

# Large Amplitude Wave Trains in Cosmic Ray Intensity

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## Abstract

Using ground-based neutron monitor data of Deep River, the high amplitude anisotropic wave train events (HAE) in cosmic ray intensity have been investigated during the period 1991–1994. It has been observed that the phase of diurnal anisotropy for majority of HAE cases remains in the same co-rotational direction, whereas for some HAE cases the phase of diurnal anisotropy has shifted to later hours. For the majority of HAE cases the amplitude of semi-diurnal anisotropy remains statistically the same, whereas the phase of semi-diurnal anisotropy for all HAE cases has shifted to later hours. Furthermore, for tri-diurnal anisotropy the phase shifts towards later hours while amplitude remains statistically the same.

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

## 1. Introduction

A large day-to-day variability is exhibited in the solar diurnal variation of cosmic ray (CR) intensity [1]. This variability is a reflection of the continually changing conditions in the interplanetary space [2]. 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 activity [3]. Rao et al. [4] 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 has been observed with a significant shift in the diurnal time of maximum to later hours or earlier hours [5–7]. 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. Hashim and Thambyahpillai [8] and Rao et al. [4] have shown that the enhanced diurnal variation of large amplitude events exhibits a maximum intensity in space around the anti-garden hose direction (0200 Hr) and a minimum intensity in space around the garden hose direction (0900 Hr). Kane [9] and Bussoletti [10] have noticed that quite often an enhanced intensity is presented along the corotation direction and it is not correlated with the garden hose direction.

Mavromichalaki [11] noticed the 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 point earlier than either the corotation direction or the anti-garden hose direction. The diurnal anisotropy is well understood in terms of a convective-diffusive mechanism [12]. Mavromichalaki [13, 14] has observed that the enhanced diurnal variation was 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  $\approx 8\% \text{ AU}^{-1}$ .

After a careful investigation of the diurnal anisotropy of cosmic ray intensity observed over the period 1970–1977 using the neutron monitor data of Athens and Deep River stations, Mavromichalaki [15] showed 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 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 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.

A detailed study has been conducted by Ananth et al. [16] on 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 ( $45^\circ$  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. [17] 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  $\approx 1800$  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. This indicates that the enhanced wave train event is caused by a different magnetic field configuration.

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 compared to the normal during the decreasing phase of the stream and phase is observed to remain almost constant [18], 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 [19, 20]. The diurnal variation might be influenced by the polarity of the magnetic field [21], so that the largest diurnal variation is observed during the days when the daily average magnetic field is directed outward from the Sun.

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

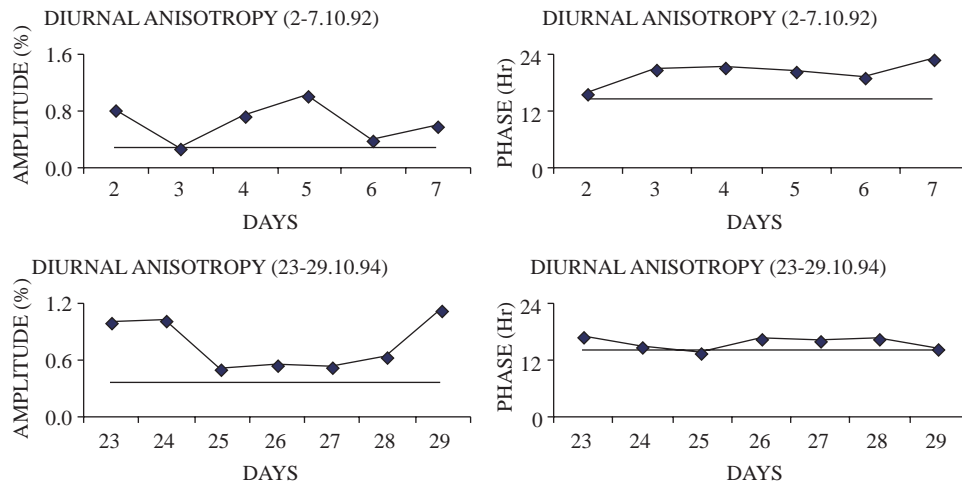
## 2. Data Analysis

The anisotropic events are identified using the hourly plots of cosmic ray intensity recorded at ground-based neutron monitoring stations and selected 16 unusually high amplitude anisotropic wave train events (HAEs) during the period 1991–1994. 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 HAEs. The days having abnormally high amplitude for five or more consecutive number of days have been selected as HAE. 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. The data related with interplanetary magnetic field (IMF) and solar wind plasma (SWP) parameters have

