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Significance of interplanetary plasma and magnetic field features in modulating cosmic rays

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Abstract - This work deals with the time evolution of the three harmonics of the unusual diurnal variation of cosmic ray intensity during high amplitude anisotropic wave trains. The relation of these harmonics to interplanetary parameters such as Dst-index, Ap-index, solar wind speed and interplanetary magnetic field (Bz) is investigated in order to found the possible origin of these anisotropic wave trains and to develop a suitable theoretical model. The first three harmonics of high amplitude anisotropic wave trains of cosmic ray intensity over the period 1991-1994 have been investigated for Deep River neutron monitoring station. It is noteworthy that the amplitude of all the three harmonics remains high whereas, the direction of first harmonic shift towards earlier hours and towards later hours for second and third harmonic compared to quite day annual average. The Bz component of interplanetary magnetic field, the disturbance storm time index (Dst) and geomagnetic activity index (Ap) shows good impact on direction of first harmonic, amplitude of third harmonic and direction of third harmonic respectively. High amplitude anisotropic wave train events seem to weakly dependent on solar wind velocity.

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Introduction

The existence of high and low amplitude anisotropic wave trains has been revealed through the long-term study of cosmic ray intensity. Periods of unusually large amplitude often occur in trains of several days. The average characteristics of cosmic-ray diurnal anisotropy are adequately explained by the co-rotational concept [1-3]. This concept supports the mean diurnal amplitude in space of 0.4% along the 1800 Hr direction using the worldwide neutron monitor data. However, the observed day-to-day variation both in amplitude and time of maximum, and the abnormally large amplitudes or abnormally low amplitudes of consecutive days, cannot be explained in co-rotational terms. Moreover, the maximum intensity of diurnal anisotropy has not appeared in the direction of 1800 Hr, which is the nominal co-rotational phase [4-5].

The average daily variation of cosmic ray intensity generally consists of diurnal variation, semi-diurnal variation and tri-diurnal variation. The amplitude of the diurnal variation (first harmonic) at a high / middle latitude station has been found to be of the order of 0.3 to 0.4%, whereas the amplitudes of two higher harmonics (semi- and tri-diurnal) are of the order of 0.02% and 0.08% respectively [6]. The average characteristics have also been found to vary with solar cycle, where the variation is much larger at higher energies. A number of investigators have reported the short-term characteristics of the daily variation, where they have selected continually occurring days of high and low amplitudes of diurnal variation [7-9]. These results have pointed out significant departures in the time of maximum as well as their association with higher harmonics.

Many workers [10-12] used a new concept for the interpretation of the diurnal variation. According to this concept the average diurnal anisotropy can be explained completely in terms of simple convection and diffusion. The radial convective flow will be balanced by the inward diffusion on an average basis causing the net radial current to be zero and resulting in a corotational anisotropy of the right magnitude. McCraken et al [13] first suggested the extension of this new concept of diurnal anisotropy from the solar cosmic events to the observed diurnal variation and theoretical formulation was provided by Forman and Gleeson [14]. Several workers have attempted to find the possible origin of the 'large amplitude wave trains' of cosmic ray neutron intensity to develop a suitable realistic theoretical model, which can explain the diurnal anisotropy in individual days.

Hashim and Thambyahpillai [15] and Rao et al [10] have shown that the enhanced diurnal variation of large amplitude events exhibits a maximum intensity in space around the anti-garden-hose direction (2100 Hr) and a minimum intensity in space around the garden-hose direction (0900 Hr). Kane [16] and Bussoletti [17] have noticed that quite often an enhanced intensity is presented along the corotational direction and it is not correlated with the garden-hose direction. The diurnal anisotropy is well understood in terms of a convective-diffusive mechanism [14]. Mavromichalaki [18] 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 $\approx 8\%\ AU^{-1}$.

