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Features of Daily Variation in Cosmic Ray Intensity During High/Low Amplitude Events

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Abstract

A detailed study has been conducted on the long-term changes in the diurnal, semi-diurnal and tri-diurnal anisotropy of cosmic rays in terms of the high/low amplitude anisotropic wave train events (HAE/LAE) during the period 1981–94 using the neutron monitor data from the Deep River neutron monitoring station. In all, 38 HAE and 28 LAE cases have been studied. An inter-comparison of the first three harmonics during these events has been made so as to understand the basic reason causing the occurrence of these types of events. It has been observed that the phase of diurnal anisotropy shifts towards earlier hours for HAEs; similarly, it shifts towards earlier hours as compared to the 18-Hr direction for LAEs. Semi-diurnal anisotropy phase is found to remain statistically the same for both HAE as well as for LAE. Further, tri-diurnal anisotropy phase is found to be evenly distributed for both types of events. The interplanetary magnetic field (IMF) and solar wind plasma (SWP) parameters during these events are also investigated. It has also been observed that HAE/LAEs are weakly dependent on high-speed solar wind velocity.

Key Words: cosmic ray, diurnal, semi-diurnal, anisotropy, high-speed solar wind streams and interplanetary magnetic field.

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1. Introduction

Long-term cosmic ray modulation at neutron monitor energies is caused by a superposition of several processes; including diffusion, convection and adiabatic energy losses plus curvature and gradient drift effects in the interplanetary magnetic field. The solar diurnal variation of cosmic ray (CR) intensity shows large day-to-day variability. This variability is a reflection of the continually changing conditions in interplanetary space [1]. The average diurnal anisotropy of cosmic radiation has generally been explained in terms of azimuthal corotation (see [2] and references therein). The systematic and significant deviations of amplitude as well as phase for diurnal/semi-diurnal anisotropies from the average values are known to occur in association with strong geomagnetic activity [3]. The enhanced diurnal variation of high amplitude anisotropic events (HAEs) exhibits a maximum intensity in space around the anti-garden hose direction and a minimum intensity around the garden hose direction. A number of HAEs and low amplitude anisotropic events (LAEs) have been observed with a significant shift towards later or earlier hours [4–6]. The changes have also been observed in the amplitude and phase during the high-speed solar wind streams (HSSWS) coming from coronal holes [7, 8]. The diurnal variation might be influenced by the polarity of the magnetic field [9], so that the largest diurnal variation is observed during the days when the daily average magnetic field is directed outward from the Sun.

Recent data acquired by the Ulysses spacecraft during its fast heliolatitude scan shows that the latitude distribution of GCR has both symmetric and asymmetric components [10, 11]. According to Ahluwalia and Fikani [12, 13], 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, and has been observed by many workers [14–16]. Theoretical interpretation regarding the modulation mechanism responsible for the tri-diurnal wave was given by Fujii [17], on the basis of the loss-cone model. Ahluwalia and Fikani [18] argued that cause of tri-diurnal variation lies in the pitch angle scattering of GCR protons in the tangled fields that permeate the heliosphere. Bieber and Pomerantz [19] proposed the unified theory of cosmic ray diurnal variation.