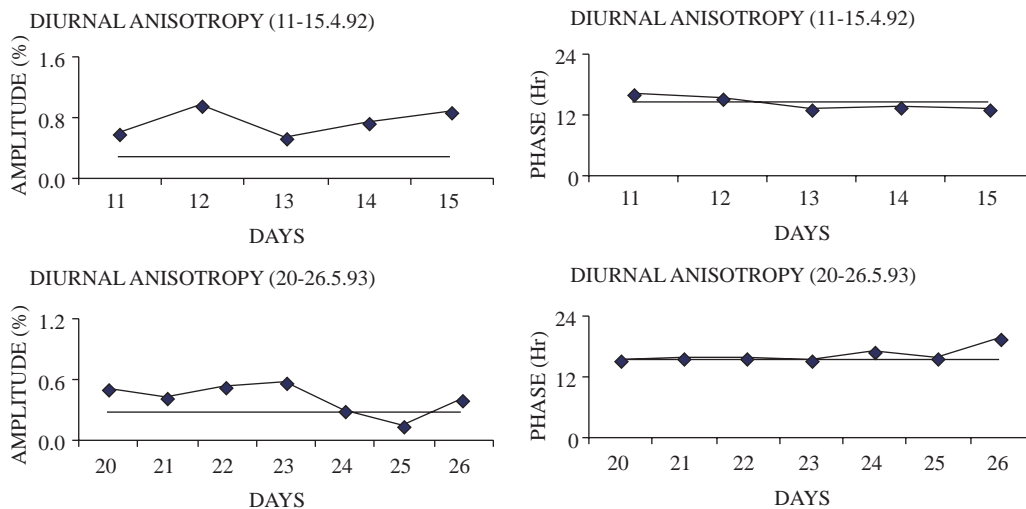
also been investigated. These IMF and SWP parameters have been used from interplanetary medium data book published by National Space Science Data Center (NSSDC).

### 3. Results and Discussion

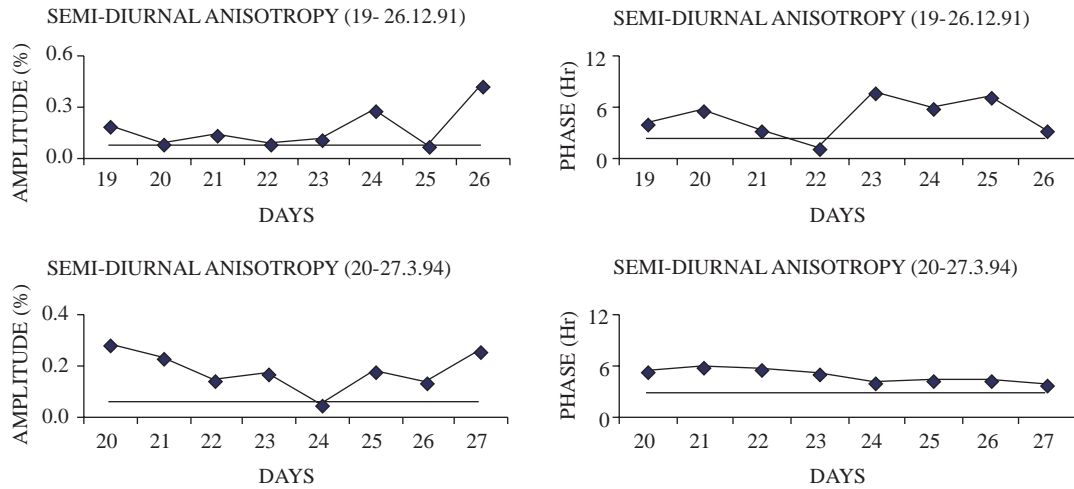
The amplitude and phase of the diurnal anisotropy has been plotted in Figure 1. It is quite apparent from Figure 1 that the phase of the diurnal anisotropy has shifted towards later hours for some of the HAEs. However, the phase of the diurnal anisotropy, as depicted in Figure 2, remains in the corotational direction for majority of the HAEs. Similarly, the amplitude and phase of the semi-diurnal anisotropy has been plotted in Figure 3. It is quite apparent from Figure 3 that the phase of the semi-diurnal anisotropy has a tendency to shift towards later hours. Further, the amplitude of the tri-diurnal anisotropy, as shown in Figure 4, remains statistically the same; whereas, the phase of the tri-diurnal anisotropy is found to shifts towards later hours for all HAEs.



