CHAPTER I
INTRODUCTION

1.1 Time Variation of Cosmic Ray Intensity

The study of time variation of cosmic ray intensity in the past two decades has been of significant help, in understanding the electromagnetic processes in the interplanetary space. Even though galactic cosmic radiation is grossly isotropic outside the solar system, these particles, as they pass through the interplanetary medium, undergo considerable modulation. Superimposed upon the cosmic ray particles of galactic origin very often relativistic particles of solar origin are also present in the interplanetary medium. Historically in the past, it is by studying the time profile and anisotropy characteristics of solar particles, the gross interplanetary field configuration was first inferred. Intensive studies in the recent past have clearly demonstrated the usefulness of time variation studies of both galactic and solar cosmic rays as probes for studying the electromagnetic conditions of interplanetary space.

Unlike the in situ measurements of interplanetary parameters the cosmic ray time variation studies yield a complete profile of electromagnetic conditions of the entire interplanetary medium between the sun and the earth. Therefore, in spite of the availability of direct means of probing with satellites
and deep space probes, the cosmic ray time variation studies will continue to be of great importance and will provide inputs which will be complementary to the direct in situ measurements.

A comprehensive survey of the results obtained so far and their theoretical interpretation have been discussed at length by various authors such as, Dorman, (1963, 1969); Parker, (1966, 1969); Forbush, (1966); Quenby, (1967); Webber, (1968); Jokipii, (1971); McCracken & Rao, (1970); Pomerantz & Duggal, (1971) and Rao, (1972). Even though a fairly accurate picture of the gross features of the average cosmic ray variations has emerged from the past studies, a clear understanding of the day to day variability of cosmic ray flux is still lacking. It is, therefore, essential that the future work should be directed to achieve a further understanding of the detailed characteristics of cosmic ray anisotropy.

Most of the cosmic ray time variation studies, particularly at high energies (>1 GeV), have been mainly carried out using ground based cosmic ray observations. Continuous registration of ground level cosmic ray intensity has been systematically done since 1936. Even though early measurements were made with ionization chambers, the emphasis of late has shifted to the use of high counting rate neutron monitors and meson telescopes. However, before being able to interpret the observed secondary cosmic ray variations on ground in terms of primary anisotropy,
it is essential to understand and correct the data for the geomagnetic effects and the atmospheric transition effects.

Several distinct types of time variations of primary cosmic ray intensity with time scales ranging from several years to a few hours have been investigated. More recently, time variations having a periodicity of a few minutes have also been discovered (Dhanju and Sarabhai, 1967). In general, the observed time variations can be broadly classified into two groups viz. periodic (regular) and aperiodic (irregular) variations. Amongst the periodic variations are (1) 11-year variations which are inversely correlated with the 11-year solar activity; (2) 27-day recurrent variations, associated with the synodic rotation of the sun and (3) diurnal and semi-diurnal variations, which are connected with the rotation of the earth and the anisotropy of cosmic ray intensity in interplanetary space. The aperiodic variations include (1) sudden increases in cosmic ray intensity due to production of relativistic cosmic ray particles in solar flares and (2) sudden decreases in cosmic ray intensity called "Forbush decreases" usually observed in association with geomagnetic storms.

1.2 Geomagnetic and Atmospheric effects

1.2.1 Geomagnetic effects

It is well known that the primary cosmic rays are deflected by the geomagnetic field. At any given place on the
earth and for a given direction, cosmic rays below a certain rigidity are excluded by the geomagnetic field. The cut-off rigidities for different directions below which particles can not arrive at the given location have been investigated by a number of workers starting with Stormer, (1936) and Lemaitre and Vallarta, (1936 a,b) using the dipole approximation to the geomagnetic field. Following Alpher (1950) the cut-off rigidity in such a field can be calculated by the formula

\[ P_c = \frac{300 \times M \cos^4 \lambda}{a^2\left\{1 + \sqrt{1 - \sin^2 \theta \cos \phi \cos \lambda}^2\right\}} \]

where 'a' is the radius of the earth, \( \theta \) is the zenith angle, \( \phi \) is the azimuth, \( \lambda \) is the geomagnetic latitude of the station and 'M' is the magnetic moment of the earth. Even though the results obtained using the above formula are correct to a first degree of approximation, for accurate calculation of the directional response characteristics of cosmic ray telescopes it is necessary to obtain more accurate cut-off rigidities based on realistic models of the geomagnetic field. Such calculations have also been done by Quenby and Webber (1959) and by Quenby and Wenk (1962) using certain approximations to include non dipole terms for the geomagnetic field. Shea et al. (1965) have calculated the cut-off rigidity very accurately by taking into account all the non dipole terms by a sixth degree simulation of the geomagnetic field (Finch and Leaton, 1957).
1.2.1.1 Asymptotic directions and Asymptotic cones of acceptance of a detector

The asymptotic direction of approach has been defined as the direction of a cosmic ray particle prior to its entry into the geomagnetic field. The asymptotic direction of approach of cosmic ray particles which arrive at a particular station on the earth from the zenith angle $\theta$ and azimuth $\phi$ is shown in Figure 1.01. For a given station and a given direction of incidence (say $\theta$ and $\phi$) the set of allowed asymptotic directions for different rigidities form a curve in the $\lambda\psi$ plane, where $\lambda$ is the asymptotic latitude and $\psi$ the asymptotic longitude measured east of the station. Calculations of asymptotic directions of approach have been done both by using numerical methods and by performing scale model experiments. For example Schluter, (1951); Firor, (1954); Lust et al., (1955); Jory, (1956) and Gall and Lifshitz, (1958) have computed the individual orbits of primary particles of energies extending up to 10 GeV. Malmfors (1945) and Brunberg and Dattner (1953), on the other hand, evaluated the asymptotic directions through model (terrella) experiments. With the advent of fast electronic computers more accurate determinations of trajectories have been possible using a realistic approximation to the geomagnetic field (McCracken et al.,1962). Very recently, the effect of the deformation of the geomagnetic field by the solar wind has also been considered for calculating the cut-off rigidity and
Fig. 1.01 The trajectory of a charged particle through geomagnetic field.
particle trajectories. Using Mead's (1964) magnetospheric model Ahluwalia and McCracken (1965) and Makino and Kondo (1965) have tried to estimate the effect of the deformed geomagnetic field. Gall (1968) and Gall et al. (1968, 1969) used Williams and Mead's (1965) model and took into account the currents, both in the magnetopause and in the neutral sheet of the magnetospheric tail. We, however, wish to emphasize that the magnetospheric models used so far are at best crude and hence these calculations need to be refined with better models of the magnetosphere. Nevertheless the theories indicate that the effect of the deformation of the magnetic field is not very significant at energies above 10 GeV.

Knowing the trajectory information, it is possible to define the asymptotic cones of acceptance of a detector as the solid angle containing the asymptotic directions of approach which make a significant contribution to the counting rate of the detector (Rao et al., 1963). The concept of the asymptotic cones of acceptance is very useful and greatly facilitates the task of relating the observed variations to the primary anisotropy.

1.2.2 Atmospheric effects

Primary cosmic rays while passing through the atmosphere collide with air nuclei and produce various types of mesons and nucleons following the well-known cascade processes. The $\mu$ mesons which form the main part of the penetrating component
at sea-level has a very low probability of interaction. The \( \mu \) mesons are also unstable and decay with a mean life-time of \( \approx 2.15 \times 10^{-6} \) sec. The observed secondary cosmic rays at sea level are subjected to absorption and decay processes in the atmosphere, all the way from the production level down to the recording level. In other words the secondary cosmic ray intensity observed at the ground is influenced by the variable atmospheric conditions above the recording instruments. The atmospheric effects are primarily due to (a) barometric pressure effect related to the absorption due to overlying atmosphere and (b) temperature effect which causes a change in the atmospheric character resulting in a change in the height of mean meson production level.

1.2.2.1 Barometric pressure effect

The dependence of cosmic ray intensity on atmospheric pressure can be described by an exponential law.

\[
I = I_{\text{Corr.}} \exp (\beta \delta h)
\]

where \( \delta h \) is the change in pressure at the observation level. Since the barometric coefficient \( \beta \) for neutrons is considerably high (\( \approx 0.75\% / \text{mb} \)) the computation of pressure correction uses the exponential formula. For the meson component, however, the pressure coefficient is low (\( \approx 0.13\% / \text{mb} \)) and therefore the series expansion of equation (1.02) as

\[
I = I_{\text{Corr.}} (1 + \beta \delta h)
\]
is generally sufficient. The pressure coefficient is usually
determined by a linear regression analysis.

