Turk J Phys
28 (2004) , 175 – 187.

Exceptionaly Low Amplitude Anisotropic Wave Train Events in Cosmic Ray Intensity

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Received 29.07.2003

Abstract

The unusually low amplitude anisotropic wave train events (LAEs) in cosmic ray intensity using the ground-based Deep River neutron monitor data has been studied during the period 1991–94. It has been observed that the phase of the diurnal anisotropy for majority of the LAE events remains in the corotational direction. However, for some of the LAE events the phase of the diurnal anisotropy shifts towards earlier hours. On the other hand, the amplitude of the semi-diurnal anisotropy remains statistically the same whereas, phase shift towards later hours; similar trend has also been found in case of tri-diurnal anisotropy. The interplanetary magnetic field (IMF) and solar wind plasma (SWP) parameters during these LAEs are also investigated.

Key Words: Cosmic ray, diurnal, semi-diurnal and anisotropy.

1. Introduction

Solar diurnal variation of cosmic ray (CR) intensity exhibits large day-to-day variability [1]. This variability is a reflection of the continually changing conditions in interplanetary space [2]. The average diurnal anisotropy of cosmic radiation is presently explained in terms of azimuthal corotation [3]. The systematic and significant deviations of amplitude, together with the phase of diurnal/semi-diurnal anisotropies, from the mean values are known to occur in association with strong geomagnetic activity [4]. The features that distinguish these systematic deviations are the unusually low or high amplitudes and (though not always) the phase shift towards earlier hours [5].

The average characteristics of cosmic ray diurnal anisotropy are adequately explained by the co-rotational concept [6, 7]. This concept supports a mean diurnal amplitude in space of 0.4% along the 1800 Hr direction. As the day-to-day deviation both in amplitude and phase and the abnormally large or low amplitudes of consecutive days cannot be explained in corotational terms, many scientists [8–10] have come to use a new concept for the interpretation of the diurnal variation. McCraken et al. [11] first suggested the extension of this new concept from the solar cosmic events to the observed diurnal variation; and a theoretical formulation was provided by Forman and Glesson [12]. On the basis of this mechanism the diurnal variation can be explained in terms of radial convection together with diffusion, which occurs mainly along the magnetic field lines. The corotational concept is a special case of the convective-diffusive model with which we can explain the characteristics of the diurnal variation—even on a day-to-day basis. The phase shift of the diurnal anisotropy to earlier hours is well understood in terms of the convective-diffusive mechanism [9]. Owens and Kash [10] have noted that the non-field-aligned diffusion on days of nominal diurnal amplitude are influenced by magnetic sector passages.

The standard picture for the diffusion of cosmic rays at neutron monitor energies in the solar system essentially involves is field-aligned diffusion [13]. Kane [9] 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. [1], comparing the diffusion vector with the magnetic field vector, pointed out that this simple concept holds well on more than 80% of days. Of the remaining 20% , the diurnal anisotropy characteristics seem to indicate the presence of a significant component of transverse diffusion current, in addition to the 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 magnetic field direction. The value of the diffusion coefficients ratio $K_{\perp}/K_{||}$, which is normally about ≤ 0.05 for field aligned days, is found to be $\sim$1.0 on non-field aligned days. It has been shown [9] 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 occurred. Owens and Kash [10], selecting only those days in which there are no complication 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 [8]. Mavromichalaki [14, 15] have shown that the diffusion vector is field aligned during days exhibiting enhanced diurnal variation, the diffusion current on an average basis being driven by large cosmic ray gradients in the ecliptic plane.

Using the neutron monitor data of Athens and Deep River stations over the period 1970–1977, Mavromichalaki [16] 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.

Long term changes in diurnal anisotropy of cosmic rays has been studied by Ananth et al. [17] and observed that the amplitude of the anisotropy is related to the characteristics of high and low amplitude days. The occurrence of low amplitude days is negatively 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 low amplitude days contribute significantly to the long-term behavior of the diurnal anisotropy as it produces an additional component of cosmic rays in the radial (1200 Hr) direction. Ananth et al. [18] examined the occurrence of a large number of high and low amplitude cosmic ray diurnal wave trains during the two solar cycles (20 and 21) over the years 1965–1990 as a function of solar activity. They concluded that the low amplitude days show an inverse correlation with solar activity and have a time of maximum along the $\sim$ 1500 Hr direction. The slope of the power-spectrum density roughly characterized by power spectral index n in the high frequency range 3.5–8.3 $\times 10^{-5}$ Hz (time scales of 20 min to 8 Hr) is different for the two classes of events. They suggested that different types of interplanetary magnetic field distributions produce the enhanced and low amplitude cosmic ray diurnal variations.

