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Interplanetary transients causing unusual anisotropic wave trains in CR intensity

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The study deals with short-term variations of cosmic ray intensity during the interval from 1991 to 1994. The occurrence of a large number of high and low amplitude anisotropic wave train events (HAEs/LAEs) is examined. The correlation between these unusual anisotropic events and SWP/IMF parameters is studied to locate the possible cause responsible for occurrence of these types of events. Our results indicate that the time of maximum of diurnal variation shows a remarkable systematic shift towards earlier hours for LAE; whereas it remains in the 18-Hr direction for HAE. It is also noteworthy that the occurrence of low as well as high amplitude anisotropic wave train events is independent of nature of IMF polarity.

INTRODUCTION

Special type of consecutive days having abnormally high or low amplitudes in daily variation of cosmic rays (CR) have been reported several times earlier with explanation of sources and sinks in anti-garden-hose and garden-hose directions. The existence of high and low amplitude anisotropic wave trains was revealed through the long-term study of cosmic ray intensity. The average characteristics of cosmic ray diurnal anisotropy are adequately explained by the co-rotational concept [6, 7, 26]. This concept supports the mean diurnal amplitude in space of 0.4 % along the 18 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 corotational terms. Periods of unusually large amplitude often occur in trains of several days. The amplitudes of these interesting variations cannot be explained by the corotation effect, which usually predicts values of 0.4 %. Moreover, the maximum intensity of diurnal anisotropy has not appeared in the direction of 18 Hr, which is the nominal co-rotational phase [23, 28].

The characteristics of the diurnal/semi-diurnal/tri-diurnal variation of cosmic rays and their variability have been continuously studied by many workers [34]. A systematic anti-clockwise shift of diurnal anisotropy was observed by Duggal and Pomerantz [9] over a period of days during the study of large amplitude anisotropic diurnal wave trains. The occurrence of trains of continuous days having unusually high diurnal amplitude with a phase shift towards later hours was observed by Mathews et al. [21] during both quiet and disturbed days. These trends are caused due to a large decrease of cosmic ray intensity along the garden-hose direction rather than the streaming along the anti-garden-hose direction. According to Rao et al. [29], the phase of diurnal anisotropy shifts towards later hours due to enhanced radial streaming. The trains of days having negligibly small diurnal amplitude are also observed [1].

A large day-to-day variability is exhibited in the solar diurnal variation of cosmic ray intensity [5].

This variability is a reflection of the continually changing conditions in the interplanetary space [10]. 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 [17]. Rao et al. [29] showed 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 was observed with a significant shift in the diurnal time of maximum to later hours or earlier hours [18—20]. Such days are of particular significance when occur during undisturbed solar/interplanetary conditions, as the superposed universal time effects are expected to be negligible.

Jadhav et al. [14] 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 to 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 [2], which infers 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 were also observed in the amplitude and phase during the high-speed solar wind streams (HSSWS) coming from coronal holes [12, 25]. The diurnal variation might be influenced by the polarity of the magnetic field [27], so that the largest diurnal variation is observed during the days when the daily average magnetic field is directed outward from the Sun.

The significant variations were observed in the amplitude and phase of the diurnal anisotropy with reversal of the average IMF in the alternate sectors. Due to the presence of North-South gradient in cosmic ray density, density increasing southward, i. e., below the equatorial plane of the Sun [11, 32, 33] the expected diurnal amplitude will be larger and time of maximum shifts towards earlier hours for positive IMF, i. e., away from the Sun as compared to the days having negative IMF polarity, i. e., towards the Sun. It was observed by Mavromichalaki [22] that an enhanced mean diurnal amplitude correlates with positively directed sectors; whereas, the amplitude is found to decrease during sector boundaries.

The harmonics of CR intensity have also been associated with geomagnetic conditions. The amplitude of diurnal anisotropy increases with increasing geomagnetic activity. The time of maximum is found to shift towards earlier hours as compared to the average values for higher values of geomagnetic field variation indices, i. e., K_p or A_p [30]. This trend has been found to vary with the change in the solar poloidal magnetic field after 1971, i. e., the time of maximum is found to shift towards later hours with the increase in A_p-index [3, 16].

The three harmonics of HAE/LAE during 1991-94 and their correlation with IMF/SWP parameters are presented in this paper to investigate the possible cause responsible for the occurrence of these types of unusual events.

