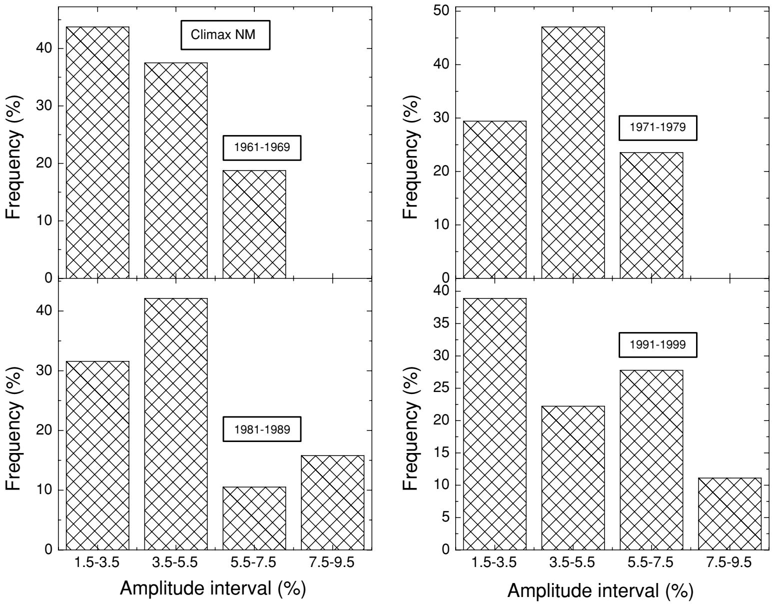

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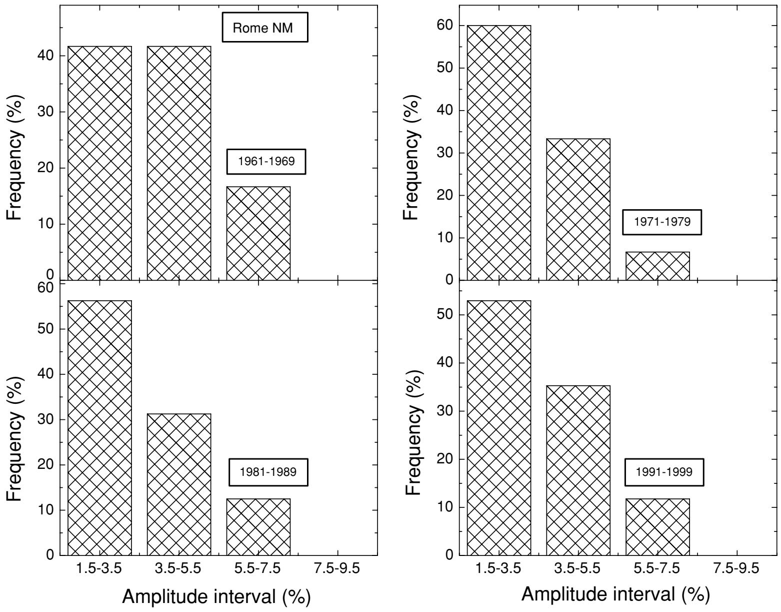
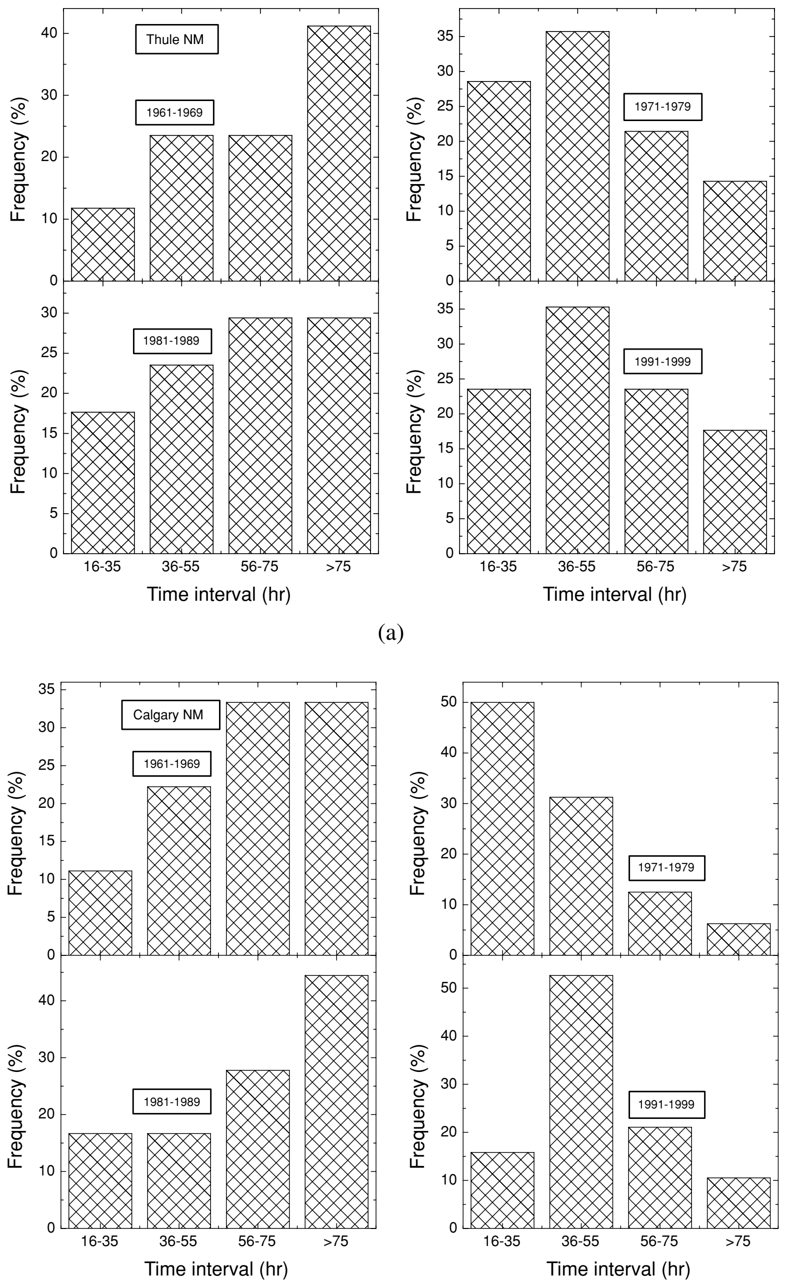


