CHAPTER IV

COSMIC RAY DIURNAL ANISOTROPY DURING INTERPLANETARY MAGNETIC CLOUDS
4.1 INTRODUCTION

'The daily variation' is defined as that portion of the total intensity variation with a frequency of $\frac{1}{24}$ h$^{-1}$ or harmonics thereof. It includes the diurnal variation which is the repetitive portion of the daily variation over many solar rotations. The diurnal variation, in contrast to daily variation is not a true time variation in space, but rather arises because the observations of the cosmic radiation are made from the reference frame of the Earth. The diurnal variation represents a net drift of cosmic ray gas with respect to the reference frame of the Earth. The diurnal variation remains approximately fixed in spatial orientation and is produced by the corotation of the cosmic ray gas with the Sun.

Even though occasional attempts (Rao and Sarabhai, 1964) have been made by few workers to study the cosmic ray daily variation in its entirety without resorting to divide it into its harmonics, most of our information on cosmic ray daily variation has been derived through a study of diurnal and semidiurnal components. A great body of experimental observations has been accumulated in the past concerning the daily variation of cosmic radiation. With the availability of data from neutron monitors for which the atmospheric effects are fairly well understood, it has been possible to examine the daily variation of cosmic radiation in a great detail. The improved statistics provided by the high counting rate neutron-monitors has further improved our knowledge of the daily variation.
The amplitude and the phase of the daily variation of the galactic cosmic ray intensity have been observed to change over various time scales, from day to day up to at least the 22-year solar activity cycle. (Pomerantz and Duggal, 1971; Forbush, 1973; Ananth et al., 1974). Also on theoretical basis it is contemplated that, even during periods of quasi-stationary cosmic ray intensity, the diurnal effect could vary (Parker, 1964) in the extreme case in which the interplanetary magnetic field $\vec{B}$ is highly regular and steady ($\frac{\partial \vec{B}}{\partial t} = 0$), the corotation of the cosmic ray gas with the Sun is prevented by the Liouville theorem (Stern, 1964); in fact as shown by Parker (1964) under such a condition, for a solar wind velocity $\vec{V}$, there results a cosmic ray gradient perpendicular to the ecliptic plane and oriented as $-\vec{V} \times \vec{B}$, which conceals the streaming due to the corotation term. Similarly, in the other extreme case in which on the ecliptic plane the perpendicular diffusion is comparable with the diffusion parallel to the magnetic field lines (i.e. cosmic ray isotropic diffusion), the anisotropy tends to vanish (Pomerantz and Duggal, 1971; Rao, 1972), as it happens, for example, on the occasion of frequent polarity inversions in the interplanetary magnetic field in quasi-stationary condition (Iucci and Storini, 1973). The diurnal effect will be comparable with the one expected on the basis of corotation when at the Earth orbit $K_1 << K_\perp$ and when somewhere along the magnetic lines of force crossing the Earth, inside or outside the Earth orbit, the cosmic-ray diffusion perpendicular to the field lines annuls the cosmic-ray gradient perpendicular to
the ecliptic plane (Parker, 1964, Axford, 1965).

It is evident, however, that the amount of the anisotropy on each individual day will depend on the existing structure of the interplanetary magnetic field, on the cosmic ray density gradient and solar wind speed; the anisotropy may, therefore, reach values much higher than that provided by pure corotation; as it occurs for instance during some Forbush decreases in which the cosmic ray gas is far from the stationary condition.

More than four decades of studies of the diurnal variation of cosmic ray intensity, since the appearance of the first paper by Forbush (1937), have not completed our understanding of this aspect of the solar modulation of cosmic rays. New sets of data that are becoming available have thrown fresh light on an old problem. For example the possible influence of interplanetary magnetic field lines originating above coronal holes on the amplitude of the diurnal variation at neutron monitor energies has been pointed out by Roelof et al. (1975). Extensive reviews by Pomerantz and Duggal (1971, 1974) and Rao (1972) and the references within these reviews provide a comprehensive survey of the subject.

Mc Cracken et al. (1968), Forman (1970), and Forman and Gleeson (1975), following up on their studies of the anisotropies with low-energy solar flare particles, have pointed out that the diurnal anisotropy of galactic cosmic rays also arises from a superposition of convective and diffusive processes. Hashim et al. (1972) have clearly demonstrated that the observed
anisotropies can be satisfactorily explained by considering two components of the streaming galactic cosmic rays: (1) Convective streaming radially away from the Sun with solar wind speed and (2) diffusive streaming along the interplanetary magnetic field (IMF). This streaming is mostly towards the Sun. Hashim et. al. (1972) have further pointed out that the quiet time anisotropy can also be satisfactorily accounted for by such a description. Additional support for these ideas has also come from Mathews et. al. (1969), Ananth et. al. (1974) and Kane (1974, 1975).

With the assumption of an absence of both significant cosmic ray diffusion across the magnetic field and large values of cosmic ray gradients perpendicular to the ecliptic plane, the theories discussed above predict that the diffusive component of the anisotropy should be aligned along the mean ecliptic direction of the IMF. The occasions of significant departure from this alignment observed on a day to day basis have been attributed to the diffusion of cosmic rays normal to the mean IMF arising from enhanced magnetic field fluctuations and/or to the existence of perpendicular cosmic ray gradients (see also Owens, 1977,a,b). Gradients perpendicular to the ecliptic are observed for short periods in association with disturbed interplanetary conditions, [Duggal and Pomerantz, 1976].

If there is a transient disturbance in the interplanetary medium due to a shock wave associated with a solar flare, the balance between sunward diffusion and outwards convection by the solar wind of the galactic cosmic rays is upset; thus
during a Forbush decrease the streaming of the cosmic ray gas might change considerably in both magnitude and direction. Cosmic ray streaming other than corotation with the Sun must occur as a result of departures of the solar wind cavity from spherical symmetry as pointed out by Parker (1964).

