Unusual behaviour caused by interplanetary turbulences in cosmic ray intensity

Rajesh K Mishra¹ & Rekha Agarwal Mishra²

¹Computer and IT Section, Tropical Forest Research Institute, Jabalpur (MP) 482 001, India
²Government Autonomous Model Science College, Jabalpur (MP) 482 001, India

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The unusually high/low amplitude anisotropic wave train events (HAEs/LAEs) in cosmic ray intensity using the ground based Deep River neutron monitor data have been studied during the period 1991-94. It has been observed that the phase of diurnal anisotropy for majority of HAE/LAE cases remains in the same co-rotational direction. The phase of diurnal anisotropy has shifted to later hours for some of the HAE cases, whereas it shifts towards earlier hours for some of the LAE cases. Further, for majority of HAE/LAE cases the amplitude of semi-diurnal anisotropy remains statistically the same; whereas, the phase of semi-diurnal anisotropy for all HAE/LAE cases has shifted to later hours. Furthermore, for tri-diurnal anisotropy the phase shifts towards later hours for both type of events; while, amplitude remains statistically the same. The interplanetary magnetic field (IMF) and solar wind plasma (SWP) parameters during these events are also investigated. The possible sources causing these types of unusual events have been proposed.

Keywords: Cosmic rays, Diurnal anisotropy, Semi-diurnal anisotropy

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1 Introduction

The amplitude and phase of the diurnal variation of cosmic rays (CRs) vary significantly on a day-to-day basis¹. The characteristics of the diurnal/semi-diurnal/tri-diurnal variation of CRs and their variability have been continuously studied by many workers². Duggal and Pomerantz³ have observed a systematic anti-clockwise shift of diurnal anisotropy over a period of days during the study of large amplitude anisotropic diurnal wave trains. The occurrence of trains of continuous days having unusually high diurnal amplitude with a phase shift towards later hours has been observed by Mathews et al.⁴, both during quiet as well as for disturbed days. These trends are caused due to a large decrease of CR intensity along the garden-hose direction rather than the streaming along the anti-garden-hose direction. According to Rao et al.⁵ the phase of diurnal anisotropy shifts towards later hours due to enhanced radial streaming. The trains of days having negligibly small diurnal amplitude are also observed⁶.

A large day-to-day variability is exhibited in the solar diurnal variation of CR intensity. This variability is a reflection of the continually changing conditions in the interplanetary space. The systematic and significant deviations in the amplitude/phase of the diurnal/semi-diurnal anisotropy from the average values are known to occur in association with strong geomagnetic activity⁷. Rao et al.⁵ have shown that the enhanced diurnal variation of high amplitude events exhibits a maximum intensity in space around the anti-garden-hose direction and a minimum intensity around the garden-hose direction. Number of high amplitude events have been observed with a significant shift in the diurnal time of maximum to later hours or earlier hours⁸-¹¹. Such days are of particular significance when they occur during undisturbed solar/interplanetary conditions, as the superposed universal time effects are expected to be negligible.

Jadhav et al.¹² have studied the behaviour of semi-diurnal anisotropy for LAE by comparing the average semi-diurnal amplitude for each event with 27-day or annual average semi-diurnal amplitude. They found that there is no significant difference between the two wave trains. For these LAE cases the semi-diurnal amplitude is found to be normal, which shows that the diurnal and semi-diurnal anisotropies are not related with each other for these LAEs.

The average amplitude of diurnal and semi-diurnal anisotropy is found to be larger than normal during the initial phase of the stream, while it is smaller as compared to the normal during the decreasing phase of the stream and phase is observed to remain almost
constant\(^1\), which infers that the diurnal as well as semi-diurnal variation of galactic CR intensity may be influenced by the solar polar coronal holes. The changes have also been observed in the amplitude and phase during the high speed solar wind streams (HSSWS) coming from coronal holes\(^4,15\). The diurnal variation might be influenced by the polarity of the magnetic field\(^4\), so that the largest diurnal variation is observed during the days when the daily average magnetic field is directed outward from the Sun.