Analysis of Data

The effect of the changing meteorological conditions on cosmic ray variation have been studied quite extensively both theoretically and by employing well-known correlation techniques between the observed cosmic ray intensity variations and the meteorological parameters. Mainly, two major correction are to be applied to cosmic ray data, the first one is to correct for barometric or absorption effect and the second is to correct for temperature effect. Earlier observations have clearly indicated that the neutron intensity at ground is significantly affected by pressure variations, whereas the temperature effect for nucleonic component is very small. However, it may not always be negligible, since the neutron intensity as measured by the neutron monitors, results due to neutron production in the monitor by the nucleons as well as mesons.The investigation made by Dudok de Wit et al. [19] have revealed how small variations in the energetic particle flux, when observed coherently by several neutron monitors, can be significantly enhanced by multivariate statistical analysis based on the Singular Value Decomposition (SVD) technique [20]. Fleysher et al. [21] introduced a self-consistent scheme for source detection. This method allows incorporating background anisotropies by vetoing existing small-scale regions on the sky and compensating for known large-scale anisotropies. This method is universal and can be used with any large field-of-view detector, where the object of investigation, steady or transient, point or extended, traverses its field of view.

The amplitude and phase of the harmonics of daily variation in cosmic ray intensity have been derived by Fourier analysis [22] by noting the hourly counting rate of the observed cosmic ray intensity over a period of twenty-four hours.

The Fourier analysis yields reliable measures of the amplitude and phase on a day-to-day basis, provided the time series is reasonably stationary. However, this method cannot estimate the amplitude of the ambient anisotropy, which, for small amplitudes, contributes to large uncertainties in the Fourier coefficients.

The pressure corrected data of Deep River Neutron Monitor (NM) station has been subjected to Fourier analysis for the period 1991-94 after applying the trend correction. While performing the analysis of the data all those days are discarded having more than three continuous hourly data missing.

Using the long-term plots of the cosmic ray intensity data as well as the amplitude observed from the cosmic ray pressure corrected hourly neutron monitor data using harmonic analysis the High amplitude wave train events (HAE) have been selected on the basis of following criteria:

- High amplitude wave train events of continuous days have been selected when the amplitude of diurnal anisotropy remains higher than 0.4% on each day of the event for at least five or more days.
- In the selection of both types of events, special care has been taken, i.e. if there occurred any pre-Forbush decreases or post-Forbush decrease before or after the event or the event is in recovery phase or declining phase are not considered.

On the basis of above selection criteria we have selected 16 high amplitude wave train events during the period 1991-94. The hourly cosmic ray intensity data for Deep River neutron monitoring station [Geog. Lat. 46.10 (Deg.), Geog. Long. 282.50 (Deg.), Vertical cut off rigidity 1.02 (GV)] has been investigated in the present study.

Results and Discussion

The amplitude (%) and phase (Hr) of cosmic ray diurnal/semi-diurnal/tri-diurnal anisotropy alongwith the respective quite day annual average value, statistical error bars (I) and best fit lines (The linear best fit line is observed by calculating the least squares fit for a line represented by the equation: $y = mx + b$, where m is the slope and b is the intercept) are plotted and shown in Fig 1 (a, b, c) for all the HAE events. The amplitude of the diurnal anisotropy as depicted in figure is observed to remain significantly high as compared to the quiet day annual average value throughout the period, whereas, the phase remains in the co-rotational direction for majority of the event. Further, the amplitude of the semi-diurnal anisotropy is significantly large as compared to the quiet day annual average values for majority of the events, whereas, the phase has no definite trend for the semi-diurnal anisotropy. Furthermore, the amplitude of the tri-diurnal anisotropy is significantly higher for all HAEs as compared to the quiet day annual average value throughout the period. As it is quite apparent from these plots that the tri-diurnal time of maximum has a tendency to shifts towards later hours as compared to quiet day annual average value for majority of the events; which is in agreement with the low amplitude wave trains where it also shifts towards later hours for the majority of the events. The diurnal time of maximum remains in the corotational direction and shifts towards earlier hours compared to the quiet day annual average for majority of the HAE events. The phase of semi-diurnal anisotropy has no definite trend in case of HAE. However, the phase of tri-diurnal anisotropy for HAE shift towards later hours compared to the quiet day annual average values for majority of the events.

