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Solar poloidal magnetic field orientation causing periodicity in daily variation of cosmic ray intensity

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Abstract. A detailed analysis of the Deep River neutron monitor (NM) data for four different phases of solar activity cycle and for four groups of days chosen according to their different geomagnetic conditions is being carried out. It is found that the 60 quiet day (QD) in a year serve a better purpose for investigating the short/long term variation in cosmic ray (CR) intensity. Further, data has been harmonically analysed for the period 1964-95 to investigate the effect of solar poloidal magnetic field (SPMF) orientation in daily variation (diurnal/semi-diurnal) of CR on geomagnetically QD. The phase of the diurnal and semi-diurnal anisotropy vectors on QD has shown a significant shift to early hours when the SPMF in the northern hemisphere (NH) is positive during the periods 1971-79 and 1992-95 as compared to that during the periods 1964-70 and 1981-90 when the SPMF in NH is negative, showing a periodic nature of daily variation in CR intensity with SPMF.

Keywords : Cosmic ray, quiet day, solar poloidal magnetic field, daily variation.

1. Introduction

Various CR anisotropies are found to depend on the solar magnetic field orientation, which extend in the interplanetary space, embedded within by the solar wind, in turn affecting the polarity configuration of interplanetary magnetic field (IMF). The abrupt reversal of vectors for annual and semi-annual anisotropy is associated with the reversal of polarities of solar polar magnetic fields (Antonucci et al., 1978). Studies of solar magnetic field have revealed that these fields change sign about every 11/22 year near the time of maximum solar activity (Webber and Lockwood, 1988). The nature of the long-term variation in CR intensity is likely to depend upon the polarity of the SPMF (Nagashima and Fujimoto, 1989), the cumulative effect of Forbush decreases (Fds) (Lockwood and Webber, 1984) and other solar activities. Many workers have attempted to derive relationship between the mean daily variation and the level of solar and geomagnetic activity (Rao, 1972; Venkatesan and Badruddin, 1990 and references therein). Ballif et al. (1969) correlated Kp and Ap with the mean fluctuations in

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amplitude of IMF, which in turn is related to diffusive component of convection-diffusion theory. Ap is also found to be related with solar wind velocity, V; which is related to convective component of convection-diffusion theory. Kumar et al. (1981a, b) have examined neutron monitor data on geomagnetically QD in a year. The phase shift in CR solar diurnal variation following the heliomagnetic polarity reversal has been pointed out by many researchers (Kumar et al., 1998, Sabbah, 1999a, b).

2. Experimental data and analysis

Solar daily variation (diurnal/semi-diurnal) has been studied in terms of heliomagnetic activity. A new concept of data analysis has been introduced for studying the long/short term daily variation in CR intensity recorded with NM/meson telescope. Fourier Technique has been applied on four different types of groups of days chosen according to their different geomagnetic conditions. The selected groups are :

1. **All days :** This means all the 365/366 days in a year. The days are termed as AD. Of course, ignoring the days with abrupt changes.

Quiet days : Days on which the transient magnetic variations are regular and smooth are said to be magnetically quiet or calm or Q days. The criteria of selection is based upon Ap and Kp values. There are two types of Q days:

2. **60 Quiet days :** According to solar geophysical data (SGD) lowest mean order number are the five quietest days in a month. These days are called the International quiet-quiet-days or QQ days. Thus, 60 Q days in a year; termed as 60 QD.

3. **120 Quiet days :** First ten Q days in a month. Thus, 120 Q days in a year; termed as 120 QD.

4. **Continuous quiet days :** The need and criteria for the selection of this group of days is discussed in detail as follows :

Need for the selection of continuous quiet days (CQD)

(a) 60/120 quiet days selected are discrete and scattered all over in a years span of 365 days.

(b) In many cases the quiet days are preceded or followed by the days having larger values of geomagnetic disturbance index. Such days may be disturbed days.

(c) Kp is the mean standardized K-index from 13 observatories between geomagnetic latitudes 47 and 63 degrees. The scale is 0 (very quiet) to 9 (extremely disturbed) expressed in thirds of a unit e.g. 5_- is 4 and 2/3, 5_0 is 5 and 0/3 and 5_+ is 5 and 1/3 (Rangarajan, 1989). Ap is a daily index of magnetic activity on a linear scale. It is the average of the eight values of an intermediate 3 hourly index a_p. a_p is computed from Kp for the 3 hour interval. In the catalogue of SGD, letters C and K refer to a classification of the quiet days of the month, C=really quiet, K=quiet but with slightly disturbed three-hourly intervals. A selected "quiet day" considered "not really quiet" is marked by the letter A if Ap > 6 for that day, or marked

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by the letter K if Ap ≤ 6 but with one Kp ≥ 3_0 or two Kp values are ≥ 3. To avoid such days and to get a set of days having values of Ap index low continuously atleast for a span of three days, a group of days called continuous quiet days (CQD) is being selected.