Recent developments indicate that anisotropies perpendicular to the ecliptic plane can provide a powerful diagnostic tool for understanding the mechanisms that produce the transient intensity variations. It has been established that anisotropy perpendicular to the ecliptic is a characteristic feature of cosmic ray storms (Duggal and Pomerantz, 1971, Mercer et al. 1971). Both the onset and the recovery phases of cosmic ray storms are often characterised by several types of transient phenomena. The most prominent superimposed modulations that occur during Forbush decreases (FD) are (1) enhanced diurnal variations (Lockwood, 1971; Pomerantz and Duggal, 1971) and (2) north-south anisotropies (Duggal and Pomerantz, 1976).

To explain the observed solar semi-diurnal cosmic ray variation, Subramanian and Sarabhai (1967) and Lietti and Quenby (1968) proposed the existence of a cosmic ray density gradient perpendicular to the ecliptic plane. The proposed gradient required a minimum density of cosmic rays in the ecliptic plane for the density increasing with distance both above and below the plane. A cosmic ray density gradient $\nabla U$ in the presence of the interplanetary magnetic field (IMF) $\vec{B}$ causes a particle drift proportional to $\vec{B} \times \nabla U$. If $\vec{B}$ is considered to lie in the ecliptic plane, the N-S component
of $\vec{U}$ produces a flow in the ecliptic plane perpendicular to $\vec{B}$ whose sense depends on the sense of $\vec{B}$ (e.g. for $\vec{B}$ pointing away from the sun (positive) at an angle of $45^\circ$ to the Sun-Earth line a south pointing gradient produces a flow from the direction $45^\circ \ E$ of the Sun-Earth lines). This will be observed as a field correlated vector addition to the usual azimuthal streaming. The effect may be detected by separating the diurnal variation vectors into groups corresponding to positive and negative fields (Hashim and Bercovitch, 1972, Swinson, 1970).

It has been pointed out by Thambyapillai and Elliot (1953) that the solar diurnal variation of cosmic rays shows a 22-year variation depending on the solar activity. Since then, the existence of this phenomenon has been confirmed by many researchers (e.g. Forbush 1967, 1973; Duggal and Pomerantz, 1975; Mori et.al. 1981; and references therein). On the other hand, by the discovery of the polarity reversal of the helio-magnetic field every maximum solar activity period (Babcock, 1959, 61; Howard 1974) together with the development of the cosmic ray diffusion – convection theory (Parker, 1958, 1965; Gleeson and Axford, 1967), it became clear that the cosmic ray density in space shows a polarity state dependence due to the drift effect in the ordered magnetic field as pointed out by Jokipii et.al. (1977).

Recently, Munakata and Nagaslima (1984, 1986) have theoretically derived the first three order anisotropies in interplanetary space based on the diffusion – convection theory
and have qualitatively explained the observed long term variation. These anisotropies produce sector dependant daily variations at the Earth. Moreover, they have pointed out the possibility of observing the phase shifts of the semi and tri-diurnal variations for the transition of the polarity state.

It is noteworthy that these anisotropies are not symmetric for an arbitrary rotation around the IMF-axis. In other words, they cannot be expressed in terms of only the pitch angle with respect to the IMF-axis and therefore cannot be derived from an alternative theory proposed by Bieber and Pomerantz (1983) on the basis of the diffusion of the pitch angle distribution along the IMF-axis (Earl, 1976). In this respect, observation of these anisotropies gives a decisive clue for determining which theory is more suitable for an explanation of cosmic ray anisotropies of solar origin.

The existence of ordered interplanetary field configurations with a radial dimension of the order of 0.25 AU at 1 AU, characterised by higher than average field strengths and a rotation of the field vectors parallel to a plane, was demonstrated by Burlaga and Klein (1980) and Burlaga et al. (1981) who called them 'magnetic clouds' following an idea proposed by Morrison (1954). A statistical study of magnetic clouds at 1 AU showed that during the period from 1967 to 1978 they occurred at the rate of at least one every three months and that their average radial dimension was 0.25 AU (Klein and Burlaga, 1982).
In magnetic clouds at 1 AU the pressure, principally due to the high magnetic field strengths, is generally higher than the ambient pressure, suggesting that they might be expanding as they move away from the Sun. In fact, Klein and Burlaga (1982) argued that between the Sun and 1 AU magnetic clouds expand at a rate of approximately one-half of the local Alfven speed in the directions transverse to \( \mathbf{B} \). If this expansion continues beyond 1 AU, one should find that the radial dimension of magnetic clouds beyond 1 AU should be larger than 0.25 AU, assuming that clouds are stable enough to maintain their identity beyond 1 AU. Specifically, the magnetic clouds possess the following characteristics:

1. a duration of approximately 1 day, corresponding to a characteristic dimension \( \approx 0.25 \) AU;

2. the magnetic field direction changing from large southern (northern) directions to large northern (southern) directions, and in some cases back again to the original direction;

3. magnetic field strength higher than average (\( > 10 \gamma \)).

In this Chapter we shall analyse mainly the behaviour of the diurnal anisotropy during the days on which Earth is engulfed by the magnetic clouds. Our analysis covers the period from 1967 - 1978, during which 46 magnetic clouds, identified by Klein and Burlaga (1982), were observed at the Earth. Most of the clouds produce Forbush type decreases, hence our main interest is to study the diurnal variation under
disturbed interplanetary conditions which are produced by the passage of these magnetic clouds.

4.2 METHOD OF ANALYSIS

As we wished to include in our study the variation of diurnal anisotropy during the passage of the magnetic clouds over the Earth which often produces temporal world-wide decreases we were led to remove these world-wide decreases from the neutron monitor time record. This removal can be accomplished by the use of numerical filtering technique over a single station. We have found that numerical filtering of the data from a single station is simple and more convenient for our purpose, conserving at the same time the essential characteristics we wished to play. The filtering technique used to separate diurnal and world-wide components from the neutron monitor time records has been described previously in detail in Chapter II in the thesis. The data of Deep River neutron monitor has been filtered with the help of Alert neutron monitor.