Jadhav et al. [19] have studied the behavior 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 are 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 [20], which infer that the diurnal as well as semi-diurnal variation of galactic cosmic ray 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 [21, 22]. The diurnal variation might be influenced by the polarity of the magnetic field [23], so that the largest diurnal variation is observed during the days when the daily average magnetic field is directed outward from the Sun.

Two types of high-speed solar wind streams—namely, flare generated streams (FGS) and corotating streams (CS) —are found equally effective in producing cosmic ray intensity decreases. Iucci et al. [24] and Shukla et al. [25] have shown that the close correspondence between the cosmic ray intensity decreases observed by high latitude neutron monitors and the increase in the solar wind speed during the period of high-speed streams, which probably originate in coronal holes. They have also shown that the high-speed streams produced by solar flares are accompanied by Forbush decreases, whose amplitudes are not directly correlated with the increase in solar wind speed. These latter decreases are usually large and are dependent on the location of the solar flares.

Venkatesan et al. [26] observed a difference in the rigidity spectrum of the short-term variation of cosmic ray intensity; which is attributed to the two types of high-speed solar wind streams of different solar origin, e.g., coronal hole and solar active regions. This difference in the rigidity spectrum of cosmic ray intensity has implications on the understanding of both the short- and long-term variations of cosmic ray intensity [27, 28]. They noticed that the small but significant cosmic ray intensity decreases with almost a flat rigidity spectral variation (exponent ≈ 0) are associated with a large number of high speed streams essentially predominant during the declining phase of the sunspot cycle. The number, as well as the effect of large solar active centers, is minimal during these periods; which is consistent with the significant residual modulation of galactic cosmic ray intensity during years of minimum sunspot activity [27], when effects of solar polar coronal holes are more dominant [28–30]. It is also observed that during periods of sunspot maximum activity; these high-speed streams decline in number, but the ones present produce much larger decreases in cosmic ray intensity, the magnitude of which decreases with increasing particle rigidity (spectral exponent $\approx$ -1). In fact, during high sunspot activity period, large Forbush decreases are observed during which the solar wind speed hardly exceeds 600 km s^{-1} and that, too, for much shorter periods. Nevertheless, their effects have been reported at large distances from the Sun [30] as well as in the long-term modulation of cosmic ray intensity [27]. Thus due to the time-varying rigidity-dependent effects on cosmic ray intensity which are attributed to two types of high speed solar wind streams emanating from two different solar sources, namely solar coronal holes and flare-associated solar active regions; the rigidity dependence of the long-term modulation of cosmic rays should vary with the phase of the solar cycle. Which is consistent with the results observed by Hatton [27] and Nagashima and Morishita [32, 33].

It has been reported that solar flare generated high-speed solar wind streams dominate during high solar activity period and produce large transient decrease in cosmic ray intensity [34]. After the identification of two types of solar wind plasma streams in 1988, several attempts have been made to show their influence on cosmic ray intensity on short-term basis [35]. More recently, Shrivastava and Jaiswal [36] reported almost equal influence of FGS and CS solar wind streams on cosmic ray transient decreases for the period of 1991 to 1996, using the Oulu neutron monitors data. Shrivastava and Shukla [37] noticed that flare generated streams are more effective to produce cosmic ray decreases. SSC association with FGS enhanced in cosmic ray decreases. During the study of high-speed solar wind streams and cosmic ray intensity variation for the period 1991 to 1996, Shrivastava [38] observed that both the FGS and CS streams produce short-term transient decreases in cosmic ray intensity. It is also found that medium range (5 to 6 days duration) solar wind streams are found to be more effective in producing cosmic ray transient decreases.

The study of diurnal/semi-diurnal/tri-diurnal anisotropies during 1991–94 for LAE has 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 cosmic ray intensity recorded at ground based neutron monitoring stations and selected 13 unusually low amplitude anisotropic wave train events (LAEs) during the period 1991–94. The amplitude of the diurnal anisotropy on an annual average basis is found to be 0.4%, which has been taken as a reference line to select LAEs. The days having abnormally low amplitude for five or more consecutive number of days have been selected as LAE. The pressure corrected hourly neutron monitor data after applying trend correction is harmonically analyzed to have amplitude (in %) and phase (in Hr) of the diurnal, semi-diurnal and tri-diurnal anisotropies of cosmic ray intensity for LAE. The data related with interplanetary magnetic field (IMF) and solar wind plasma (SWP) parameters have also been investigated. These IMF and SWP parameters have been used from interplanetary medium data book published by National Space Science Data Center (NSSDC).

