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Comparative Study of First Two Harmonics in Cosmic Ray Intensity for the Period 1964–95

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Abstract

The Deep River neutron monitor data has been harmonically analyzed for the period 1964–95 covering three solar cycles 20, 21 and 22, looking for a long term trend of the diurnal and semi-diurnal anisotropies of cosmic ray intensity on geomagnetically 60 quiet days. The amplitude of both the harmonics remains statistically constant during 1964–70. The amplitudes of the first harmonic is found to be low during 1965, 1967, 1976–77, 1986–87, 1991, 1993 and 1995. The amplitude of diurnal anisotropy acquired exceptionally large values in 1985, whereas semi-diurnal anisotropy acquired large values in 1974–75 and in 1984, which coincided with epochs of high-speed solar wind stream (HSSWS). The phase of the diurnal anisotropy has shifted to earlier hours in 1976 and 1995, whereas the phase of semi-diurnal anisotropy has significantly shifted to earlier hours during 1967, 1977, 1991 and 1995, periods of close to minimum solar activity. The diurnal phase shows a shift to later hours during 1971, 1985, 1987 and 1991, whereas semidiurnal phase shows a shift to later hours during 1980, 1984 and 1989.

Key Words: Cosmic rays, Diurnal, Semi-diurnal, Anisotropy and Solar poloidal magnetic field.

1. Introduction

A number of physical mechanisms for causing different harmonics of daily variation have been proposed from time-to-time. The streaming of particles in interplanetary space, due to convection, diffusion, adiabatic deceleration, causes the diurnal anisotropy and particle drifts. Subramanian and Sarabhai [1] and Quenby and Lietti [2], both attributed the origin of semi-diurnal anisotropy to symmetric latitudinal cosmic ray density gradient in the heliosphere with particle density rising on both sides of the equatorial plane [3]. According to Nagashima et al. [4] semi-diurnal anisotropy arises mainly as a result of the contribution from the pitch angle scattering rather than in the manner suggested by Subramanian and Sarabhai [1] and Quenby and Lietti [2]. Recent data acquired by the Ulysses spacecraft during its fast heliolatitude scan shows that the latitude distribution of galactic cosmic ray (GCR) has both symmetric and asymmetric components [5, 6]. According to Ahluwalia and Fikani [7, 8] the contribution of the symmetric transverse gradient to semi-diurnal anisotropy is minimal and the larger contribution comes from some other source(s). Nagashima's treatment also implies that semi-diurnal and tri-diurnal anisotropies have common features. This is observed by many workers [9, 10, 11]. Bieber and Pomerantz [12] proposed the unified theory of cosmic ray diurnal variation. A careful investigation of the characteristics of the different components of the daily variation is therefore important in contributing towards understanding the mechanism.

1.1. Experimental data and analysis

CR modulation is a complex phenomenon, which occurs all over the heliosphere and depends on many factors. No single solar index can be responsible for CR variations. Numerous theoretical and experimental works discuss a strong influence of the heliospheric tilt and the polarity of the general magnetic field on the long-term CR variations [13, 14]. The existence of a relation between solar wind velocity, IMF module and long-term CR variations has been established [15, 16, 17]. The global network of cosmic ray stations located at different geomagnetic cut-off rigidities and altitudes can be used to study long-term cosmic ray modulation. Neutron monitors are sensitive to cosmic rays of about 0.5–20 GeV, which coincides with the energy range of most effective solar modulation. NM records is a unique data set to study the detailed time behavior of modulation since 1950s.

Simpson first installed the neutron monitors around the year 1952. A paraffin moderator, lead producer and a shield of hydrogenous material surround these BF3 filled proportional counters. During the period of International Geophysical Year (IGY), i.e. 1957–58, about 50 standard neutron monitors are installed neutron monitors are installed all over the world, which are designed as IGY-type neutron monitors. It consists of 12 BF_3 counters sensitive to thermal neutrons. Around each other there is an "inner moderator", i.e. paraffin, the function of which is to slow down or moderate the locally produced neutrons to near thermal energies to facilitate their capture in BF3 gas. The counter assembly consisting of the inner moderator and counter is surrounded by lead "producer" of purity greater than 99.9% in which evaporation neutrons are produced by the interaction of the nucleonic components. This arrangement is completely shielded by a paraffin "reflector" which prevents the escape of neutrons that would otherwise fail to be detected. This reflector also excludes the low energy neutrons produced in the vicinity of the monitor.