The amplitude (%) and phase (Hr) of cosmic ray diurnal/semi-diurnal/tri-diurnal anisotropy alongwith the variation in associated value of Bz component of interplanetary magnetic field, correlation

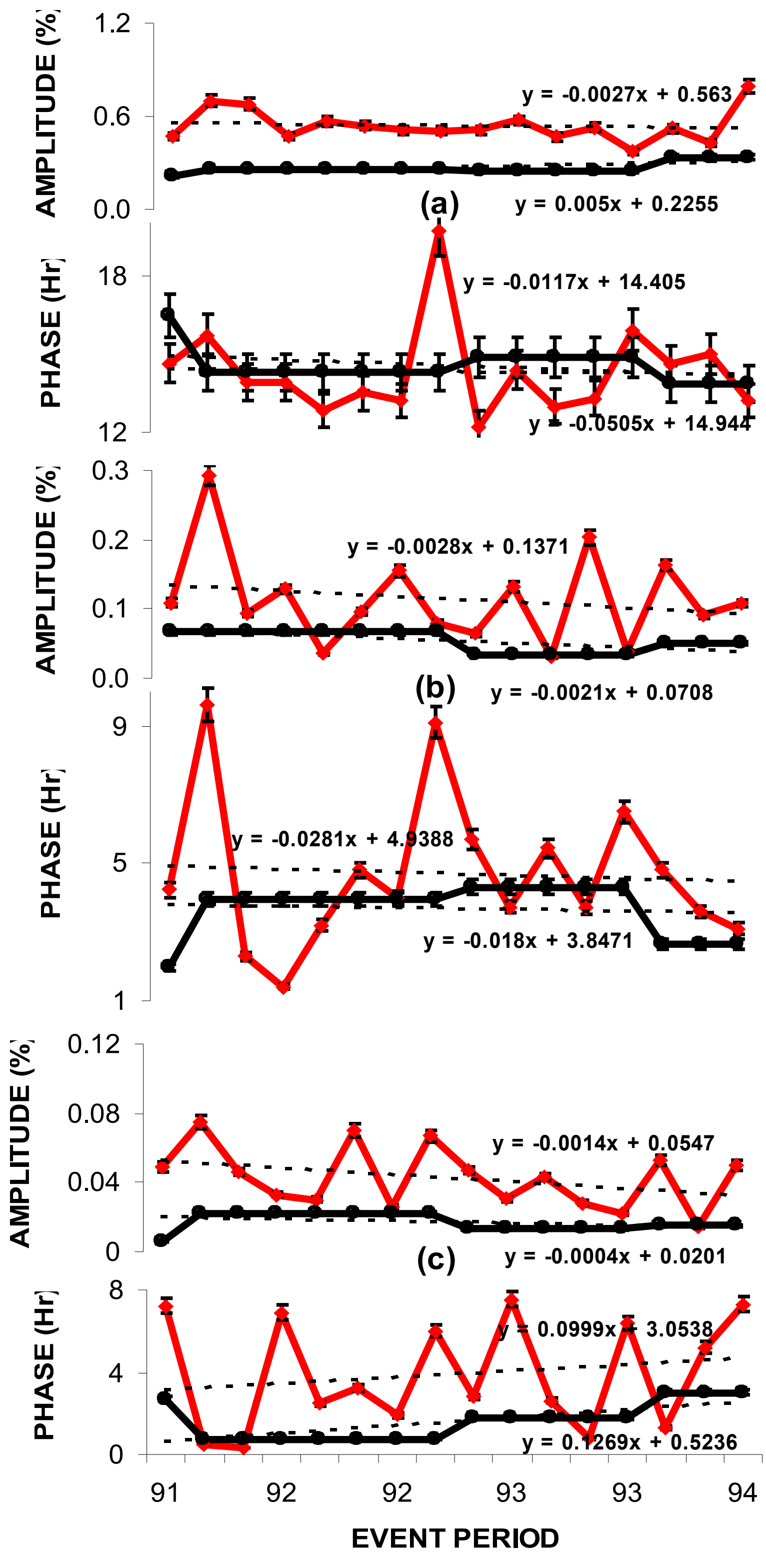

Fig 1. Amplitude and phase of (a) diurnal, (b) semi-diurnal and (c) tri-diurnal anisotropy for HAEs along with the quiet day annual average values during the period 1991-94.