The significant variations have been observed in the amplitude and phase of the diurnal anisotropy with reversal of the average IMF in the alternate sectors. Due to the presence of north-south gradient in CR density, density increasing southward, i.e. below the equatorial plane of the Sun\(^17\), the expected diurnal amplitude will be larger and time of maximum shifts towards earlier hours for positive IMF, i.e. away from the Sun as compared to the days having negative IMF polarity, i.e. towards the Sun. It has been observed by Mavromichalaki\(^20\) that an enhanced mean diurnal amplitude correlates with positively directed sectors; whereas, the amplitude found to decrease during sector boundaries.

The harmonics of CR intensity has also been associated with geomagnetic conditions. The amplitude of diurnal anisotropy increases with increasing geomagnetic activity. The time of maximum is found to shift towards earlier hours as compared to the average values, for higher values of geomagnetic field variation indices\(^11\), i.e. \(K_p\) or \(A_p\). This trend has been found to vary with the change in the solar poloidal magnetic field after 1971, i.e. the time of maximum is found to shift towards later hours with the increase in \(A_p\)-index\(^12,23\).

The diurnal/semi-diurnal/tri-diurnal anisotropies during 1991-94 for HAE/LAE have been presented in this paper to investigate the basic reason causing the occurrence of these types of unusual events.

### 2 Data analysis

The anisotropic events are identified using the hourly plots of CR intensity recorded at ground-based neutron monitoring stations and selected 16 unusually high amplitude anisotropic wave train events (HAEs) and 13 unusually low amplitude anisotropic wave train events (LAEs) during the period 1991-94. The days having abnormally high amplitude or unusually low amplitude for five or more consecutive number of days have been selected as HAE/LAE. The pressure-corrected hourly neutron monitor data after applying trend correction are harmonically analysed to have amplitude (\%) and phase (hr) of the diurnal, semi-diurnal and tri-diurnal anisotropies of CR intensity for HAE/LAE. The data related with interplanetary magnetic field (IMF) and solar wind plasma (SWP) parameters have also been investigated.

### 3 Results and discussion

The amplitude and phase of the diurnal anisotropy have been plotted in Fig 1. It is quite apparent from Fig. 1 that the phase of the diurnal anisotropy has shifted towards later hours for some of the HAEs. However, the phase of the diurnal anisotropy, as depicted in Fig. 2, remains in the co-rotational direction for majority of the HAEs. This is in agreement with earlier findings\(^9,11\) during the period 1981-90. Similarly, the amplitude and phase of the semi-diurnal anisotropy have been plotted in Fig. 3. It is quite apparent from Fig. 3 that the phase of the

![Fig. 1-Amplitude and phase of the diurnal anisotropy for HAE of (a) 2-7 Oct. 1992 and (b) 23-29 Oct. 1994](image-url)
semi-diurnal anisotropy has a tendency to shift towards later hours. Similar trends have been reported\(^9,\!^{11}\) for the period 1981-90. Further, the amplitude of the tri-diurnal anisotropy, as shown in Fig. 4, remains statistically the same; whereas, the phase of the tri-diurnal anisotropy is found to shift towards later hours for all HAEs.

The amplitude and phase of the diurnal anisotropy for the LAE events have been plotted in Figs 5 and 6. As depicted in Fig. 5, it is quite apparent that the phase of the diurnal anisotropy has shifted towards earlier hours in some of the LAE events; whereas, in Fig. 6, the phase of the diurnal anisotropy for majority of the LAE events remains in the co-rotational direction. This agrees with the earlier findings\(^9,\!^{11}\) for the period 1981-90. Similarly, the amplitude and phase of the semi-diurnal anisotropy have been plotted in Fig. 7. It is quite apparent from Fig. 7 that the amplitude of the semi-diurnal anisotropy remains statistically the same for majority of the events; whereas, the phase has a tendency to shift towards later hours. Similar results have been found by Jadhav et al.\(^{12}\) for the period 1966-73 and Kumar and Chauhan\(^10\) and Kumar et al.\(^{11}\) for the period 1981-90. Further, the amplitude and the phase of the tri-diurnal anisotropy have been plotted in Fig. 8. It is quite clear from Fig. 8 that the amplitude of tri-diurnal anisotropy remains statistically the same; whereas, the phase shifts towards later hours for most of the LAE events.