3. Results and Discussion

The amplitude and phase of the diurnal anisotropy for the LAE events have been plotted in Figures 1 & 2. As depicted in Figure 1, it is quite apparent that the phase of the diurnal anisotropy has shifted towards earlier hours in some of the LAE events; whereas in Figure 2, the phase of the diurnal anisotropy for majority of the LAE events remains in the corotational direction. However, in case of HAE the diurnal time of maximum remains in the corotational direction for majority of the events either or, or it shifts towards later hours for rest of the events [40]. These findings are in good agreement with earlier results for highly enhanced daily variation [41]. Similarly, the amplitude and phase of the semi-diurnal anisotropy have been plotted in Figure 3. It is quite apparent from Figure 3 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, which is consistent with the earlier findings of Jadhav et al. [19] for the period 1966–73 for LAE. However in case of HAE the time of maximum of semi-diurnal component found to shifts towards later hours for majority of the events [40]. Further, the amplitude and the phase of the tri-diurnal anisotropy have been plotted in Figure 4. It is quite clear from Figure 4 that the amplitude of tri-diurnal anisotropy remains statistically the same; whereas, the phase shifts towards later hours for most of the LAE events. However in case of HAE the amplitude of tri-diurnal anisotropy remains statistically the same; whereas the phase shifts towards later hours for all the HAEs [40].

The amplitude and phase of diurnal, semi-diurnal and tri-diurnal anisotropies for all LAEs alongwith the corresponding quiet-day annual average values have been plotted in Figures 5–7. It has been found that the amplitude of the diurnal anisotropy for majority of the LAE events attains significantly lower values as compared to the quiet day annual average amplitude throughout the period as depicted in Figure 5 and the phase of the diurnal anisotropy has a tendency to shift towards earlier hours as compared to the quiet day annual average value for majority of the LAEs. However, incase of HAE the diurnal amplitude attains significantly large values; whereas the time of maximum of diurnal anisotropy remains in the corotational direction, as compared to the quiet day annual average values for majority of the events [40]. In Figure 6, one can see that 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. However in case of HAE, the amplitude of semi-diurnal

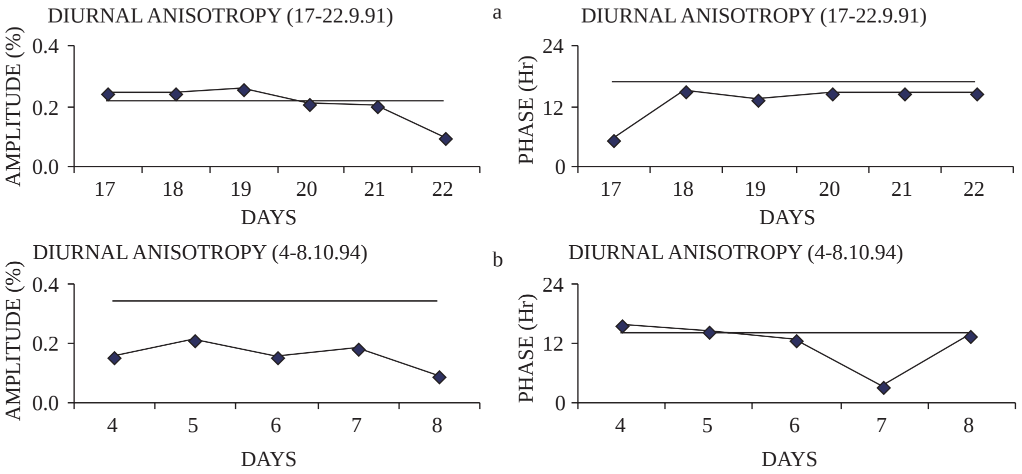

Figure 1. Amplitude and phase of the diurnal anisotropy for LAE of (a) 17–22 Sept. 1991 and (b) 4–8 Oct., 1994.

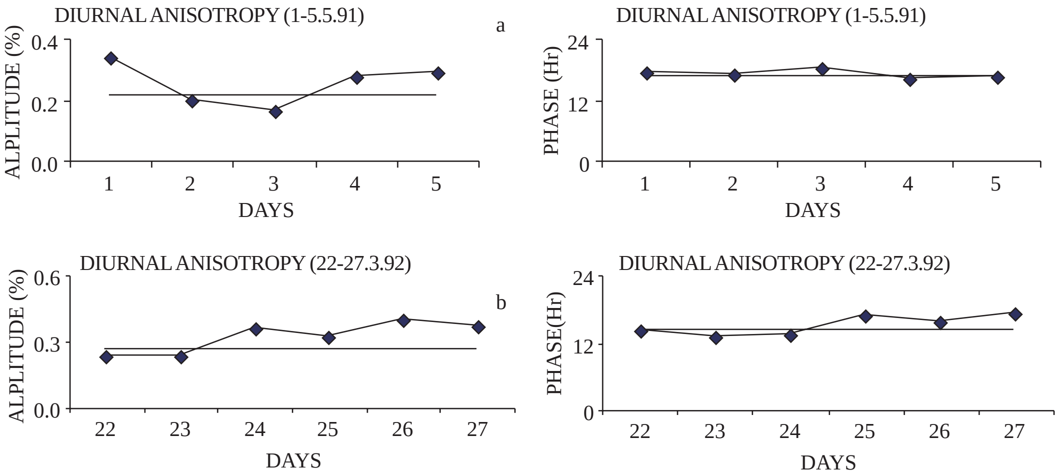

Figure 2. Amplitude and phase of the diurnal anisotropy for LAE of (a) 1–5 May 1991 and (b) 22–27 Mar., 1992.