The barometric coefficient varies with altitude,
latitude and solar cycle. Systematic measurements of barometric
coefficient for neutron monitors have been carried out by
Bachelet et al. (1964, 1965 a) in 1963-64 and by Carmichael et al.
(1965, 1968) in 1965-66. Bachelet et al. (1965 b) have
suggested that the decrease of $\beta$ in the lower atmosphere is
due to the contribution of muons to the counting rate of the
neutron monitor. Similarly a 6% change in the barometric co­
efficient has been reported by Griffiths et al. (1966) during the
last solar cycle. From a careful analysis of $\beta$ during Forbush
decrees, McCracken and Johns (1959) have been able to show
that change in $\beta$ is spectrum dependent. However, since the
pressure coefficient applicable to mesons is quite small compared
to that of neutrons, such changes are not very important in the
case of meson monitors.

1.2.2.2 Temperature effect

The temperature variation in the atmosphere mainly
affects the meson component due to its short decay time.
Increase in the atmospheric temperature without any accompanying
change in pressure, will increase the height of the mean meson
production layer resulting in an increase in the path length of
the mesons reaching the detector. Increased path length means
a greater probability of $\mu$ meson decay which will cause a decrease in the intensity of the registered meson component at the ground. In addition to the predominant negative temperature effect there is also a small positive temperature effect which arises from the competitive processes of $\pi^-\mu$ decay and nuclear capture of $\pi$ mesons near the meson production level ($\approx 100$ to $200$ mb). With the increase in temperature at this height, the density decreases and the interaction distance increases. With the result more $\pi^-\mu$ mesons decay and fewer interact. Thus an increase in temperature at this level, will cause an increase in the production of $\mu$ mesons. The positive temperature effect is relatively small for a sea level meson monitor. It increases linearly with pion energy and therefore becomes progressively important for underground monitors. Even though the neutron monitors, by virtue of their dependence mainly on local production are more or less free from the atmospheric temperature effect, a small residual temperature effect does exist due to the neutron production through capture of $\mu$ mesons.

Unlike the evaluation of barometric correction, quantitative evaluation of temperature effect for $\mu$ mesons is quite complicated since it involves a knowledge of the temperature distribution throughout the atmosphere. A number of workers such as Maeda and Wada, (1954) and Dorman and Feinberg, (1955) have worked out a comprehensive theory of meteorological
effects. Following Dorman (1957) we can express the change in intensity as

\[ \frac{\delta I}{I} = \beta \delta p + \int W_T(h) \delta T(h) \delta h \]

where \( \delta p \) is the change in pressure, \( \beta \) is the pressure coefficient, \( \delta T(h) \) is the change in temperature of isobaric level of pressure \( h \), and \( W_T(h) \) is the density of the temperature coefficient.

From a detailed theoretical treatment of muon production and propagation in the atmosphere, Dorman (1957) has derived \( W_T(h) \) for meson monitors at sea-level and at 25 and 55 m.w.e. For a sea-level telescope, \( W_T(h) \) is approximately constant throughout the atmosphere from about 50 mb down to the ground level as proposed by Wada (1961) and has a mean value of \( \approx 0.3\%/\text{deg.atm.} \). Maeda (1960) extended the calculations for \( W_T(h) \), to include obliquely incident muons and the effect of the curvature of the isobaric levels. Even though one needs to consider the atmospheric temperature variations at all levels, for practical purposes Dorman found that it is adequate if the atmosphere is divided into 11 isobaric levels in which case the integral of equation (1.04) can be replaced by a summation as follows

\[ \frac{\delta I}{I} = \beta \delta p + \sum_{i=1}^{11} K_i \delta T_i \]

where \( K_i \) is the partial temperature coefficient for the \( i \)'th
Comparisons of various methods of temperature corrections have been published by Bachelet and Conforto, (1956); Mathews, (1959); Wada, (1961); Lindgren and Lindholm, (1961) and Carmichael et al., (1967) and a comprehensive review of the atmospheric effects on meson and nucleonic components of cosmic rays is given by Bercovitch (’68).

Though, theoretically, the atmospheric effect on meson intensity near sea-level is fairly well understood, in practice, a simple and satisfactory method of applying the corrections for temperature variations on meson intensity has not yet been achieved. The major difficulty encountered is the non-availability of radio-sonde temperature data for different levels and at different times of the day. Besides, due to the large uncertainty in the radio-sonde data, resulting from insolation and lag errors, the available data is not sufficiently accurate for our purpose which poses a serious problem in the wider usage of meson data for time variation studies.

To overcome this difficulty pairs of directional telescopes inclined at the same angle to the zenith but pointing to different azimuths, have been used by several workers (Malmfors, 1949; Elliot and Dolbear, 1951; Rao and Sarabhai, 1962; Sandstrom, 1965; Sandstrom et al., 1968; Dorman, 1963; Fujii et al., 1969). Since the cosmic ray particles which are
registered by the two telescopes traverse an equal amount of the atmosphere in both the directions, the meteorological corrections applicable to both telescopes should be identical if the geomagnetic cut-off rigidity for the two directions are same. Even when the cut-off rigidities in the two directions differ slightly, we may consider that the atmospheric effect observed by both telescopes would be same to a first degree of approximation. Thus the difference in intensity recorded by the two telescopes would be free from the meteorological effects and therefore can be directly related to the primary anisotropy in space.

1.2.3 Relationship of Secondary variations to the Primary variations

Since the ground stations record only secondary cosmic rays, it is necessary to find how the secondary component is related to the primary cosmic ray particles. The function which generally describes the relation between the secondary component and the primary component has been called as the 'Multiplicity function', 'Generating function or Yield function' by various workers (Treiman, 1952; Fonger, 1953; Nagashima, 1953; Simpson et al., 1953; Dorman, 1957). In principle 'Multiplicity function' can be theoretically calculated from a knowledge of various interaction processes occurring in the atmosphere. Such calculations, however, are quite cumbersome and not reliable due to the number of uncertainties that exist
in our knowledge of high energy interactions. Most of the workers (Neher, 1952; Treiman, 1952; Simpson et al., 1953; Dorman, 1957) have, therefore, resorted to an experimental approach by making use of the observed latitude effect. Dorman's work in this field is the most comprehensive and we will take it as representative of such an attempt.

Following Dorman, the observed intensity \( N^i(h) \) of a secondary component of type \( i \) at a latitude \( \lambda \) and at an atmospheric height of 'h' can be represented as

\[
N^i(h) = \int_{E}^{\infty} D(E) \cdot M^i(E, h) \, dE
\]

where \( D(E) \) is the differential energy spectrum of primary particles and \( M^i(E, h) \) is the multiplicity function that gives the number of secondary particles of type \( i \) produced at an atmospheric depth \( h \), by a single primary particle of energy \( E \) and \( E_C \) is the geomagnetic cut-off energy at the station latitude.

Variations in \( N^i(h) \) can result from variations in \( D(E) \), \( M^i(E, h) \) or in \( E_C \). Differentiating equation (1.06) with respect to all these parameters and dividing by \( N^i(h) \) we obtain the expression for the change in intensity as

\[
\frac{\delta N^i(h)}{N^i(h)} = \frac{\delta E}{E} \cdot W^i(E, h) + \int_{E}^{\infty} \frac{\partial D(E)}{D(E)} \cdot W^i(E, h) \, dE + \int_{\lambda}^{\rho} \frac{\delta M^i(E, h)}{M^i(E, h)} \cdot W^i(E, h) \, dE
\]

\[
\frac{\delta E_C}{E_C}
\]
is called the 'coupling coefficient' between the primary and secondary variation. It gives the percentage contribution of primaries of energy 'E' to the secondary component of type i at an atmospheric depth 'h' and at a latitude \( \lambda \).

First term on the right hand side of equation (1.07) represents variation due to change in the geomagnetic cut-off energy which is not significant for all ground based observations even for large geomagnetic disturbances. Third term in equation (1.07) can be accounted for by appropriate meteorological corrections. Neglecting the change in cut-off energy, the variations in observed intensity \( N^i(h) \) after appropriate meteorological corrections can be expressed as

\[
\frac{\delta N^i(h)}{N^i(h)} = \int_{E_\infty}^{E} \frac{\delta D(E)}{D(E)} W^i(E, h) \, dE
\]

Knowing the coupling coefficients we can relate the observed variations in the secondary cosmic ray intensity to \( \frac{\delta D(E)}{D(E)} \) which is called the energy spectrum of the variational part of the primary cosmic rays.

