АСТРОФИЗИКА

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HARMONICS OF EXCEPTIONALY LOW AMPLITUDE ANISOTROPIC WAVE TRAIN EVENTS IN COSMIC RAY INTENSITY

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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 co-rotational direction. However, for some of the LAE events the phase of the diurnal anisotropy shifts towards earlier hours as compared to the annual average values. 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 high-speed solar wind streams do not play a significant role in causing the LAE events. The occurrence of LAE is independent of nature of *Bz* component of IMF polarity.

Key words: *cosmic ray:anisotropy:interplanetary magnetic field:solar wind*

1. *Introduction*. The solar diurnal variation of the cosmic ray intensity was interpreted initially on the basis of an outward radial convection and an inward diffusion along the IMF. The balance between the convection and diffusion generates an energy independent anisotropic flow of cosmic ray particles from the 18-hour co-rotational direction. Ananth et al. [1] on their study of diurnal anisotropy on day to day concluded that on an average basis the diurnal anisotropy of cosmic radiation is completely understood as a superposition of simple convection and field aligned diffusion. Cosmic ray intensity observed on the ground is subject to the solar semi-diurnal variation of extraterrestrial origin. The variation is due to the second order anisotropy produced by the diffusion-convection of cosmic rays in interplanetary space [2,3]. Studies of the solar semi-diurnal variation have been made by many authors [4,5] to obtain information about solar modulation in various conditions of the heliosphere. Mori et al. [6] and Nagashima et al. [7] have investigated the existence of the tri-diurnal variation i.e., the third harmonic of daily variation in the recorded cosmic ray intensity.

Solar diurnal variation of cosmic ray (CR) intensity shows a large day-to-day variability [1]. This variability is a reflection of the continually changing conditions in the interplanetary space [8]. The average diurnal anisotropy of cosmic radiation is being explained in terms of azimuthal corotation [9]. 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 [10]. The distinguishing features of these systematic deviations are the unusually low or high amplitude and usually, though not always, a shift in the phase towards earlier hours [11].

The average characteristics of cosmic ray diurnal anisotropy are adequately explained by the co-rotational concept [12,13]. Though, the day-to-day deviation both in amplitude and phase and the abnormally large amplitudes or abnormally low amplitudes of consecutive days cannot be explained in co-rotational terms. Many scientists [14-16] used a new concept for the interpretation of the diurnal variation. McCraken et al. [17] first suggested the extension of this new concept from the solar cosmic events to the observed diurnal variation and theoretical formulation was provided by Forman and Glesson [18]. The phase shift of the diurnal anisotropy to earlier hours is well understood in terms of the convective-diffusive mechanism [15]. Owens and Kash [16] have noted that the non-field-aligned diffusion on the days of nominal diurnal amplitude which are influenced by magnetic sector passages.

The standard picture for the diffusion of cosmic rays at neutron monitor energies in the solar system involves diffusion, which is essentially field-aligned [19]. Owens and Kash [16] 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 [14]. Mavromichalaki [20,21] 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. Mavromichalaki [22] 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 normal. This phase shift continued until the solar activity minimum, except for a sudden shift to later hours for one year, in 1974, the secondary maximum of solar activity.

Long term changes in diurnal anisotropy of cosmic rays has been studied by Ananth et al. [23] 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. Ananth et al. [24] 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 ~1500 Hr direction. They suggested that different types of interplanetary magnetic field distributions produce the enhanced and low amplitude cosmic ray diurnal variations. Jadhav et al. [25] have studied the behaviour 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 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 Sources and Analysis.*** The anisotropic events are identified using the hourly plots of cosmic ray intensity recorded at ground based Deep River neutron monitoring station (data from http://spidr.ngdc.noaa.gov/NeutronMonitor) and selected 13 unusually low amplitude anisotropic wave

