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Unusually low/high-amplitude anisotropic wave train events in cosmic-ray intensity as an effect of interplanetary turbulences

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Abstract

Using the ground-based neutron monitor data of Deep River we have studied the low- and high-amplitude anisotropic wave train events (LAE/HAE) in cosmic-ray intensity for different latitudes. The investigation has been made for both LAE and HAE during the period 1981–1994. It has been observed that the phase of diurnal anisotropy in the majority of HAE/LAE cases remains in the same co-rotational direction, but has shifted to later hours in some HAE cases and to early hours in some LAE cases. Further, for majority of HAE/LAE cases, the amplitude of semi-diurnal anisotropy remains statistically the same, while the phase for all HAE cases shifted to later hours. The HAE appears dominant during the declining phase of solar activity, whereas LAE appears dominant during minimum solar activity.

Keywords: Cosmic ray, anisotropy, interplanetary magnetic field, and high-speed solar wind streams.

1. Introduction

Solar diurnal variation of cosmic-ray (CR) intensity shows a large day-to-day variability. This variability appears even in the case of high-counting rate instruments like super neutron monitors and at least a part of it is a reflection of the conditions available in the interplanetary space. The annual average diurnal variations are highly significant. Apart from the above-mentioned systematic and significant departures in amplitude and phase of diurnal anisotropy from average values, they are known to occur in association with strong geomagnetic activity [1]. The duration when these types of deviations occur during undisturbed solar conditions has particular significance.

The anisotropies occurred without accompanying geomagnetic disturbances or Forbush decrease indicating that they are not due to solar activity on the visible side of the Sun [2]. The average characteristics of cosmic-ray diurnal variation are adequately explained by the co-rotational concept. This concept supports mean diurnal amplitude in space of 0.4% along the 18-h direction.

The average characteristics of cosmic-ray diurnal anisotropy are adequately explained by the co-rotational concept. However, the observed day-to-day variation both in amplitude and time of maximum and the abnormally large amplitudes or abnormally low-amplitudes

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of consecutive days cannot be explained in co-rotational term. The average diurnal anisotropy of cosmic radiation has generally been explained in terms of azimuthal co-rotation [3]. Mavromichalaki [4] reported the existence of the consecutive days having abnormally high diurnal amplitude. 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 [5].

The diurnal variation might be influenced by the polarity of the magnetic field [6]. The largest diurnal variation is observed during the period when the daily average magnetic field is directed away from the Sun. The variation in the amplitude and phase of the high-speed solar wind streams (HSSWSs) has been observed coming from coronal holes [7, 8]. For diurnal as well as for semi-diurnal anisotropy the mean amplitudes are found to be greater than normal during the initial phase of the stream, whereas it becomes smaller compared to the normal during the decreasing phase of the stream. The phase remains almost constant [9].

Some low-amplitude anisotropic wave train events have been identified by Ananth *et al.* [10] which were essentially representing the quasi-permanent anomalous conditions in the interplanetary medium. Jadhav *et al.* [11] studied the behaviour of semi-diurnal anisotropy of LAEs by comparing the average semi-diurnal amplitude. They observed that there is no significant difference between these two wave train events [11]. An attempt has been made in this paper to investigate the interplanetary turbulence effects causing unusually high/low-amplitude anisotropic wave train events during the period 1981–1994.

2. Data analysis

The pressure-corrected data of Deep River Neutron monitor NM (cutoff rigidity = 1.02 GV, latitude = 46.1°N, longitude = 282.5°E, altitude = 145 M) has been subjected to Fourier analysis for the period 1981–1994 after applying the trend correction to have the amplitude (%) and phase (h) of the diurnal and semi-diurnal anisotropies of cosmic-ray intensity for unusually low/high-amplitude events. The amplitude of the diurnal anisotropy on an annual average basis is found to be 0.4%, which has been taken as reference line in order to select low/high-amplitude events.

The days having abnormally low/high-amplitude for a successive number of five or more days have been selected as high/low-amplitude anisotropic wave train events. The anisotropic wave train events are identified using the hourly plots of cosmic-ray intensity recorded at ground-based neutron monitoring station and 38 unusually high-amplitude wave train events and 28 unusually low-amplitude wave train events during the period 1981–1994 have been selected. The solar wind plasma (SWP) and interplanetary magnetic field (IMF) have also been investigated.

