

Tri-diurnal anisotropy of cosmic ray daily variation for the solar cycle 23

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An extensive study of tri-diurnal anisotropy of cosmic ray daily variations for the period 1996 – 2006 has been carried out using cosmic ray neutron monitor data of Kiel and Beijing. The daily and yearly averages of tri-diurnal wave amplitude and phase have been obtained to observe long term behaviour of third harmonic of cosmic ray daily variation. The relation between amplitudes and phases (annual and daily averages) of tri-diurnal data for these two different cut off rigidities has been shown. No long-term variational trend is seen in tri-diurnal anisotropy. On day-to-day analysis, a well defined peak in tri-diurnal amplitude between 0.06% and 0.010% is observed.

Keywords: Cosmic rays, Tri-diurnal anisotropy, Solar activity

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1 Introduction

The continuous outward flow of solar wind and frozen-in magnetic field produces time variations in cosmic ray intensity of different periodicities, viz. 22 years, 11 years, 27 days and 24 hours. The systematic study of the time variations of relativistic cosmic rays started some 60 years ago by using the ground based detectors. The ground based observations, its anisotropies and their relationship with other geomagnetic and interplanetary parameters, provide the base to understand the time variation characteristics of cosmic ray intensity.

Daily variation in cosmic ray intensities arise from anisotropies produced in the interplanetary medium. Daily variations are recorded by ground based detectors once a day as their asymptotic cones of acceptance sweep through the directions containing the spatial anisotropy. Detailed studies in this field were reviewed in the past by several researches¹⁻³. In addition to the diurnal component in daily variation, two other semi-diurnal and tri-diurnal components are also observed. Higher harmonics of cosmic ray daily variation such as semi and tri-diurnal variation were interpreted on the basis of pitch angle distribution theory. During the past decades, the characteristics of tri-diurnal variation (third harmonic of the daily variation) have been studied by a number of researchers. They have mostly used the data from the world wide network of high counting rate neutron

detectors⁴⁻⁷. In the present paper, the long-term behaviour of tri-diurnal variation of cosmic rays for the period 1996-2006 has been analysed.

2 Data analysis

Harmonic analysis technique has been adopted to derive various vector components of anisotropic variations of cosmic ray intensity. The pressure corrected hourly counting rate data of the neutron monitors of two stations Kiel and Beijing have been analysed to obtain the amplitude and phase for each individual day after correcting the hourly data for long-term trend in cosmic ray intensity.

Diurnal, semi-diurnal and tri-diurnal amplitudes and phases can be derived by using simple harmonic analysis. A periodic function $y = f(t)$ can be expressed in the form of trigonometric fourier series:

$$y = f(t) = a_0 + \sum (a_k \cos kt + b_k \sin kt) \\ = \frac{a_0}{2} + \sum_{k=1} r_k \cos(kt - \varphi_k)$$

With the help of the sine and cosine components, the amplitude and phase angles can be determined by the following relation:

$$a_k = A_k \cos \phi_k \quad b_k = A_k \sin \phi_k \\ A_k = \sqrt{(a_k^2 + b_k^2)}, \quad \varphi_k = \tan^{-1} \left(\frac{b_k}{a_k} \right)$$

3 Results and discussion

In earlier studies on cosmic ray tri-diurnal anisotropy, it has been reported that the tri-diurnal amplitude generally decreases by a factor of 4 to 5 from the semi-diurnal amplitude. The signal-to-noise ratio is generally found to be poor even on annual average basis^{5,8}. Agrawal⁵ and Shrivastava⁶ have reported the detailed characteristics of tri-diurnal anisotropy of cosmic ray intensity for the period 1973-1975 and 1976-1980, respectively. They have reported a positive correlation between semi-diurnal and tri-diurnal amplitudes. Their results suggest that solar polar coronal holes may influence both the solar tri-diurnal and semi-diurnal variation of galactic cosmic ray intensity. Tiwari *et al.*⁹ have reported a significant relationship of first two harmonics of cosmic ray daily variation with solar activity. They found a significant and positive correlation of diurnal amplitude and phase with sunspot numbers. Similarly, positive correlation with sunspot numbers was also reported for semi-diurnal phase. Recently, Pandey *et al.*¹⁰ have reported the long-term trend of the first three harmonics of the daily variation of cosmic ray intensity for the period 1991-2004, using the Haleakala neutron monitor data. They have reported the 11-year cycle trend in diurnal and semi-diurnal component but did not find any long-term variational trend in tri-diurnal component. Kudela *et al.*¹¹ reported the long-term behaviour of the diurnal wave of cosmic ray anisotropy in relation with inter-planetary magnetic field. Long-term characteristics of cosmic ray diurnal variations are also reported in recent publications¹²⁻¹³. In the present analysis, the amplitude and phase has been derived, first on daily basis and then on average basis, for the Kiel and