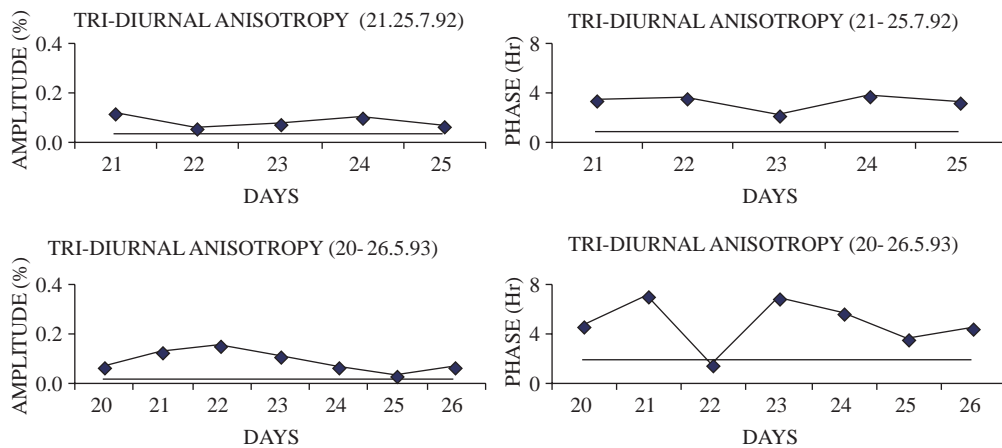
**Figure 1.** Amplitude and phase of the diurnal anisotropy for HAE of (a) 2–7 Oct., 1992 and (b) 23–29 Oct., 1994.



**Figure 2.** Amplitude and phase of the diurnal anisotropy for HAE of (a) 11–15 Apr., 1992, (b) 20–26 May, 1993.

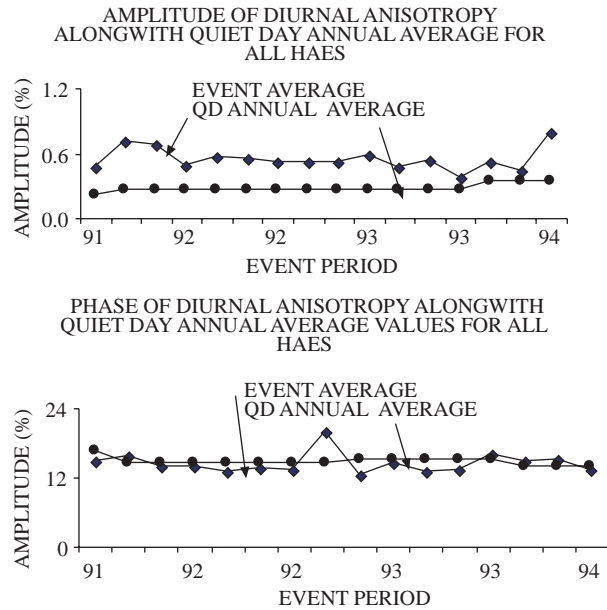


**Figure 3.** Amplitude and phase of the semi-diurnal anisotropy for HAE of (a) 19–26 Dec., 1991 and (b) 20–27 Mar., 1994.