3. Results and discussion

The amplitude and phase of each HAE has been plotted in Fig. 1. It is apparent from the figure that the phase of diurnal anisotropy has shifted to earlier hours in some of the events. However, for majority of HAEs plotted in Fig. 2 the phase of diurnal anisotropy remains in the co-rotational direction. The amplitude and phase of semi-diurnal anisotropy

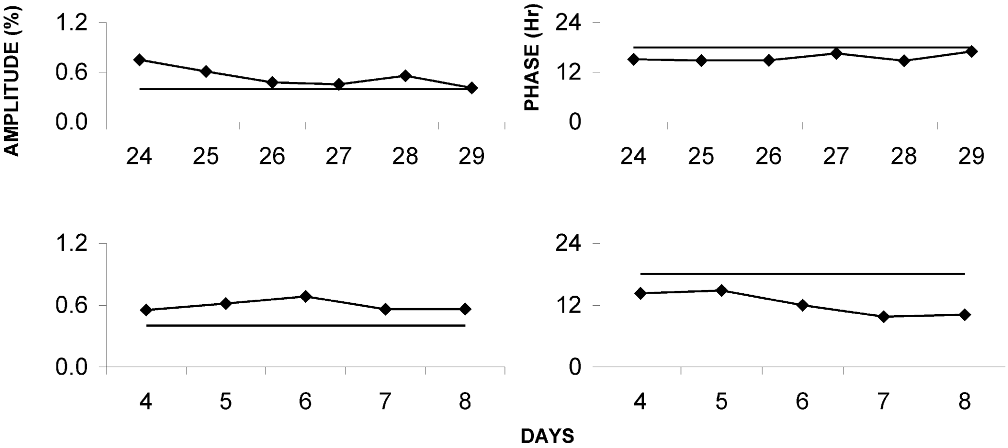

FIG. 1. Amplitude and phase of the diurnal anisotropy for HAE of Sept. 24–29, 1983 and Feb. 4–8, 1993.

for HAE, plotted in Fig. 3, show that the amplitude of the semi-diurnal anisotropy for each HAE remains statistically the same, whereas the phase has shifted to later hours.

The amplitude and phase of the diurnal anisotropy along with quiet days annual average values, plotted in Fig. 4, show that the amplitude of the diurnal anisotropy for each HAE

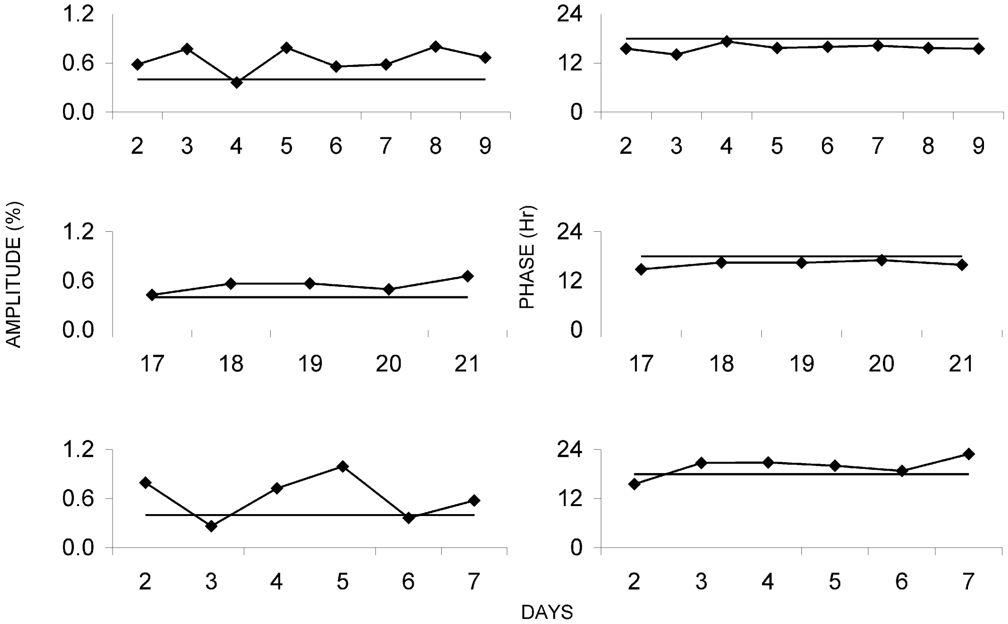

FIG. 2. Amplitude and phase of the diurnal anisotropy for HAE of Sept. 2–9, 1981, July 17–21, 1983 and Oct. 2–7, 1992.