The output from 12 counters is divided into two sections each containing six counters. Each section is associated with its own independent electronic circuits. The division of the counters into two half sections provides a check on the performance of the detecting system by comparing the counting rate from two half-sections. The proportional counters filled with pure Boron Trifluoride (BF_3) gas enriched to more than 90% B^{10} isotope at a pressure of 60 cm Hg are used for the detection of thermal neutrons.

Principle of Neutron Monitor: The thermal neutrons are detected by means of proportional counters filled with BF_3 gas. The Thermal neutron, which is captured by a B^{10} nucleus, induces the exothermic reaction

$$_5B^{10} + {}_0N^1 \textit{–long} \rightarrow {}_3Li^7 + {}_2He^4 + 2.78 \text{ MeV},$$

producing lithium and α-particles. The cross section of this reaction follows a $1/V$ dependence, where V is the velocity of thermal neutrons, being ∼3820 barns at thermal energies or 1/40 eV.

The $_3Li^7$nucleus is left in a 480 keV excited state in 94% reaction and 2.3 MeV being shared by the $_3Li^7$ and $_2He^4$nuclei. In the remaining 6% of reaction, the $_3Li^7$nucleus is left in the ground state and the $_3Li^7$and $_2He^4$ nuclei have a total kinetic energy of 2.78 MeV. The output pulse height, which is generally ∼1 milivolt, depends strongly on the high voltage applied to the proportional counter. However the pulse produced by other particles are a factor of more than 5 less in amplitude to enable easy discrimination.

Geomagnetic quiet day: Days on which the transient magnetic variations are regular and smooth are said to be magnetically quiet or calm, or Q, days. These are the days with low values of Ap and Kp. According to solar geophysical data (SGD), the five quietest days in a month thus—60 Q days in a year—are selected. These days are called the International quiet-quiet-days, or QQ days. Kumar et al. [18, 19, 56] have studied long/short term daily variation on geomagnetically 60 QD. The 60 QD are better suited for long/short term studies of daily variation. The distribution of phase and amplitude on 60 QD are more regular and some of the variations are observed more clearly [20]. Present study has been performed on 60 QD.

Pressure corrected data of Deep River neutron-monitoring (NM) station (cutoff rigidity 1.02 GV; latitude 46.1° N; longitude 282.5° E; altitude 145 M) has been Fourier analyzed after applying trend corrections to obtain the first and second harmonics at ground for the period 1964–95. According to solar geophysical data, the five quietest days are selected in a month; thus 60 quietest days in a year. These are called the International Quiet-Quiet days or QQ days. The study of diurnal and semi-diurnal variation has been performed on 60 QQ for the period 1964–95. The justification for the selection of only geomagnetic quiet days for the analysis purpose has been discussed elsewhere. The days with extraordinarily large amplitude, if any, have not been taken into consideration. Also, all those days are discarded having more than three continuous hourly data missing.