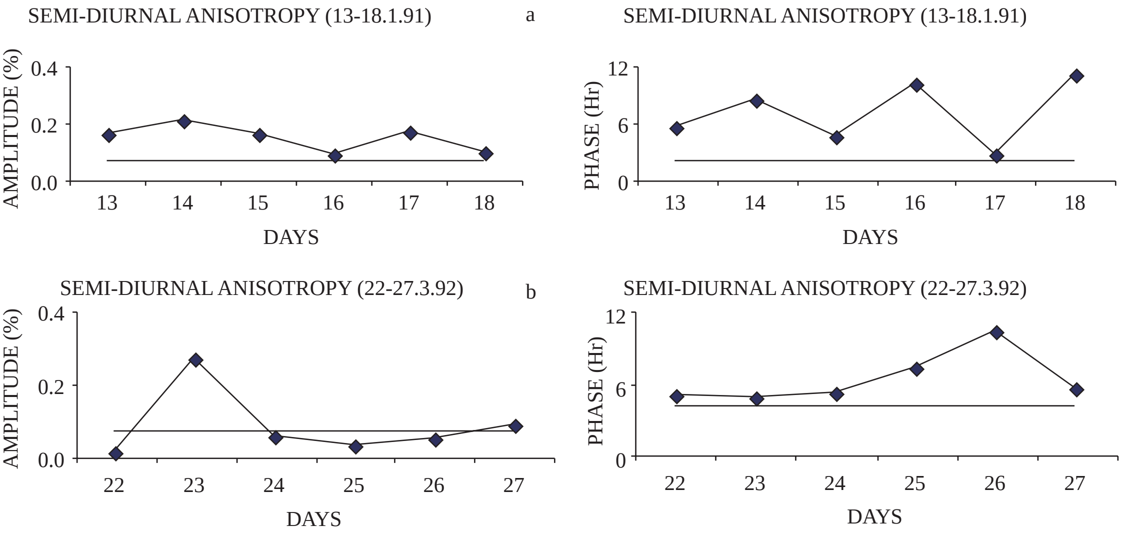

Figure 3. Amplitude and phase of the semi-diurnal anisotropy for LAE of (a) 13–18 Jan., 1991 and (b) 22–27 Mar., 1992.

component is significantly large as compared to the quiet day annual average values for some of the events; whereas the phase has no definite trend [40]. Further, it is quite apparent from Figure 7 that 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. Similar trends reported for HAE in case of tri-diurnal anisotropy [40].

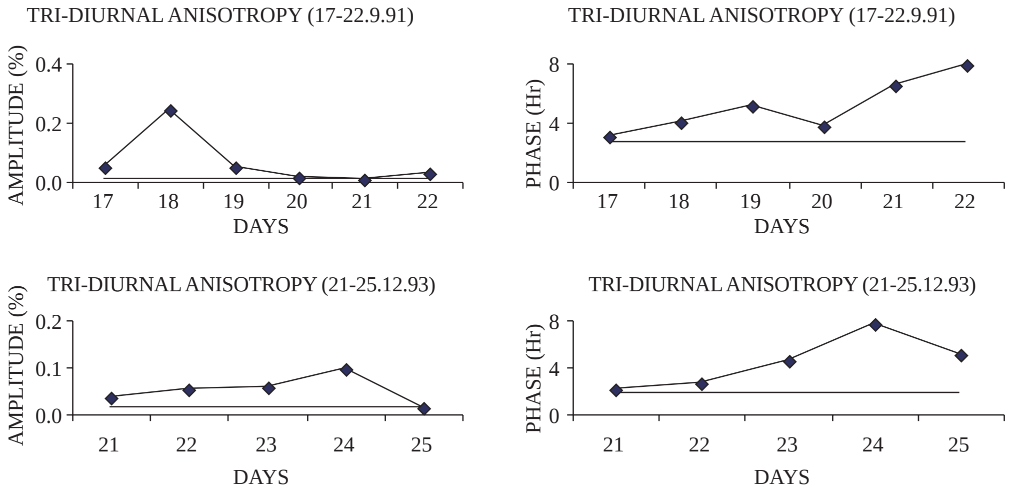

Figure 4. Amplitude and phase of the tri-diurnal anisotropy for LAE of (a) 17–22 Sep., 1991 and (b) 21–25 Dec., 1993.