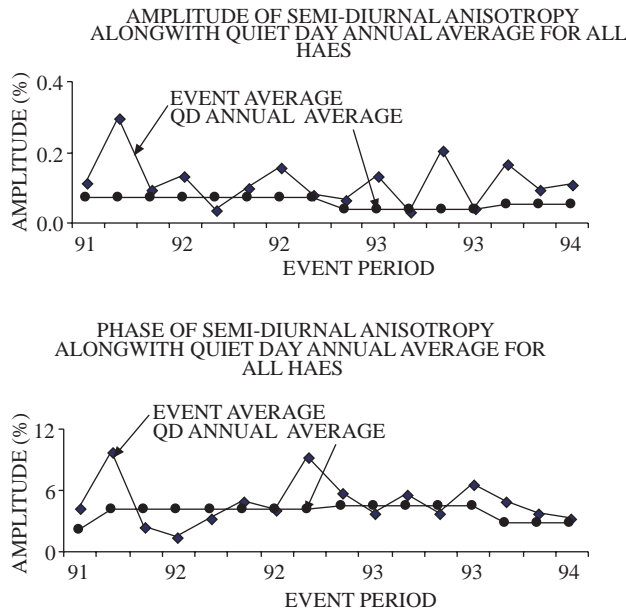


**Figure 4.** Amplitude and phase of the tri-diurnal anisotropy for HAE of (a) 21–25 Jul., 1992 and (b) 20–26 May, 1993.

The amplitude and phase of diurnal, semi-diurnal and tri-diurnal anisotropies for all HAEs along with the corresponding quiet-day annual average values have been plotted in Figures 5, 6 & 7. It has been found that the amplitude of the diurnal anisotropy for all HAE attains significantly large values, compared to quiet day annual average amplitude throughout the period, as shown in Figure 5; and the phase of the diurnal anisotropy remains in the corotational direction for most of the HAEs. The amplitude of the semi-diurnal anisotropy, as depicted in Figure 6, 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, as also shown in Figure 6. Further, the amplitude of the tri-diurnal anisotropy, as depicted in Figure 7, 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.

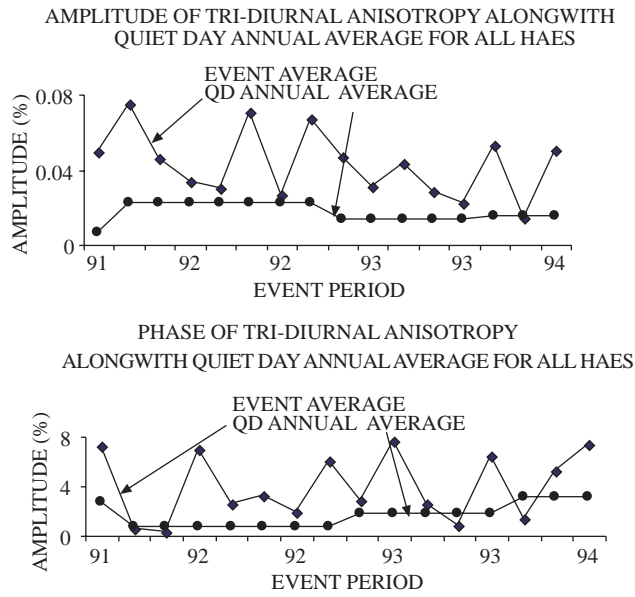


**Figure 5.** Amplitude and phase of the diurnal anisotropy for HAEs alongwith the quiet day annual average values during the period 1991-94.

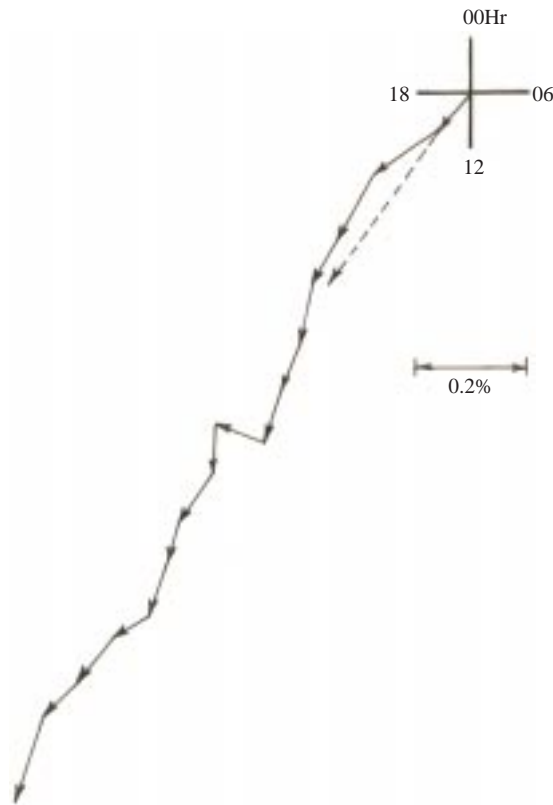


**Figure 6.** Amplitude and phase of the semi-diurnal anisotropy for HAEs alongwith the quiet day annual average values during the period 1991-94.

The amplitude and phases of the diurnal, semi-diurnal and tri-diurnal anisotropies for each HAE events are plotted in Figures 8, 9 & 10 as a vector addition diagram. As depicted in Figure 8, the phase of the diurnal anisotropy shifts to earlier hours for most of the HAE events. For semi-diurnal anisotropy, the distribution of phase lies in the second quadrant for most of the HAE events, as shown in Figure 9. Further, the phase of tri-diurnal anisotropy, as depicted in Figure 10, is evenly distributed in all the quadrants for HAEs.