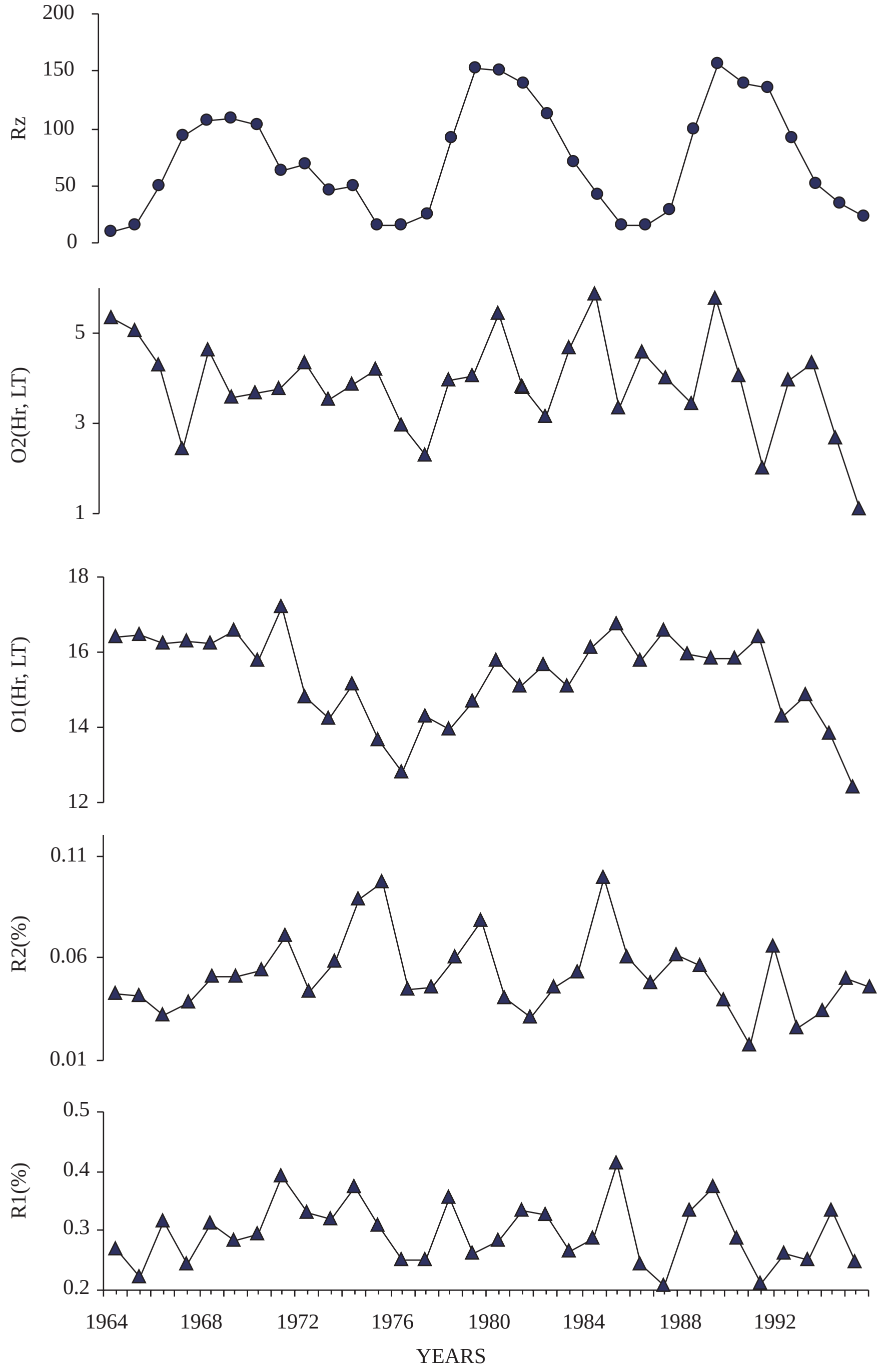
2. Results and Discussion

The average annual diurnal and semi-diurnal phases ϕ_1 and ϕ_2(Hr, LT), amplitudes $R_1$and R_2(in %) on 60 QD for Deep River neutron monitoring station, sunspot number R_z and the polarity of solar poloidal magnetic field (SPMF) in the northern hemisphere (NH) and southern hemisphere (SH) of the Sun for the period 1964–95 have been plotted in Figure 1.

It is observable from Figure 1 that the amplitudes R_1 and R_2 are smaller during the years 1964–65, 1976–77, 1986–87 and 1995 compared to the two preceding years. These are the periods of minimum solar activity. Ahluwalia et al. [21] observed large values of diurnal amplitude during high solar activity and low values when the activity is low. The amplitude of semi-diurnal variation is found to be proportional to the solar activity [22]. El-Borie et al. [23] observed low values of semi-diurnal variation near the years of solar activity minimum. Pransky et al. [24] using ionization chamber data for the period 1954–89 obtained similar results, observing a decrease in amplitude during 1964, 76 and 86, i.e. the years of minimum solar activity. They also noticed the decrease in amplitude during magnetic field inversion of the Sun. The decrease in amplitude during solar activity minimum may be explained by a decrease in the regular component of the interplanetary magnetic field intensity. The reason for decrease in amplitude during magnetic field inversion has been thought to be due to an increase of IMF irregularities originated from solar polar coronal holes. On the contrary, Ahluwalia and Fikani [11], using the muon telescope data for the period 1966–88, observed increases in the amplitude after the epochs of SPMF reversal. They also observed the amplitudes to be smaller when the solar activity is low, which is in agreement with the findings of Pransky et al. [24]. Pandey et al. [25] observed the diurnal vectors to be composed of, a static vector with its amplitude 0.47% from the 16.8 hour direction, the ∼11- year wave and the ∼22-year wave for the period 1955–84.