The amplitude and phase of diurnal, semi-diurnal and tri-diurnal anisotropies for all HAEs along with
Fig. 4—Amplitude and phase of the tri-diurnal anisotropy for HAE of (a) 21-25 July 1992 and (b) 20-26 May 1993

Fig. 5—Amplitude and phase of the diurnal anisotropy for LAE of (a) 17-22 Sep. 1991 and (b) 4-8 Oct. 1994

Fig. 6—Amplitude and phase of the diurnal anisotropy for LAE of (a) 1-5 May 1991 and (b) 22-27 Mar. 1992
the corresponding quiet-day annual average values have been plotted elsewhere and the results here are given in Table 1. It has been found that the amplitude of the diurnal anisotropy for all HAE attains significantly large values as compared to quiet-day annual average amplitude and the phase of the diurnal anisotropy remains in the co-rotational direction for most of the HAEs throughout the period of investigation, i.e., 1991-94. The same trend has been reported by Kumar et al.\cite{Kumar} during 1981-90 for diurnal amplitude, but the variation of phase of diurnal anisotropy differs significantly. They found that the phase of the diurnal anisotropy has shifted to later hours for majority of the HAE events as compared to the annual average values. The amplitude of the semi-diurnal anisotropy is significantly larger for some of the events as compared to the quiet-day annual average values; whereas, no definite trend has been found for phase of the semi-diurnal anisotropy. Further, the amplitude of the tri-diurnal anisotropy attains significantly larger values for all HAEs as compared to the quiet-day annual average values throughout the period; whereas, the phase of the tri-diurnal anisotropy is found to shift towards later hours as compared to the quiet-day annual average values for most of the events. The nature of the plots of tri-diurnal anisotropy during the period of investigation resembles with the plots obtained for diurnal anisotropy by Kumar et al.\cite{Kumar} during the period 1981-90. Similarly, the amplitude and phase of diurnal, semi-diurnal and tri-diurnal anisotropies for all LAEs along with the corresponding quiet-day annual average values have been plotted elsewhere and the results here are given in Table 2. It has been found that the amplitude of the diurnal anisotropy for majority of the LAE events attains significantly lower
average value for majority of the events. The amplitude of the tri-

diurnal anisotropy has a tendency to shift towards values as compared to the quiet-day annual average values for majority of the LAEs. Similar results have been reported by Kumar and Chauhan\textsuperscript{10} and Kumar et al.\textsuperscript{11} for the period 1981-90. There is no definite trend for the amplitude of the semi-diurnal anisotropy; whereas, the phase of the semi-diurnal anisotropy has a tendency to shift towards later hours as compared to the quiet-day annual average values for majority of the events. The amplitude of the tri-
diurnal anisotropy attains significantly higher values for majority of the LAE events as compared to the quiet-day annual average amplitude throughout the period; whereas, the phase of the tri-diurnal anisotropy has a tendency to shift towards later hours as compared to the quiet-day annual average values for majority of the LAE events.

When the vector addition diagram for amplitudes and phases of the diurnal, semi-diurnal and tri-diurnal anisotropies for each HA/E/LAE events has been plotted, it is observed that the phase of the diurnal anisotropy shifts towards earlier hours for most of the
HAE events and the distribution lies in the third quadrant except for one event; whereas the phase of diurnal anisotropy remains in the co-rotational direction for all the LAEs and the distribution lies in the third quadrant except for two events. For semi-diurnal anisotropy, the distribution of phase lies in the first and second quadrants for all the HAE events except for one event; whereas, the distribution of phase lies in the first two quadrants for majority of the LAE events, which is inconsistent with the concept that the transient changes in the intensity that occur over all hours may cause the semi-diurnal component. Further, the phase of tri-diurnal anisotropy is well distributed over all hours for HAEs as well as for LAEs.

The IMF and SWP parameters have also been studied during the period of all HAEs. The frequency histogram of solar wind velocity for all HAEs/LAEs has been plotted in Figs 9 and 10. It is observable from Figs 9 and 10 that the majority of the HAE/LAE events have occurred when the solar wind velocity is in the interval 400-500 km/s, i.e. having a nearly average value. Usually, the velocity of high-speed solar wind streams (HSSWSs) is 700 km/s. Therefore, it may be deduced from these plots that HAE/LAE events are not caused either by the HSSWSs or by the sources on the Sun responsible for producing the HSSWS, such as polar coronal holes (PCH), etc. Thus, we may infer that HAEs/LAEs are weakly dependent on solar wind velocity, which is in agreement with earlier findings and contradicts the earlier results that the solar diurnal amplitude is enhanced during the HSSWSs coming from coronal holes. According to Ahluwalia and Riker, there is no relation between solar wind speed and diurnal variation in high rigidity region. The modulation of solar diurnal anisotropy is weakly or less dependent on the solar wind velocity. No significant difference has been found between the variation of diurnal vectors in high-speed days and the days when the speed is normal.