Mavromichalaki [20] has observed that enhanced diurnal variation is caused by a source around 1600 Hr or by a sink at about 0400 Hr. It was pointed out that this diurnal variation by the superposition of convection and field-aligned diffusion due to an enhanced density gradient of $\approx 8\%\ \mathrm{AU}^{-1}$. Ananth et al. [21] studied the long-term changes in diurnal anisotropy of cosmic rays for the two solar cycles (20 and 21) during the period 1965–1990. They observed that the amplitude of the anisotropy is related to the characteristics of high and low amplitude days. The occurrence of high amplitude days is found to be positively correlated with the sunspot cycle. Further, the variability of the time of maximum of the anisotropy indicates that it is essentially composed of two components: one in the 1800 Hr (corotation) direction; and the other, an additional component in the 1500 Hr direction (45° east of the S-N line), apparently caused by the reversal of the solar polar magnetic field. They also suggest that the direction of the anisotropy of high amplitude days contribute significantly to the long-term behaviour of the diurnal anisotropy, as it produces an additional component of cosmic rays in the radial (1200 Hr) direction. Ananth et al. [22] suggested that the enhanced wave trains do not reveal any correlation with the solar or geomagnetic activity index and the direction of the anisotropy lies along the ≈1800 Hr (corotational) direction. They also noticed that the spectral index n of the cosmic ray power spectrum is distinctly different with a higher value for the enhanced wave train event that indicates that the enhanced wave train event are caused by different magnetic field configuration.

The characteristics of the diurnal/semi-diurnal/tri-diurnal anisotropy during 1981–94 for HAE/LAE have been presented in this paper to investigate the basic reason causing the occurrence of these types of unusual events.

2. Experimental Data and Analysis

Using the long term plots of cosmic ray intensity data as well as the amplitude calculated from the cosmic ray pressure corrected hourly neutron monitor data by using harmonic analysis, the High amplitude wave train events (HAE) and Low amplitude wave train events (LAE) have been selected. The high amplitude events for consecutive days have been selected when the diurnal amplitude was found higher than 0.5% for each day of the event for at least five or more days. The low amplitude wave train events of consecutive days have been selected when the diurnal amplitude remains less than 0.3% for each day of the event for at least five or more days. On the basis of these selection criteria we have selected 38 unusually high amplitude anisotropic wave train events (HAEs) and 28 unusually low amplitude anisotropic wave train events (LAEs) during the period 1981–94. 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 cosmic ray intensity for HAE and LAE. The data related with interplanetary magnetic field and solar wind plasma parameters have also been investigated.

3. Results and Discussion

The variations observed near the Earth are an integral result of numerous solar and heliospheric phenomena, so it would be difficult to believe that any parameter alone can determine behaviour of CR. The existence of a relation between the solar wind (SW) magnetic field and long-term CR variations seems to be apparent. However, only with the accumulation of a long data series of SW measurements could there be established a strong correlation between the CR modulation and the IMF module, as was done in [23, 24]. A role of the solar wind velocity V for CR modulation was mentioned previously [25]. It seems necessary to account its influence, because the SW velocity determines two components of the CR modulation mechanism: the convection and adiabatic energy changes. Some evidences have appeared that changes in the solar wind velocity near the Earth may have not only local, but also global character [26, 27]. Solar wind and IMF play an important role in controlling the electrodynamics of the heliosphere [28]. Solar wind speed V and IMF parameters, such as vector $\mathbf{B}$, spiral angle and tilt are important for the transport of energetic cosmic ray particles in the heliosphere, for the modulation of CR and creation of CR anisotropy in the interplanetary space. Kondoh et al. [29] found that the peak solar wind velocity have good anti-correlation with the high-energy galactic cosmic ray intensity. Recent enhancements of solar wind velocity are closely associated with the long-term decreases in the galactic cosmic ray intensity. The IMF magnitude and fluctuations are responsible for the depression of CR intensity during high-speed solar wind events [30]. The frequency histograms of solar wind velocity for HAE/LAE are plotted in Figures 1a, 1b. One can observe from these figures that the majority of the HAE occur when the solar wind velocity lies in the interval 300–500 km/s, and LAE occur when the solar wind velocity lies in the interval 300–600 km/s (i.e. being nearly average). Very few HAE/LAE occurred when solar wind velocity is 700 and above. Usually, the velocity of high-speed solar wind streams (HSSWSs) is about 700 km/s [7]. Therefore it is quite apparent from Figure 1a, b that HAE/LAE events are not caused either by the HSSWS 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 high-speed solar wind streams. Similar findings have been reported by Munakata et al. [7] for LAEs. Duggal and Pomerantz [31] and Iucci et al. [32] pointed out that the effect of HSSWS on CR intensity is -0.5% per 100 km/s in the case of high-speed wind emerging from the coronal holes. An analysis using groups of days with high and low solar wind speeds shows greater amplitude of both the tri-diurnal and semi-diurnal waves for the group of days with high wind speed [15, 33]. Agrawal et al. [33] suggested that the solar polar coronal holes could influence both semi/tri-diurnal variations.