From a study of the latitude effect, Dorman, (1957); and Quenby and Webber, (1959) have evaluated coupling coefficients for vertically incident nucleons and mesons up to 15 GeV. Beyond this energy the coupling coefficients have

where

\[
W^i(E, h) = \frac{D(E) M^i(E, h)}{N^i(h)}
\]

\[1.08\]
been estimated by using extrapolation formulae of the type
\[ W(E) = aE^{-a} + b(E/E) \]
Constants A, 'a' and 'b' are fixed by tying in with the experimental values at \( E = 15 \) GeV.

Using primary cosmic ray energy spectrum of the type \( KE^{-2.5} \), and the multiplicity, calculated by considering the Pal and Peters (1963) model of the elementary interaction of excited nucleons, Krimsky et al. (1966) have calculated the coupling coefficients for mesons incident from different zenith angles. The estimated response functions for the meson component incident at zenith angles 0°, 8°, 24°, 48°, 64° are shown in Fig.(1.02).

1.3 Relevant Experimental results on Daily Variation of Cosmic Ray intensity

Since the present work is mainly concerned with the daily variation of cosmic ray intensity, we shall discuss here only the relevant experimental observations. In the following sections we shall attempt to discuss these results in the framework of the presently known properties of the interplanetary medium and the available theoretical formulations. Extensive analysis of the data obtained from the ionization chambers, neutron and meson monitors have now firmly established the existence of diurnal and semi-diurnal components in the daily variation of cosmic ray intensity. The average properties of these variations which are now reasonably well established are discussed in the next section.
Fig. 1. Coupling coefficients for the meson component at sea level for various zenith angles.
1.3.1 Average properties of Diurnal Variation

The observed yearly average cosmic ray diurnal variation in space obtained after correcting for the width of the asymptotic cones of acceptance of the detector and the geomagnetic bending have an amplitude \( \approx 0.4\% \) (McCracken and Rao, 1965) and a time of maximum around 1800 hours in space (Rac et al., 1963; Bercovitch, 1953; McCracken and Rao, 1965; Faller and Marsden, 1966). The diurnal anisotropy is found to be energy independent in the energy range 2 GeV to \( E_{\text{max}} \). The upper limit of energy, \( E_{\text{max}} \), which is about 55 GeV, during 1965 seems to show a solar cycle variation (Jacklyn and Humble, 1965; Ahluwalia and Erricksen, 1969). The anisotropy is also found to vary as the cosine of the declination (Sandstrom et al., 1962; McCracken and Rao, 1965).

1.3.1.1 Long term changes of average diurnal variations

Long term variations, both in the amplitude and in the phase of the diurnal anisotropy with a period of one and two solar cycles, have been reported by many investigators (Sarabhai and Kane, 1953; Thambyahpillai and Elliot, 1953; Sarabhai et al., 1954; Steinmaurer and Gheri, 1955; Lorman, 1957; Forbush and Venkatesan, 1960; Forbush, 1967, 1969; Wada and Kudo, 1968; Duggal et al., 1970 a,b). The amplitude of the diurnal anisotropy seems to be lower during the minimum of solar activity. From an analysis of ionization chamber data recorded
over a period of more than 30 years at Cheltenham, Christchurch and Huancayo, Forbush, (1967, 1969) concluded that the average annual diurnal variation results from two distinct components $W$ and $V$. The $W$ component has its maximum (or minimum) in the direction $128^\circ$ east of the sun-earth line. It varies sinusoidally about zero mean with a period of 20 years in the interval 1937-1966. The second component $V$ has its maximum along $90^\circ$ east of the sun-earth line and is subjected to larger variations, well correlated with the geomagnetic activity. It contains a wave with a periodicity corresponding to a single solar cycle having an amplitude of about 60% of that of $W$. The $W$ component is directed along the Archimedean spiral. Duggal et al., (1970 a,b) have reported that the energy spectrum of diurnal variation for both the components ($V$ and $W$) is same within the experimental uncertainties. It is important to realise that in all the above results, the meson observations have been used substantially.

However, study of the average diurnal variation as observed by neutron monitors over the period 1957-1965 by McCracken and Rao (1965) as well as by Duggal et al., (1967) have shown that it has been remarkably constant over these years, except for a decrease in the amplitude of about 30% in 1965. The time of maximum of the diurnal variation derived from neutron data, however, has remained practically constant over the entire solar cycle (McCracken and Rao, 1965).
Year to year changes of amplitude and phase in the diurnal variations registered by instrumentation having higher mean rigidities of response (sea-level and underground meson monitors) have always been found to be greater than the corresponding observations by instruments having low energy response. Some of the long term changes observed, particularly in amplitude, are attributable to changes in the upper limit of energy $E_{\text{max}}$. It is evident that changes in $E_{\text{max}}$ will affect the higher energy response detectors substantially more than the lower energy ones. Using extensive data from neutron and underground meson monitors, Jacklyn et al., (1969, 1970) have concluded that the observed long term changes in diurnal anisotropy is understandable in terms of the changes in $E_{\text{max}}$, $E_{\text{max}}$ varying from 55 GeV during sunspot minimum to about 100 GeV during sunspot maximum. Observations by Peacock et al. (1968); Hashim et al. (1968) and Ahluwalia and Ericksen (1969) are also in substantial agreement with the above conclusions. The changes of $E_{\text{max}}$ derived from a comparison of Deep River neutron and Deep River meson data corrected with appropriate temperature coefficients by Agrawal et al. (1971) are also in agreement with the above observations. It is found that the cosmic ray data, particularly the neutron monitor data after 1957, do not indicate a solar cycle change except for a small decrease in amplitude observed in 1965, which can be attributed to a change in $E_{\text{max}}$. Recent meson monitor observations including underground
observations also indicate (Jacklyn et al. 1970) only a change in amplitude which is explainable as due to change in $E_{\text{max}}$. These do not show any conclusive evidence for a systematic change in phase between 1958-1966. However the ion-chamber observations have always indicated a change in both amplitude and phase particularly during years of solar minimum around 1954, which is not completely understood in view of other evidences.

1.3.2 Semi-diurnal variation

It is only recently with the availability of high counting super neutron monitors and large area meson telescopes, the existence of a significant semi-diurnal component has been firmly established. The use of sophisticated analytical techniques including power spectrum analysis and complex demodulation has also considerably helped in this investigation (Ables et al. 1966).

Average properties

The observed semi-diurnal anisotropy has an average amplitude of $\approx 0.1\%$, with a time of maximum, in space $\approx 0300$ hours, which is roughly perpendicular to the interplanetary magnetic field direction. The anisotropy is found to be energy dependent varying as the first power of rigidity (Ables et al. 1966; Patel et al. 1968; Liétti and Quenby, 1968; Quenby and Liétti, 1968; Rao and Agrawal, 1970; Fujii et al., 1970 and Subramanian, 1971b). The anisotropy is further found to vary as $\cos^2 \lambda$. 
where $\lambda$ is the mean asymptotic latitude of the station. Thus, it is found that the observed semi-diurnal component is higher for low latitude station and for detectors having higher mean energy of response.

Examination of the yearly average semi-diurnal variation from a number of neutron monitor stations (Rao and Agrawal, 1970) has shown that the semi-diurnal anisotropy is time invariant between 1958 to 1968. The amplitude and the time of maximum do not seem to exhibit any significant changes with solar cycle during this period.

1.3.3 Short term changes in daily variation

Even though the average characteristics of the daily variation are fairly well understood, the day to day variations are found to be very complex. Study of daily variation on a day to day basis by a number of authors (Rao and Sarabhai, 1964; Subramanian, 1964; Sarabhai and Subramanian, 1965 and Patel et al. 1968) has conclusively shown that both the amplitude and the time of maximum of the diurnal as well as the semi-diurnal component, vary considerably on a day to day basis. Sarabhai et al. (1965) have reported that on a majority of days there exists a virtual sink of galactic cosmic rays along the garden hose direction. From an analysis of neutron and meson data from several stations, Sarabhai and Subramanian (1965) have shown that the spectral exponent $\frac{\beta}{2}$ for diurnal anisotropy
fluctuates over a wide range on individual days. Similar analysis by Patel et al. (1968) has shown that the semi-diurnal variation also exhibits similar spectral changes on a day to day basis. From a detailed analysis of the characteristics of the diurnal anisotropy these authors further conclude that a number of different mechanisms (processes) must be operative in the intensity variation on a day to day basis, to account for the large variability observed. Amongst these processes are

1. the azimuthal streaming (Parker, 1964; Axford, 1965 and Krimsky, 1964);
2. streaming due to non-uniform diffusion in a longitudinal sector structure of the interplanetary magnetic field (Parker, 1964);
3. scattering at irregularities along the interplanetary magnetic field, short circuiting latitudinal gradients (Sarabhai and Subramanian, 1966) and
4. latitudinal gradients in a relatively smooth magnetic field (Subramanian and Sarabhai, 1967 and Lietti and Quenby, 1968) may be mentioned.