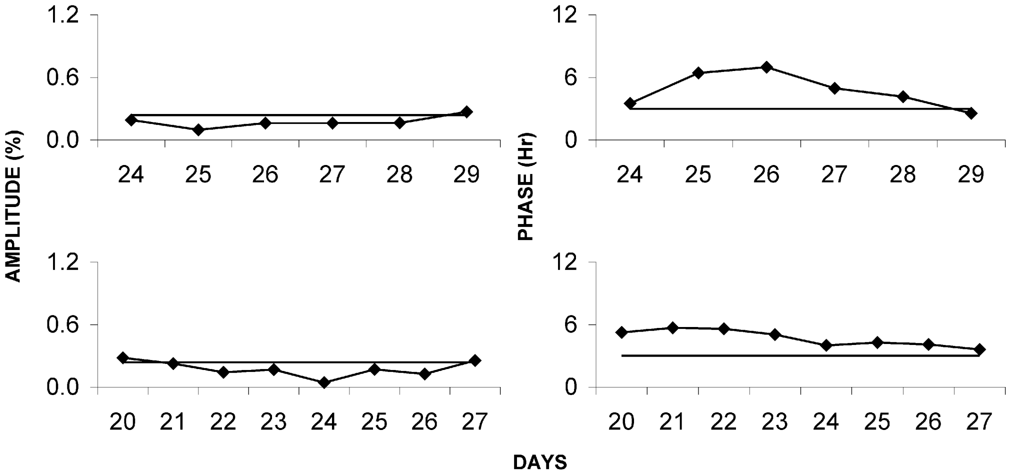

FIG. 3. Amplitude and phase of the semi-diurnal anisotropy for HAE of Sept. 24–29, 1983 and March 20–27, 1994.

is significantly larger than the quite day annual average amplitude throughout the period and the phase of the diurnal anisotropy has shifted to earlier hours for majority of the HAEs as compared to the quiet day annual average values.

It is apparent from the amplitude and phase of LAEs, plotted in Fig. 5, that for most of the LAEs the phase of the diurnal anisotropy remains in the 18-h or co-rotational direction,

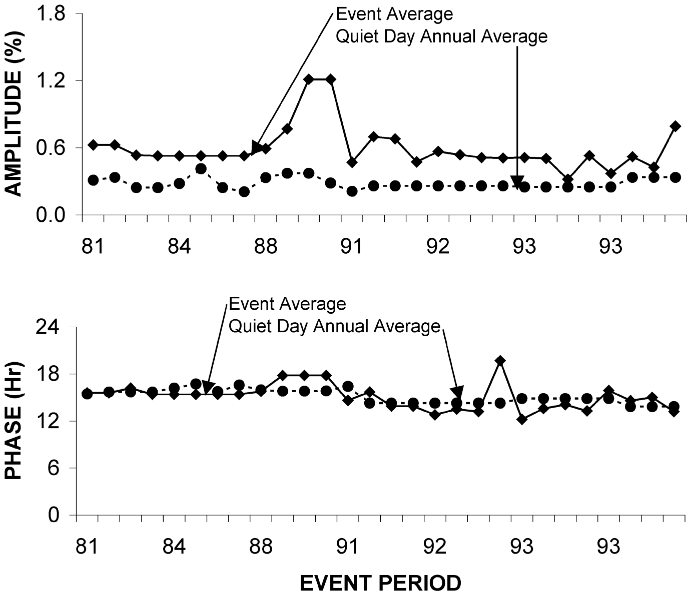

FIG. 4. Amplitude and phase of the diurnal anisotropy for each HAE along with quiet day annual average values during 1981–1994.