The dependence of the IMF sense on solar diurnal variation has been studied by many researchers [34]. Of the annual mean amplitudes of the diurnal anisotropy observed with the Deep River neutron monitoring station for "away" and "towards" polarities of the IMF for the period 1965–93, the amplitude for the "away" group exceeds that for the "toward" group for the period 1965–68 and from 1969–73, the amplitude for the "toward" group exceeds that for the "away" group [35]. At the most northerly viewing latitudes there are larger variations in the solar diurnal amplitude for the "toward" polarity than for the "away" polarity days (northward pointing gradient); while as the viewing latitudes become more southerly, there are greater and greater years in which the amplitude for the away polarity days is greater than that for the "toward" polarity days (a predominant southward gradient) [36]. Burlaga and Ness [37] argue that it is ultimately the strong magnetic field and their associated fluctuations that produce the modulation of cosmic rays. Cane et al. [23, 38] have found that the cosmic ray profile tracks rather well variations in the interplanetary magnetic field strength. The effect of interplanetary magnetic field $\mathbf{B}$ and its B_z component on cosmic ray intensity and geomagnetic field variations have been examined by Singh et al. [39]. They observed that (1) $\mathbf{B}$ not less than 10 gamma (magnetic blobs) is a pre-requisite in producing cosmic ray intensity and geomagnetic field variations of varying magnitudes; (2) the longer existence of magnetic blobs on successive days produces larger decreases in cosmic ray intensity and geomagnetic field; (3) the southward component (B_z) of IMF generally gives rise to large Ap changes, though it is not effective in producing cosmic ray intensity decreases. Alania et al. [40] studied the effects of the sector structure of the interplanetary magnetic field (IMF) on the

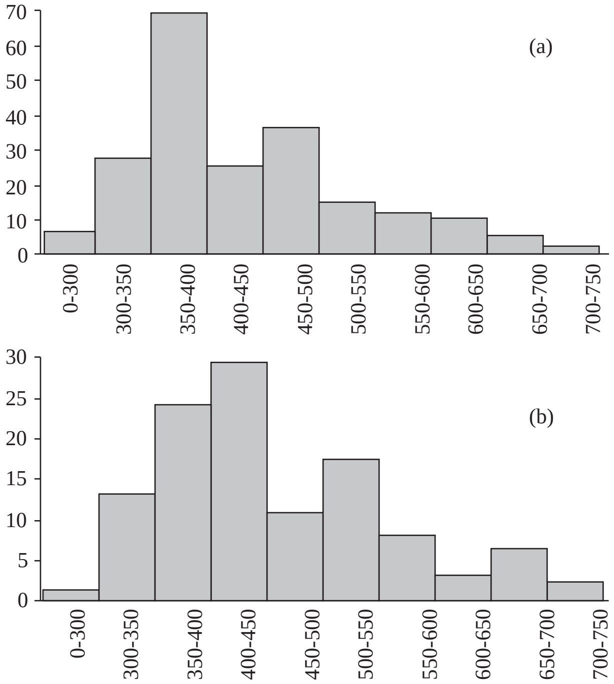

Figure 1. Frequency histogram of solar wind velocity for all the (a) HAE and (b) LAE events during 1981–94.

Galactic cosmic ray (GCR) anisotropy at solar minimum by using Global Network neutron monitor data. They noticed that the magnitude of the GCR anisotropy vector is larger in the positive IMF sector and that the phase shifts towards early hours.