The amplitude of both the harmonics remains statistically constant during 1964–70. The small changes in the diurnal amplitude may be attributed to the variation of maximum cutoff rigidity R_{max} [26]. The regime of invariant diurnal anisotropy prevails all through the period 1957–70, i.e. for 14 years. Charged particle drifts do not make any identifiable contribution to the diurnal anisotropy during this period [27].

The amplitude of diurnal and semi-diurnal anisotropy is observed to be high during declining phase of solar activity cycle (SAC) 20, 21. Ahluwalia and Riker [28] observed large values of diurnal amplitude during 1973–75; whereas, Ahluwalia et al. [21] observed similar large values of diurnal amplitude for the period 1984–85 at Deep River. Pathak et al. [29] reported an increase in the amplitude of semi-diurnal as well as tri-diurnal anisotropy during the period 1973–75 by a factor of two. Fikani et al. [30] using the Deep River NM data for 1966–88 observed a broad enhancement in the amplitude for the year 1973 through 1976. Agrawal [10] has pointed out that the amplitudes of semi-diurnal as well as tri-diurnal anisotropies increase during 1973–75. It has been suggested that such an increase is associated with the days of high-speed solar wind streams (HSSWS) originated from solar polar coronal holes. The interaction between HSSWS and Earth's magnetosphere transfers vital information to the magnetosphere, which manifests itself in changes



SP	NH	- - - - - - - - - - -	++++++++++	- - - - - - - - - - - -	++++++++
MF	SH	+++++++++++++++	- - - - - - - - -	++ +++++++++++	- - - - - -

Figure 1. The average annual diurnal amplitude R_1(%), semi-diurnal amplitude R_2 (%), average annual diurnal phase ϕ_1(Hr, LT), semi-diurnal phase ϕ_2(Hr, LT), sunspot number (R_z) on 60 QD plotted along with SPMF polarity in NH and SH for the period 1964–95.

in geomagnetic activities as monitored by its geomagnetic indices Ap and aa [31, 32]. A relationship exists between solar wind velocity, Ap and southward component of IMF. The present study performed on 60 QD leads to high value of amplitude of diurnal and semi-diurnal anisotropy during the years 1973–74 and

1984–85 which is in agreement with the findings of Ahluwalia et al. [21] for diurnal anisotropy and El-Borie et al. [15] for semi-diurnal anisotropy. Nigam et al. [33] have observed the semi-diurnal amplitude to be low during 1973, which has been attributed to high-speed solar wind stream (HSSWS) from the coronal holes, in contradiction to the findings of Ahluwalia et al. [21]. Kudo and Mori [34] showed the 11-year periodicity of the amplitude enhancement in the solar diurnal variation of cosmic rays in the declining periods of solar activity. Using the data from the world-wide neutron monitors, including Deep River for the period 1957 to 1987, they found that observed amplitudes show minimum in 1954, 64, 76 and 86, when the sunspot numbers are minimum. They noticed the enhancement in amplitudes in 1962–63, 1973–74 and 1984–85 and suggested that these enhancements may be correlated with the interplanetary plasma parameters and the structure of the heliomagnetic fields. Diurnal amplitude depends on interplanetary magnetic field (IMF) magnitude, direction and the solar wind velocity [35, 36, 37]. The amplitude of the total diurnal anisotropy varies by 30% following a polarity reversal of IMF [38]. The amplitude of diurnal anisotropy has a large value during 1971, 78 and 89, which are during, or in proximity, of the periods of polar reversal. The amplitude of semi-diurnal anisotropy increases during the years 1971, 1979 and 1991 followed by the decrease for all the three consecutive epochs of SPMF inversions. The changes in amplitude are significantly high during the polarity reversal of 1979–80 and 1990–91; however they are less prominent during the polarity reversal of 1970–71. On the contrary, Ahluwalia and Fikani [8] denied the effect of the polarity of IMF on semi-diurnal anisotropy parameters (amplitude as well as direction).