Table 1

LOW AMPLITUDE EVENTS (LAE) DURING 1991-94

LAE Events		LAE Events	
Event No.	Duration	Event No.	Duration
1	13-23.1.91	8	22-27.3.92
2	4-9.2.91	9	17-23.10.92
3	1-5.5.91	10	12-21.11.92
4	24-29.7.91	11	21-25.12.93
5	11-16.9.91	12	8-13.9.94
6	17-22.9.91	13	4-8.10.94
7	4-8.12.91		

train events (LAEs) during the period 1991-94 as shown in Table 1. 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. Low amplitude wave train events of continuous days have been selected when the amplitude of diurnal anisotropy remains lower than 0.3% on each day of the event for at least five or more days. The pressure corrected hourly neutron monitor data after applying trend correction is harmonically analysed to have amplitude (%) and phase (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 (from http://nssdc.gsfc.nasa.gov/omniweb) have been investigated.

3. ***Results and discussion.*** The amplitude and phase of the diurnal anisotropy for the LAE events have been plotted in Fig.1a, b. As depicted in Fig.1, it is quite apparent that the phase of the diurnal anisotropy has shifted towards earlier hours in some of the LAE events as compared to the annual

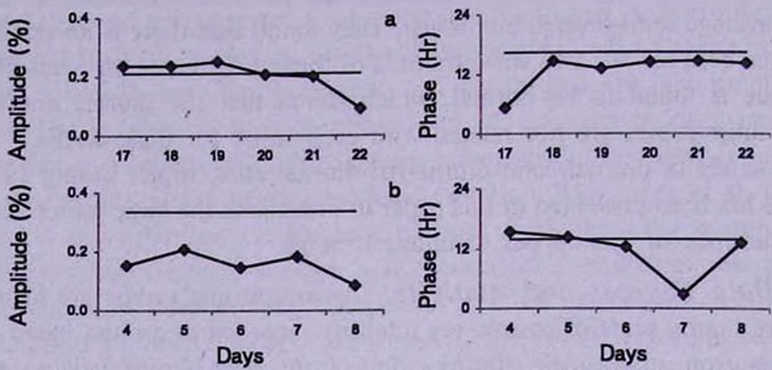

Fig.1. Amplitude and phase of the diurnal anisotropy for LAE of (a) 17-22 Sept. 1991 and (b) 4-8 Oct. 1994.

average value for the corresponding year, whereas the amplitude significantly deviates from the annual average amplitude. The time of maximum as shown in Fig.1a remains in the co-rotational/18-Hr direction for majority of the days of the event. These findings are in good agreement with earlier results for highly enhanced daily variation [26]. Similarly, the amplitude and phase of the semi-diurnal anisotropy have been plotted in Fig.2. It is quite apparent from Fig.2

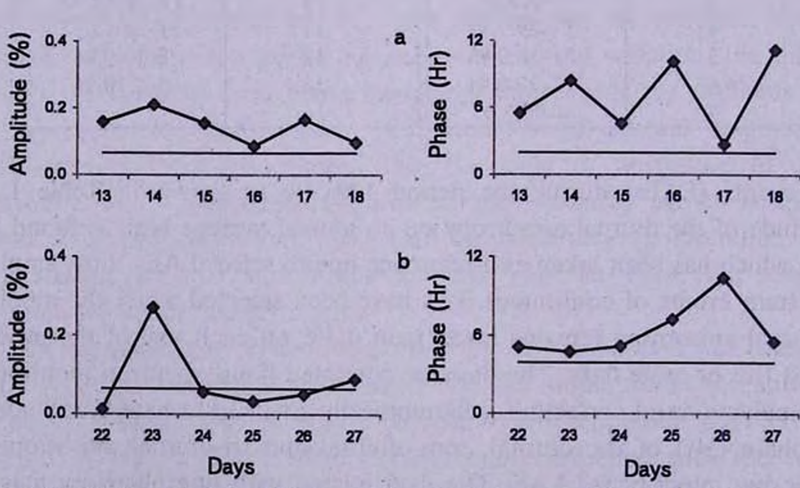

Fig.2. Amplitude and phase of the semi-diurnal anisotropy for LAE of (a) 13-18 Jan., 1991 and (b) 22-27 Mar., 1992.