Criteria for selection of CQD

The mean of all Ap values for all the days in a year is calculated. All those days having Ap values larger than twice the annual mean values are discarded. Again, the mean of all remaining Ap values of this new set of days is calculated and all those days are discarded which have Ap index larger than twice the new mean value. This procedure is repeated till the number of discarded days becomes zero. Thus, the last set possesses almost a statistically normal distribution of Ap values. From this last set, the mean value of Ap index is calculated and only those days having Ap values less than the mean for atleast three continuous days are chosen. This set of days is termed as continuous quiet days (CQD).

Finally, pressure corrected data obtained from Canadian Station: Deep River NM (Geographic Latitude = 46.1°, Geographic Longitude = 282.5°, Altitude = 145m, Vertical Cutoff Rigidity = 1.02 GV) has been harmonically analysed through Fourier Technique after applying trend correction to obtain the first and second harmonics on QD for the period 1964-95. A study of daily variation on QD has been performed to investigate the effect of orientation of SPMF. The days with extraordinary large amplitude, if any, have not been taken into consideration.

3. Results and discussion

The variation of mean values of Ap index with the number of iterations performed for the years 1986 and 1991 is depicted in Fig 1. It is clearly observable that the mean Ap index gradually reduces as the number of discarded days becomes zero. It is apparent from Fig 1 that the mean values of Ap index are higher for the year 1991, the period of maximum solar activity as compared to 1986, the period of minimum solar activity. Further, the distribution of the number of days with Ap index after different iterations of discarding process for the years 1986 and 1991 is depicted in Fig 2. The outermost dashed curve represents the original distribution. It is clearly observable from the curves for years 1986 and 1991 that the distribution is spread initially over a wide range of Ap index; whereas, the distribution curves become more and more regular with each iteration performed during minimum as well as maximum solar activity periods. Finally, when the discarding process is over, the curves have most regular and symmetrical distribution about the mean. During the year 1986, the mean of Ap stabilises after larger number of iterations; whereas, in case of the year 1991, it requires lesser number of iterations. The reason for this is quite obvious that the level of solar activity is low during the year 1986, while it is high during 1991.

The occurrence of days (%) has been plotted histographically with amplitude (%) and phase (hrs) at ground, of diurnal anisotropy in CR intensity on (a) 60 QD, (b) 120 QD, (c) CQD and (d) AD for all the four phases of solar activity cycle (SAC) i.e., ascending phase of SAC, solar maxima period, descending phase of SAC and solar minima. One of them is shown in Fig 3 drawn for minimum solar activity period, 1986. It is observed from the

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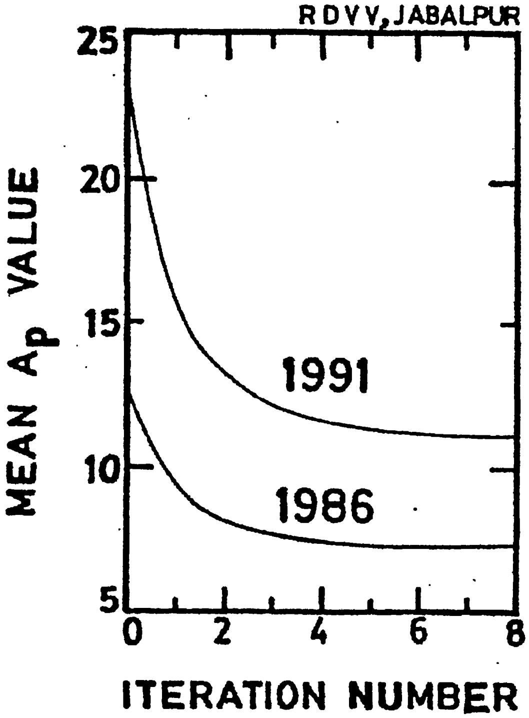

Figure 1. The mean value of Ap-index, after different iterations of discarding process, plotted for the years 1986 and 1991.