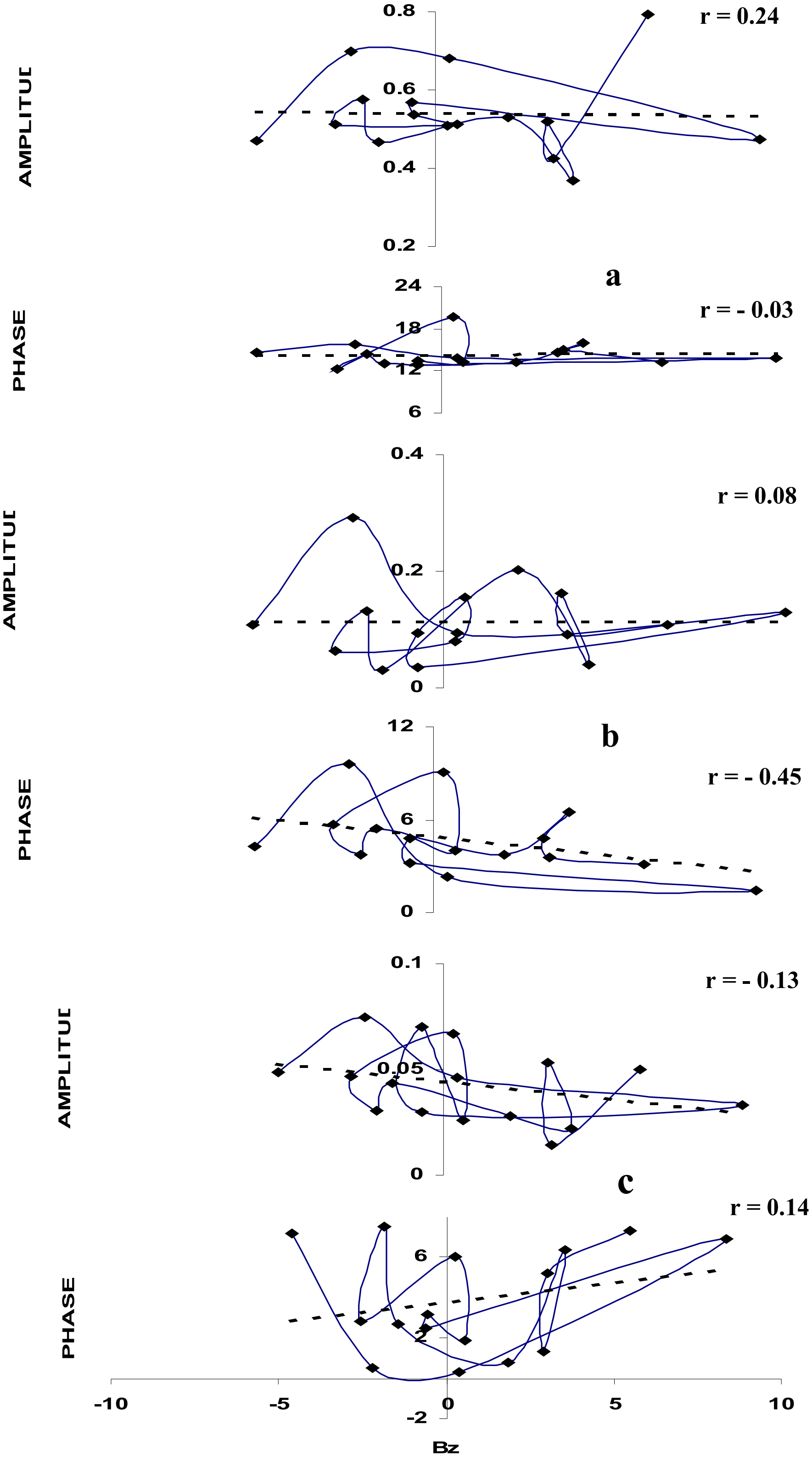

Fig 2. Amplitude and phase of (a) diurnal, (b) semi-diurnal and (c) tri-diurnal anisotropy for each HAE with the variation in associated values of Bz component of IMF

coefficient (r) and the regression line (---) are plotted and shown in Fig 2 (a, b, c) for all the HAE events.