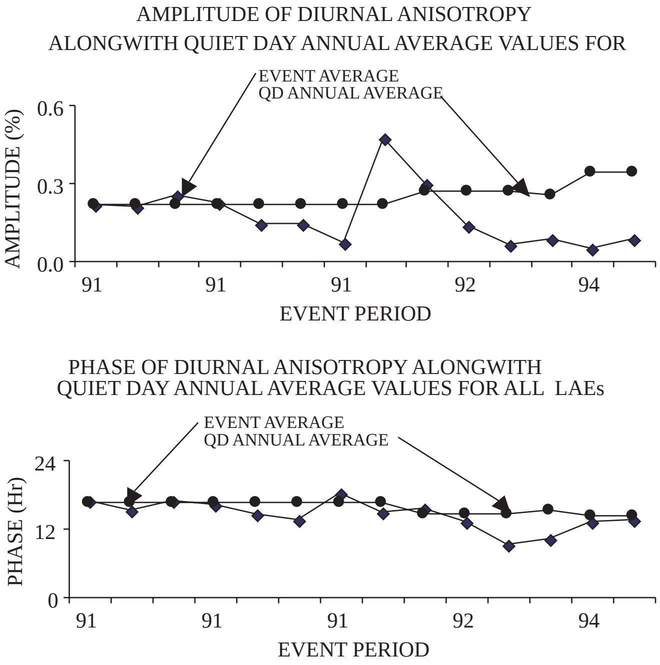

Figure 5. Amplitude and phase of the diurnal anisotropy for LAEs alongwith the quiet day annual average values during the period 1991–94.

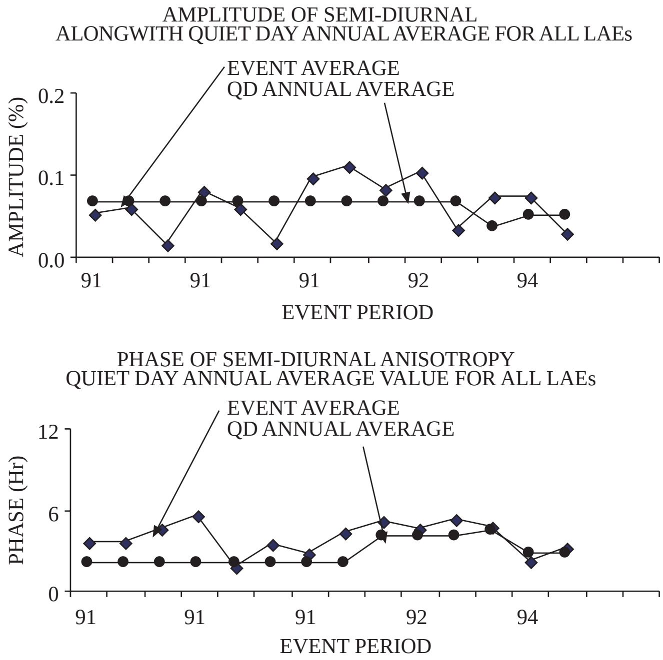

Figure 6. Amplitude and phase of the semi-diurnal anisotropy for LAEs alongwith the quiet day annual average values during the period 1991–94.