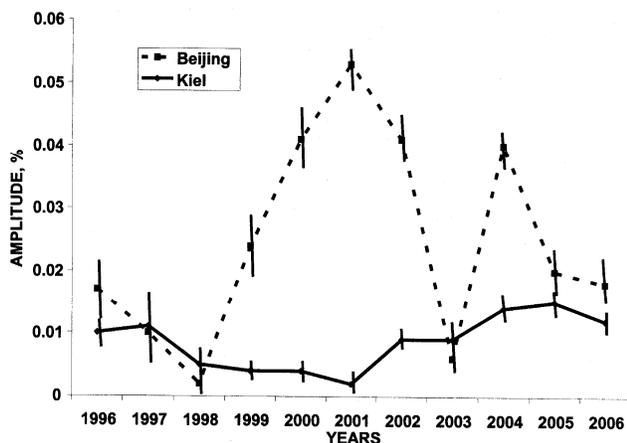


Fig. 1 — Amplitudes (%) for the annual average tri-diurnal variation for Kiel and Beijing neutron monitors

Beijing neutron monitors covering different cut off rigidities.

Figure 1 shows a plot of annual mean tri-diurnal amplitude and phase of Kiel and Beijing neutrons for the period 1996-2006. Most of the values are statistical [significant standard error of mean ($\pm 1\sigma$) are shown for each point]. As seen in the figure, the amplitudes of cosmic ray tri-diurnal variation of cosmic ray daily variation are invariant in different time scales. The values of amplitudes are found much larger during 2002-2006 (at Kiel station), which covers the descending phase of solar activity cycle 23. No other long-term trends in the tri-diurnal amplitudes are observed. Low values of tri-diurnal amplitudes are observed at Kiel station particularly for higher solar activity period (1998-2001). However, these solar cycle changes are not seen in Beijing station.

Changes in phases are large from year to year. Linear plots for Kiel and Beijing stations for phase (in degrees) are shown in Fig. 2. Standard errors of means are also plotted in each point. Changes in variational profiles are seen particularly for the years of ascending period of solar activity (1996-1999). Nevertheless, for all other years, the two stations show similar variability with phase around 200° . Beijing neutron data show a different trend in tri-diurnal amplitudes, where the high amplitudes are noticed during the years of high solar activity.

The 11-year (1996-2006) average tri-diurnal amplitudes and phases derived from harmonic analysis along with the geographic co-ordinates of the two stations are given in Table 1.

The first station, Kiel, is situated in high latitude and second, Beijing, is situated in low latitude. These two stations consist of low and high cut off rigidities, which respond to different energy range of cosmic ray particles.

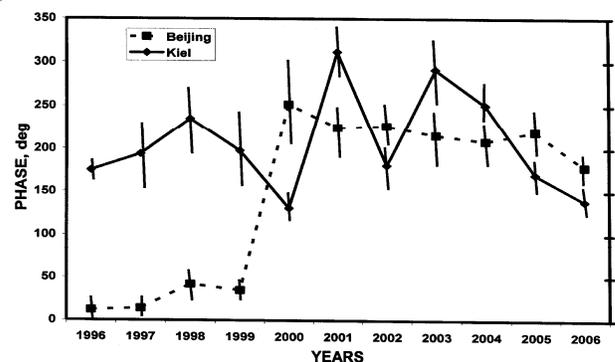


Fig. 2 — Phases (degree) for the annual average tri-diurnal variation for Kiel and Beijing neutron monitors

Table 1 — 11-year averages of tri-diurnal amplitude and phases of cosmic ray daily variation

Stations	Geographic coordinates		Cut off rigidity, GV	Tri-diurnal amplitude	
	Latitude	Longitude		Amplitude, %	Phase degree
Kiel	54.31	10.10	2.32	0.0105±0.0024	189±28
Beijing	40.08	116.26	8.86	0.016±0.0048	221±32

It is noticed from Fig. 1 that tri-diurnal amplitudes have almost recovered during 1999-2002 at high latitudes. It is also seen that tri-diurnal amplitudes are much larger by a factor of two at Kiel (high latitude station) as compared to that of Beijing, which is situated in almost low (nearly mid) latitude. In the case of phase, it is found that the phases have shifted significantly to earlier hours during 1996-1999 at Beijing only. The different spread in phases for different stations is found to be minima during solar activity maxima. The spread is maxima during the period of solar activity minima. These are expected to some extent as different cones of acceptance for different stations.