Although the diurnal variation is altered during cosmic ray storms, no general relationships between the two have been established so far. There have been some reports that the amplitude of the diurnal variation increases and the phase advances to earlier hours when disturbances occur (Sekido and Yoshida, 1950; Yoshida, 1955; Dormar, 1957; Tanskanen, 1968; Ostman and Awadalla, 1970). However, these conclusions have not been supported by others (Crowden and Marsden, 1962; Kane, 1962).
The existence of trains of consecutive days having both abnormally large amplitudes (> 1% enhanced diurnal variations) and negligible diurnal variations have been pointed out by Mathews et al. (1969) and Hashim and Thambyahpillai, (1969). Enhanced diurnal variation occasionally occurs even when there are no accompanying geomagnetic disturbances or Forbush decreases. Mathews et al. (1969) and Hashim and Thambyahpillai (1969) have independently concluded that during many days exhibiting large amplitude waves, the anisotropy was predominantly caused by a large decrease along the garden-hose direction. Often during disturbed periods, the time of maximum of enhanced diurnal variation is found to shift to later hours (Mathews et al. 1969; Hashim and Thambyahpillai, 1969 and Rao et al., 1972). However, a few occasions have also been reported when the time of maximum shifts to morning (9-12) hours, associated with the recovery of Forbush decreases (Lindgren, 1970, and Razdan and Bemalkhedkar, 1971).

Using the available interplanetary magnetic field data in conjunction with the observed enhanced diurnal variation at Deep River Hashim et al. (1972) have shown that the diurnal anisotropy consists of two vectors one corresponding to radial convection and the other diffusion along the interplanetary magnetic field line. Rao et al. (1972) have shown that the enhanced diurnal variation which shows a maximum around 2000 hours is caused by the superposition of normal convection and
enhanced field aligned diffusion due to an enhanced positive density gradient. They also show that the diurnal variation during both quiet and disturbed periods can be understood in terms of convection and field aligned diffusion. Superimposed on the diurnal variations caused by radial gradients, it is also possible to have some contributions from latitudinal gradients.

Subramanian and Sarabhai (1965, 1967) suggested that the diurnal anisotropy caused by such latitudinal gradients should reverse as the magnetic field or the gradient reverses. Patel et al. (1968) have shown that during IMP-1 period when the interplanetary magnetic field was directed away from the sun, the amplitude of the diurnal anisotropy was larger compared to the observed amplitude when the field was directed towards the sun. Venkatesan and Mathews (1968) have indicated that during IMP-1 period the days of enhanced diurnal variation were observed corresponding to the sectors having positive polarity. Using a wide band filter to the Deep River neutron intensity, Ryder and Hatton (1968) have also arrived at the same conclusion. These changes have been qualitatively attributed to the north-south gradient of cosmic ray density.

With underground meson monitor data obtained from Bolivia and Embudo stations, Swinson (1971) has shown that the diurnal amplitude was larger during days when the interplanetary magnetic field (ipmf) direction was positive than
rigidity of $\sim 100$ GeV. Assuming an interplanetary magnetic field of $4.5 \gamma$, the gradient calculated from the anisotropy was of about $5.5 \cdot R^{-0.6}/$A.U.

These results will be further critically examined in Chapter IV and discussed along with the present results obtained by the author for the years 1968 and 1969, using data from a number of neutron monitors and data from Ahmedabad meson monitors.

1.4 Interplanetary Space

The study of solar modulation of galactic cosmic radiation can be essentially reduced to the study of the motion of cosmic ray particles in the disordered interplanetary magnetic field. It is therefore of interest to clearly understand the electromagnetic properties of the interplanetary medium before we discuss the theoretical formulation of the modulation mechanisms. In this section we describe briefly the properties of the solar wind and of the interplanetary magnetic field which are relevant to the cosmic ray time variation studies.

1.4.1 Solar Wind

The idea that solar corpuscular emission is responsible for geomagnetic storms and aurorae has been known for a long time. However, the concept of a continuous emission of corpuscular matter from the sun was first put forward by Biermann (1951, 1957), in order to explain the observed acceleration of gaseous comet tails. Based on theoretical
considerations, Parker (1958) showed that since the inner part of the solar corona has a temperature of the order of $10^6 \, \text{K}$, the solar corona should expand hydrodynamically against the solar gravitational force, resulting in a continuous emission of corpuscular matter which he termed as 'solar wind'.

The initial velocity of the solar wind at the photosphere is few km/sec. It becomes supersonic with a bulk velocity of several hundred km/sec., beyond a distance of about $10-20 \, R_\odot$ (solar radius). The first direct observations of the solar wind were reported by Gringauz et al. (1960) and Shklovsky et al. (1961) from the space probe Lunik-II. Subsequent measurements by Gringauz, (1961) & Gringauz et al., (1962) on Lunik-III and Venus I, Bonetti et al. (1963 a, b) on Explorer 10 and Neugebauer and Snyder (1962) on Mariner-II confirmed the initial results. Since then a large number of direct observations have been accumulated over the last few years. A number of comprehensive reviews dealing with the observational properties of the solar wind and their theoretical implications are available in literature (Dessler, 1967; Lust, 1967; Ness, 1967; Axford, 1968; Hundhausen, 1968, 1970; Wilcox, 1968; Parker, 1967, 1969 and Holzer and Axford, 1970).

All the observations show that the density, velocity, temperature and relative chemical composition of solar wind are all highly variable. The solar wind density falls off at
the rate of $1/R^2$. From Vela Satellite results, the direction of plasma flow at the earth's orbit appears to be on an average from $\approx 1.6^\circ$ east of the sun (Strong et al., 1967; Hundhausen et al., 1967). The bulk velocity of the solar wind generally varies between 300-600 km/sec. and plasma temperature fluctuates between $10^4$K to $10^6$K. Table 1.01 lists the average properties of the solar wind.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk velocity</td>
<td>350 km/sec.</td>
</tr>
<tr>
<td>Proton or Electron density</td>
<td>8 cm$^{-3}$</td>
</tr>
<tr>
<td>Proton temperature</td>
<td>$5 \times 10^4$ K</td>
</tr>
<tr>
<td>Electron temperature</td>
<td>$1.5 \times 10^5$ K</td>
</tr>
<tr>
<td>Kinetic energy density</td>
<td>$8 \times 10^{-9}$ erg.cm$^{-3}$</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>$5 \gamma$</td>
</tr>
</tbody>
</table>

One of the most puzzling aspects of the presently available observations concerns the long term variation of solar wind properties. During short periods, the 27-day recurrence tendency and an excellent correlation between solar wind velocity and geomagnetic activity have been very convincingly demonstrated by Snyder et al. (1963 a,b) and recently by Pai et al. (1967); Bame et al. (1967); and Pathak (1971). However, on a long term basis, when one examines the variations of solar wind properties over a solar cycle by comparing the data from
different space-crafts one observes that the average density, velocity and temperature of the solar wind are relatively constant over the solar cycle (Gosling et al., 1971; Mathews et al., 1971). The implications of the observed lack of variability of solar wind flux over a solar cycle on cosmic ray modulation will be discussed in the next section.