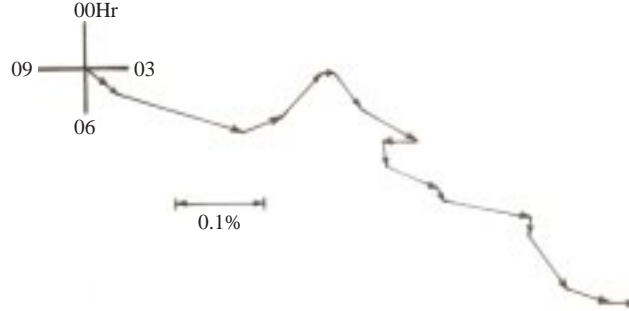
**Figure 7.** Amplitude and phase of the tri-diurnal anisotropy for HAES alongwith the quiet day annual average values during the period 1991–94.



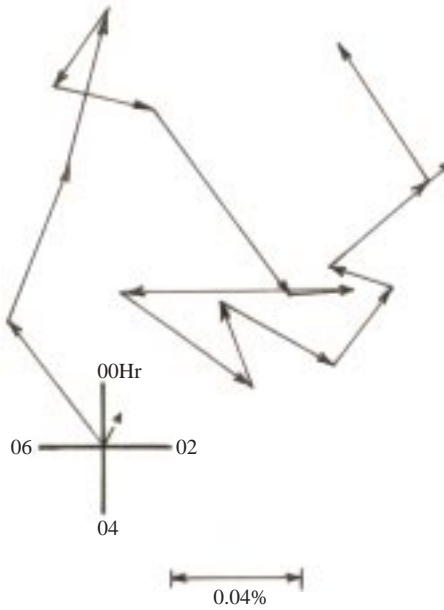
**Figure 8.** The vector addition diagram of all the HAE events during 1991–94 for diurnal anisotropic events.

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 has been plotted in Figure 11, where it is observable that the majority of the HAE events 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 [19]. Therefore, it may be deduced from Figure 11 that HAE 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 are weakly dependent on solar wind velocity.