The phases (Hr) of diurnal, semi-diurnal and tri-diurnal anisotropies for HAEs/LAEs with variations in the associated values of z-component of interplanetary magnetic field $\mathbf{B}$, i.e. B_z, have been plotted and are shown in Figures 2, 3, 4 for the period 1981–94. Figures 2a and 2b show that the phase of diurnal anisotropy is evenly aligned for both HAE and LAE; and Figures 3a and 3b show that the phase of semi-diurnal anisotropy is more aligned for HAE than for LAE. It is noteworthy that time of diurnal maximums shifts significantly towards earlier hours than the time of maximum for co-rotational values—for most HAE/LAE events of both positive and negative polarity B_z; the rest of the events remain in the corotational direction. Further, Figures 4a and 4b show that the phase for tri-diurnal anisotropy is better aligned for HAE than for LAE. The z-component of IMF B_z is found to remain positive i.e. away from the Sun for the majority of HAE as well as LAE days. However for some of the HAE/LAE it is observed to remain negative i.e. towards the Sun, as is quite apparent from Figures 4a and 4b; which significantly confirm the earlier trends reported by Kananen et al. [41], where they found that the amplitude is high and phase shifts to early hours for positive IMF polarity; whereas for negative IMF polarity, the amplitude is lower and phase shifts to earlier hours than for corotational values. Thus the occurrence of HAE/LAE is found to be dominant during the positively directed B_z component of IMF polarity, which is in good agreement with earlier findings [4–6]. On the basis of these anisotropic events for all three harmonics, it is deduced that for the positive polarity of IMF, B_z, the phase shifts towards earlier hours as compared to the corotational direction; whereas for negative IMF polarity, B_z, the phase again shifts towards earlier hours than for corotational values of HAE as well as LAE. 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 [42]. Sabbah [43] also observed that days characterized by high IMF magnitude are associated with higher diurnal variation amplitudes as well as higher solar plasma parameters. The B_z component of IMF does not usually contribute to the solar modulation of cosmic rays since the long-term average of this component near the Earth is ~0. However, Swinson [44] and Swinson et al. [45] have demonstrated that on occasions it can contribute to a field-dependent anisotropy, and especially to the extended trains of enhanced solar diurnal variation observed in 1974. They contend that this enhancement resulted from the constructive interference of the regular solar diurnal variation, that is $B_y \times \nabla N_y$ streaming. Caballero and Valdes-Galicia [46] noticed the presence of a 38-day fluctuation as a stable characteristic for all periods (1990–1999) and parameters. (In IMF and in cosmic rays: sunspots, flares, hard X-rays, B_z-IMF, Cr-cosmic rays). This fluctuation does not depend on the cutoff rigidities of the stations or the level of solar activity. This indicates that the 38-day fluctuation is present in the Sun, in the IMF z-component and in the cosmic ray intensities. The interaction between interplanetary Alfven waves of solar origin and cosmic rays is most probably the physical mechanism explaining this relation.

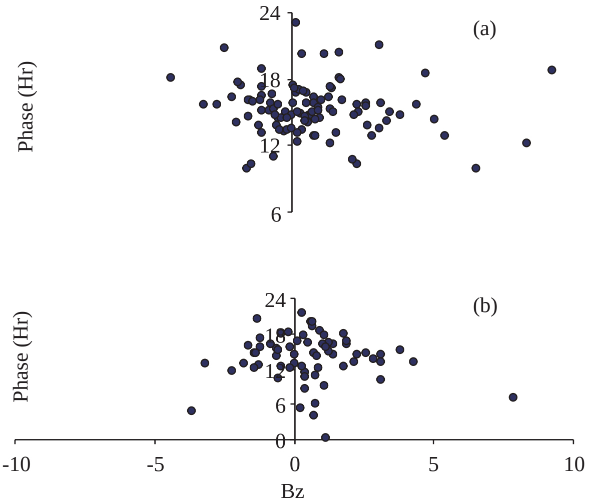

Figure 2. The phase of the diurnal anisotropy for all the (a) HAE and (b) LAE events with the variation in associated values of Bz during 1981–94.