1.4.2 Interplanetary magnetic field

Alfven (1950) pointed out that a magnetic field embedded in a highly conducting plasma tends to behave as if it is 'frozen in' the plasma. Using the 'frozen in field' concept, Parker (1958) showed that the radially blowing solar wind together with the angular rotation of the sun, will stretch the magnetic field lines into a classical Archimedes spiral. For distances beyond 0.1 A.U. the radius of the sun may be neglected and the form of the spiral is given by

$$ r = \frac{V (\phi - \phi_0)}{\Omega} $$

where 'r' is the radial distance, \( V \) is the solar wind velocity, \( \Omega \) is the angular velocity of the sun, \( \phi \) is the heliocentric longitude measured from the reference longitude \( \phi_0 \). Figure (1.03) shows the Archimedes spiral structure of the interplanetary magnetic field, in the equatorial plane of the sun, for a symmetrical solar wind velocity of 300 km/sec. The spiral angle \( \phi \) often referred to as the 'garden hose angle' is defined as the angle between the interplanetary magnetic field direction and the radius vector as
Fig. 1.03  (a) Archimedes spiral structure of the interplanetary magnetic field for a symmetric solar wind velocity of 300 kms/sec. (Parker, 1963).  
(b) Garden-hose geometry of the interplanetary magnetic field (Dessler, 1967).
shown in figure (1.03). As seen from the figure, the angle $\chi$ (complement of $\Theta$) at any radial distance $R$ from the sun is given by

$$\tan \chi = \frac{V}{\Omega R} \quad \cdots \cdots \quad 1.11$$

The three vector components of the interplanetary magnetic field are given by

$$B_r = B_1 \left( \frac{R_0}{r} \right)^2$$

$$B_\Theta = 0 \quad \cdots \cdots \quad 1.12$$

$$B_\phi = B_1 \frac{\Omega R_0}{V} \left( \frac{R_0}{r} \right) \sin \Theta$$

where $B_1$ is the radial component of the magnetic field at $r = R_0$, where $'r'$ is the radial distance, $R_0$ is the radius of the sun.

Variation in $V$, with $\Theta$, $\phi$ and $t$; instabilities in the solar wind and the variation of $B (\Theta, \phi)$ with $'t'$, will superimpose a variety of both small and large scale magnetic irregularities on the general spiral pattern of the magnetic field given above.

The first experimental demonstration of the predicted spiral structure of the interplanetary magnetic field was obtained by McCracken, (1962 ...); from a study of the initial arrival directions of the solar flare cosmic rays. Most of the direct interplanetary magnetic field measurements, made very near the ecliptic plane, have now shown a fair agreement between the predicted Archimedes spiral and the interplanetary field
as projected on the ecliptic plane. The interplanetary magnetic field has an average value of $\approx 5\, \mu T$. (Ness and Wilcox, 1964, 1966; Davis et al., 1966; Coleman, 1966; Coleman et al., 1966 a, b; Schatten, 1971) with a small north-south component of magnetic field ($< 1\, \mu T$) perpendicular to the ecliptic plane.

1.4.3 Sector structure

One of the major features of the interplanetary magnetic field is its large scale sector structure configuration first reported by Wilcox and Ness (1965). The interplanetary magnetic field seems to be well ordered into sectors; the field in one sector being predominantly away from the sun for several consecutive days, followed by another sector having the magnetic field predominantly towards the sun (Figure 1.04). The entire sector pattern corotates with the sun. The observations by several authors (Coleman et al., 1966; Wilcox and Colburn, 1969, 1970) over a long period of time between 1962 to 1968, have indicated that even during the period of maximum solar activity, the sector structure remains well established. During 1963-1964 there were four well established sectors (Figure 1.04). During the rest of the period two prominent quasi-stationary sectors have been observed with a mean period of $27 \pm 0.1$ days. A good correlation is obtained between the polarity of the mean solar photospheric field and the direction of the interplanetary magnetic field observed near earth (Ness and Wilcox, 1966;
Wilcox and Ness, 1967) with a lag of about 4.5 days corresponding to the transit time of solar wind from the sun to the earth. This indicates that the interplanetary magnetic field has its origin in the general solar photospheric field (Severny et al., 1970). Cosmic ray solar-flare particle-anisotropy observations on various Pioneer and IMP spacecrafts have shown that the field lines within each sector are in the form of inter-twined filaments.

1.4.4 **Small scale irregularities and Power Spectrum of the Interplanetary Magnetic Field**

Superimposed on such a large scale structure of the average interplanetary magnetic field, there exist small scale magnetic field irregularities (or kinks), which are essentially frozen into the solar wind and corotate with the sun. Michael (1967) and Jokipii and Parker (1963, 1969) have pointed out that since the magnetic lines of force are imbedded in turbulent fields on the sun they must necessarily be stochastic. The fluctuations in the velocity fields lead to a random-walk of adjacent lines of force. A large part of the random-walk is probably due to the horizontal displacement of the feet of the lines of force resulting from the motion of granules and supergranules. A granularity with a nominal size of $5 \times 10^3$ km on the solar surface, when projected on the earth's orbit, corresponds to a size of $\sim 10^6$ km, which is in agreement with
the typical scale sizes of filamentary inhomogeneities observed by McCracken and Ness, (1966) and Bartley et al. (1966) during solar flare events and the correlation length 'D' derived from magnetic field observations (Jokipii and Coleman, 1968). Thus the flux tubes in the 'Wet spaghetti' model of interplanetary field suggested by Bartley et al. (1966) and McCracken et al. (1967); can be considered as a direct proof for the existence of random-walk of field lines.

The introduction of random small scale irregularities into a uniform field will cause random changes in the pitch angle of the cosmic ray particles, as they move along the lines of force. The integrated effect of a large number of scattering irregularities is maximum for particles whose cyclotron radius is of the same order as the scale size of the irregularities. Thus the scattering for particles of rigidity $R(GV)$, depends mainly on the power in the transverse component of the field in the vicinity of the 'resonant frequency' which is given by $f(R) = 10^{-4} R^{-1} Hz$. Figure (1.05) shows the representative power spectra of the interplanetary magnetic field during 1962-1966, obtained by several authors (Coleman, 1966; Holzer et al., 1966; Jokipii and Coleman, 1968; Sisco et al., 1968; Sari and Ness, 1969).

The power spectral density of the interplanetary magnetic field shows a large variation from day to day. The
Fig. 1.05

The representative power spectra of the co-latitudinal component of the interplanetary magnetic field, near the orbit of the earth. The epochs are: Mariner II, 1962; Mariner III, late 1962; Pioneer 6, early 1966. The two graphs for Pioneer 6 correspond to low and intermediate disturbance of the magnetic field.

Fig. 1.04

The observed sector structure of the interplanetary magnetic field during November 1963 to February 1964 (Wilcox & Ness, 1965).
spectral density on a disturbed day often shows an increase by as much as a factor of 10 compared to the spectral density on a quiet day with the spectral shape, however remaining practically unaltered. For particles in the rigidity range \(10 \text{ MV} < R < 5 \text{ GV}\), the spectral exponent \(\alpha\) of the power density shows significantly different values at different epochs indicating different rigidity dependence for the parallel diffusion coefficient \(K_{II}\). The available power spectral density information corresponding to rigidities above 1 GV is scanty and unreliable and there are some indications that it is constant at frequencies below \(5 \times 10^{-4}\) Hertz (corresponding to rigidities above 5 GV). Hence the magnetic field observations, presently available, are not adequate to derive quantitative conclusions regarding the propagation of high rigidity cosmic ray particles.

1.5 Modulation mechanisms and theories for the daily variation of cosmic ray intensity

Various theoretical models have been proposed to account for the experimental observations of cosmic ray modulation. These can be classified under two main headings, models which invoke modulation by static or time varying electric fields and the diffusion convection models. A number of reviews on this subject are available in literature. We mention here a few of them (e.g. Nagashima et al., 1966; Webber, 1969;
It is now generally accepted that the elegant formulation of the diffusion-convection model including the energy loss term (Gleeson and Axford, 1967, 1968 a, b) leads to a satisfactory explanation of the observed long term modulation, the radial density gradient and anisotropy. Here we will therefore briefly discuss this model before we describe the different mechanism that have been put forward to explain the daily variation of cosmic ray intensity.

1.5.1 Diffusion-Convection Model

The diffusion-convection model originally proposed by Morrison (1956) and later by Parker (1958 a) has since been modified greatly by a number of workers to include the energy loss term due to adiabatic deceleration in the solar wind (Parker, 1965, 1966; Gleeson and Axford, 1967, 1968 a, 1968 b; Skadron, 1967; Jokipii and Parker, 1967, 1968 ; Jokipii, 1967; Fisk and Axford, 1968, 1969). According to this model the modulation of the galactic cosmic ray intensity is attributed to the motion of cosmic ray particles in a spherically symmetric model of the interplanetary medium, in which the cosmic ray particles undergo convection, diffusion and energy changes as they move in the irregular magnetic fields. The cosmic ray particles undergo energy losses due to adiabatic deceleration in the expanding solar wind (Parker, 1965); the deceleration resulting from repeated scattering by the magnetic field
irregularities, which are moving outward from the sun at the solar wind speed. Jokipii and Parker (1967) and Jokipii (1971) have treated the cosmic ray transport problem as a problem of diffusion in the frame moving with the solar wind and have included the adiabatic deceleration. Gleeson and Axford (1967) and Fisk and Axford (1969) have considered the scattering processes. Both treatments lead essentially to similar equations.