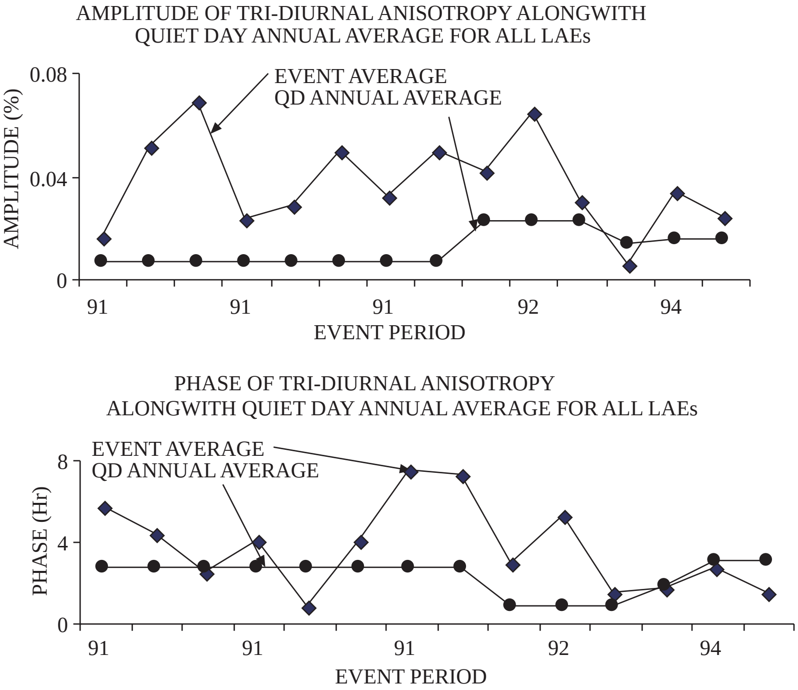

Figure 7. Amplitude and phase of the tri-diurnal anisotropy for LAEs alongwith the quiet day annual average values during the period 1991–94.

The vector addition diagrams for diurnal, semi-diurnal and tri-diurnal anisotropies for all the LAE events have been plotted in Figures 8–10. For diurnal anisotropy, as depicted in Figure 8, the phase of diurnal anisotropy remains in the corotational direction for all the LAEs; whereas it shifts towards earlier hours for majority of the events in case of HAE [40]. For semi-diurnal anisotropy, the distribution of phase lies in the second quadrant for majority of the LAE events. Similar trends are noticed for semi-diurnal anisotropy for the majority of HAE events [40]. Further, the phase of tri-diurnal anisotropy, as shown in Figure 14, is evenly distributed in all the quadrants for the majority of LAEs. The time of maximum for tri-diurnal anisotropy is also evenly distributed over all the quadrants for HAEs [40].

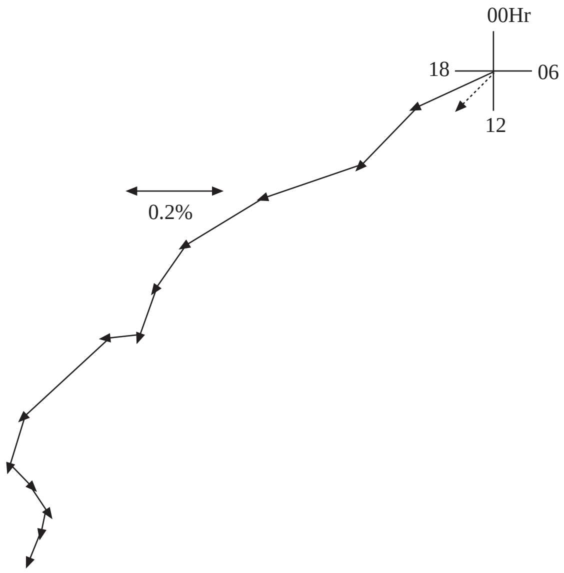

Figure 8. The vector addition diagram of all the LAE events during 1991–94 for diurnal anisotropic events.

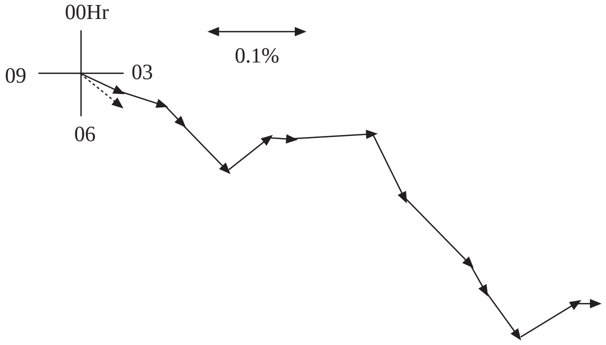

Figure 9. The vector addition diagram of all the LAE events during 1991–94 for semi-diurnal anisotropic events.

During the period of each LAE event, the interplanetary magnetic field (IMF) and solar wind plasma (SWP) parameters have also been investigated. It is quite apparent from the frequency histogram of solar wind velocity for all LAEs, as depicted in Figure 11 that majority of the LAE events have occurred when the solar wind velocity lies in the interval 400–500 km/s i.e., being nearly average. Usually, the velocity of high-speed solar wind streams (HSSWSs) is 700 km/s [21]. Therefore, it is quite apparent from Figure 8 that 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, it is inferred that HSSWS do not serve a significant role in causing the LAE events. Which is consistent with the earlier results for HAE events [40].