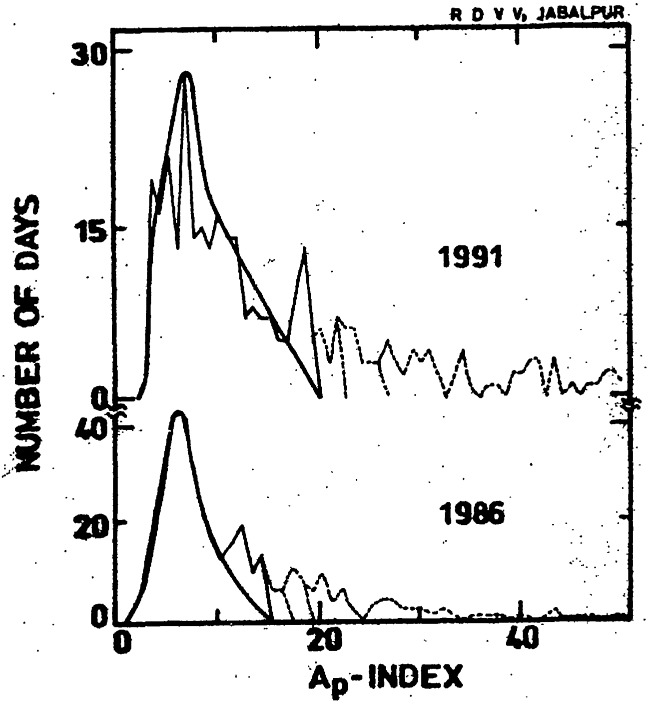

Figure 2. The distribution of Ap-index, after different iterations of discarding process (----), plotted for the years 1986 and 1991. Actual distribution curve is shown by thin line while thick line shows the approximated distribution curve.

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histograph, that the phase has occurred within the time interval near the corotational/azimuthal/ 90°E of Sun-Earth line/18-Hr direction in space value on maximum number of days in case of 60 QD and this trend is almost same when AD are selected. The frequency distribution over different range intervals is well scattered when 120 QD and CQD are selected. It is also evident from the plot that the amplitude peak is quite distinctly sharp in case of 60 QD. However, it becomes quite wider when AD are selected for analysis. As the level of the solar activity is low, the trend for the distribution of amplitude remains the same for all the four groups.

It is observed that the general trend as shown by the distribution for the phase and amplitude for all the four types of days is quite comparable. The distribution in most of the cases is sharper in case of 60 QD; whereas, some of the finer features of anisotropic variations are suppressed in AD. In some cases sharper peaks are also seen in case of CQD, because of sustained quiet conditions and small deviations on a day-to-day basis are suppressed. The statistical errors are found to be comparatively larger in case of 60 QD but are low in case of AD. However, the distributions are more regular and symmetrical in case of 60 QD. In Fig 4 the annual average values of the phase (Hr) and amplitude (%) at ground of the diurnal and semi-diurnal anisotropies during 1985-95 are plotted for 60 QD, 120 QD, CQD and AD. Height of the legend represents twice the error contained in the values; what has been referred above is also apparent from this Fig 4 as well. Therefore, for further investigations on long/ short term basis, the 60 QD are preferred.

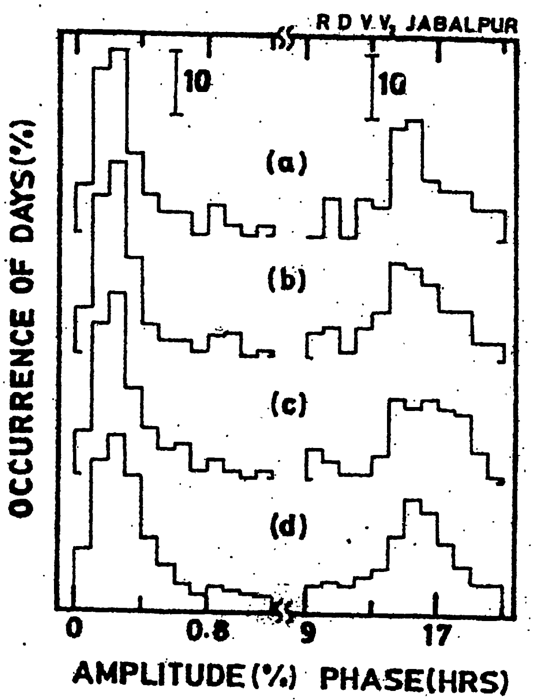

Figure 3. The amplitude (%) and phase (Hrs) of the diurnal anisotropy in CR intensity plotted histographically during 1986 for (a) 60 QD, (b) 120 QD, (c) CQD and (d) AD.