The amplitude of the diurnal anisotropy for majority of the HAE events is observed to remain significantly high, whereas, the phase is found to remain in the corotational direction statistically. No significant correlation between the amplitude of semi-diurnal anisotropy and Bz has been observed for HAE events. The phase is observed to shifts towards earlier hour as the polarity of Bz component of IMF directed from negative to positive values showing a negative correlation as depicted in the figure.

The amplitude of tri-diurnal anisotropy for HAE events is observed to remain high for negative polarity of Bz, whereas it is found to remain slightly low for positive polarity of Bz showing a negative correlation. The phase of the tri-diurnal anisotropy does not show significant correlation with Bz due to large scattering of points.

The amplitude (%) and phase (Hr) of cosmic ray diurnal/semi-diurnal/tri-diurnal anisotropy alongwith the variation in associated value of disturbance storm time index (Dst), correlation coefficient (r) and the regression line (---) are plotted and shown in Fig 3 (a, b, c) for all the HAE events. The amplitude of the diurnal anisotropy for HAE events is observed to increase with the decrease of Dst-index showing a negative correlation. The amplitude of the semi-diurnal anisotropy is found to slightly increase with the decrease in the value of Dst-index showing weakly negative correlation. The amplitude of the tri-diurnal anisotropy is observed to increase with the decrease in the value of Dst-index showing a negative correlation.