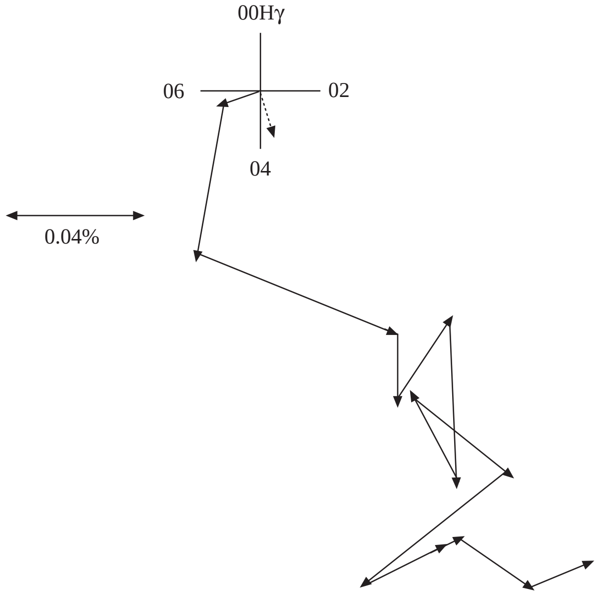

Figure 10. The vector addition diagram of all the LAE events during 1991–94 for tri-diurnal anisotropic events.

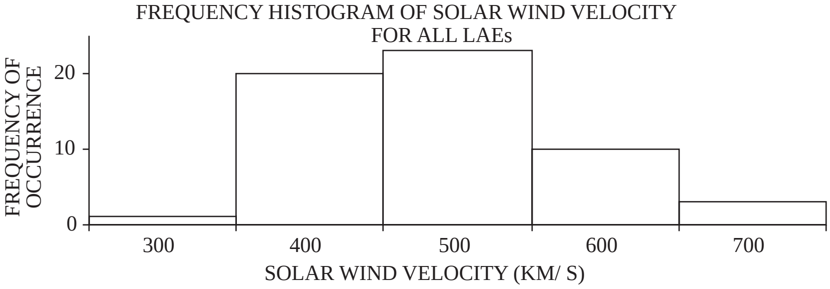

Figure 11. The frequency histogram of the solar wind velocity for all LAEs.

The amplitudes (in %) and phases (in units of 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, i.e. B_z have been plotted in Figures 12–14 during the period 1991–94. It is observable from the Figure 12 that the amplitude of the diurnal anisotropy for positively directed IMF ($+B_z$) attains higher values for some of the LAE events; whereas, the amplitude remains low for negatively directed IMF ($-B_z$) for most of the LAE events. The phase of the diurnal anisotropy, as shown in Figure 12, for both positive and negative polarity of B_z has a tendency to shift towards earlier hours as compared to corotational value for all the LAE events. However incase of HAE the amplitude of diurnal anisotropy is higher for both positive and negative polarity IMF; whereas the phase shifts towards earlier hours as compared to the corotational values for majority of the HAEs [40]. For semi-diurnal anisotropy, as shown in Figure 13, B_z is found to remain positive, i.e. away from the Sun for majority of the days of LAE events. However, for some of the days of LAE events B_z is found to remain negative, i.e. towards the Sun. However for semi-diurnal anisotropy, HAEs may occur independent of nature of B_z component of IMF [40]. Further, in case of tri-diurnal anisotropy, as depicted in Figure 14, the B_z is found to remain positive for majority of the days of LAE events; whereas, for some of the events it is also found to remain negative, which indicates that the occurrence of LAE is dominant when the IMF polarity is positively directed. The amplitude of the tri-diurnal anisotropy is evenly aligned for majority of the HAEs [40]. Kananen et al. [39] have found that for positive polarity of IMF the amplitude is high and phase shifts to early hours; whereas, for negative polarity of IMF the amplitude is lower and phase shifts to early hours as compared to corotational values.

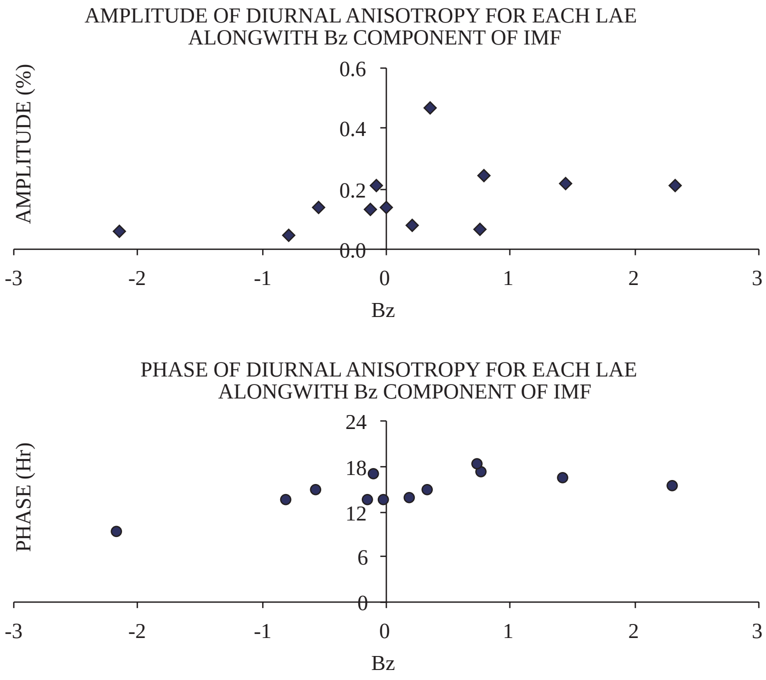

Figure 12. Amplitude and phase of the diurnal anisotropy for each LAE with the variation in associated values of B_z during 1991–94.