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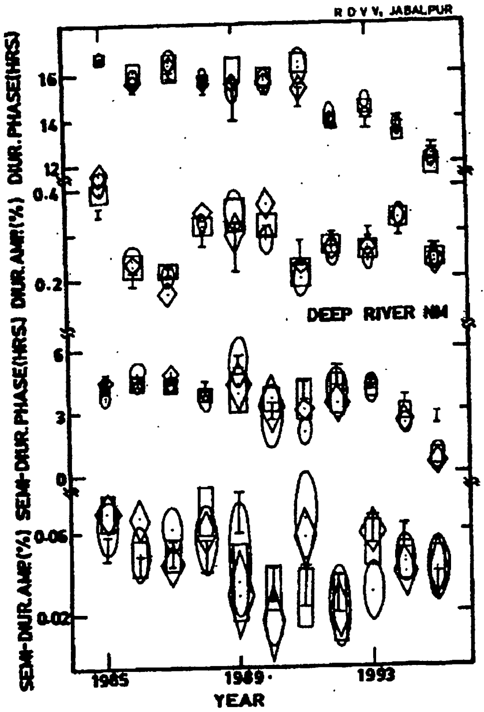

Figure 4. Amplitude (%) and phase (Hrs) of the diurnal and semi-diurnal anisotropies in CR intensity plotted during 1985-95 for 60 QD (0), 120 QD (□), CQD (◇) and AD (I). The height of legend represents twice the error contained in the values.

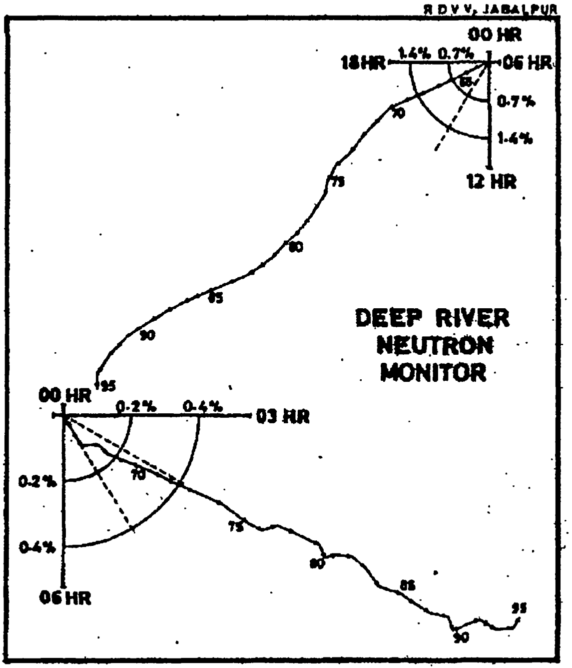

Figure 5. The vector addition plots of diurnal/semi-diurnal anisotropy on 60 QD plotted on harmonic dial for the period 1964-95.

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Fig 5 shows the values of vector addition plots (diurnal/semi-diurnal) anisotropy on different harmonic dials for the period 1964-95. The diurnal vectors are constantly in the same direction ~16 Hrs Lt at ground during the period 1964-70 and then shows a wave like nature. During 1975-76 and 1995 the diurnal anisotropy vectors are in ~12 Hr direction, which is in agreement with the findings of Bieber and Evenson (1997) for Newark NM station. For semi-diurnal anisotropy vectors, the phase has significantly shifted to earlier hours during 1967, 77, 1981-82, 1990-91 and 1995; whereas, it has shown a shift to later hours during 1964, 79 and 1986.

To examine the dependence of phase of solar daily variation, on the basis of the polarity of SPMF in the two hemispheres, the period of investigation 1964-95 has been classified into two groups i.e., when the polarity in the NH is negative and southern hemisphere (SH) is positive or vice-versa. The average diurnal/semi-diurnal anisotropy vectors, for the period 1964-70 and 1981-90 when the SPMF in NH is negative and 1972-79 and 1992-95 when it is positive, have been plotted in Fig 6 on harmonic dials alongwith the average anisotropy vectors for the entire period of investigation. It has been observed that the average anisotropy vectors (diurnal/semi-diurnal) for the periods of negative polarity of SPMF in NH have shifted to later hours with respect to average anisotropy vectors (diurnal/semi-diurnal) for the entire period of study; whereas, during the periods of positive polarity, the shift is towards earlier hours which is in agreement with the findings of Munakata et al. (1995).