The 45 magnetic clouds identified by Klein and Burlaga (1982) have been subdivided into three classes by themselves. These are: (1) cloud preceded by a shock (2) cloud followed by a stream interface (3) cloud associated with a CME (a region in which the plasma temperature is anomalously low and the magnetic field strength is enhanced). There are approximately equal numbers of clouds in each class.
When the front boundary of the cloud touches the Earth or Earth's orbit, we arranged that day as the key-day i.e. the arrival day of the cloud on the Earth. Then we took five days before and 5 days after the arrival of the cloud. Thus for all three categories of clouds the data was arranged from -5 to +5 days from the key-day. Chree-epoch analysis is performed to get the decreases. After removing the world-wide component from the data, we analysed the filtered data by harmonic analysis for each set to calculate the diurnal amplitude and phase.

We have also analysed the data for the maximum stay of the clouds on the Earth and for total duration of stay of the clouds on the Earth. Average of $A_p$ index for the days regarding each class of clouds was also obtained from -5 to +5 days taking arrival, maximum duration and total duration days as key-days. The graphs are plotted showing the relation between diurnal amplitude, phase and $A_p$ index.

4.3 RESULTS AND DISCUSSION

In Figure 4.1 we have shown the superposed epoch plots of cosmic ray intensity data from the Deep River neutron monitor corresponding to three classes of clouds. It is found that the decrease in cosmic ray intensity, with the clouds preceded by a shock, is higher in comparison to the decreases observed in association with the other two classes of clouds and the decrease starts earlier than the arrival of the clouds. Moreover, recovery is complete in nearly a week. The decrease in cosmic ray intensity in relation to the clouds followed by
Fig. 4.1 Cosmic ray intensity reduction by three classes of clouds. Zero day is the arrival day of the clouds.
a stream interface is much smaller than the one mentioned above. The decrease time is also elevated and the onset of the decrease takes place on the arrival of the cloud. The decrease observed in association with the third category of clouds, i.e., clouds associated with cold magnetic enhancement is of still smaller amplitude and duration. However, in this also, the decrease in cosmic ray intensity starts when the cloud arrives at the Earth (Badruddin et al. 1986). However, our main interest here is to find out diurnal anisotropy and discuss it in detail.

The diurnal amplitude ($\%$) and phase (LT) of three category of clouds viz.

(i) Clouds preceded by a shock or shock associated clouds in which the direction of the magnetic field of the front boundary is southward (+) and magnitude of magnetic field 12 $\gamma$ (table 4.1)

(ii) Clouds followed by stream interface or clouds associated with interaction region (IR) in which nearly two third (2/3) clouds have southward (+) magnetic field and one third (1/3) clouds have northward (-) magnetic field and magnitude of this field is nearly 12 $\gamma$ (table 4.1)

and (iii) Clouds associated with a CME (Cold magnetic enhancement) in which the direction of the magnetic field is northward (-) and its magnitude is nearly 12 $\gamma$ (table 4.1)

have been shown on the harmonic dial in Fig. 4.2 (a,b,c). For comparison the diurnal amplitude and phase for geomagnetically quiet days during the years (1967-1978) have also been shown
Fig. 4.2 (a) Diurnal amplitude and phase on harmonic dial for three classes of clouds. Zero day is the arrival day of clouds on the Earth.

- SAC: Shock associated clouds
- IR: Interaction region associated clouds
- CME: Cold magnetic enhancement associated clouds
- QD: Quiet days.
<table>
<thead>
<tr>
<th>S.No.</th>
<th>Cloud type</th>
<th>Number</th>
<th>Average field Y</th>
<th>Average speed Km S$^{-1}$</th>
<th>Average travel time hrs.</th>
<th>Mean duration hrs.</th>
<th>Associated Cosmic ray decrease (%)</th>
<th>Direction of the magnetic field in the front boundary.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Shock associated</td>
<td>14</td>
<td>12</td>
<td>460</td>
<td>90.6</td>
<td>26.6</td>
<td>1.8</td>
<td>Southward (+)</td>
</tr>
<tr>
<td>2.</td>
<td>Interface associated</td>
<td>16</td>
<td>12</td>
<td>411.1*</td>
<td>105.0*</td>
<td>20.8*</td>
<td>1.0</td>
<td>Mixed 2/3 southward (+) and one third northward (-)</td>
</tr>
<tr>
<td>3.</td>
<td>Cold magnetic enhancement associated</td>
<td>16</td>
<td>12</td>
<td>383.4*</td>
<td>109.9*</td>
<td>30.0*</td>
<td>0.35</td>
<td>Northward (-)</td>
</tr>
</tbody>
</table>

* From Wilson and Hildner (1984)
on the same harmonic dial.

It is apparent from the table 4.2 and Fig. 4.2 (a) that the amplitude for shock associated clouds (SAC) is largest $(0.6\% \pm 0.03)$ while for the clouds associated with cold magnetic enhancement (CME) is least $(0.4\% \pm 0.02)$ and for the clouds associated with interaction region (IR) is in between the two $(0.48 \pm 0.02)$. Thus we see that the diurnal amplitude for all three category of clouds is higher in comparison with the diurnal amplitude of geomagnetically quiet days. Fig. 4.2 (a) and table 4.2 shows that the phases for shock associated clouds (SAC), clouds associated with interaction region (IR) and clouds associated with cold magnetic enhancement (CME) are $13.1$ hrs, $13.4$ hrs and $12.8$ hrs respectively. We see that there is clearcut phase shift towards earlier hours in comparison to the phase of geomagnetically quiet days (Table 4.2). Figure 4.2 (a) and table 4.2 also shows that the differences of the diurnal amplitudes and phases are significant for all three categories of clouds in comparison with quiet days values as well as among themselves also. These values of diurnal amplitude and phase have been obtained on the day when respective category of clouds reaches on Earth (or Earth's orbit).