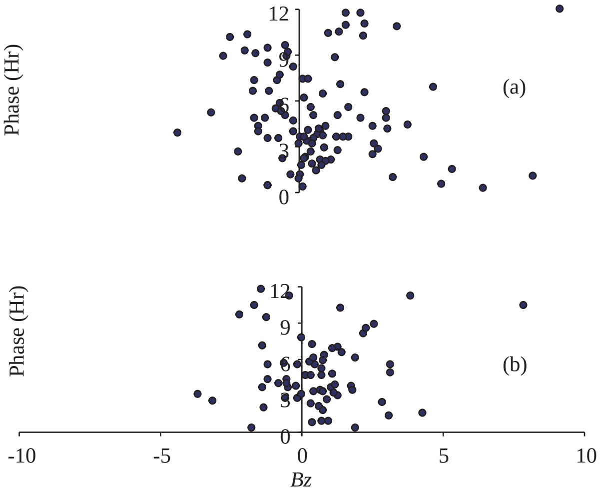

Figure 3. The phase of the semi-diurnal anisotropy for all the (a) HAE and (b) LAE events with the variation in associated values of Bz during 1981–94.

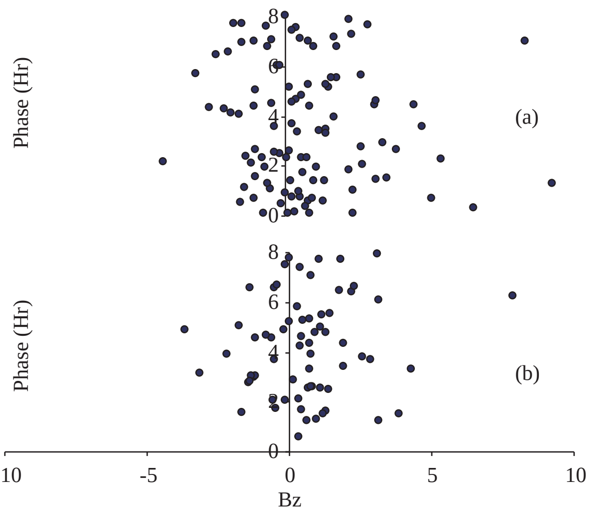

Figure 4. The phase of the tri-diurnal anisotropy for all the (a) HAE and (b) LAE events with the variation in associated values of Bz during 1981–94.

The amplitude and phases of the diurnal, semi-diurnal and tri-diurnal anisotropies for each HAE/LAE event are plotted graphically on a harmonic dial or clock diagram as a cloud of points having their origin at a fixed point and are shown in Figures 5, 6 and 7. As depicted in Figure 5(a) and 5(b), the phase of the diurnal anisotropy shifts to earlier hours for most HAE events, and for more events than co-rotational values; and we see also that the phase of the diurnal anisotropy has a tendency to shift toward earlier hours, a tendency as compared to co-rotational value for most of the LAEs. For semi-diurnal anisotropy, the situation is quite similar for the distribution of phase for both the HAE and LAE cases, as shown in Figures 6a and 6b. Note how the phase is evenly distributed in first and second quadrant for majority of HAE/LAE. Further, the phase of tri-diurnal anisotropy, as depicted in Figures 7a and 7b, is evenly distributed in all the quadrants for HAEs as well as for LAEs.