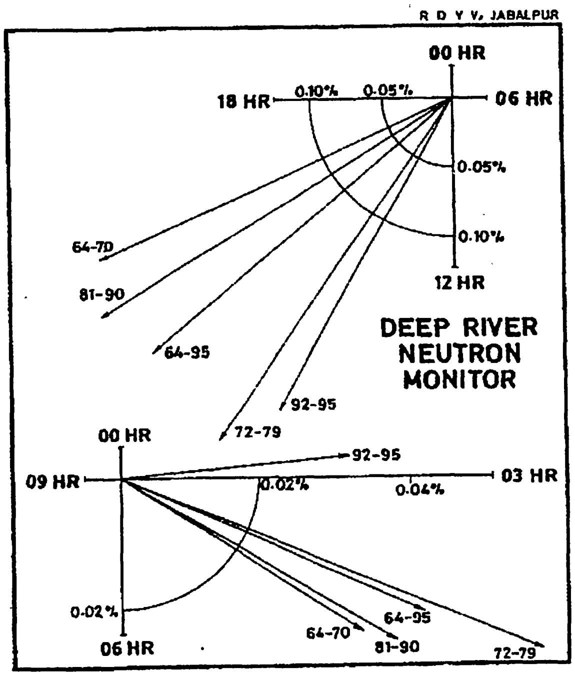

Figure 6. The average diurnal/semi-diurnal anisotropy vectors on 60 QD for the negative (i.e., 1964-70 and 1981-90) and positive (i.e., 1972-79 and 1992-95) SPMF polarity in NH alongwith the average anisotropy vectors for the entire period (i.e., 1964-95) plotted on harmonic dial.

It is found that there exist a clear 11/22 year variations of the solar daily variations (diurnal/semi-diurnal), the first is due to the variation of the solar activity while the second is due to the polarity of the solar magnetic cycle (El-Borie et al., 1995a, b). The recovery from CR 11-

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year modulation follows two distinct repetitive patterns (Ahluwalia, 1994a) when the magnetic polarity of the Sun in the NH is negative, the recovery is completed in 5 to 8 years but for the positive magnetic polarity epochs the recovery period is reduced to less than half as much (Ahluwalia, 1996). The 22-year modulation consists of two discrete states each corresponding respectively to parallel and anti-parallel states of the polarity of polar magnetic field of the Sun to galactic magnetic field. When the polar magnetic field of the Sun is nearly parallel to the galactic magnetic field, they could easily connect with each other, so that the galactic cosmic rays could intrude more easily into the heliomagnetosphere along the magnetic lines of forces, as compared with those in the antiparallel state of the magnetic fields (Nagashima and Morishita, 1979).

According to the theoretical investigation by Munakata and Nagashima (1984), the polarity dependence of the phase change has been interpreted as a result of the change in CR density distribution in space caused by the difference of CR drift motion in the positive and negative polarity states (Jokipii et al., 1977). The study state drift models predicts that the phase of the diurnal anisotropy responds significantly to a polarity change and shifts from ~18-Hr LT in space for negative polarity epoch to ~15-Hr LT in space during positive polarity epoch (Van Staden and Potgieter, 1991; Kumar et al., 1993). Sign of the transverse particle density gradient changes with a change in the solar magnetic polarity. Its annual mean value is positive for positive polarity epoch and negative for negative polarity epoch (Ahluwalia, 1994b).

The two components of the solar diurnal variation observed with two detectors characterized by linearly independent coupling functions have been used by Sabbah (1999a, b) to estimate the free space anisotropy vector during the period 1968-95. The amplitude of the radial anisotropy shows ~20-year magnetic cycle with the highest values around solar activity minima for positive polarity; whereas, the east-west anisotropy is minimum. The annual diurnal anisotropy vectors, A_1 (%) obtained on 60 QD for Deep River NM have been resolved into two components as depicted in Fig 7. One along the 12-Hr direction i.e., the radial anisotropy component, A_{1R} (%) and the other is along 18-Hr direction i.e, east-west anisotropy component, $A_{1\phi}$ (%). The trend of the plots is very similar to that obtained by Sabbah (1999 b) for the Deep River NM coupled with UMT located at Socorro. Prior to 1971, when the polarity of SPMF in NH is negative, the diurnal anisotropy vector, A_1 has almost constant ≈16 Hr-LT direction, ϕ_1 at ground. After 1971, the radial anisotropy component increases sharply; whereas, east-west anisotropy component decreases gradually and attains its minimum in 1976. This results in shifting the diurnal anisotropy vector towards earlier hours during positive polarity epoch. During negative polarity epoch, the east-west anisotropy component attains its maximum in 1985 and the radial anisotropy component is minimum in 1987 which results in shifting the anisotropy vector gradually towards later hours. The east-west component has its lowest again in 1995 around solar activity minima; whereas, radial component has its highest which is responsible for the early hour shift of diurnal anisotropy vector.