Fig. 4.2 (b) shows the diurnal amplitude and phase on the day when the respective category of clouds remained for maximum time on the Earth i.e. the zero day was taken the maximum duration day of the respective category of clouds. We see that there is not much difference between these values and values obtained on the arrival day of the clouds. Although the
Fig. 4.2 (b) Same as Fig. 4.2(a). Zero day is the maximum duration of stay of these clouds on the Earth.
<table>
<thead>
<tr>
<th>S.No.</th>
<th>Category of clouds</th>
<th>Zero day is the arrival day of cloud (a)</th>
<th>Zero day is the maximum duration day of the cloud (b)</th>
<th>Zero day is the total duration of the cloud (c)</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amplitude % at ground.</td>
<td>Phase hours (LT) at ground.</td>
<td>Amplitude % at ground.</td>
<td>Phase hours (LT) at ground.</td>
<td>Amplitude % at ground.</td>
</tr>
<tr>
<td>1.</td>
<td>Shock associated cloud (SAC)</td>
<td>0.6±0.03</td>
<td>13.1±0.14</td>
<td>0.58±0.03</td>
<td>12.6±0.12</td>
</tr>
<tr>
<td>2.</td>
<td>Clouds associated with interaction region (IR)</td>
<td>0.48±0.02</td>
<td>13.4±0.16</td>
<td>0.50±0.02</td>
<td>13.3±0.16</td>
</tr>
<tr>
<td>3.</td>
<td>Clouds associated with cold magnetic enhancement (CME)</td>
<td>0.4±0.02</td>
<td>12.8±0.12</td>
<td>0.38±0.02</td>
<td>12.7±0.12</td>
</tr>
<tr>
<td>4.</td>
<td>Quiet days</td>
<td>0.30±0.02</td>
<td>15.0±0.19</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
phase of shock associated clouds and clouds associated with cold magnetic enhancement becomes nearly equal as is clear from the Fig. 4.2 (b) and table 4.2.

Fig. 4.2 (c) shows the diurnal amplitude and phase of the total duration of the clouds remaining on the Earth, the zero day is considered as the days for total duration days of clouds. Here we see that the amplitudes of three category of clouds reach nearly equal values i.e. there is not much difference among themselves but the amplitudes are higher in comparison to quiet days amplitude. Although the phases are very close to the value of Fig. 4.2 (b).

Now these results are discussed in the light of available results and theories. The anisotropies are determined by the instantaneous conditions in the interplanetary space, and it is of interest here to examine this relationship between cosmic ray density, interplanetary magnetic field and anisotropy, and to infer the cause of the observed anisotropies.

The expression for the differential cosmic ray current density $\mathcal{S}$ is given (Pomerantz and Duggal, 1971; Forman and Glesson, 1975) by

$$
\mathcal{S} = \mathcal{S}_c - K ||\left(\frac{\partial u}{\partial \mathcal{S}}\right)|| - K \left(\frac{\partial u}{\partial \mathcal{S}}\right) \perp - \frac{v^2(\omega \tau)^2}{3\omega(1+(\omega \tau)^2)} \left[\frac{\partial u}{\partial \mathcal{S}} \times \mathbf{B}\right]
$$

$$
\mathcal{S}_c = C_G u \mathcal{V}
$$

\_\_\_\_ (4.1)
Fig. 4.2 (c) Same as Fig. 4.2(a). Zero day is the total duration of the stay of these clouds on the Earth.
where

\( C_G \) = Compton -Getting factor ( \( \sim 1.5 \) )

\( U \) = differential number density

\( \vec{V} \) = Solar wind velocity

\( \vec{B} \) = magnetic field (IMF)

\( K_{\parallel} \) = diffusion coefficient parallel to IMF \( \vec{B} \)

\( K_{\perp} \) = diffusion coefficient perpendicular to IMF \( \vec{B} \)

\( \omega \) = 2\( \pi \) (gyrofrequency)

\( \tau \) = Collision time

\( v \) = Speed of the cosmic ray particles.

The first term on the right of equation 4.1 is the convective component, the next two are diffusive components and last is a component due to the density gradient.

The anisotropy vector \( \vec{\xi} \) is related to \( \vec{S} \) by

\[
\vec{\xi} = \frac{3\vec{S}}{\nu v} \quad \ldots \quad (4.2)
\]

and introducing the gyroradius \( \varrho \), the convective anisotropy \( \vec{\xi}_{\parallel c} \) and the vector gradient \( \vec{G} \) defined below

\[
\vec{\xi}_{\parallel c} = \frac{3 \, C_G \, \vec{V}}{\nu u} = \frac{3 \, C_G \, \vec{V}}{v} \quad \ldots \quad (4.3)
\]

we obtain from equation 4.1 and 4.2, the convenient form as follows:
This may also be written as

\[
\frac{3\mathbf{v}}{v u} = \frac{3\mathbf{v}}{v u} - \frac{3K}{v u} \left( \frac{\partial u}{\partial t} \right) || - \frac{3K}{v u} \left( \frac{\partial u}{\partial t} \right) \perp - \frac{3v^2 (\omega \tau)^2}{3\omega v u 1+(\omega \tau)^2} \left[ \frac{\partial u}{\partial t} \times \frac{\mathbf{B}}{B} \right] 
\]

\[
\frac{\omega}{\lambda} = \frac{\omega}{\lambda} - \frac{3K}{v} \mathbf{G} || - \frac{3K}{v} \mathbf{G} \perp - \frac{(\omega \tau)^2}{1+(\omega \tau)^2} \mathbf{G} \times \frac{\mathbf{B}}{B} \quad \ldots (4.4)
\]

The successive terms being due to convection (radially outward), parallel diffusion, perpendicular diffusion and the density gradient current.

\[
K || = \frac{\lambda v}{3} \quad [ \lambda = \text{mean scattering free path}] 
\]

\[
K \perp = \frac{1}{1+(\omega \tau)^2} K || 
\]

\[
\omega = \frac{qB}{mc} 
\]

\[
\mathcal{Q} = \frac{pC}{qB} \quad [ p = \text{particle momentum}] 
\]