that the amplitude of the semi-diurnal anisotropy remains statistically the same for majority of the events; whereas, the phase of the semi-diurnal anisotropy has a tendency to shift towards later hours as compared to the annual average value

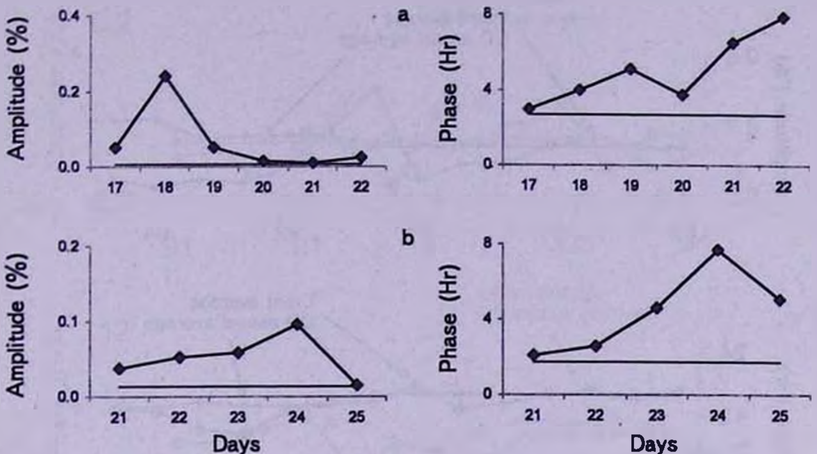

Fig.3. Amplitude and phase of the tri-diurnal anisotropy for LAE of (a) 17-22 Sep., 1991 and (b) 21-25 Dec., 1993.

of the corresponding year. Similar results have found by Jadhav et al. [25] for the period 1966-73 for LAE. Previously, similar trend has also been reported for the period 1981-90 [27,28]. Further, the amplitude and the phase of the tri-diurnal anisotropy have been plotted in Fig.3. It is quite clear from Fig.3 that the amplitude of tri-diurnal anisotropy remains statistically the same; whereas, the phase shifts towards later hours as compared to the annual average phase of the corresponding year for majority of the LAE events.

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 Fig.4, 5, 6. The observed vectors for each LAE are also shown in Fig.4, 5, 6 as vector addition diagram. The overall average values are also noted and shown as dashed line in the Figs. 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 shown in upper panel 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 as depicted in middle panel. The similar result have also been reported by Kumar et al. [28] for diurnal amplitude but the variation of the diurnal time of maximum differs quite significantly. They observed that the time of maximum of diurnal anisotropy shifts towards earlier hour for majority of the events in comparison to the quiet day annual average values.

As depicted in the lower panel the time of maximum of the diurnal anisotropy shifts towards earlier hours for most of the LAE events. The distribution of phase lies in the third quadrant except for two events.