There is a sharp decrease in diurnal amplitude during the year 1986 compared to that during 1985, and remains low during the year 1987, which is in accordance with the findings of Ahluwalia et al. [21] for Deep River neutron monitor for the period 1980–87. It remains almost constant for the period 1988–90. It again falls to lower values during 1991 and gradually attains higher values during 1992–94. Le Roux and Potgieter [39] observed four global merged interaction region (GMIR) during 1977–87. Each simulated GMIR affected cosmic ray intensity for a maximum of two years so that long term modulation for the first and last 2–3 years of the 1977–87 cycle is totally controlled by the changing heliospheric neutral sheet (HNS). Le Roux and Potgieter [39] according to their 2D model, illustrated that the incorporation of GMIR gave a natural and convincing explanation for the observed large step decreases in long term modulation. They concluded that long-term modulation is a process determined by the interplay between the changing waviness of the HNS and the outward propagating GMIRs that originate beyond 10 AU. During times of lower solar activity the HNS controls the modulation because of the absence of large GMIR in the heliosphere; while during times of larger solar activity successive GMIRs dominate the HNS in determining the time variation in long-term cosmic ray modulation.

Krainev and Webber [40] supported the combined merged interaction region (MIR)-Drift picture of modulation, whereas Potgieter and Le Roux [41] concluded that drifts are of primary importance as long as the waviness of the HNS is moderate [39], i.e., tilt angle $\alpha \leq (35 \pm 5)^\circ$ is a good indicator of solar activity and this strongly suggests that several years around solar maximum modulation may not be drift dominated. The transition may happen either gradually (1984–87; increasing drift effects) or rapidly (after 1987; decreasing drift effects), depending on the rate of change in global solar activity and therefore on global modulation conditions. The rapid increase in solar activity after minimum modulation in 1987 favors a situation where drift occurred progressively less, simply because conditions had deteriorated to the extent that drifts could no longer accumulate on the large time scales required for major long term modulation [42]. There has been a little increase of diurnal amplitude during 1994 after a decrease observable for all type of days during 1991, which is period of maximum solar activity. Large shock associated flux increases in late 1991.

A high correlation has been noted between the current sheet tilt angle and the neutrons recorded during May–June of 1987, which seems to be directly responsible for the intensity decrease [43]. The variation in the amplitude of the diurnal anisotropy $\sim$7% when the neutral sheet tilt angle varies from 0° to 60° when $A < 0$ and only 2% when $A > 0$ [38].