It is useful here to have a set of typical quiet time values for the above quantities in mind. With \( V = 400 \) Kms/Sec, the rigidity \( R \) in gigavolts (GV), \( B \) in gammas and \( \beta = \frac{V}{C} \), these values are

\[
\Xi_{IC} = 0.6\% \quad \ldots \quad (i) 
\]

\[
K || = 6 \times 10^{21} R\beta \text{ Cm}^2/\text{Sec} \quad \ldots \quad (ii) 
\]

\[
\frac{K \perp}{K ||} \leq 0.1 
\]
\[
\frac{3K \parallel}{\nu} = \lambda = 6 \times 10^{11} \text{ R Cms} = 4 \times 10^{-2} \text{ R AU}
\]

\[
G = \frac{30}{R^\beta} \approx \frac{30}{R} \% \text{ per AU} \quad \ldots \quad (\text{iii})
\]
directed radially outward

\[
G \parallel = G \cos 45^\circ = \frac{30}{R} \times 0.7\% \text{ per AU} = \frac{21}{R} \% \text{ per AU}
\]

\[
\frac{3K \parallel}{\nu} G \parallel = \varepsilon \parallel \approx 0.84\%
\]

\[
G = \frac{R}{40 \beta} \text{ AU} \quad \ldots \quad (\text{iv})
\]

\[
\omega_c = 8 ; \quad \frac{(\omega_c)^2}{1+(\omega_c)^2} = 1 \quad \ldots \quad (\text{v})
\]
when \( B = 5\gamma \), \( K \parallel = 6 \times 10^{21} \text{ R}\beta \text{ cm}^2/\text{sec} \)

and then

\[
\frac{(\omega_c)^2}{1+(\omega_c)^2} \rho G \times \frac{R}{B} = 0.1 \quad \ldots \quad (\text{vi})
\]

Hence the last terms in equations 4.4 and 4.5 are insignificant under quiet time conditions. Here the value for \( K \parallel \) is for 1965 (Urch and Gleeson, 1972), and changes for other years are obtained by replacing \( R \) by \( MR \) in (i), (ii) and (iii) by putting \( \omega_c = 8 M \) in (iv) and by replacing 0.1 by \( \frac{0.1}{M} \) in (vi), with \( M \) values of 1, 0.58, 0.42 and 0.37 for 1965, 1968, 1969 and 1970 respectively. Under quiet time conditions, \( \varepsilon \parallel \) and \( \varepsilon \parallel G \) are insignificant and only \( \varepsilon \perp \) and \( \varepsilon \perp G \) are significant in equation 4.5 and should be considered.
Variations of three dimensional anisotropy of cosmic rays during Forbush decreases were examined by Yoshida et al. (1973). They examined the high anisotropy of (\(-4\%\)) in terms of the convective, diffusive and density gradient components of the differential streaming as well as the interplanetary magnetic field and solar wind. Based on the flow of the particles due to convection, diffusion and gradient effects, they provided possible explanations for high (\(-4\%\)) anisotropies observed during Forbush decreases. Their significant conclusion is that density gradients are required that are transverse to the magnetic field and these have magnitudes of the order of 10 - 20 times the quiet time gradients. Hence it is clear that the last terms of equations 4.4 and 4.5 are also significant and \(\frac{\vec{\rho}}{\parallel} \) and \(\frac{\vec{\rho}}{\parallel G} \) should also be considered.

Barouch and Burlaga (1975) have reported that the high magnetic field regions ('blobs') in the interplanetary space are associated with Forbush decreases. Duggal and Pomerantz (1983) concluded that modulations produced by changes in IMF intensity alone are significant. Abnormally high values of this IMF parameter \((B > 8 \gamma)\) produce cosmic ray intensity decreases, the magnitudes of which is related to the extent of the departure of \(B\) from average. Barouch and Sari (1976) further demonstrated that these cosmic ray decreases are not related to the turbulence and random motions in the field and that only the large scale features of the interplanetary magnetic field (IMF) are important.
The formation of density gradient perpendicular to the ecliptic plane is discussed below. As the cloud moves outward, it 'sweeps away' the cosmic ray particles ahead of it. Since one only occasionally observes enhancements before a Forbush decrease, it is possible that the particles are deflected out of the ecliptic. One can form conceptual images of several ways in which the particles could be deflected out of the ecliptic plane. One of these is gradient drift.

Since the scale length of the cross-section of the cloud is \( L = 0.25 \text{ AU} \), particles with rigidities up to 100 GV can be deflected. Since the magnetic field intensity increases from 5 \( \gamma \) to 12 \( \gamma \) and in some cases up to 35 \( \gamma \) in a cloud, the gradients are of the order of 100 \( \gamma/\text{AU} \). As a consequence of shearing in \( \vec{B} \), the perpendicular drift appears. Such a high gradient (\( \sim 100 \gamma/\text{AU} \)) in the cloud causes the particle to drift with the velocity

\[
\vec{v}_D = \frac{W_\perp}{q} \left( \frac{1}{B} \right) \left( \frac{\vec{B} \times \nabla B}{B^2} \right)
\]

[Northrop, 1963, Parker, 1957, 1963]. Here \( W_\perp \) is the kinetic energy of the particle perpendicular to \( \vec{B} \). The direction of \( \vec{v}_D \) is perpendicular to both \( \vec{B} \) and \( \nabla |\vec{B}| \). For the interplanetary magnetic field both \( \vec{B} \) and \( \nabla |\vec{B}| \) are situated in the ecliptic plane, so that \( \vec{v}_D \) is perpendicular to ecliptic plane. Let \( L = \rho \) where \( \rho \) is the number of steps and \( \rho \) is the gyroradius. For a 1 GeV proton in a 20 \( \gamma \) field, \( \rho \approx 0.01 \text{ AU} \) and for \( \frac{L}{2} = 0.13 \text{ AU} \), \( \rho = 13 \). Nothing that
One finds that

\[ V_D = \frac{c}{25} \]

This drift velocity is much larger than the rate at which the cloud advances \( \frac{V_D}{V_w} = \frac{c}{25} \frac{V_w}{V_w} = 30 \), where \( V_w \) is the speed of the cloud or solar wind velocity. Suppose that a cloud has a square cross-section and extends \( \pm \frac{L}{2} \) above and below the ecliptic plane. Assume that the gradients normal to the ecliptic are small, except near the boundaries. As the cloud advances radially outward from the Sun, it engulfs cosmic rays. Since a particle drifts out of the ecliptic much faster than the cloud advances, it is effectively removed from the region swept out by the cloud and is deposited somewhere near the top or bottom of the cloud depending upon the sign of \( B \) and \( \nabla B \).