The analysis has been extended on a day-to-day basis using the daily values of cosmic ray third harmonics to understand the behaviour of tri-diurnal variation of cosmic rays. The day-to-day variability can be better represented by generating frequency distribution. The histogrammic frequency distribution both for the amplitude and phase for each year during 1996-2006 for Kiel (high latitude) and Beijing (low latitude) are drawn in Figs 3 and 4, respectively. These figures show the frequency of occurrence of each year for tri-diurnal amplitude (left hand side) and a similar distribution for phase on the right hand side. On a day-to-day basis, it is found that large numbers of days are observed with amplitude $\geq 0.10\%$ for most of the years particularly at Beijing (Fig. 4). The phases show almost flat distribution for both the stations and also for each year during 1996-2006, with some indication of maxima around 200° - 240° .

Cosmic rays in the interplanetary space are influenced by the process of diffusion, convection and adiabatic deceleration in the expanding solar wind, gradient and curvature drifts, and adiabatic focusing in the diverging interplanetary magnetic fields. Although they may be important in the overall modulation of relativistic cosmic rays, particle drift near earth produce anisotropies much smaller than diffusion or convection and deceleration. The daily variation of cosmic rays and its three components (diurnal, semi-diurnal and tri-diurnal) are established. The diurnal anisotropy is caused by the streaming of

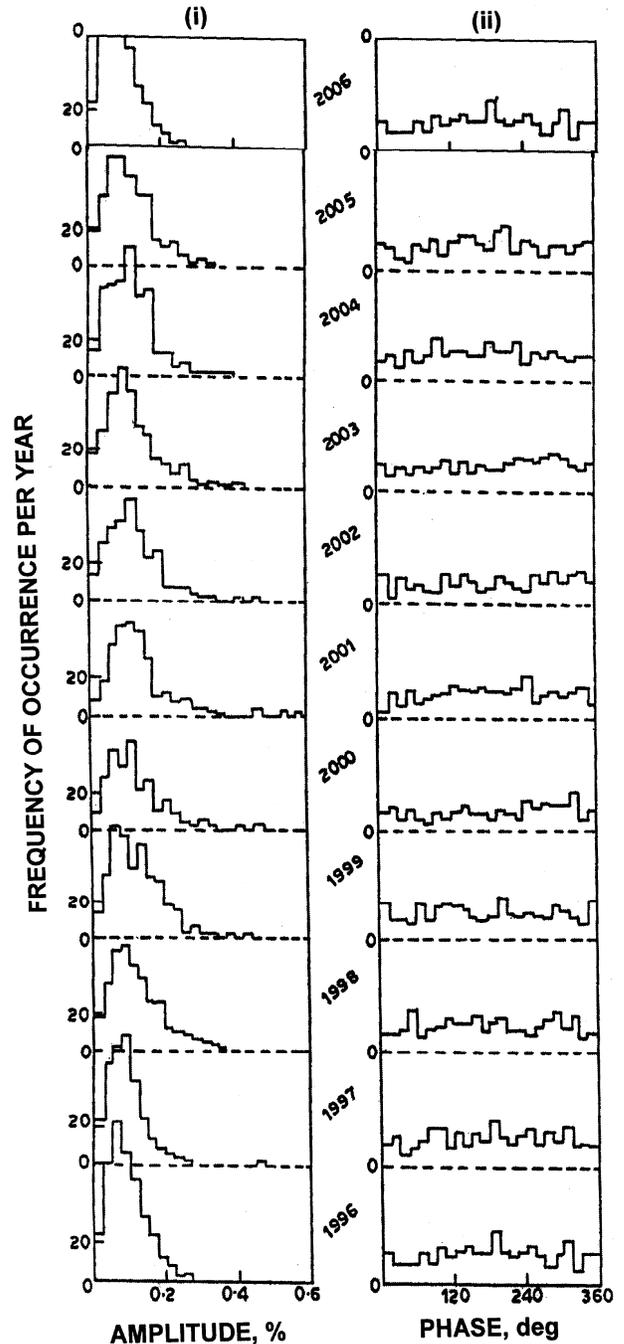


Fig. 3 — Frequency of occurrence of daily values of: (i) amplitude (%); and (ii) phase (degrees) of third harmonic of the daily variation of cosmic ray intensity for Kiel neutron monitor during 1996-2006