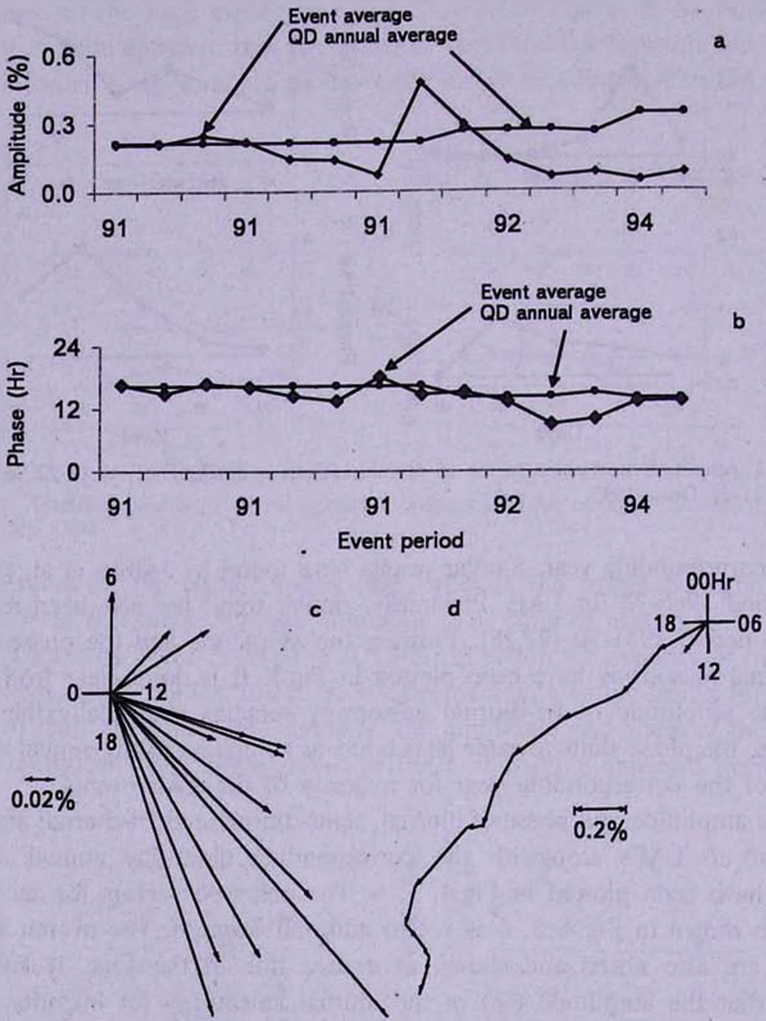

Fig.4. (a) Amplitude and (b) phase of the diurnal anisotropy for LAEs alongwith the quiet day annual average values and diurnal anisotropy vectors for all the LAE plotted as (c) cloud of points and as (d) end to end during the period 1991-94.

The amplitude (%) of the semi-diurnal anisotropy (upper panel), as depicted in Fig.5, is significantly low for some of the events as compared to the quiet day annual average values; 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 (middle panel). The distribution of phase (lower panel) lies in the first and second quadrant for all the LAE events, which is inconsistent with the concept that the transient changes in the intensity that occurs over all hours may cause the semi-diurnal component [29].