This mechanism leads to strong N-S gradients normal to the ecliptic. If there is some scattering in the cloud, this might lead to N-S asymmetries in the cosmic ray flux, Pomerantz and Duggal (1972) point out that nearly all Forbush decreases are accompanied by N-S anisotropies. It has been established that anisotropy perpendicular to the plane of ecliptic is a characteristic feature of cosmic ray storms (Duggal and Pomerantz, 1971, 1976; Mercer et al. 1971). Moraal and Mulder (1985) presented the evidence that the drift effect on the modulation of galactic cosmic rays can be seen on Forbush decreases observed by Deep River neutron monitor.
It has been established that the beginning of the change of vector of solar diurnal anisotropy of galactic cosmic rays precedes the beginning of Forbush decrease which is due to the disturbed region (Naskidashvili et. al., 1985).

Flow perpendicular to the ecliptic plane causes north-south asymmetry in ground observations of cosmic rays and the grad-B drift can be recognised for its characteristic dependence on the polarity of the magnetic field. The result of this drift will be a local redistribution of the cosmic ray number density. Thus a particle density gradient is established perpendicular to the ecliptic. Enhancement of the grad-B drift have also been detected during the Forbush decrease by Yoshida et. al. (1973) and Suda et. al. (1981). Being dependent on the IMF polarity which is toward or away, the transport by the particle density gradient drift should bring cosmic rays toward the ecliptic plane.

It has been demonstrated that the cosmic ray drift motion in the heliosphere produces the change of the cosmic ray density distribution for the transition of the polarity state and, as a result, produces the rise and fall of the axis-asymmetric anisotropies for the observed phase shifts in the solar daily variations (Nagashima et. al. 1986). These phase shifts are due to the change of the cosmic ray density distribution in space caused by the change of the drift motion of the cosmic rays in the heliosphere for the transition of the polarity state, as emphasized by Jokipii et. al. (1977).
One of the methods of detecting the cosmic ray distribution perpendicular to the ecliptic is to use the cosmic ray flow in the ecliptic plane arising from $\mathbf{B} \times \nabla U$. If $\mathbf{B}$ lie in the ecliptic plane, the direction of this flow (in the 3 hr or 15 hr direction) is perpendicular to $\mathbf{B}$ and depends on the sense of $\mathbf{B}$. This flow will be superposed on the so-called corotation streaming. If the difference is taken between observed diurnal variations sorted according to the toward (T) and away (A) polarity of IMF, common corotation streaming will be almost cancelled. Then, the resultant T-A vector can represent mainly the field dependent one, and this may be reflected by the behaviour of the perpendicular cosmic ray gradient to the ecliptic plane. Hashim and Bercovitch (1972), Swinson and Kananen (1982), Swinson et al. (1986) and Badruddin et al. (1985) have applied this method to the solar diurnal variation data and obtained almost a similar result to the above.

The $\mathbf{B} \times \nabla U$ anisotropy arises as a result of the anti-symmetric term of the diffusion tensor. The magnitude of the resulting anisotropy is $\varphi \nabla U$, where $\nabla U$ is the density gradient in the direction normal to the field. Being polarity-dependent this anisotropy can be disentangled from other terms of the anisotropy, and then, knowing the Larmour radius, $\varphi$, the gradient can be determined (Bercovitch, 1970).

4.3.1. Diurnal Amplitude and Phase During The Passage of Shock Associated Clouds

The direction of the magnetic field in the front boundary
of the shock associated clouds is southward (+) or away from the Sun with average value of 12 γ nearly. Due to the association with shocks these clouds moves faster than all other category of clouds (Table 4.1). Fig. 4.2 (a,b,c) and table 4.2 shows that the diurnal amplitude of these clouds is largest among all category of clouds.

Patel et.al.(1968) found that the diurnal anisotropy caused by the latitudinal gradients should reverse as the magnetic field or the gradient reverses. When the gradient is such that solar activity north of the equatorial plane is greater than south, the latitudinal gradient should give rise to a diurnal anisotropy with its direction of maximum on the average along 1500 hrs (U.T) when the field is directed away from the Sun (+) and along 300 hrs (U.T) when the field is directed toward the Sun (−). Such an asymmetry will increase the amplitude of the diurnal component due to azimuthal streaming when the field is away (+) from the Sun. This is verified using a set of neutron monitors during IMP-1 period (Wilcox and Ness, 1964) for six solar rotations when interplanetary magnetic field direction in different sectors has been identified.

Ichinose et.al. (1983), following the work by Fujimoto et.al. (1979), used 470 station years of data from the world-wide neutron monitor net work to demonstrate that the field dependent component of the cosmic ray solar diurnal variation, arising from the perpendicular density gradient changed phase significantly. The diurnal component diminished for the negative state while that may exist significantly in the positive state. Also Owens et.al. (1980) proposed that the component of the corotating cosmic ray
gradient in the ecliptic plane gives rise to a north-south anisotropy and the component of the corotating cosmic ray gradient perpendicular to the ecliptic gives rise to an anisotropy in the ecliptic seen in the diurnal variation. Mavromichalaki (1981) found that an enhanced mean amplitude of the diurnal anisotropy correlates with positively directed sectors.