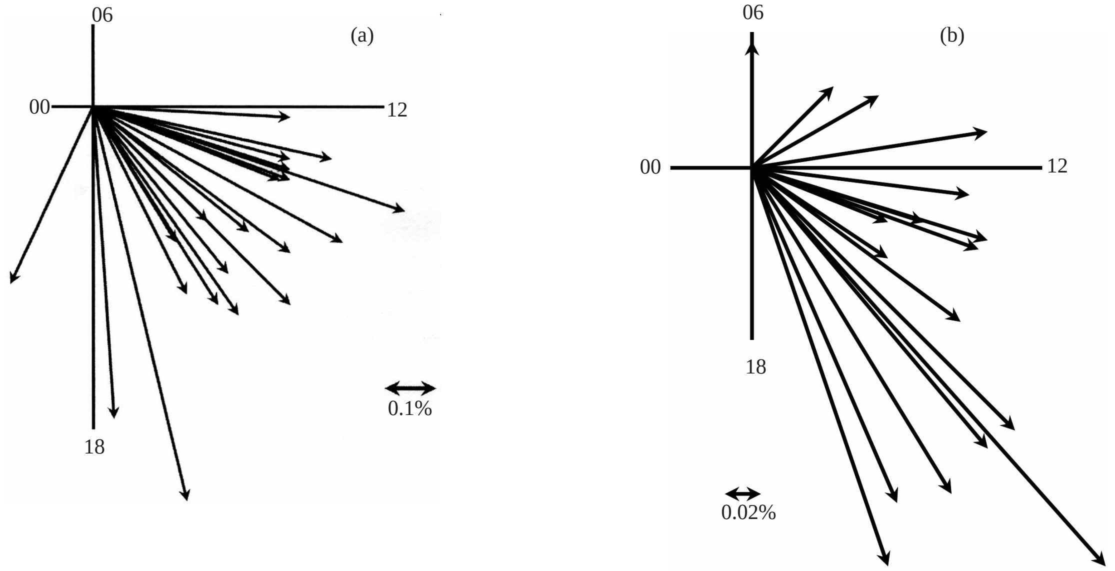

Figure 5. The amplitude and phase of the diurnal anisotropy of all the (a) HAE and (b) LAE events plotted on harmonic dial during 1981–94.