Assuming an isotropic velocity distribution of cosmic ray gas, the differential number density \( U(r,E) \) and the differential streaming current density \( S(r,E) \) in a steady state for particles having a kinetic energy \( E \) and at a radial distance 'r' from the sun is given by (Gleeson and Axford, 1967; Fisk and Axford, 1969, 1970; Gleeson, 1971)

\[
\frac{1}{r^2} \frac{\delta}{\delta r} (r^2 S) + \frac{V}{3} \frac{\delta^2}{\delta r \delta E} (\propto EU) = 0
\]

\[
S = C U V - K \frac{\delta U}{\delta r}
\]

where

\[
C(r,E) = 1 - \frac{1}{3} U \frac{\delta}{\delta E} (\propto EU)
\]

is the Compton-Getting factor (Gleeson and Axford, 1968 b; Forman, 1970 a), \( V(r) \) is the solar wind velocity, \( K(r,E) \) is the diffusion coefficient and \( \propto = (E+2m_0c^2)/(E+m_0c^2) \), \( m_0c^2 \) being the rest energy of the particle under consideration.
Eliminating 'S' between equations (1.13) and (1.14) one obtains the well known Fokker-Planck equation similar to the one derived by Parker (1965) and Jokipii and Parker (1967).

\[
\frac{1}{r} \frac{\delta}{\delta r} (r^2 U V) - \frac{1}{3} \frac{\delta}{\delta r} (r^2 V) \frac{\delta}{\delta E} (\alpha E U) - \frac{1}{2} \frac{\delta}{\delta r} (r^2 K \frac{\delta U}{\delta r}) = 0 \quad \ldots \ldots 1.16
\]

The second term on the left hand side of equation (1.16), arises as a result of energy changes suffered by cosmic ray particles in the expanding solar wind. Using this equation the intensity at any point and epoch can be derived, knowing the diffusion coefficient valid for that energy and epoch.

1.5.1.1 Isotropic diffusion

The solution of the equation (1.16), in the steady-state convection diffusion theory can be obtained by neglecting the energy loss term. Substituting \( \alpha = 0 \), the solution of the equation yields the well known expression for the modulated cosmic ray density \( U(R, \beta, t) \) at a time 't' at the orbit of the earth.

\[
U(R_0, \beta, t) = U_0(R_0, \beta, t) \exp \left[ - \int_{r}^{L} \frac{V(r, t)}{K(R, \beta, \beta, t)} \frac{dR}{r} \right] \quad \ldots \ldots 1.17
\]

where 'K' is the isotropic diffusion coefficient and 'L' is the dimension of the modulating region beyond which the cosmic ray flux is assumed to be the same as the interstellar cosmic ray density \( U_0(R, \beta, t) \).
The cosmic ray intensity at any point, therefore depends upon \( V, L \) and the diffusion coefficient \( (K) \), which may be a function of rigidity and distance. Moreover the theory also predicts the change in modulation at any given rigidity, the change being caused by the change in any of these parameters \((V, L \text{ or } K)\). Whereas the changes in \( V \) are easily measured, the changes in \( L \) and \( K \) are to be inferred from the observed changes in the inter-relationship between cosmic ray intensity and solar activity parameters and the changes in the power spectral density of the interplanetary magnetic field respectively.

1.5.1.2 Radial Gradient

The magnetic irregularities moving with the speed of solar wind sweep back the galactic cosmic ray particles and a positive outward radial density gradient is produced inside the solar system. It can be approximated by

\[
G = \frac{1}{U} \frac{\partial U}{\partial r} = \frac{V(\tau, t)}{K(R, \beta, \tau, t)} \quad \ldots \ldots \ldots \ldots \ldots \ldots 1.18
\]

It is seen from the above expression that the rigidity dependence of the radial gradient, will depend on the rigidity dependence of \( K \). At low energies the energy losses may be quite significant and consequently it is not possible to obtain explicit analytic solutions of equation (1.16) valid at all energies. However, useful deductions can be made by
assuming simple forms for the diffusion coefficient \( K \) and \( Q_c \).

\( \alpha = 2 \) at very low energies and \( \alpha = 1 \) at extreme relativistic energies).

1.5.1.3 Anisotropic diffusion

The cyclotron frequency of cosmic ray particles is generally more than the scattering frequency, hence the diffusion process is generally anisotropic. The diffusion coefficient along the field line \( (K_\parallel) \) is more than the diffusion coefficient perpendicular \( (K_\perp) \) to the field line. For an idealized spiral interplanetary magnetic field, the cosmic ray density at a radial distance \( 'r' \) and colatitude \( \Theta \) is given by

\[
U(r, \Theta) = U_0 \exp \left[ - \frac{V}{K_{||}} (R-r) \left\{ 1 + \frac{1}{3} \frac{\Omega \sin^2 \Theta}{V} (r^2 + 2rr + r^2) \right\} \right] \quad \cdots \quad 1.19
\]

where \( \Omega \) is the angular velocity of the sun and \( V \) and \( K_{||} \) are independent of \( r \). The radial gradient for anisotropic diffusion is given by

\[
G = \frac{1}{U} \frac{dU}{dr} = \frac{V}{K_{||}} \left[ 1 + \frac{r^2 \Omega^2 \sin^2 \Theta}{V^2} \right] \quad \cdots \quad 1.20a
\]

Near the orbit of the earth, \( r \Omega = V \) and \( \Theta \approx 90^\circ \)

\[
G = \frac{1}{U} \frac{dU}{dr} = \frac{2V}{K_{||}} \quad \cdots \quad 1.20b
\]
1.5.2 Theories for the Diurnal Variation

To explain the observed diurnal variation of cosmic ray intensity, several mechanisms have been proposed. We will briefly discuss here only those mechanisms (Ahluwalia and Dessler, 1962; Parker, 1964; Axford, 1965; Krimsky, 1964; Gleeson, 1969; Forman and Gleeson, 1970; Jokipii and Parker, 1969, 1970), which take into account the well established solar wind theory and the spiral interplanetary magnetic field configuration.

Considering a smooth spiral magnetic field, Ahluwalia and Dessler (1962), showed that such a field corotating with the sun in the equatorial plane, produces an electric drift which results in the diurnal variation of cosmic ray intensity whose amplitude can be calculated using the well known Compton-Getting (1935) effect. The direction of the anisotropy according to this theory is perpendicular to the interplanetary magnetic field direction and is dependent on the solar wind velocity. This is completely at variance with the observed properties of the average diurnal anisotropy, viz. its time of maximum along 1800 hour direction (Rao et al., 1963; Bercovitch, 1963) and its lack of any correlation with solar wind velocity (Snyder et al. 1963). Further, the cosmic ray streaming as envisaged in this theory will have a component radially outwards from the sun which would make the sun appear to be a continuous source.
Severe theoretical objection to this model was made by Stern (1964) on the basis of Liouville's theorem according to which the cosmic ray density in phase space should be preserved in a conservative system. In other words, if the cosmic ray intensity is the same in all directions at any given point outside the solar system, it must be the same in all directions at any accessible point inside the solar system. Consequently, a time independent magnetic field \( \frac{\delta B}{\delta t} = 0 \) system can not produce a diurnal anisotropy.

Solution to this problem was pointed out by Parker (1964) and Axford (1965), who showed that for a realistic model of the interplanetary magnetic field \( \frac{\delta B}{\delta t} \) is, in fact not equal to zero. Magnetic field irregularities would wipe out a major portion of the cosmic ray density gradient which is established by the electric field \( E = -V \times B \). Parker (1964), considered the presence of magnetic field irregularities beyond the orbit of the earth, while Axford (1965) considered the existence of the scattering centers throughout the interplanetary medium. Under the assumption that \( K_{II} \gg K_L \) and the gradient perpendicular to the ecliptic is zero, their results lead to the same conclusion that the cosmic ray gas will rigidly corotate with the sun. In this mechanism, the streaming velocity does not depend either on the solar wind velocity or on the interplanetary magnetic field. The corotation amplitude of the anisotropy produced by azimuthal streaming at a distance 'r' from the sun.
is given by the well known Compton-Getting effect as
\[ a_1(r) = \frac{3CV_{co}}{v} \] ........................1.21
Where \( V_{co} \) is the velocity of the rotating spiral magnetic field and \( v \) is the particle velocity (\( v=c \)), \( C \) is the Compton-Getting factor.