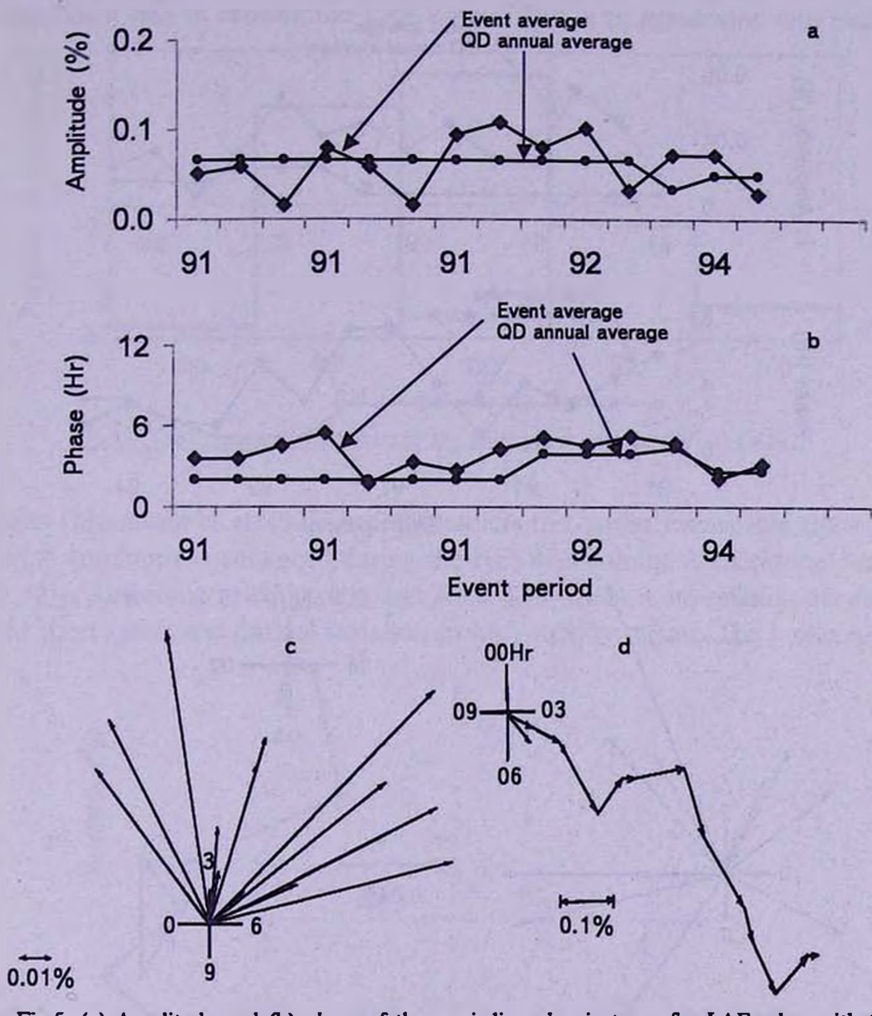

Fig.5. (a) Amplitude and (b) phase of the semi-diurnal anisotropy for LAEs alongwith the quiet day annual average values and semi-diurnal anisotropy vectors for all the LAE plotted as (c) cloud of points and as (d) end to end during the period 1991-94.

Further, the amplitude of the tri-diurnal anisotropy (upper panel), as depicted in Fig.6, attains significantly larger values for all LAEs as compared to the quiet day annual average values throughout the period; whereas, the time of maximum of the tri-diurnal anisotropy (middle panel) is found to shift towards later hours as compared to the quiet day annual average values for most of the events. The phase of tri-diurnal anisotropy (lower panel) is evenly distributed in all the quadrants for LAEs.

During the period of each LAE event, the interplanetary magnetic field (IMF) and solar wind plasma (SWP) parameters have also been investigated. The frequency histogram of daily values of solar wind velocity for all LAEs has been