Ahluwalia [44] computed the mean values of the transverse particle density gradient in the heliosphere G_θ for the period 1965–90.The sign of $G_\theta$changes with a change in the solar magnetic polarity. Its computed annual mean value is positive for $qA > 0$ epochs and negative for $qA < 0$ epochs, in accordance with predictions of the drift hypothesis. The magnitude of the transverse gradient is nearly zero for 1973–76, 1981–82 and 1984–85 but has a larger value during 1977–80. Asymmetric gradients become unstable after 1973 [45]. Ahluwalia and Fikani [8] observed the high value of the amplitude of semi-diurnal anisotropy during 1972–77 and low values for the period 1978–80. The semi-diurnal anisotropy is most persistent during the period when transverse gradients (symmetric as well as asymmetric) are unstable or non-existent. They suggested that the contribution from the symmetric transverse gradients ($G_{\theta s}$) to semi-diurnal anisotropy appears to be minimal and a major contribution comes from pitch angle scattering. According to Nagashima et al. [4] the existence of a negative symmetric gradient enhances the effect of pitch angle scattering. $G_\theta$has large negative value for the years 1986–87. The present study on 60 QD leads to high values of the semi-diurnal amplitude during 1974–75 and 1984 while values obtained during 1977, 1980 and 1986 being $R_2 < 0.05\%$. The results are partially in agreement with findings of Ahluwalia and Fikani [8] and Nagashima et al. [4]. Subramanian and Sarabhai [1] and Quenby and Lietti [2] attributed the symmetric latitudinal gradients for the origin of semi-diurnal anisotropy. Thus, it appears as if there is more than one process active or responsible for the origin of semi-diurnal anisotropy. The latitudinal cosmic ray gradient contributes to the cosmic ray solar diurnal variation [46]. Asymmetric gradients contribute to diurnal and not to semi-diurnal anisotropy [8]. The amplitude of the diurnal anisotropy is determined by many factors besides the transverse gradient. The asymmetric transverse gradient, $G_{\theta a}$ is well behaved over an intermediate rigidity range 10 Gv $\leq R_m \leq$ 67 Gv, where it is inversely proportional to the rigidity of the GCR protons. The direction of $G_{\theta a}$changes consistently immediately after a solar polar field reversal [47]. In the real world, both symmetric as well as asymmetric gradients may be present $G_\theta = G_{\theta a} + G_{\theta s}$[48]. For the period 1965–68, a persistent southward pointing gradient exists. From 1969–73, it points northward. The gradient becomes southward again in 1974, 81, 84, 92 and reverts to being northward in 1975, 79–80, 82–83, 87, 89. The gradient disappears for the period 1976–78, 1985–86, 88. The gradient has large magnitude during the year's 1968(s), 1973(n), 1984(s), and 1987(n) [47]. It is observable from the plots of diurnal anisotropy that the amplitude is high. In 1971, 74, 78, 85, 89, which are the periods close to the periods when the transverse asymmetric gradient has large magnitude in 1975–76. $G_{\theta s}$=0 and have large negative values in 1986–87 when obtained diurnal amplitude found to be very low.

The amplitude of the semi-diurnal variation depends upon the primary rigidity whereas the amplitude of the diurnal anisotropy is independent of the primary rigidity up to a limiting rigidity R_c [1, 2, 49]. The amplitude and phase of semi-diurnal variation are rigidity dependent [50]. The variational spectrum applicable to semi-diurnal anisotropy may be represented by a double power law, with exponents γ_1 for a range of primary rigidities $R \leq R_p$ and $\gamma_2$for $R > R_p$; R_p being the peak rigidity. Ahluwalia and Fikani [7] found $\gamma_1 = 0.7 \pm 0.3$ and $\gamma_2 = -0.4 \pm 0.2$. The upper cut-off rigidity Rc applicable to diurnal and semi-diurnal anisotropy has higher values near solar activity maxima and low values around solar activity minima. During the epoch when the solar wind speed is high (1973–75, 1982–85) the value of the upper cut-off rigidity is also high when the high amplitudes of diurnal and semi-diurnal amplitudes are observed. A close correspondence exists between the magnitude of IMF and the value of R_c and the peak rigidity R_p. Both exhibit the solar as well as the hale cycle variation [7]. Ahluwalia and Fikani [7] with 39 globally distributed detectors and Sabbah [36] for Deep River NM coupled with underground meson telescope independently calculated the value of Rc. Rc has low values during 1965, 76–77, 86–87, 1995 and large values during 1968–70, 78–80, 89 and 1991. From the plots of Figure 1 it is observable that diurnal amplitude is low in 1964–65, 76–77, 86–877, 91, 95 and has quite large values during 1971, 78 and in 1989. Further, semi-diurnal amplitudes have low values during 1966, 76–77, 90. Thus, a close relationship seems to exist between the amplitude of daily variation and Rc as suggested by Sabbah [36]. The amplitude of the semi-diurnal variation depends on the azimuthal direction of arrival of the particles incident at an angle of 45° to the zenith; whereas, it is three times larger for the particles coming from south than for those coming from north [51, 52].