The amplitudes (%) and phases (hr) of diurnal, semi-diurnal and tri-diurnal anisotropies for HAEs with the variations in the associated values of $B_z$-component of interplanetary magnetic field $B$, i.e. $B_z$, have been plotted in Figs 11-13 during the period 1991-94. It is quite apparent from Fig. 11 that the amplitude of diurnal anisotropy is evenly aligned for both positive and negative polarities of IMF for all HAEs. The amplitude of diurnal anisotropy for both the polarities is higher and phase shifts towards earlier hours as compared to the co-rotational values for most of the HAEs. For semi-diurnal anisotropy as depicted in Fig. 12, the amplitude of semi-diurnal anisotropy is evenly aligned for both positive and negative polarities of IMF for all HAEs. Further, for tri-diurnal anisotropy, as shown in Fig. 13, the amplitude is evenly aligned for most of the HAEs, which shows that HAEs occur independent of the nature of $B_z$. The trends we found in this study for HAE reveal that, for both away and towards polarities days, the time of maximum for diurnal anisotropy shifts to later hours, or it remains in the 18-hr direction with an exception for one event. An enhanced mean amplitude of diurnal anisotropy correlates with positively directed sectors, while the amplitude of the diurnal anisotropy seems to decrease during sector boundaries, which
Fig. 12—Amplitude and phase of the semi-dyurnal anisotropy for each HAE with the variation in associated values of $B_z$ during 1991-94

Fig. 13—Amplitude and phase of the tri-dyurnal anisotropy for each HAE with the variation in associated values of $B_z$ during 1991-94

significantly differs with the present findings; i.e. the occurrence of high amplitude anisotropic wave train events is independent of the nature of IMF polarity.

The amplitudes (%) and phases (hr) of diurnal, semi-diurnal and tri-diurnal anisotropies for all the LAE events with the variations in the associated values of $z$-component of interplanetary magnetic field $B_z$, i.e. $B_z$, have been plotted in Figs 14-16 during the period 1991-94. It is observed from Fig. 14 that the amplitude of the diurnal anisotropy for positively directed IMF (+$B_z$) is significantly large for most of the events; whereas, the amplitude remains significantly low for negatively directed IMF ($-$ $B_z$) for most of the LAE events. The phase of the diurnal

Fig. 14—Amplitude and phase of the diurnal anisotropy for each LAE with the variation in associated values of $B_z$ during 1991-94

Fig. 15—Amplitude and phase of the semi-diurnal anisotropy for each LAE with the variation in associated values of $B_z$ during 1991-94

Fig. 16—Amplitude and phase of the tri-diurnal anisotropy for each LAE with the variation in associated values of $B_z$ during 1991-94
anisotropy, as shown in Fig. 14, for both positive and negative polarities of $B_z$ has a tendency to shift towards earlier hours as compared to co-rotational value for all the LAE events. For semi-diurnal anisotropy, as shown in Fig. 15, the amplitude of semi-diurnal anisotropy is evenly aligned for both positive and negative polarities of IMF for all LAEs. Further, for tri-diurnal anisotropy, as shown in Fig. 16, the amplitude is evenly aligned for most of the LAEs, which shows that LAEs occur independent of the nature of $B_z$.

4 Conclusions

On the basis of the present investigation the following conclusions have emerged:

(i) The phase of the diurnal anisotropy remains in the co-rotational direction for most of the HAE/LAE cases. However, it shifts towards later hours for some of the HAEs; whereas it shifts towards earlier hours for some of the LAEs.

(ii) The amplitude remains statistically the same; whereas, the phase has a tendency to shift towards later hours for both semi-diurnal and tri-diurnal anisotropies for majority of the HAE/LAE cases.

(iii) Most of the HAE/LAE cases have occurred when solar wind velocity is being nearly average; which, shows that the HSSWs do not play a significant role in causing the HAE/LAE events.

(iv) The occurrences of HAEs/LAEs are independent of nature of $B_z$ component of IMF polarity.

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