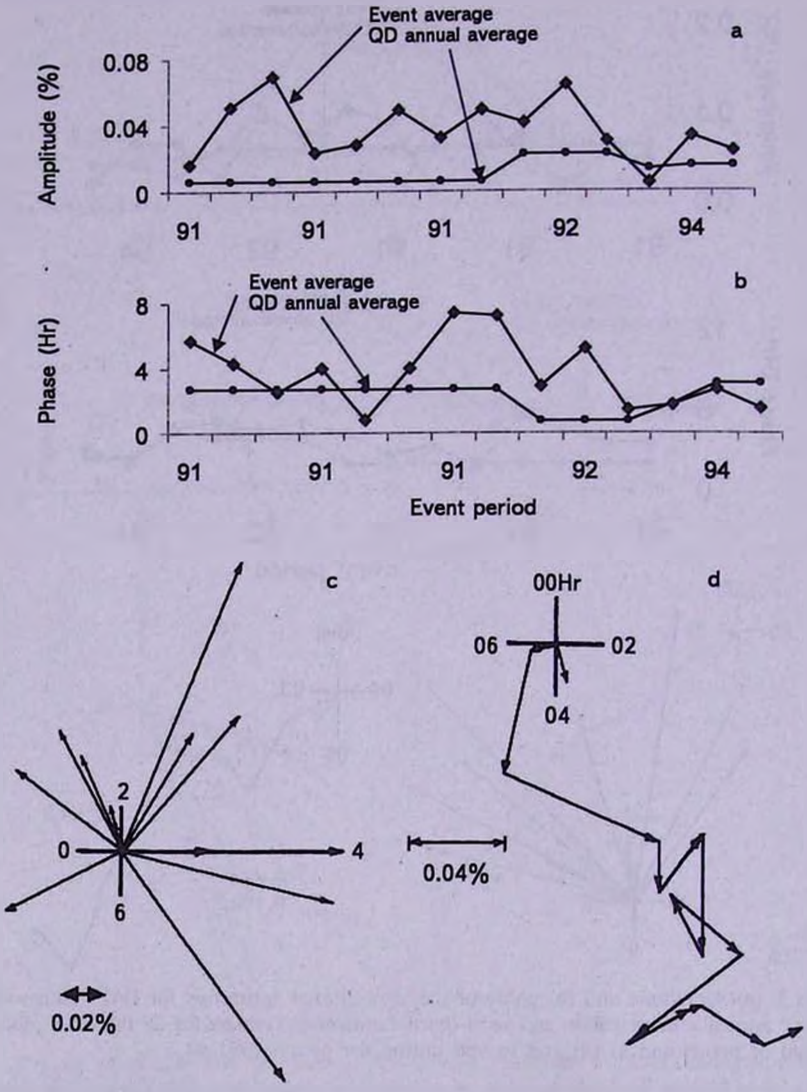

Fig.6. (a) Amplitude and (b) phase of the tri-diurnal anisotropy for LAEs alongwith the quiet day annual average values and tri-diurnal anisotropy vectors for all the LAE plotted as (c) cloud of points and as (d) end to end during the period 1991-94.

plotted in Fig.7. It is observable from Fig.7 that the 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 for the overall period 1991-94. Usually, the velocity of high-speed solar wind streams (HSSWSs) is 700 km/s [30]. Therefore, it is quite apparent from Fig.7 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. This is in agreement with earlier

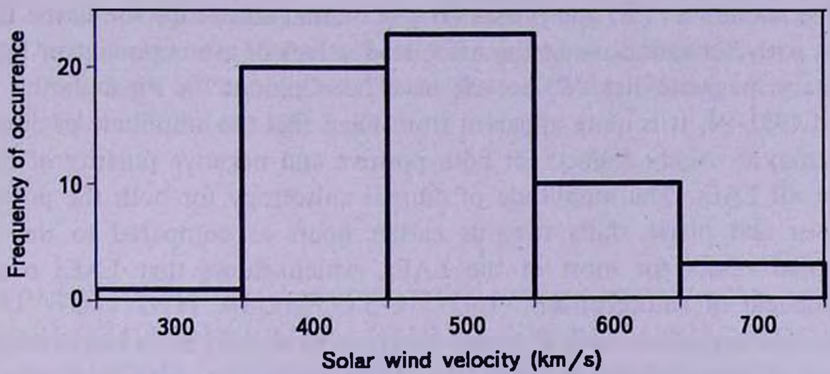

Fig.7. The frequency histogram of the solar wind velocity for all LAEs.

results (Munakata et al. [30]) and contradicts the earlier results that the solar diurnal amplitude is enhanced during the HSSWSs coming from coronal holes [31,32]). According to Ahluwalia and Riker [33] there is no relation between solar wind speed and diurnal variation in high rigidity region. The modulation

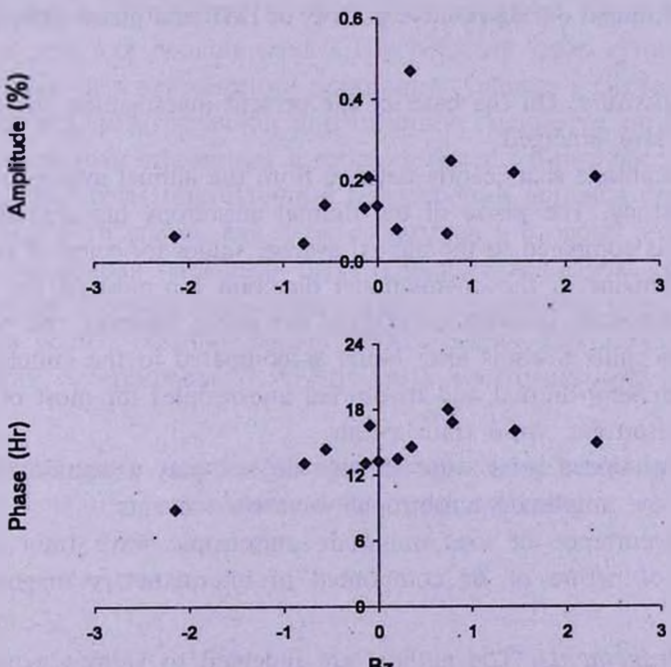

Fig.8. Amplitude and phase of the diurnal anisotropy for each LAE with the variation in associated values of Bz during 1991-94.