(d)

Figure 2. (*Continued*)



(a)

(b)

Figure 3. Frequency distribution of characteristic recovery time of FDs during two $A < 0$ and two $A > 0$ epochs as observed at (a) Thule Neutron Monitor ($R_c = 0.00$ GV); (b) Calgary Neutron Monitor ($R_c = 1.09$ GV); (c) Climax Neutron Monitor ($R_c = 2.97$ GV); (d) Rome Neutron Monitor ($R_c = 6.24$ GV).

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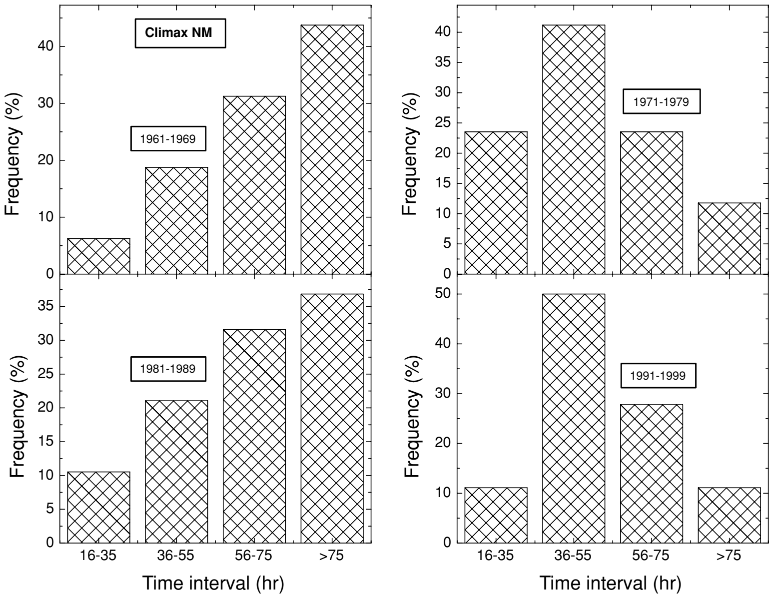