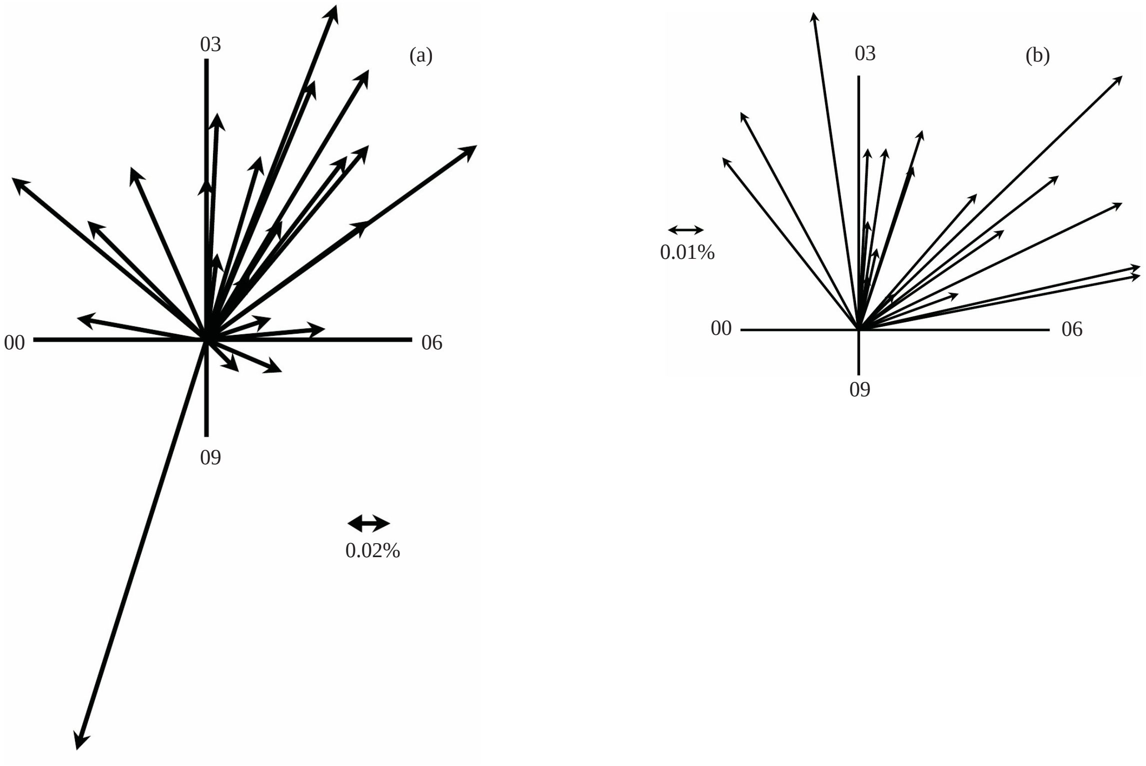

Figure 6. The amplitude and phase of the semi-diurnal anisotropy of all the (a) HAE and (b) LAE events plotted on harmonic dial during 1981–94.

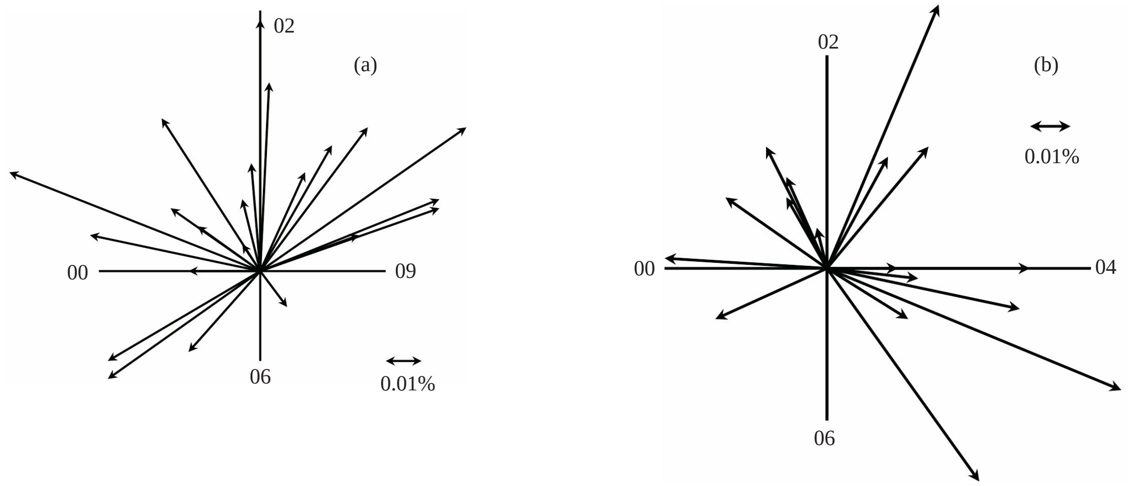

Figure 7. The amplitude and phase of the tri-diurnal anisotropy of all the (a) HAE and (b) LAE events plotted on harmonic dial during 1981–94.

4. Conclusion

On the basis of this investigation, the following conclusions have emerged:

1. HSSWSs do not play a significant role in causing HAEs/LAEs.

2. The phase of diurnal anisotropy for both HAEs and LAEs shift away from the corotational direction towards earlier hours. For semi-diurnal anisotropy, the phase remains statistically the same for both HAE and LAE events; and in the case of tri-diurnal anisotropy, the phase distributes evenly for both types of events.
3. The occurrence of HAEs and LAEs is dominant for the positive polarity of the z-component of IMF, i.e. B_z.
4. The time for the occurrence of maximums shifts towards earlier hours for both positive and negative polarity of IMF, B_z, for both HAEs and LAEs.

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