It is observable from Figure 1 that the phase of the diurnal anisotropy remains constant during 1964–70, then it started shifting towards earlier hours until 1976. The shift to earlier hours is larger in 1973 and 1995 which are the periods close to minimum solar activity, confirming a ~22-year periodicity in the phase of diurnal anisotropy. The direction of the diurnal anisotropy is quite variable and rigidity dependent during the epoch that lasted from 1971–79 [27]. The phase of diurnal anisotropy recovered gradually to 18-Hr/ azimuthal/corotational directions from 1976 to around 1986, which is in agreement with the findings of Fujii and Ueno [53]. Using the neutron monitor data of Athens and Deep River stations over the period 1970–1977, Mavromichalaki [54] studied the diurnal anisotropy of cosmic-ray intensity and pointed that the time of maximum of diurnal variation shows a remarkable systematic shift towards earlier hours than normally beginning in 1971. This phase shift continued until 1976, the solar activity minimum, except for a sudden shift to later hours for one year, in 1974, the secondary maximum of solar activity. It is noticed that the behavior of the diurnal time of maximum has been consistent with the convective-diffusive mechanism, which relates the solar diurnal anisotropy of cosmic rays to the dynamics of the solar wind and of the interplanetary magnetic field. It once again confirmed the field-aligned direction of the diffusive vector independently of the interplanetary magnetic field polarity. It is also noteworthy that the diurnal phase may follow in time the variation of the size of the polar coronal holes. All these are in agreement with the drift motions of cosmic-ray particles in the interplanetary magnetic field during this time period. The long-term behavior of the diurnal anisotropy, especially the phase shift from one solar minimum period to another, depends on the polarity of IMF [55]. It is observed from the Fig. 1 that the phase of the diurnal anisotropy ϕ_1 has the tendency to shift towards the corotational direction when the sunspot number (R_z) is high and when it lowers down ϕ_1 to shift towards earlier hours. The plots of the phase of the semi-diurnal anisotropy ϕ_2 doesn't show any significant trend with variation in R_z. Tiwari et al. [56] found significant positive correlation for the diurnal amplitude and phase with the sunspot number. For semi-diurnal phase correlation is positive and for the semi-diurnal amplitude they observed small negative correlation with R_z. A correlative analysis has been done by Tiwari et al. [57] between cosmic ray intensity and sunspot numbers for the solar cycle 19 to ascending phase of recent solar cycle 23. They noticed that the correlation between sunspot number and cosmic ray is negative and high. The variation trend is similar for odd solar cycles (21 and 23) and even solar cycles (20 and 22), thus confirming the odd-even hypothesis in correlative analysis. During positive IMF polarity (when the IMF pointed away from the Sun above the neutral sheet) period, the phase of the diurnal variation shifts closer to the noon hour than in the case during the negative IMF polarity (when the IMF pointed towards the Sun above the neutral sheet) period [58]. In 1982–85, the IMF pointed towards the Sun above the neutral sheet; while in 1972–78 the IMF pointed away from the Sun above the neutral sheet. Again during 1992–95, the positive IMF polarity appears which may be associated with a large shift in phase of diurnal anisotropy towards early hours during 1994–95. The phase of the diurnal anisotropy shows a shift to early hours when the polarity of the solar magnetic field in the northern hemisphere changes from negative to positive [59]. The polarity of the solar magnetic field changes from positive to negative during 1979–80. During the period from 1981–87 the phase of the diurnal anisotropy recovered to its usual direction of corotation. For the period 1993–95, NH has positive polarity and a large shift in phase of diurnal anisotropy towards early hours is observed.

It is apparent from Fig. 1 that the semi-diurnal phase decreases gradually from 1964–67. It is statistically constant for the period 1968–74. The phase shifts too much earlier hours during 1967, 77, 91 and 95. During the polarity reversal of 1979–80 it has shifted to later hours; whereas, during 1990–91 reversals it has shifted too much earlier hours. In the year 1991 the shift in phase is accompanied by large change in the amplitude of the anisotropy.

3. Conclusions

On the basis of the above investigation, the following conclusions may be drawn:

The amplitude of semi-diurnal anisotropy acquired large value in 1974–75 and in 1984, which are the epochs of HSSWS.

The amplitude of diurnal anisotropy acquired exceptionally large value in 1985 and very low value in 1986–87, which may be attributed to the combined HNS and drift effect [31].

The amplitude of the first harmonic is found to be low during 1965, 1976–77, 87 and 95, which are the periods of minimum solar activity, or close to it.

The phase of the diurnal anisotropy has shifted to earlier hours in 1973 and 95 the periods close to minimum solar activity confirming once again the periodic nature of diurnal anisotropy.

The time of maximum of diurnal anisotropy remains in the corotational direction when solar activity is high; whereas it shifts to earlier hours for minimum solar activity.

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