METHOD OF ANALYSIS

To study the characteristics of HAE/LAE the 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) and 13 unusually low amplitude anisotropic wave train events (LAEs) during 1991—1994. The days having abnormally high amplitude or unusually low amplitude for five or more consecutive number of days were selected as HAE/LAE. The pressure corrected hourly neutron monitor data after applying trend correction are harmonically analyzed to have amplitude (%) and phase (Hr) of the diurnal, semi-diurnal and tri-diurnal anisotropies of cosmic ray intensity for HAE/LAE. The data related to interplanetary magnetic field (IMF) and solar wind plasma (SWP) parameters were also investigated.

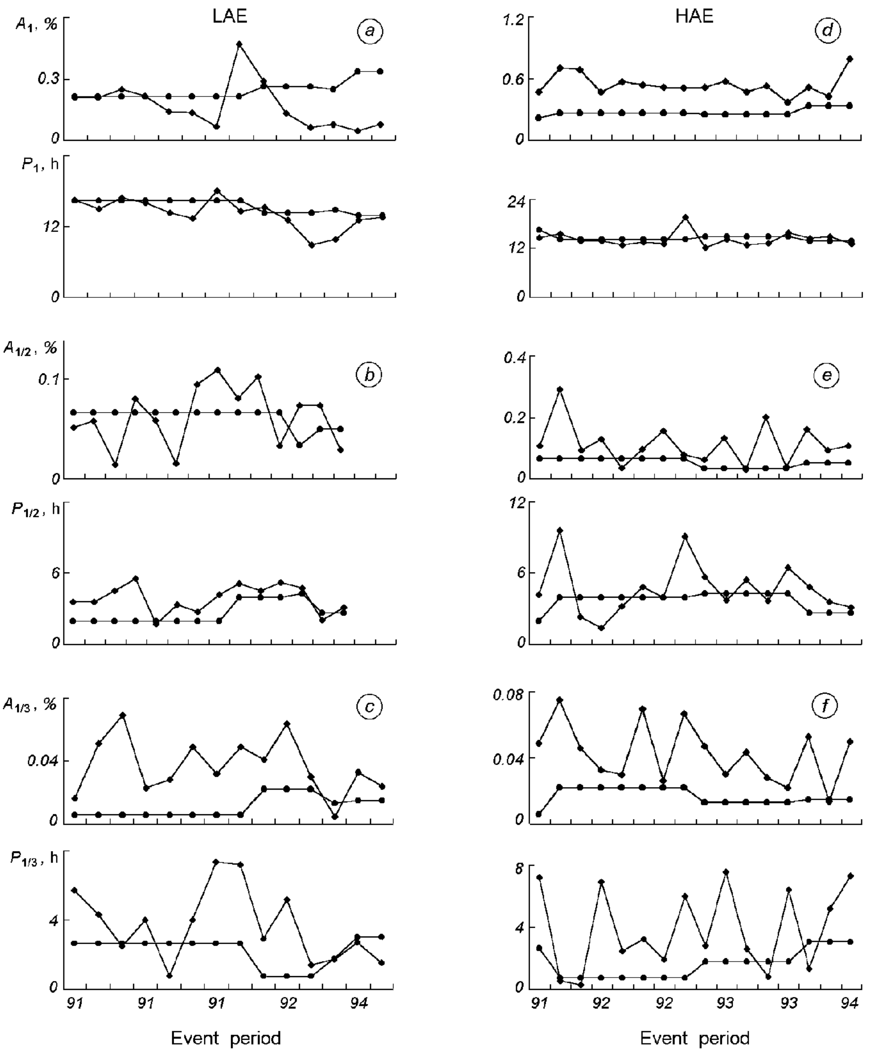

Fig. 1. Amplitudes A_1, $A_{1/2}$, $A_{1/3}$ and phases P_1, $P_{1/2}$, $P_{1/3}$ of the diurnal, semi-diurnal and tri-diurnal anisotropies (diamonds) alongwith quiet day annual average values (dots) for LAEs and HAEs during the period from 1991 to 1994

RESULTS AND DISCUSSION

Fig. 1, *a*—*c* give the amplitude and phase of the diurnal (A_1, P_1), semi-diurnal ($A_{1/2}$, $P_{1/2}$) and tri-diurnal ($A_{1/3}$, $P_{1/3}$) anisotropies of cosmic ray intensity for each LAE alongwith the corresponding quiet-day annual average values. The amplitude of the diurnal anisotropy as depicted in Fig. 1, *a* is observed to remain significantly low as compared to the quiet day annual average value for majority of the event throughout the period; whereas, the phase has a tendency to shift towards earlier hours as compared to quiet day annual average value for majority of the event. Further, the amplitude of the semi-diurnal anisotropy as depicted in Fig. 1, *b* has no definite trend; whereas, the phase shifts towards later hours as compared to quiet day annual average values for majority of the events. Furthermore, the amplitude of the tri-diurnal anisotropy as shown in Fig. 1, *c* is significantly higher as compared to the quiet day annual average value throughout the period; whereas, the phase has a tendency to shift towards later hours as compared to quiet day annual