Potgieter et al. (1980) pointed out that during the periods when northern hemispheric field points towards the Sun, positively charged particles will flow from the ecliptic towards the solar poles, leading to decrease in intensities of positively charged particles observed near the Earth and hardening the primary spectra of particles to which neutron monitors respond. When the southern hemispheric field points towards the Sun, particles flow towards the ecliptic and

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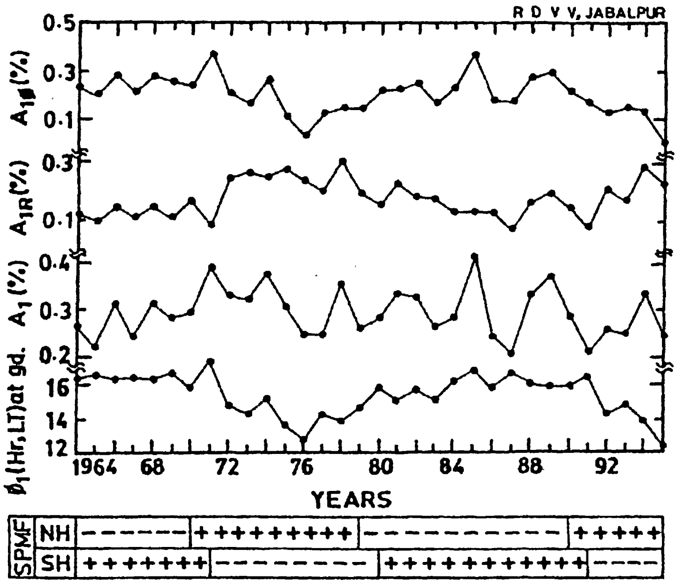

Figure 7. The phase ϕ_1 (Hr, LT), amplitude A_1 (%), radial component A_{1R} (%) and east-west component $A_{1\phi}$ (%) at ground of the annual diurnal anisotropy in CR intensity on 60 QD plotted alongwith SPMF polarity in NH and SH for the period 1964-95.

near to the Earth intensities are increased and the spectra is softened. Nagashima and Fujimoto (1989) pointed out the existence of polarity dependence in the rigidity spectrum of the semi-diurnal anisotropy. The semi-diurnal anisotropy vectors suddenly change their relative configuration from the usual direction to another for the polarity reversal of polar magnetic field of Sun from positive to negative state in NH. The state is defined as "positive" when the polar magnetic field is away from the Sun in NH and towards the Sun in SH, while it is called "negative" when the polar magnetic fields are reversed. Duldig (1991), using the data from the underground Mawson telescope for the period 1973-89, observed that the solar semi-diurnal variation is remarkably constant throughout the solar polarity reversal of cycle-21. Thus, confirming that the semi-diurnal anisotropy changes only at low rigidities with the solar polarity reversal but the higher rigidity spectrum remains constant (Nagashima and Fujimoto, 1989). A clear dependence of both the harmonics on the magnetic polarity of the heliosphere has been pointed out during the 1970's and 1990's when the magnetic polarity of the heliosphere is positive in NH (Munakata et al., 1995). The phases of the first two harmonics are significantly shifted towards earlier hours than those during 1980's when the polarity of the heliosphere is negative in NH. On the contrary, according to Ahluwalia (1996) the polarity of IMF has no effect on semi-diurnal anisotropy parameters i.e., the amplitude as well as direction in free space at all primary rigidities.

4. Conclusions

The following conclusions have been drawn on the basis of present investigations :

1. The 60 QD are better suited for long/short term studies of diurnal/semi-diurnal anisotropy. The distribution of phase and amplitude on 60 QD are more regular and some of the variations are observed more clearly.

2. The average anisotropy vectors (diurnal/semi-diurnal) for the periods of negative polarity of SPMF in NH have shifted to later hours with respect to average anisotropy vectors (diurnal/semi-diurnal) for the entire period of study; whereas, during the periods of positive polarity the shift is towards earlier hours, showing their oscillatory nature.

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