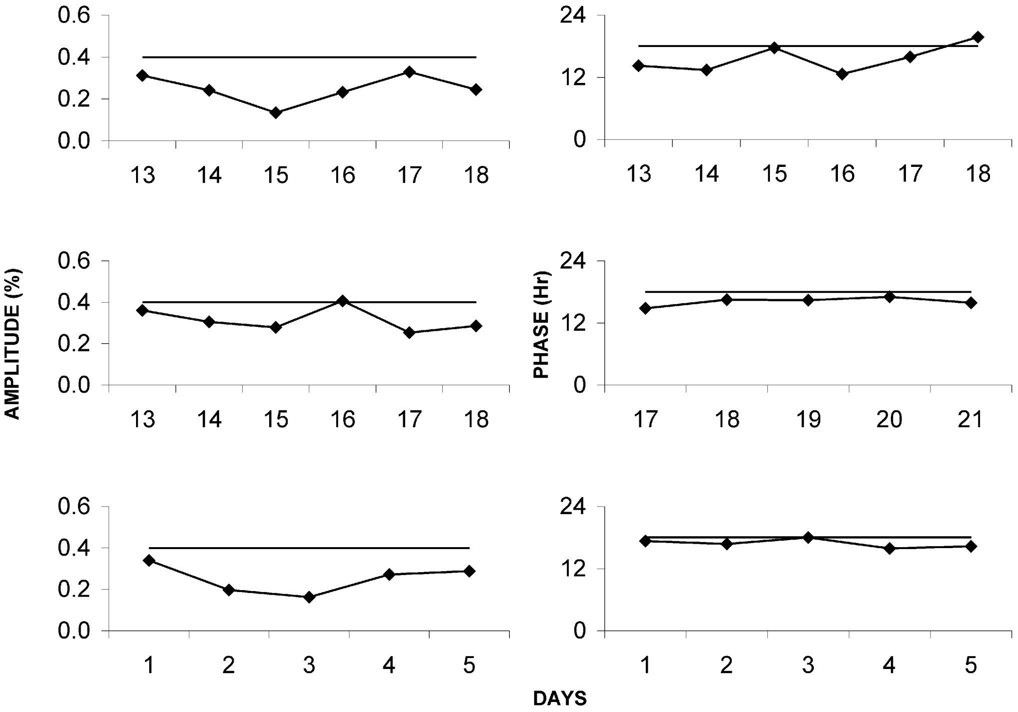

FIG. 5. Amplitude and phase of the diurnal anisotropy of LAE for the events on June 13–18, 1985, Jan 13–18, 1991, and May 1–5, 1991.

whereas it has shifted to earlier hours for some LAEs (Fig. 6). The amplitude and phase of the diurnal anisotropy for all the LAEs along with amplitude and phase of quiet day annual average have been plotted in Fig. 7. It is clear from the figure that the phase of the diurnal anisotropy has shifted to earlier hours as compared to quiet day annual average values for majority of the LAEs. Further, the amplitude and phase of the semi-diurnal anisotropy, plotted in Fig. 8, show that the amplitude of the semi-diurnal anisotropy remains statistically the same for all LAEs, whereas the phase is shifted to later hours. Similar results have been found by Jadhav *et al.* [11] for the period 1966–1973.

For each HAE/LAE case, the interplanetary magnetic field (IMF) and solar wind parameter (SWP) have also been investigated. The amplitude and phase of the diurnal anisotropy for each HAE/LAE along with variation in the associate values of the z-component of the interplanetary magnetic field, i.e. Bz have been plotted in Fig. 9. It is apparent from these figures that for majority of the HAEs/LAEs, the Bz is +ve, i.e. away from the Sun. However, Bz remains –ve, i.e. towards the Sun for some of the HAEs/LAEs, which shows that HAEs/LAEs occurred dominantly during the positively directed IMF polarity. Kananen *et al.* [12] found that for positive Bz or away polarity of IMF, amplitude is higher and phase shifts to early hours, whereas for negative Bz or towards polarity of IMF, the amplitude is lower and phase shifts to early hours as compared to co-rotational values for the period 1967–1968.