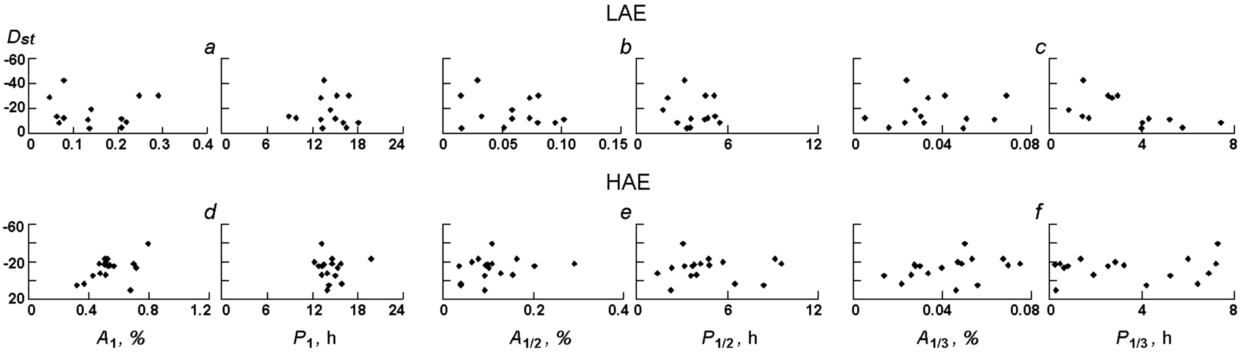

Fig. 2. Amplitudes A_1, $A_{1/2}$, $A_{1/3}$ and phases P_1, $P_{1/2}$, $P_{1/3}$ of the diurnal, semi-diurnal and tri-diurnal anisotropies for each LAE and HAE alongwith D_{st}-index

average value for majority of the events.

Fig 1, *d—f* give the amplitude and phase of the diurnal, semi-diurnal and tri-diurnal anisotropies of cosmic ray intensity for each HAE alongwith the corresponding quiet-day annual average values. The amplitude of the diurnal anisotropy as depicted in Fig. 1, *d* is observed to remain significantly high as compared to the quiet day annual average value throughout the period; whereas, the phase remains in the corotational direction for majority of the event. Further, the amplitude of the semi-diurnal anisotropy as depicted in Fig. 1, *e*, 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 as shown in Fig. 1, *f* 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, the tri-diurnal time of maximum has a tendency to shift towards later hours as compared to quiet day annual average value for majority of the events; which is in good agreement with the low amplitude wave trains where it has also shifts towards later hours for the majority of the events.

Fig. 2, *a—c* show the amplitude and phase of the diurnal, semi-diurnal and tri-diurnal anisotropies for each LAE alongwith the corresponding average D_{st} values. The amplitude of the diurnal anisotropy as shown in Fig. 2, *a* is observed to remain low for more negative values of D_{st}; whereas, the phase shifts towards earlier hours. It was observed that the shift in phase of diurnal anisotropy towards earlier hours is independent of the decrease in the values of D_{st} in respective of events. Further, the amplitude of the semi-diurnal anisotropy as shown in Fig. 2, *b* is found to remain low for more negative values of D_{st} likewise the amplitude of the diurnal anisotropy; whereas, the phase has no definite trend as amount of scattering is very large. Furthermore, the amplitude of the tri-diurnal anisotropy as shown in Fig. 2, *c* is found to be lower for more negative values of D_{st} likewise the amplitude of the diurnal and semi-diurnal anisotropy, showing a correlation between the amplitude of the first three harmonics and D_{st}-index for the low amplitude anisotropic wave train events. However, no significant correlation between tri-diurnal phase and D_{st}-index was found, as the scattering is very large.