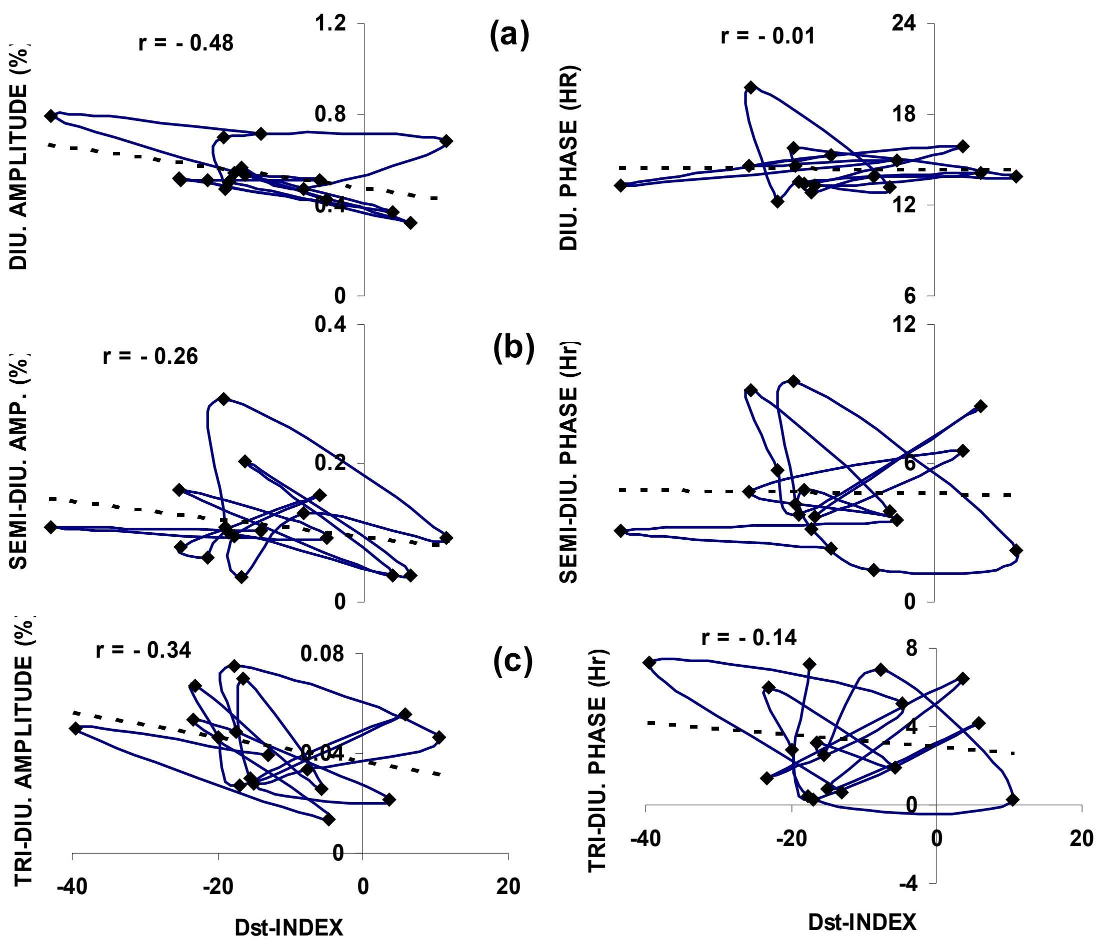

Fig 3. Amplitude and Phase of (a) diurnal, (b) semi-diurnal and (c) tri-diurnal anisotropy for each HAE along with Dst-index.

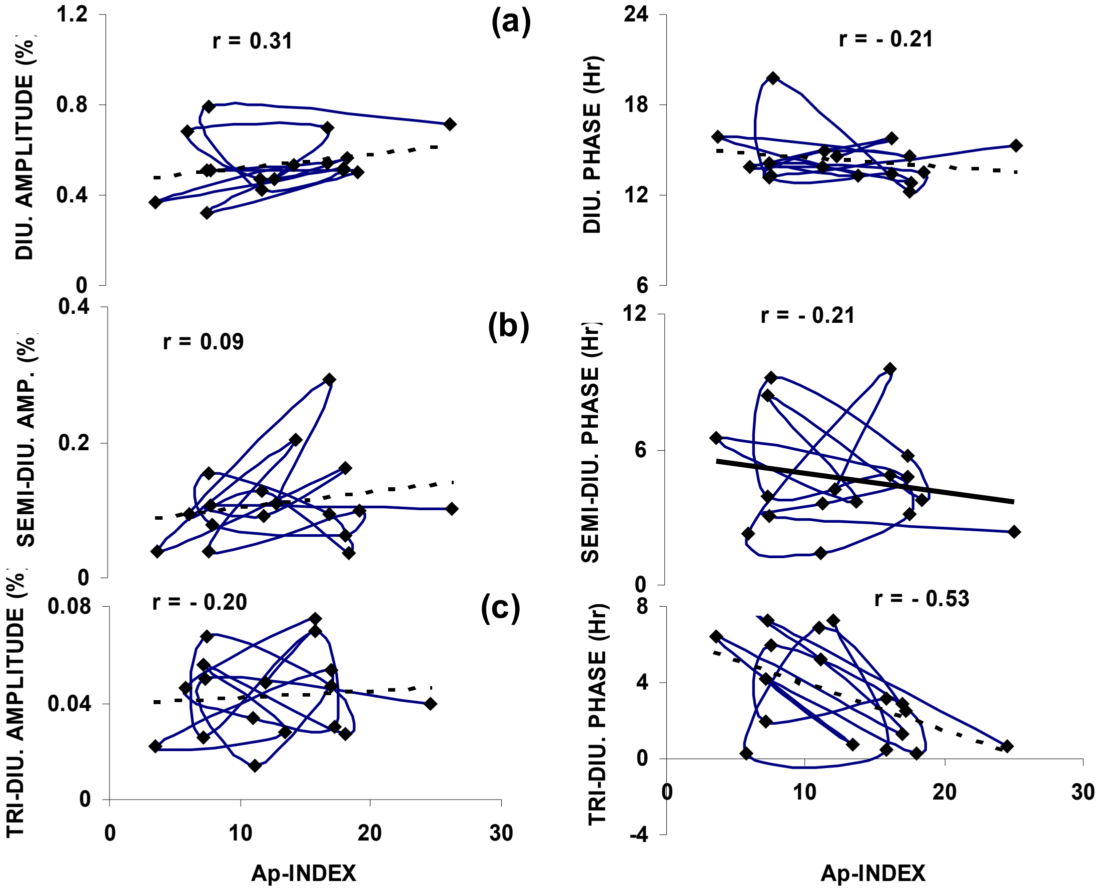

Fig 4. Amplitude and Phase of (a) diurnal, (b) semi-diurnal and (c) tri-diurnal anisotropy for each HAE along with Ap-index

The weak correlation has been observed with Dst-index for diurnal, semi-diurnal and tri-diurnal phase of HAE events.