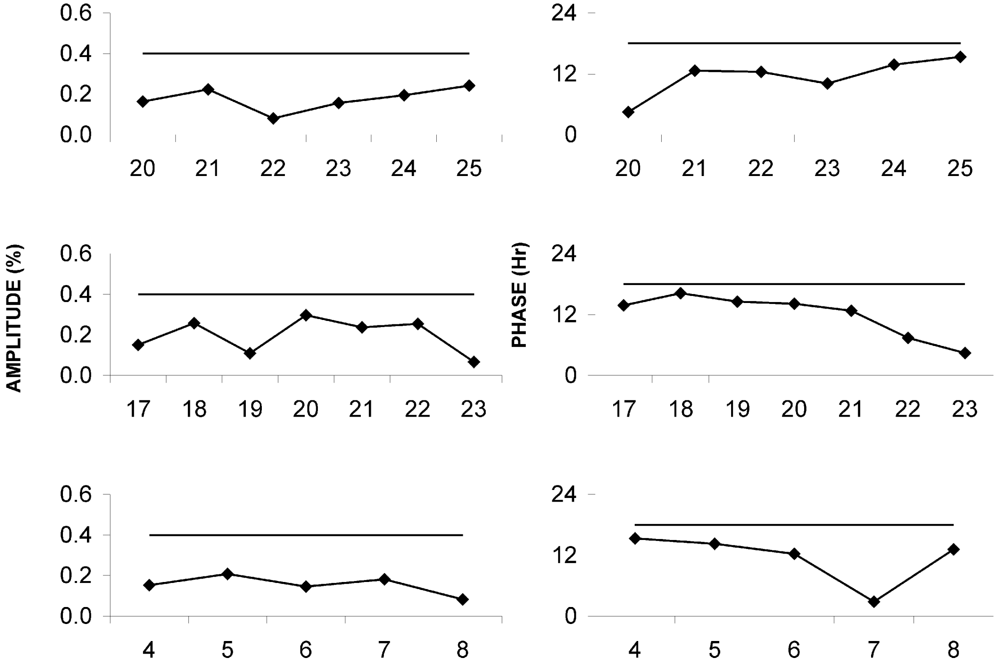

FIG. 6. Amplitude and phase of the diurnal anisotropy of LAE for the events on Apr. 20–25, 1981, Oct. 17–23, 1992, and Oct. 4–8, 1994.

Mavromichalaki [13] noticed large amplitude wave trains of cosmic-ray intensity during June, July and August 1973. These events exhibit the same characteristics as the event of May 1973. During these days, the phase of the enhanced diurnal anisotropy is shifted to a

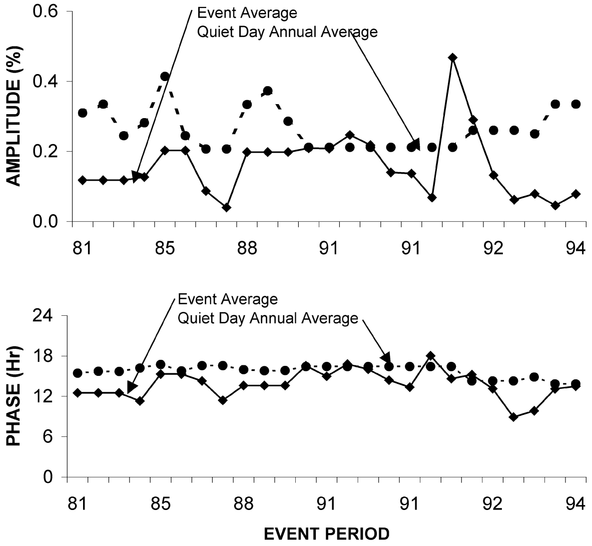

FIG. 7. Amplitude and phase of diurnal anisotropy for LAE along with quiet day annual average values during 1981–1994.