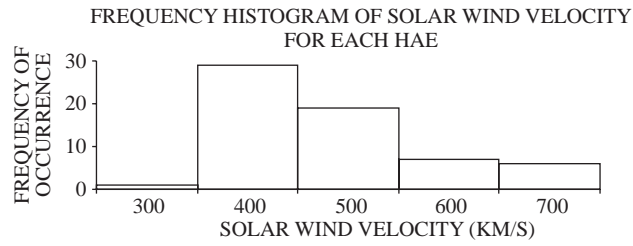


**Figure 9.** The vector addition diagram of all the HAE events during 1991–94 for semi-diurnal anisotropic events.

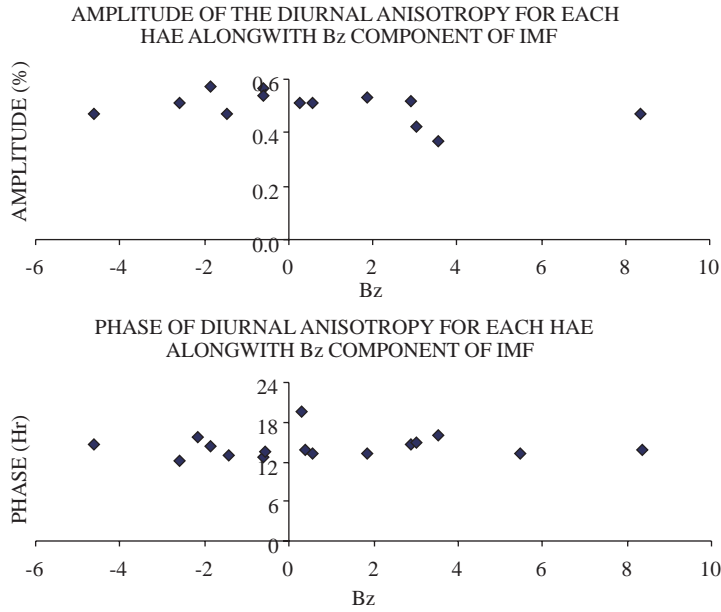


**Figure 10.** The vector addition diagram of all the HAE events during 1991–94 for tri-diurnal anisotropic events.

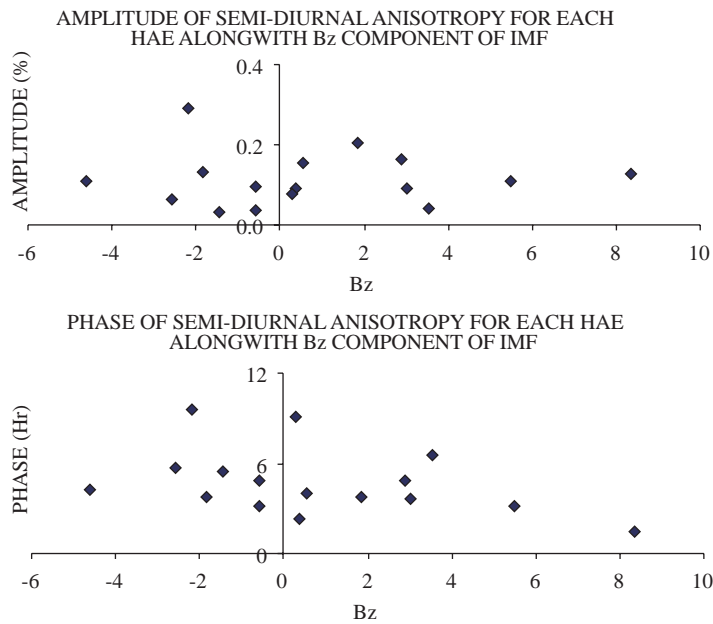
The amplitudes (in %) and phases (Hr) of diurnal, semi-diurnal and tri-diurnal anisotropies for HAEs with the variations in the associated values of  $z$ -component of interplanetary magnetic field  $B$ , i.e.  $B_z$  have been plotted in Figures 12–14 during the period 1991–94. It is quite apparent from Figure 12 that the amplitude of diurnal anisotropy is evenly aligned for both positive and negative polarity of IMF for all HAEs. The amplitude of diurnal anisotropy for both the polarity is higher and phase shifts towards earlier hours as compared to the corotational values for most of the HAEs. For semi-diurnal anisotropy as depicted in Figure 13; HAEs may occur independent of nature of  $B_z$  component of IMF. Further, for tri-diurnal anisotropy, as shown in Figure 14, the amplitude is evenly aligned for most of the HAEs. Kananen et al. [22] 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 value.



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

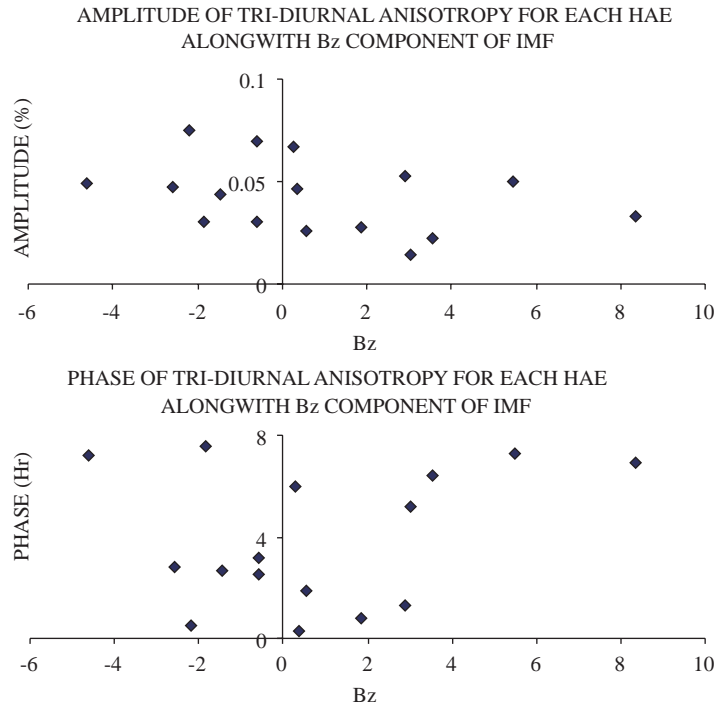


**Figure 12.** Amplitude and phase of the diurnal anisotropy for each HAE with the variation in associated values of  $B_z$  during 1991–94.



**Figure 13.** Amplitude and phase of the semi-diurnal anisotropy for each HAE with the variation in associated values of  $B_z$  during 1991–94.





**Figure 14.** Amplitude and phase of the tri-diurnal anisotropy for each HAE 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:

1. The phase of the diurnal anisotropy has shifted towards later hours for some of the HAEs; whereas it remains in the co-rotational direction for most of the HAEs.
2. The amplitude remains statistically the same; whereas phase has a tendency to shift towards later hours for both semi-diurnal and tri-diurnal anisotropies for most of the HAE events.
3. The high-speed solar wind streams do not play a significant role in causing the HAE events.

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