The presence of the $\mathbf{B} \times \nabla U$ streaming was also demonstrated in the work of Takahashi et al. (1985) who deduced the first zonal harmonic from the data of the world-wide neutron monitor network, and showed that it undergoes sudden jumps at sector crossings. A good correlation was found between the anisotropy and the component of the magnetic field by Xue et al. (1985). The $\mathbf{B} \times \nabla U$ anisotropy can also be applied to detect a steady north-south gradient as it has been shown by Swinson et al. (1986). The $\mathbf{B} \times \nabla U$ streaming, in this case, adds a polarity dependent component to the daily variation in solar time.

Taking zeroth day as the arrival day of the shock associated clouds the $A_p$ index, diurnal amplitude and phase have been plotted in the upper, middle and lower panels of the Fig. 4.3 (a) from -5 to +5 days. It is clear from the middle panel that there is no appreciable change in the diurnal amplitude from -5 to -2 day from the zeroth day. The increase in diurnal amplitude at -1 day from the zero day is clearly indicating the arrival of the shocks which are coming ahead of the cloud. The maximum increase of diurnal amplitude on zero day indicates the effect of the genuine
Fig. 4.3(a) Superposed epoch analysis results for \( \pm 5 \) days about zero day of \( A_p \) index, diurnal amplitude and phase on upper, middle and lower panels respectively for shock associated clouds (SAC). Zero day is the arrival day of these clouds on the Earth.
disturbance caused by these clouds. On +1 day (i.e. after one day of the arrival of the clouds), the diurnal amplitude decreases. On +2 day and onward the diurnal amplitude returns back to slightly greater values and remains constant for further 3 days in comparison to the days before the arrival of the shocks and clouds. In the upper panel the behaviour of $A_p$ values is shown. These values show the similar behaviour like diurnal amplitude. Although the value of $A_p$ on zero day and +1 day remains almost constant while diurnal amplitude on +1 day decreases. A clearcut phase shift towards earlier hours in comparison to -1 day or earlier days is seen on the lower panel of Fig. 4.2(a). The recovery of phase starts after +2 day and recovers on +3 day and then remains constant as before the arrival of the cloud.

In Fig. 4.3(b) the $A_p$ index, diurnal amplitude and phase have been plotted on the upper, middle and lower panels respectively from -5 to +5 days from the zeroth day. Here the zero day have been taken as the day on which the duration of the stay of these clouds on Earth remained maximum i.e. maximum duration days. In this figure the behaviour of $A_p$, diurnal amplitude and phase is more clear on the zeroth day. Rest of the behaviour is as in the Fig. 4.3(a).

Fig. 4.3(c) have been plotted by taking zeroth day as the days for total duration of stay of these clouds on the Earth. Although the magnitude of the diurnal amplitude has decreased while the phase and $A_p$ values remained as in fig. 4.3(b).
Fig. 4.3(b) Same as Fig. 4.3(a). Zero day is the maximum duration of stay of these clouds on the Earth (SACM).
Fig. 4.3(c) Same as Fig. 4.3(a). Zero day is the total duration of stay of these clouds on the Earth (SACT).
Recently, Kadokura and Nishida (1986), in the theoretical calculation of two-dimensional numerical modeling of the cosmic ray storm, showed that preceding the arrival of the shock, the phase shifts to the earlier hours and the amplitude becomes large which is compatible with observations of Wada and Suda (1980). Both phase and amplitude return to almost the undisturbed value when the solar wind disturbance has passed, while the cosmic ray density perturbation remains. Our observations during the disturbance caused by the magnetic clouds is more or less in agreement with the above prediction made on the basis of theoretical calculation by Kadokura and Nishida (1986).

4.3.2 Diurnal Amplitude and Phase During The Passage of Clouds Followed by Interaction Region

Fig. 4.4(a) shows the plots of $A_p$ index, diurnal amplitude and its phase on upper, middle and lower panels respectively from -5 to +5 days from zero day. The zeroth day is taken as the arrival day of these category of clouds. It is seen from the upper and middle panels of this figure that $A_p$ value and diurnal amplitude are higher at zero-day in comparison to the -1 day i.e. before arrival of the clouds. The decrease in diurnal amplitude on +1 day shows that duration of stay of these clouds on Earth is short i.e. less than one day (table 4.1). It is seen from the upper panel of this figure that $A_p$ increases much on +1 day showing the fact that the magnetic field and solar wind velocity increase gradually and it is largest at the rear boundary of these clouds. Since these clouds are followed by interaction region which arrives after 12 to 18
Fig. 4.4(a) Superposed epoch analysis results for ± 5 days about zero day of $A_p$ index, diurnal amplitude and phase on upper, middle and lower panels respectively for interaction region (IR) associated clouds. Zero day is the arrival day of these clouds on the Earth.
hours from the departure of the clouds from the Earth. Hence the magnetic field remained enhanced while solar wind still increases due to interaction region (Klein and Burlaga, 1982) and its effect is clearly seen on +2 day in the figure 4.4 (a) in the diurnal amplitude which again increases in comparison to +1 day and even -1 day. After the removal of the clouds and interaction region the diurnal amplitude recovers on +3 day and remains constant onward. The lower panel of this Fig. 4.4(a) shows the phase shift towards earlier hours on zero-day. The phase recovers after the removal of the disturbance due to clouds and interaction region from +3 day and onward. Here again our observations are in agreement with the theoretical calculations of Kadokura and Nishida (1986) on the two-dimensional numerical modeling on cosmic ray storms.

In Fig. 4.4(b) the maximum duration of stay of these clouds on the Earth is taken as zero day and $A_p$ index, diurnal amplitude and phase are plotted on upper, middle and lower panels respectively from -5 to +5 days from the zero day. The features are similar as in fig. 4.4(a) above with a slight decrease in the magnitude of $A_p$ on zero day. The effect of interaction region (IR) is visible in the diurnal amplitude (middle panel of fig. 4.4(b)) here also on +1 day which is the arrival day of interaction region which comes behind the clouds.