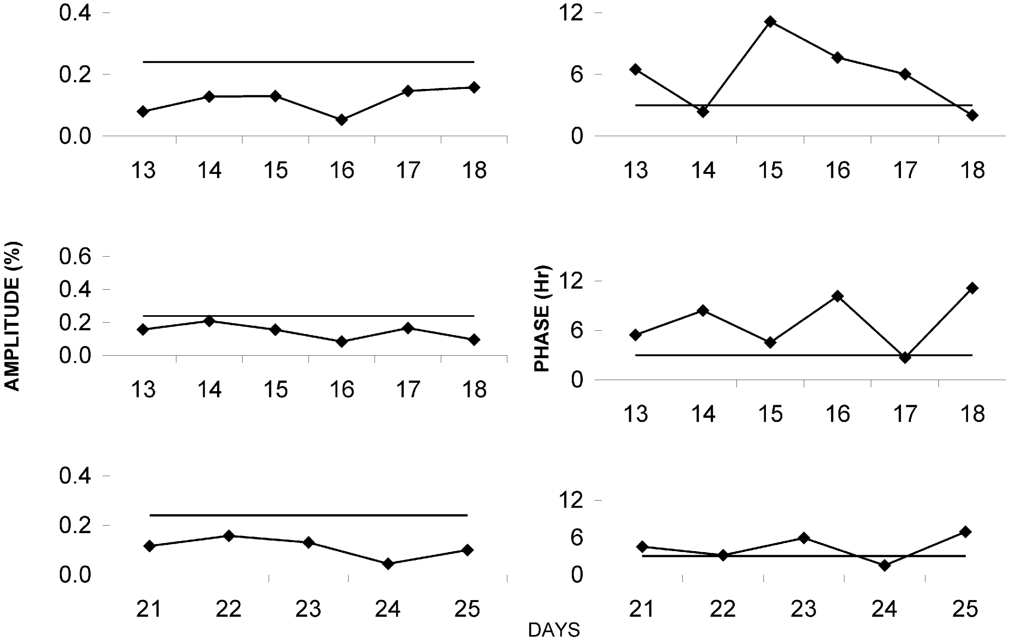

FIG. 8. Amplitude and phase of the semi-diurnal anisotropy of LAE for the events on June 13–18, 1985, Jan. 13–18, 1991, and Dec. 21–25, 1993.

point earlier than either the co-rotation or the anti-garden-hose direction. The diurnal anisotropy is well understood in terms of a convective–diffusive mechanism [14]. Mavromichalaki [15, 13] has observed that the enhanced diurnal variation was caused by a source around 1600 h or by a sink at about 0400 h. It was pointed out that this diurnal variation is

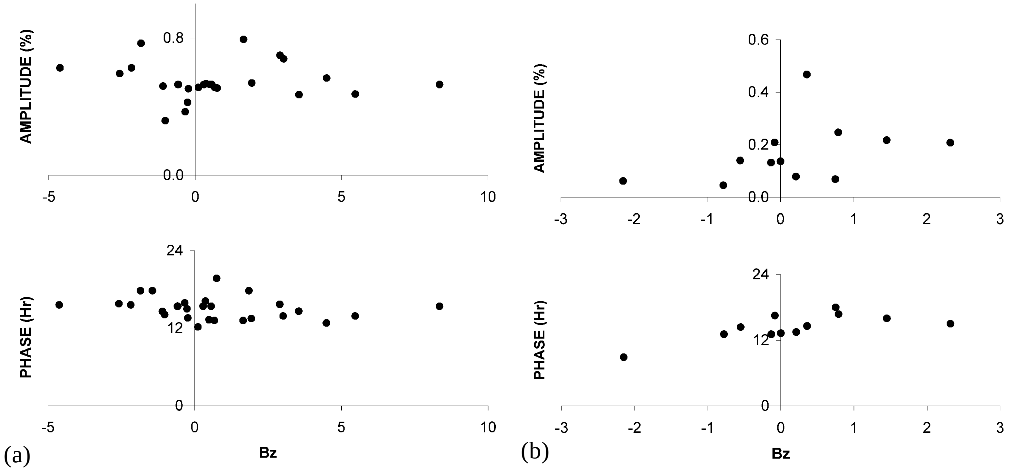

FIG. 9. Amplitude and phase of the diurnal anisotropy for each (a) HAE and (b) LAE along with variation in associated value of Bz.

caused by the superposition of convection and field-aligned diffusion due to an enhanced density gradient of ≈ 8% AU^{-1}.