The amplitude (%) and phase (Hr) of cosmic ray diurnal/semi-diurnal/tri-diurnal anisotropy alongwith the variation in associated value of geomagnetic activity index (Ap), correlation coefficient (r) and the regression line (---) are plotted and shown in Fig 4 (a, b, c) for all the HAE events. The weak correlation has been observed with Ap-index for diurnal, semi-diurnal anisotropy vectors and tri-diurnal amplitude for the HAE events. However, the phase of tri-diurnal anisotropy for HAE events is found to shifts towards earlier hours with the increase of Ap-index showing a significant negative correlation.

The frequency pie diagram of solar wind velocity for all HAEs has been plotted in Fig 5. It is quite observable from these plots that the majority of the HAE 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 [23]. Therefore, it may be deduced from these plots 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, which is in agreement with earlier findings [23] and significantly contradicts with the earlier results reported by Iucci et al. [24] and Dorman et al. [25], that the solar diurnal amplitude is enhanced during the HSSWSs coming from coronal holes. According to Ahluwalia and Riker [26] 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 [23]. Earlier, Mishra [27] reported the similar trends discussed above for HAEs.

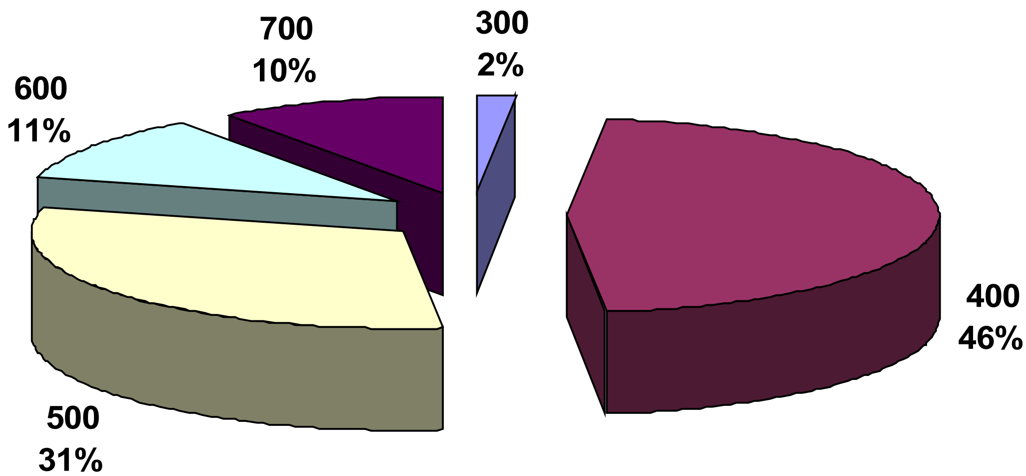

Fig 5. The frequency pie diagram of the solar wind velocity for all HAEs

Conclusions

From the present investigation following conclusions have been emerged:

- The direction of the anisotropy (i.e. phase) for first harmonic remains in corotational direction and shift towards later hours for second harmonic compared to quite day annual average.
- The amplitude of first harmonics shows some positive correlation (r = 0.24) and phase of second harmonic shows good anti-correlation (r = - 0.45) with Bz component of interplanetary magnetic field.
- High amplitude anisotropic wave train events seem to weakly dependent on solar wind velocity.
- The amplitude of first harmonic shows a good anti-correlation (r = - 0.48) and amplitude of third harmonic shows some anti-correlation (r = - 0.34) with disturbance storm time index (Dst).
- The amplitude of first harmonic shows some correlation (r = 0.31) and direction of third harmonic shows good anti-correlation (r = - 0.53) with geomagnetic activity index (Ap).

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