of solar diurnal anisotropy is weakly or less dependent on the solar wind velocity [30]. No significant difference has been found between the variation of diurnal vectors in high-speed days and the days, when the speed is normal.

The amplitudes (%) and phases (Hr) of diurnal anisotropy for all the LAE events with the variations in the associated values of z-component of interplanetary magnetic field B, i.e. Bz have been plotted in Fig.8 during the period 1991-94. It is quite apparent from Fig.8 that the amplitude of diurnal anisotropy is evenly aligned for both positive and negative polarity of IMF Bz for all LAEs. The amplitude of diurnal anisotropy for both the polarity is lower and phase shifts towards earlier hours as compared to the co-rotational values for most of the LAEs, which shows that LAEs occurs independent of nature of Bz.

Hashim and Bercovitch [34] and Kananen et al. [35] have found that for positive or away polarity of IMF, the amplitude is high and phase shifts to early hours; whereas, for negative or towards polarity of IMF the amplitude is lower and phase shifts to early hours as compared to co-rotational value during 1967-68. The trends we noticed in this study for LAE reveals that for both away and towards polarity days the time of maximum for diurnal anisotropy shifts towards earlier hours or it remains in the corotational/18-Hr direction. This partially confirms the earlier results [34,35] i.e. the occurrence of LAEs is dominant during positive polarity of IMF and phase shifts to earlier hours.

4. *Conclusions*. On the basis of the present investigation the following conclusions have emerged:

1. The amplitude significantly deviates from the annual average values for diurnal anisotropy. The phase of the diurnal anisotropy has shifted towards earlier hours as compared to the annual average values for some of the LAEs; whereas, it remains in the co-rotational direction for most of the LAEs.
2. The amplitude remains statistically the same; whereas, the phase has a tendency to shifts towards later hours as compared to the annual average value for both semi-diurnal and tri-diurnal anisotropies for most of the low amplitude anisotropic wave train events.
3. The high-speed solar wind streams do not play a significant role in causing the low amplitude anisotropic wave train events.
4. The occurrence of low amplitude anisotropic wave train events is independent of nature of Bz component of interplanetary magnetic field polarity.

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ГАРМОНИКИ АНИЗОТРОПНОГО ВОЛНОВОГО ЦУГА СОБЫТИЙ ЧРЕЗВЫЧАЙНО НИЗКОЙ АМПЛИТУДЫ В ИНТЕНСИВНОСТИ КОСМИЧЕСКИХ ЛУЧЕЙ

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В период времени 1991-1994 изучались данные, относящиеся к анизотропному волновому цугу событий необычно низкой амплитуды (СНА) в интенсивности космического луча, которые были получены в результате мониторинга на наземной станции Deep River. Было выявлено, что для большинства СНА событий фаза суточной анизотропии остается в направлении коротации. Однако в случае некоторых СНА событий фаза суточной анизотропии смещается по срачвнению с среднегодичным значением в сторону более ранних часов. С другой стороны, амплитуда полусуточной анизотропии остается статистически неизменной в то время, как фаза смещается в сторону более поздних часов. Аналогичная тенденция была обнаружена в случае трехсуточной анизотропии. Потоки высокоскоростного солнечного ветра не играют ощутимой роли в возникновении СНА событий. Происхождение СНА не зависит от природы B_z компонента межпланетного магнитного поля.

Ключевые слова: *космические лучи: анизотропия: межпланетарное магнитное поле: солнечный ветер*

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