After a careful investigation of the diurnal anisotropy of cosmic-ray intensity observed, using the neutron monitor data of Athens and Deep River stations, over the period 1970–1977, Mavromichalaki [16] pointed out that the time of maximum of diurnal variation shows a remarkable systematic shift towards earlier hours than normally beginning in 1971. The phase continually shifts towards earlier hours 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 behaviour 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 independent 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 large variation observed in phases and amplitudes of cosmic-ray diurnal anisotropy on a day-to-day basis cannot be explained by the co-rotational concept [17, 18]. Therefore, many scientists [5, 19–21] have attempted to understand this variation in terms of convective–diffusive mechanism. The standard picture for the diffusion of cosmic rays at neutron monitoring energies in the solar system involves diffusion which is essentially field-aligned [22]. Later, Kane [19] showed that, on a day-to-day-basis, the diffusion vector deviates from the interplanetary magnetic field (IMF) direction in the ecliptic plane by more than 30° on about 35% of the quiet days. Ananth *et al.* [23] comparing the diffusion vector with magnetic field vector pointed out that this simple concept holds well on more than 80% of days. Of the rest of 20% of days, the diurnal anisotropy characteristics seem to indicate the presence of a significant component of a transverse diffusion current in addition to normal convection and diffusion flow. Such days are found to be present in the form of trains of consecutive days and to be associated with abrupt changes in the interplanetary field direction. The value of the diffusion coefficients ratio, $K_\perp/K_\parallel$, which is normally about ≤ 0.05 for field-aligned days, is found to be ~ 1.0 on non-field-aligned days. It has been shown [18] that on many days the interplanetary field seems to stick to the garden-hose direction, while the diffusion vector deviates significantly from the garden-hose direction and on some other days the reverse situation obtains. Owens and Kash [21] selecting only those days in which there are no complications from changing magnetic sectors and eliminating days with a poorly determined anisotropy or mean magnetic field direction, showed that the diffusion is field-aligned on essentially all well-determined days [5]. Mavromichalaki [4, 13] has shown that the diffusion vector is field-aligned during days exhibiting enhanced diurnal variation. The diffusion current on an average basis is being driven by large cosmic-ray gradients in the ecliptic plane. So, even though the average picture of the diurnal variation has now been explained quite satisfactorily in terms of a good physical model, the detailed picture of the diurnal variation, on day-to-day basis, is still not clearly understood.

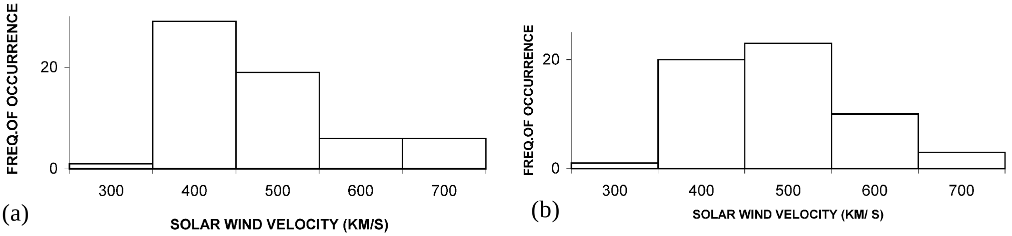

FIG. 10. Frequency histogram of solar wind velocity for all (a) HAEs and (b) LAEs.

The frequency histogram of solar wind velocity for each HAE/LAE has been plotted in Fig. 10. It is observed that the majority of the HAEs/LAEs have occurred with solar wind velocity becoming average. Usually the velocity of HSSWSs is 600–700 km/s [8]. So it is apparent from these figures that HAEs/LAEs are not caused during the period of occurrence of HSSWSs. We can infer that polar coronal holes, which are the major sources of HSSWs, do not play a significant role in causing the HAEs/LAEs. It is further noted that these trains of the days of HAEs/LAEs are not associated with either geomagnetic storms or any Forbush decrease.

4. Conclusion

On the basis of the above findings the following conclusions may be drawn:

- The phase of the diurnal anisotropy continually remains in the co-rotational direction for majority of the HAE/LAE. However, it shifts to earlier hours for some HAE/LAE.
- The amplitude of semi-diurnal anisotropy for majority of HAE/LAE remains statistically invariant, while the phase has shifted to later hours for some HAE/LAE.
- Majority of the HAE/LAE occurred when solar wind velocity is average.
- The occurrence of HAE/LAE is dominant during positively directed IMF polarity.

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