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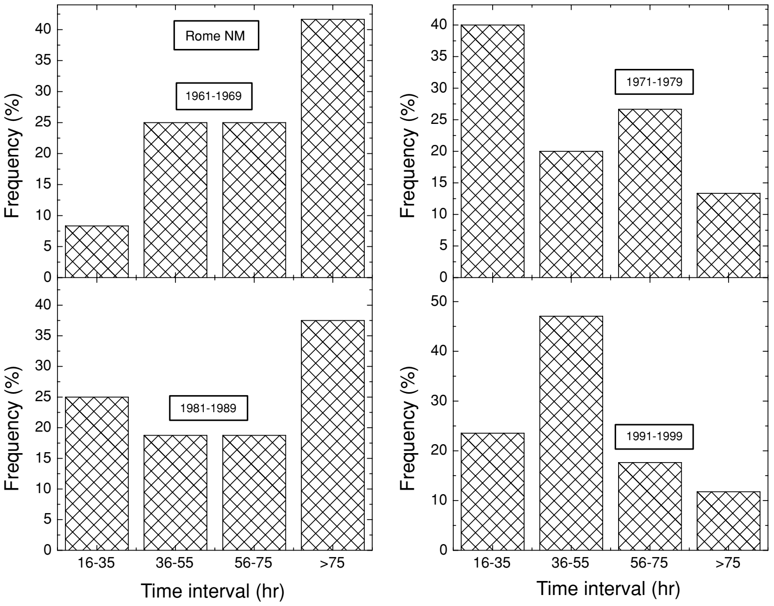

(d)

Figure 3. (*Continued*)

Le Roux and Potgieter (1991) simulated FDs by assuming that turbulent field regions of enhanced scattering cause them and drift effects are diminished in the region that originate at the Sun and propagate onwards. This model predicts almost same amplitude of decrease in both the polarity conditions of HMF ($A < 0$ and $A > 0$) in contrast to two-dimensional numerical model results of Kadokura and Nishida (1986). Kadokura and Nishida model predicts a larger amplitude during $A > 0$ as compared to $A < 0$ polarity conditions. Regarding the recovery time, two-dimensional models of FDs (Kadokura and Nishida, 1986; Le Roux and Potgieter, 1991), which include the effect of the large scale drifts, predict much larger recovery time in $A < 0$ polarity condition of HMF than in $A > 0$ polarity condition. However, when simulation was done by scaling down the drift effect by a factor of 3, the recovery time is much closer in two polarity states. But, the experimental evidences regarding difference in recovery time with reversal of the field remain inconclusive. For example, Lockwood, Webber, and Jokipii (1986) observed no significant change in the recovery time with the reversal of the field. But apparently in contrast with conclusions of Lockwood, Webber, and Jokipii (1986), Mulder and Moraal (1986) and Rana, Sharma, and Yadav (1996) observed that recovery time is less during $A > 0$ as compared during opposite polarity condition $A < 0$.

The rigidity dependence of the amplitude of FDs is given by power law $R^{-\gamma}$, where γ ranges from about 0.4 – 1.2 (Cane, 2000). A number of researchers have examined whether the rigidity dependence of FDs varies with the Sun's polarity and all groups have concluded that it does not (*e.g.* see Morishita *et al.*, 1990; Lockwood, Webber, and Debrunner, 1991; Cane, 2000). The two-dimensional numerical model of FDs (Kadokura and Nishida, 1986) incorporating drift effect predict $\gamma = 0.66$ for $A > 0$ polarity state, 0.54 for $A < 0$ polarity state, when fitted with a power law $R^{-\gamma}$. Their model predicts $\gamma = 0.88$ when drift effects are neglected.