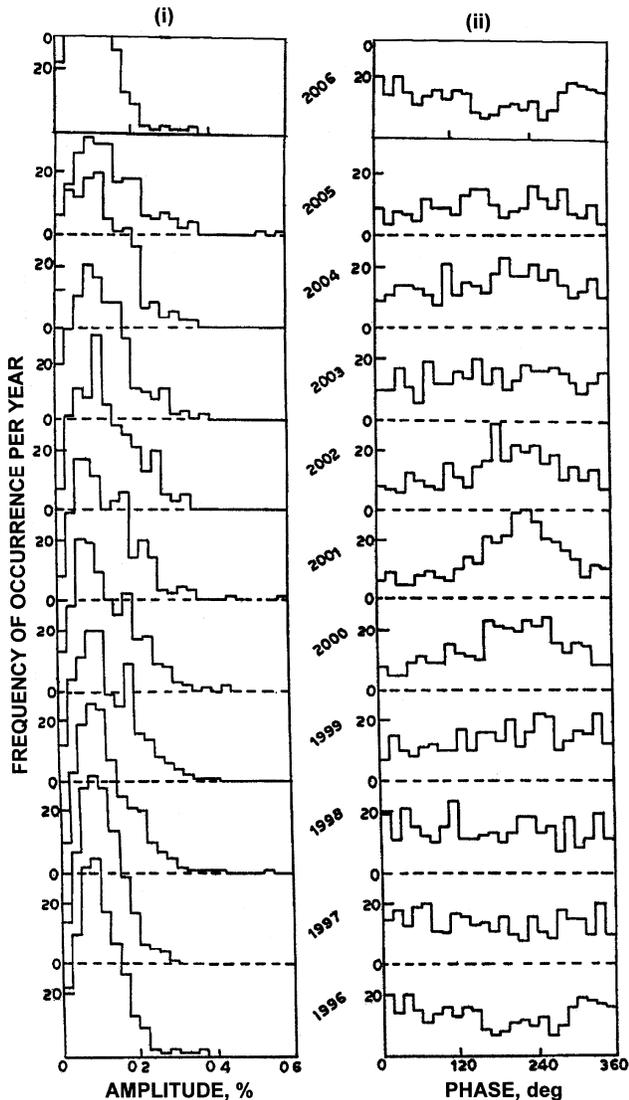


Fig. 4 — Frequency of occurrence of daily values of: (i) amplitude (%); and (ii) phase (degrees) of third harmonic of the daily variation of cosmic ray intensity for Beijing neutron monitor during 1996 – 2006

particles in interplanetary space due to convection, diffusion, adiabatic deceleration and particle drift. The semi-diurnal harmonic may be due to a symmetric latitudinal cosmic ray gradient in the heliosphere.

The observation of a third persistent periodicity related to the interplanetary propagation of galactic cosmic rays may give additional insight into local scattering conditions. A dynamical model was proposed by Owens¹⁴ for the tri-diurnal harmonic which was derived from the classical diffusion picture for cosmic ray pitch angle scattering in the heliosphere. For the tri-diurnal anisotropy of cosmic radiation, Bieber *et al.*¹⁵ also provided the theoretical

explanations. They tried to explain the anisotropy as a result of the normal processes of pitch angle scattering of cosmic rays with an outwardly positive density gradient along the spiral magnetic field. As a necessary consequence of such processes, the obtained intensity distribution is symmetric with respect to the magnetic field since the observed tri-diurnal variation suggests the existence of an intensity distribution with respect to the spiral magnetic field.

4 Conclusions

From the above discussion, the following conclusions can be drawn:

1. Average tri-diurnal amplitude varies in a very low range. It mostly varies in the range 0.005-0.05%. The tri-diurnal amplitude values are found to be significantly larger during the descending phase of solar cycle 23. It is found that tri-diurnal amplitude in two different stations significantly differ from each other.
2. The most probable average direction of tri-diurnal phase is observed around 190 to 220 degrees. Almost flat distributions in phases are found on day-to-day basis for all the hours.
3. Tri-diurnal anisotropy does not show any long-term variation trend.
4. In frequency distribution analysis on a day-to-day basis, one can observe a well defined peak of tri-diurnal amplitude between 0.06 and 0.010% for most of the years.

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