For protons of energies \( >1 \) GeV, equation (1.21) reduces to \( a_1 = \frac{(2+\gamma)V_{co}}{c} \) at the orbit of the earth (\( r=a \)), where \( \gamma \) is the primary differential energy spectral index. Substituting \( V_{co}=400 \) km/sec. and \( \gamma = 2.60 \) for the solar minimum the expected value of the diurnal anisotropy would be \( \lesssim 0.6\% \), which exceeds the observed average amplitude of \( \approx 0.4\% \) (McCracken and Rao, 1965) by about \( \sim 50 \) percent.

The mechanism put forward by Parker and Axford explains satisfactorily most of the features of the average diurnal variation such as the time of maximum, the spectral behaviour and the declination dependence. The only major discrepancy between the experimental observation and the theoretical prediction is in the amplitude of the diurnal variation.

Considering a general magnetic field (\( B \)) and also an electric field (\( E \)), the generalised expression for the differential current density can be given by (Gleeson, 1969)
Where $C$ is the Compton-Getting factor, '$U'$ is the differential number density, '$V'$ is the solar wind velocity, $K = \frac{1}{3} \frac{v^2}{\gamma}$ is the isotropic diffusion coefficient ($v$ = the velocity of the particle), '$r'$ the radial distance from the sun, $\omega = \frac{EB}{m}$ is the gyrofrequency of the particles ('$m'$ is the relativistic mass) and $\tau'$ is the average collision time.

Assuming $\omega \tau' \gg 1$, Gleeson (1969) approximated the expression of differential current density '$S'$ as

$$S = CUV - K \left( \frac{\partial U}{\partial r} \right)_{||} - \frac{1}{3} \frac{v^2}{\omega} \left( \frac{\partial U}{\partial r} \right)_{\perp} x \frac{E}{B} + CU \frac{E x B}{B^2} \quad \ldots \ldots \quad 1.23$$

In this approximation however the term $CUV_{||}$ is left out. Assuming further that the gradient perpendicular to the ecliptic plane ($\frac{\partial U}{\partial r}$) is zero and that there are no energy sources or sinks of cosmic ray particles within the interplanetary region, Gleeson (1969) equated the radial component of streaming vector to zero. He showed that the streaming in the azimuthal direction will be given by

$$S = CUV \tan \chi = CU \Omega r \quad \ldots \ldots \quad 1.24$$
Where \( \omega \) is the angular velocity of the sun and \( r = 1 \text{ A.U.} \). Considering electric field \( E = -V \times B \), generated by the magnetic field in the interplanetary region, Forman and Gleeson (1970) showed that the equation (1.22) for \( S \) in terms of the electric field \( E \) can be written as

\[
S = C U V - \frac{K}{r} \left( \frac{\partial U}{\partial r} \right) - K \left( \frac{\partial U}{\partial r} \right) \frac{r^2}{3} \omega^2 \gamma^2 \left( \frac{\partial U}{\partial r} \right) \frac{B}{B^2} U \frac{\partial U}{\partial r} B \frac{\partial U}{\partial B} B^2 \ldots 1.25
\]

Where \( K_{||} \) and \( K_\perp \) are the parallel and perpendicular diffusion coefficients respectively. They are given by

\[
K_{||} = K, \quad K_\perp = \frac{K}{1 + (\omega \gamma)^2} \quad \ldots \ldots \ldots 1.26
\]

Forman and Gleeson (1970) also showed that in the interplanetary space, the electric field drifts and the convection of the cosmic ray particles parallel to the interplanetary magnetic field, combine as a simple convective flow along the solar wind. (Figure 1.06).

\[
i.e. \quad C U V = C U V_{||} + C U \frac{E \times B}{B^2} = S_c \quad \ldots \ldots \ldots 1.27
\]

\[
S = S_c - K_{||} \left( \frac{\partial U}{\partial r} \right) - K_\perp \left( \frac{\partial U}{\partial r} \right) \frac{r^2}{3} \omega^2 \gamma^2 \left( \frac{\partial U}{\partial r} \right) \frac{B}{B^2} \frac{\partial U}{\partial B} \frac{B}{B^2} \ldots \ldots \ldots 1.28
\]

Thus the streaming of cosmic ray particles \( S(r, E) \) in the interplanetary space is given by the radially outward convection and the diffusion along and perpendicular to the
field line. Fourth term represents the anisotropy due to the
gradient and the interplanetary magnetic field. This anisotropy
is perpendicular to the interplanetary magnetic field and the
gradient of the cosmic ray density. The anisotropy reverses its
direction with the reversal of the interplanetary magnetic
field or with the reversal of the gradient. Hence for average
anisotropy (average of 27 day or more) the fourth term will
average out to zero or become negligible. In general all the
terms of equation (1.26) have to be considered to account for
the magnitude and direction of the observed anisotropy.

Assuming that the gradient perpendicular to the ecliptic
plane is zero, $K \perp$ negligible and that there is no radial
streaming, Forman and Gleeson (1970) showed that the streaming
in the azimuthal direction will be given as

$$ S = C U V \tan \chi = C U V \tan \theta $$

This is shown in Figure 1.06.

The anisotropy $\xi_j$ is given by

$$ \xi_j = \frac{3S}{U V} $$

which is in the 1800 hour direction. For particles having
energies above 1 GeV/nucleon,

$$ C (r, E) = \left(2 + \nu \right)/3 $$

$$ \therefore \xi_j = \left(2 + \nu \right) \frac{V_{co}}{V} $$
At lower energies (\(< 1\) GeV) the condition that the radial streaming or current density is zero (or negligible) is not generally valid. Hence strictly azimuthal streaming cannot be expected at very low energies. In this energy region the Compton-Getting factor is greatly reduced and may even become negative (Gleeson and Axford, 1968 c).

To explain the discrepancy between the observed and expected amplitude of the diurnal anisotropy, a cosmic ray pressure gradient, perpendicular to the solar equatorial plane was suggested by McCracken and Rao, (1965); Parker, (1967a); Gleeson and Axford, (1968) and Jokipii and Parker (1969). Gleeson (1969) attributed the entire discrepancy between the observed and expected value to the perpendicular gradient through the fourth term in equation (1.26). This implied a gradient (Forman and Gleeson, 1970) with magnitude \(\sim 45/P(GV)\) per cent per A.U., which appears to be large and has not been confirmed experimentally.

Jokipii and Parker (1969) have attempted also to take into account the effect of the "random-walk" of the magnetic field lines which enhances \(K_1\) even to the order of \(K_1\) particularly at low energies. Inclusion of this effect introduces an additional term in \(K\), which as Jokipii and
Parker (1969), pointed out could readily account for the observed reduction in the amplitude, by providing an additional component of the differential current density as shown in Figure (1.07). The anisotropy becomes

\[ \xi = 3C \frac{V}{V} \frac{K_{||} - K_{\perp} \tan \chi}{K_{||} - K_{\perp} \tan^2 \chi} \]

\[ \xi = 3C \frac{V}{V} \frac{1 - \xi \tan \chi}{1 + \xi \tan^2 \chi} \text{ where } \xi = \frac{K_{\perp}}{K_{||}} \ldots \ldots 1.32 \]

When \( K_{\perp} \ll K_{||} \) in equation 1.32, the anisotropy corresponds to the rigid corotation of the cosmic ray gas. On the other hand if diffusion coefficient is isotropic i.e. \( K_{\perp} = K_{||} \), the diurnal anisotropy will completely vanish.

Subramanian (1971 a) has recalculated the expected amplitude according to equation (1.31) for the period of high solar activity. Using appropriate values for coupling constant \( W(B) \), and the spectral index \( \gamma(R) \), he finds that the expected amplitude is in reasonable agreement with the observed amplitude. This implies that it is no longer necessary to invoke a density gradient perpendicular to the solar equatorial plane, during this period and that \( K_{\perp} \ll K_{||} \). This conclusion is in essential agreement with the low energy flare observations by McCracken et al. (1968, 1971).