Fig. 4.4(c) shows the plots of $A_p$ index, diurnal amplitude and phase on upper, middle and lower panels respectively from -5 to +5 days from zero day. The zero day here is taken as the total
Fig. 4.4(b) Same as Fig. 4.4(a) is the maximum duration of stay of these clouds on the Earth (IRM).
Fig. 4.4(c) Same as Fig. 4.4(a). Zero day is the total duration of stay of these clouds on the Earth (IRT).
duration of stay of clouds on the Earth. The features here are similar to figure 4.4(b) with slight decrease in the magnitude of the diurnal amplitude on zero-day.

Nearly two third of the clouds in this category have the magnetic field southward (+) while one third of the clouds have northward (−) in their front boundary. Hence the diurnal amplitude is less than the shock associated clouds which have magnetic field southward (+) and large than cold magnetic enhancement (CME) associated clouds which have northward (−) magnetic field as is seen from the figure 4.2(a) and table 4.2. Thus these clouds behave just like as a mixed flow behaves. The perpendicular density gradient will be established in this case also and the streaming due to $\mathbf{B} \times \mathbf{U}$ will be added in the diurnal vector to give large value than the quiet days value.

4.3.3 Diurnal Anisotropy During The Passage of CME (Cold Magnetic Enhancement) Associated Clouds

In Fig. 4.5(a) the $A_p$ index, diurnal amplitude and its phase have been plotted on upper, middle and lower panels respectively from −5 to +5 days from the zero-day. The zero-day is taken as the arrival day of this category of clouds. From the figure it is clear that the $A_p$ index and diurnal amplitude are higher at zero day in comparison to −1 day and earlier days. These clouds move with a slower velocity than other two category of clouds (table 4.1). Since the total average duration of these clouds is more than a day, hence the increase in diurnal amplitude on +1 day is also seen in the middle panel of this figure. After the removal of the clouds
Fig. 4.5(a) Superposed epoch analysis results for ±5 days about zero day of A index, diurnal amplitude and phase on upper, middle and lower panels respectively for cold magnetic enhancement (CME) associated clouds. Zero day is the arrival day of these clouds on the Earth.
from the Earth, the diurnal amplitude returns to its undisturbed (before arrival of the clouds) values with slightly less magnitude of diurnal amplitude and remains nearly at the same level onward (Fig. 4.5a). The phase shift to earlier hours is clearly seen on the lower panel of this figure. The phase also returns to its undisturbed value after +3 day.

Considering maximum duration of stay of these clouds on the Earth, as zero-day the Fig. 4.5(b) have been plotted with \( A_p \) index, diurnal amplitude and phase on upper, middle and lower panels respectively from -5 to +5 days. The features of this figure are similar to the features of Fig. 4.5(a).

Fig. 4.5(c) shows the plots of \( A_p \) index, diurnal amplitude and phase on upper, middle and lower panels respectively from -5 to +5 days. The zero-day has been considered the total duration days of this category of clouds. The features of this figure are similar to the features of the fig. 4.5(b). These observations which are discussed above are in close agreement with the theoretical calculations made by Kadokura and Nishida (1986) on two-dimensional numerical modeling of cosmic ray storms.

The direction of the magnetic field of the front boundary of these clouds is northward (−) or toward Sun. (table 4.1). The density gradient perpendicular to the ecliptic will be established as discussed earlier. The field dependent streaming due to \( \mathbf{B} \times \nabla U \) will be added in the corotation streaming in such a way that diurnal amplitude will be less than the shock associated clouds which have southward (+) magnetic field. Although this diurnal amplitude is greater than the quiet days amplitude, showing the effect of the genuine disturbance caused by magnetic clouds.
Fig. 4.5 (b) Same as Fig. 4.5(a). Zero day is the maximum duration of stay of these clouds on the Earth. (CMEM).
Fig. 4.5(c) Same as Fig. 4.5(a). Zero day is the total duration of stay of these clouds on the Earth (CMET).
4.4 CONCLUSION

From the above discussion we conclude as follows:

1. The amplitude of (i) shock associated clouds (ii) clouds followed by interaction regions and (iii) clouds associated with CME (cold magnetic enhancement) are in descending order i.e. $A_{\text{SAC}} > A_{\text{IR}} > A_{\text{CME}}$ (0.6%, 0.48% and 0.40% at ground).

2. The ratio between the amplitudes $A_{\text{SAC}} : A_{\text{IR}} : A_{\text{CME}}$ is 1.5 : 1.25 : 1 nearly.

3. The phase are 13.1 hr, 13.4 hr and 12.8 hrs local time at Deep River neutron monitor for shocks associated clouds, clouds followed by interaction region and clouds associated with CME (cold magnetic enhancement) respectively.

4. -5 to +5 days analysis shows that roughly in all three categories of clouds the amplitude as well as phase returns to their undisturbed values after the removal of the disturbance caused by clouds in accordance with the recent theoretical calculation on two-dimensional numerical modeling in cosmic ray storms by Kadokura and Nishida (1986) and observations by Wada and Suda (1980) for such type of disturbed periods.

5. Amplitude shows direct relation with geomagnetic index $A_p$ as shown in different figures.

6. The increase and large value of amplitude for shock associated clouds and decrease and small value for the clouds associated with cold magnetic enhancements is in accordance with the contribution due to perpendicular particle density gradient and $\mathbf{B} \times \nabla U$ term.
7. The large values of amplitude and phase shifts can be explained with the help of equation (4) taking all components into consideration.

8. The mechanisms operating and the significance of not neglecting third and fourth terms in equation (4) are given in the discussion part of text.

9. The evidences relating to large perpendicular density gradient and hence contribution from $\overline{B} \times \nabla U$ term are summarized in the text in discussion part.

10. The phase shift is towards earlier hours in accordance with the earlier results.