We have determined the rigidity dependence of FDs occurring during 1960s, 1970s, 1980s and 1990s, using data from neutron monitor located at different latitudes with different cut-off rigidities (Calgary, $R_c = 1.09$ GV, Climax, $R_c = 2.97$ GV, Lomnicky Stit, $R_c = 3.84$ GV, Rome, $R_c = 6.24$ GV, Tokyo, $R_c = 11.5$ GV, Huancayo/Haleakala, $R_c = 13.01$ GV). Figure 4 shows the rigidity spectra of the FDs during 1960s, 1980s ($A < 0$) and 1970s, 1990s ($A > 0$). We fitted the spectra with a power law $R^{-\gamma}$, and obtained $\gamma = 0.43$ (1960s) and $\gamma = 0.34$ (1980s) for $A < 0, \gamma = 0.54$ (1970s) and $\gamma = 0.38$ (1990s) for $A > 0$ polarity state of the heliosphere. Although, there is no definite trend in the results, these values of γ are closer to the values obtained when drift effect were incorporated in the model. The difference in power among these cases ($A > 0$, $A < 0$ with drift, and no-drift case) can be understood by the drift effect (Kadokura and Nishida, 1986). For $A > 0$ state the drift effect acts to intensify the density depression on the rear side, and this effect is stronger for the higher rigidity particles. Thus, the spectrum for the $A > 0$ state is harder (*i.e.* γ smaller) than no-drift case. For $A < 0$ state the drift acts to increase the density at the equator and make the depression small for lower rigidity particles. However, for the particles whose rigidity is higher than a

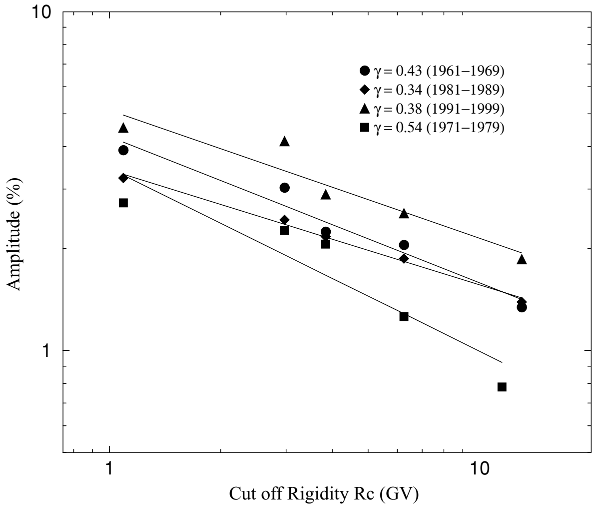

Figure 4. Rigidity spectra of Forbush decreases during 1960s, 1970s, 1980s and 1990s.

critical value it acts to intensify the density depression. As a result the spectrum for $A < 0$ state is harder (γ smaller) than no-drift case.

Our results can be explained by considering the direction of particle drift in the heliosphere (Mulder and Moraal, 1986; Kadokura and Nishida, 1986; Le Roux and Potgieter, 1991). During $A > 0$ epoch positive particles drift from high heliographic latitudes down towards the equatorial plane and outward along the heliosphere current sheet. In the equatorial region drift and radially inward directed diffusion are in opposition. Under these circumstances the cavity left behind by the propagating disturbances in the equatorial region will be filled at a more rapid rate when $A > 0$ than with the drift neglected. When $A < 0$, drift and radial diffusion are complementing each other in the equatorial region, but the particles also drift away from the equatorial plane so that the filling-in of the cavity by particle scattering through the disturbances and latitudinally around is less effective than when they drift downwards from the polar region. The recovery with $A < 0$ is consequently slower than in the no-drift case, and even more so when $A > 0$. The magnitude of the FD does not respond to the polarity change of HMF, illustrating that the drift has an almost negligible effect on the magnitude of FDs at earth (Le Roux and Potgieter, 1991), possibly due to presence of magnetically turbulent region during main (decrease) phase; such region may not be conducive for the drift effect to the observed.

4. Conclusions

- The amplitude of decreases in two polarity states of the heliosphere ($A < 0$ and $A > 0$) are not significantly different consistent with the simulation results of Le Roux and Potgieter (1991) including drifts.

- The values of exponent γ for a power law spectrum are found to be closer to the values given by model calculations including drifts as compared to no-drift case.
- The recovery rate is faster in $A > 0$ epoch as compared to $A < 0$ epoch.

The results presented in this paper, provide experimental evidence that drift effect plays an important role in the modulation of galactic cosmic rays.

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