From a study of the decay of solar flare cosmic ray events McCracken et al. (1968, 1971), showed that even late in
Fig. 1.06 Cosmic ray streaming in the plane of the ecliptic. Dot-dashed line shows the diffusion component of the convective vector along the interplanetary magnetic field line and the \( \mathbf{E} \times \mathbf{B} \) drift perpendicular to the field line. The dark dashed lines show the vectors due to radial convection and anisotropic diffusion along the field line. The solid line shows the resultant vector in the 1800 hour direction.

Fig. 1.07 Cosmic ray streaming same as in Fig. 1.06 where a correction due to finite diffusion perpendicular to the magnetic field lines is shown.
the decay, convection is the dominant mechanism in the inter-planetary medium and that $K_\perp$ is completely negligible. Very late in the decay, they observed an easterly anisotropy which has been attributed to a balance between outward convection and an inward field aligned diffusion due to density gradients. The convection which is given by Compton-Getting effect, is observed to be of the order of 10% at 1 MeV energy, and about 0.6% at GeV energy. Extending these results from low energy solar cosmic rays to higher energies, these authors suggested that the diurnal variation could be simply considered as a superposition of convection and field aligned diffusion. Specific mathematical formulation of this concept for both solar cosmic ray events and the diurnal variation, has been given by Forman and Gleeson (1970); Gleeson (1969) and Ng and Gleeson (1971). The model earlier developed by Krimsky (1964) is also in many respects similar to the above model even though it is not as detailed.

According to this concept, on an average it may be assumed that the sun is neither a sink nor a source. Consequently the inward radial component of the field aligned diffusive streaming should just balance the outward convection on an average basis leaving only a net azimuthal or 'corotational component' (Figure 1.08). On a day to day basis, however, the properties of the interplanetary medium vary over a wide range, resulting in an imbalance between the two components. Because
Fig. 1.08 Unified model to explain the cosmic ray diurnal as well as solar flare anisotropy in terms of convective and diffusive flows. (Rao et al.)
of the fluctuations in any of the relevant interplanetary parameters (solar wind velocity, magnetic field direction or diffusion coefficient), the departure from the equilibrium corotational streaming will result on a day to day basis. Since this concept is able to explain the observed anisotropic behaviour of low energy cosmic ray particles of solar origin as well as of galactic cosmic ray particles, it looks to be more attractive.

Experimental verification of the above concept has emerged from the study of Hashim et al. (1972) and Rao et al. (1972). Hashim et al. (1972) have shown that this concept is valid for explaining enhanced diurnal variation on individual days by demonstrating the field aligned nature of the diffusive vector on such days. From a detailed analysis of data over a long period (1964-1970), Rao et al. (1972) have shown that this concept is valid for both average quiet day variations and enhanced diurnal variations. Subtracting the convection vector from the observed diurnal variation, the residual diffusive vector has been shown to be field aligned during both quiet and disturbed periods. The residual field aligned diffusive vector is explainable in terms of a positive radial density gradient of $\approx 4.5\%$/A.U. during quiet periods and $\approx 10\%$/A.U. during selected periods. These estimates are quite consistent with the observed radial density gradients. The observations also
indicate that on an average $K_{\perp}/K_{\parallel} \leq 0.05$ confirming the correctness of the assumption $K_{\perp} < K_{\parallel}$.

1.5.3 Theories for the Semi-diurnal Variation

Subramanian and Sarabhai, (1967); Lietti and Quenby, (1968) and Quenby and Lietti, (1968) have independently suggested that the semi-diurnal component in the cosmic ray intensity can arise, as a result of the symmetrically rising cosmic ray density gradient, perpendicular to the solar equatorial plane. The difference between the two models which are proposed to explain the semi-diurnal variation of cosmic ray intensity is mainly in the assumed nature of the density gradient away from the equatorial plane. Subramanian and Sarabhai assume the perpendicular gradient based on the dependence of the solar activity inferred from the coronal observations at different heliolatitude. On the other hand Lietti and Quenby have assumed a symmetrical density gradient based on the considerations of simple geometry of the interplanetary magnetic field and the consequent loosening of the spiral at higher heliolatitudes. Both the models predict essentially similar properties for the semi-diurnal anisotropy.

Viewing along the interplanetary magnetic field lines in the equatorial plane, a detector on earth measures cosmic ray flux characteristics of the equatorial plane. Viewing in a direction perpendicular to the magnetic field a detector samples particles arriving from higher heliolatitudes, corresponding to
the gyroradius of the particle under consideration. Since a cosmic ray detector on the spinning earth measures cosmic ray intensity twice a day along the interplanetary magnetic field and twice perpendicular to the field lines, a positive density gradient in the perpendicular plane will give rise to a semi-diurnal component with a maximum perpendicular to the interplanetary magnetic field. The higher the energy of the particle, the higher would be the heliclatitude of sampling and hence the higher would be the resulting amplitude of anisotropy. Thus the model readily explains the observed time of maximum as well as positive energy dependence of the semi-diurnal variation.

According to Lietti and Quenby (1968) and Quenby and Lietti (1968), the perpendicular gradient of the cosmic ray flux is a consequence of the random scattering of particles by scattering centres superimposed on the simple Archimedean spiral. The galactic particles that arrive over the poles experience easy access, since, they diffuse along almost straight field lines, whereas those entering in the solar equatorial plane are constrained to follow many spiral loops. Consequently the cosmic ray density at a given distance should be less at the equatorial plane as compared to the intensities at $\Theta = 0^\circ$.

With typical values of $V = 430$ km/sec., $\lambda = 10^{12}$ p cm. and $r_s = 40$ A.U., they described the cosmic ray density distribution in the interplanetary space as

$$N_e = N_s \exp \left\{ \frac{-2.14}{P} \sin^2 \Theta \right\} \quad \ldots \ldots 1.33$$
Where \( N_e \) and \( N_s \) are the density at earth and at the boundary of the modulating region respectively. 'P' is the rigidity and \( \theta \) is the colatitude. Taylor expansion of equation (1.33) gives peak to peak amplitude of the second harmonic component. For a detector that looks at an asymptotic latitude \( \lambda \) with respect to the solar equatorial plane and at an asymptotic longitude \( \psi \) measured from the spiral field direction, Quenby and Lietti have shown that the expression for peak to peak amplitude is given by

\[
a_2 = 0.005 \left(1 - \cos^2 \psi \right) \frac{1}{\left(1 - \frac{\tan^2 \lambda}{\sin^2 \psi}\right)}^{3/2} \quad ....... 1.34
\]

Subramanian and Sarabhai (1965), on the other hand considered also other types of cosmic ray density distributions. If the density distribution, instead of being symmetrical about \( \phi = 0 \), is symmetrical about another heliolatitude (\( \neq \neq 0 \)), they find that the amplitude of the semi-diurnal anisotropy will still vary as \( \cos^2 \lambda \) and the energy spectrum will still be positive. However, such a distribution will also give rise to a diurnal component which will reverse its direction of maximum with the reversal of interplanetary magnetic field or with the reversal of the north-south asymmetry of solar activity.

Theoretically both the models predict that the semi-diurnal anisotropy, has a positive exponent of the energy spectrum of variation, anisotropy varies as \( \cos^2 \lambda \) and has a maximum flux in a direction perpendicular to the interplanetary
magnetic field direction. All these predicted properties are in agreement with the experimental observations.

Theoretical estimates, assuming the perpendicular gradient to be of the same order as the heliocentric radial density gradient ($G \approx 12-15\%$ per A.U.), have yielded amplitudes for the semi-diurnal anisotropy in reasonable agreement with the observations.

Accurate theoretical calculation of the semi-diurnal amplitude is however difficult because of the lack of any direct measurement of the latitudinal gradient. Taking advantage of the change of the earth's position between $\pm 7.25^\circ$ in an year with respect to solar equatorial plane, it is possible to estimate the characteristics of the perpendicular gradient from observations during different seasons (Dorman and Fischer, 1965). From such an analysis, however, Subramanian (1971 b) has concluded that the cosmic ray intensity distribution observed in the heliolatitude range $\pm 7.25^\circ$ cannot explain the observed semi-diurnal variation. It should also be noted that a semi-diurnal component can arise through a day to day variations of the interplanetary magnetic field. It is reasonable to assume that the particles of rigidity $\approx 200$ GV., whose gyroradius corresponds to about 1 A.U. will not show a significant semi-diurnal anisotropy.