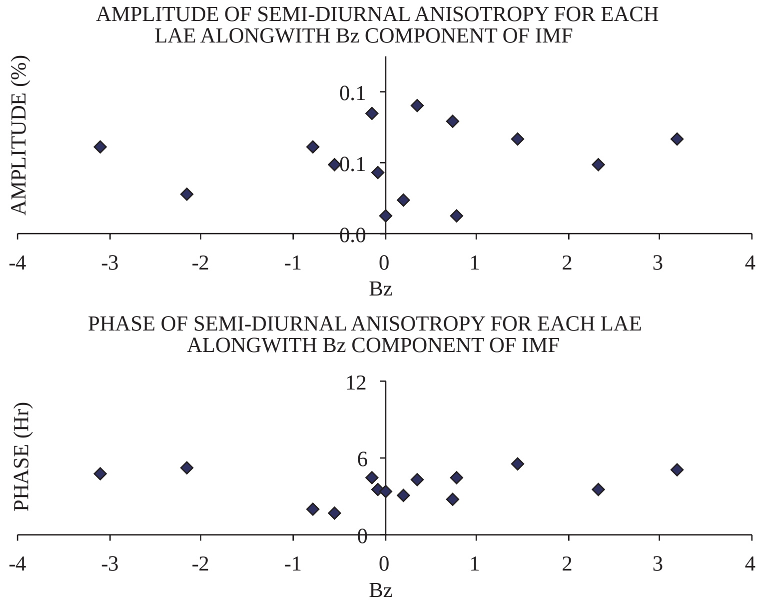

Figure 13. Amplitude and phase of the semi-diurnal anisotropy for each LAE with the variation in associated values of Bz during 1991–94.

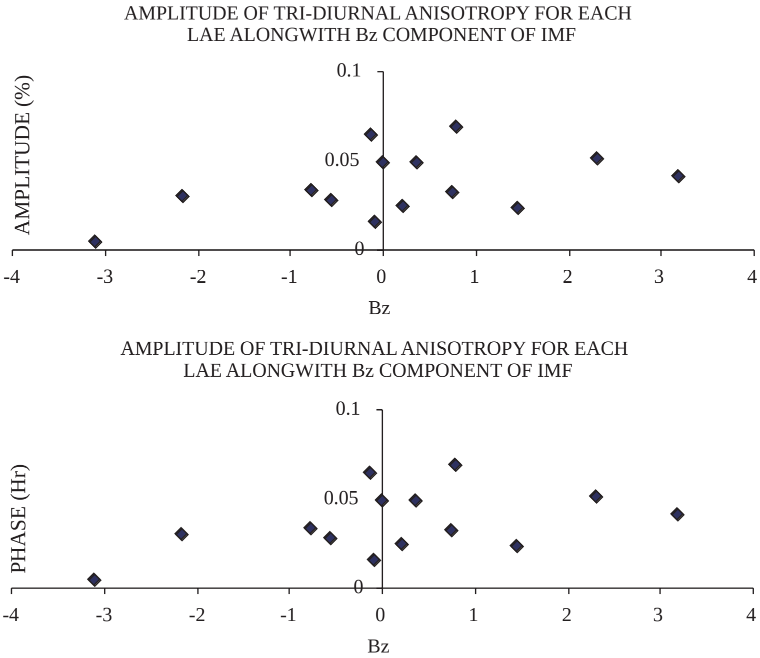

Figure 14. Amplitude and phase of the tri-diurnal anisotropy for each LAE with the variation in associated values of B_z during 1991–94.

4. Conclusions

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

The phase of the diurnal anisotropy has shifted towards earlier hours for some of the LAEs; whereas, it remains in the co-rotational direction for most of the LAEs.

The amplitude remains statistically the same; whereas, the phase has a tendency to shifts towards later hours for both semi-diurnal and tri-diurnal anisotropies for most of the LAE events.

The high-speed solar wind streams do not play a significant role in causing the LAE events.

The occurrence of LAE is dominant for the positively directed B_z component of IMF polarity.

Acknowledgements

The authors are indebted to various experimental groups, in particular, Prof. Margret D. Wilson, Prof. K. Nagashima, Miss. Aoi Inoue and Prof. J. H. King for providing the data.

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