Fig. 2, *d—f* give the amplitude and phase of the diurnal, semi-diurnal and tri-diurnal anisotropies for each HAE alongwith the corresponding average D_{st} values. The amplitude of the diurnal anisotropy as shown in Fig. 2, *d* is observed to remain high for more negative values of D_{st}; whereas, the phase remains in the corotational direction. Further, the amplitude of the semi-diurnal anisotropy as shown in Fig. 2, *e* is found to remain high for more negative values of D_{st} likewise the amplitude of the diurnal anisotropy; whereas, the phase has no definite trend as amount of scattering is very large. Furthermore, the amplitude of the tri-diurnal anisotropy as shown in Fig. 2, *f* is found to be high for more negative values of D_{st} likewise the

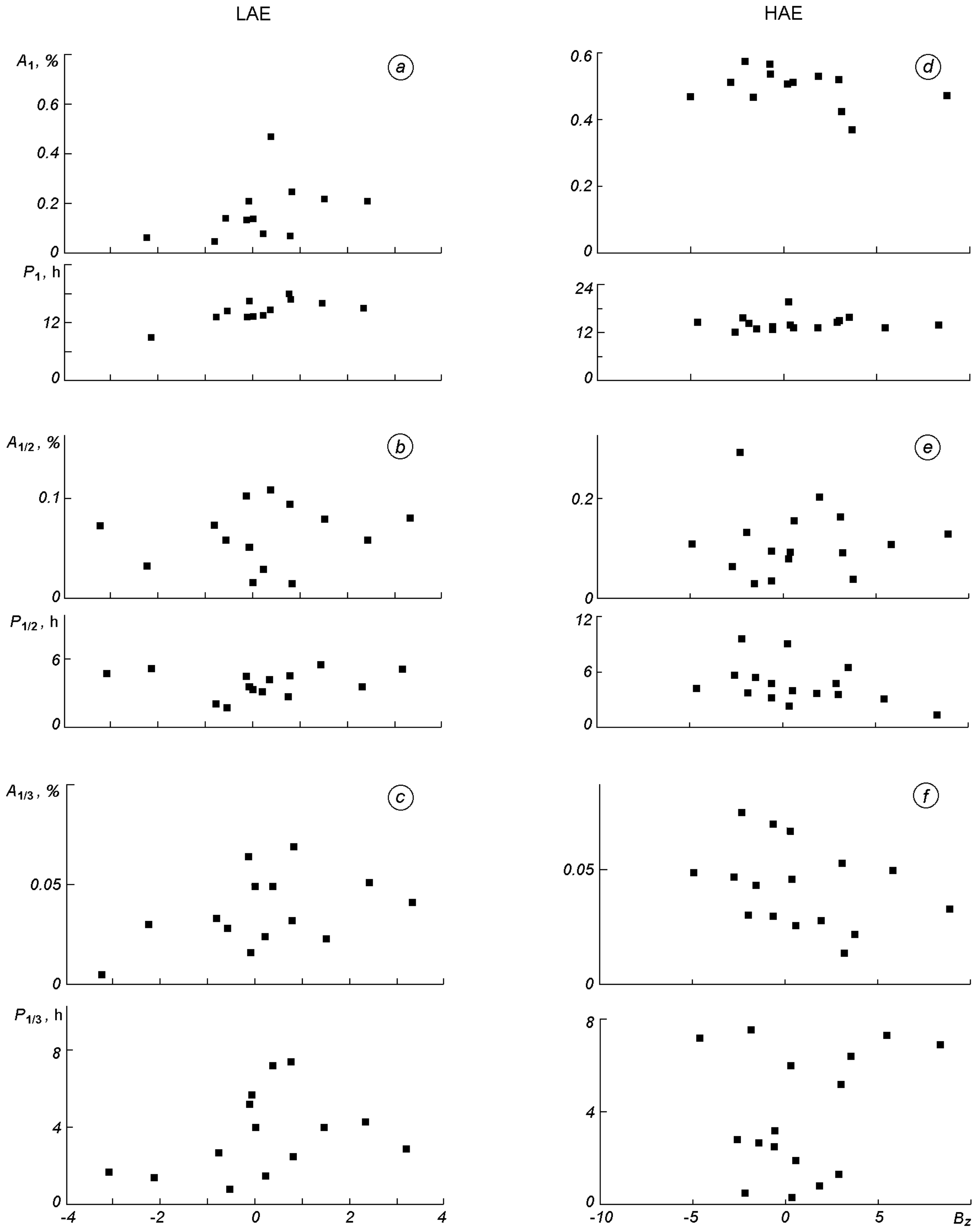

Fig. 3. Amplitudes A_1, $A_{1/2}$, $A_{1/3}$ and phases P_1, $P_{1/2}$, $P_{1/3}$ of the diurnal, semi-diurnal and tri-diurnal anisotropies for each LAE and HAE with the variation in associated values of B_z during the period from 1991 to 1994

amplitude of the diurnal and semi-diurnal anisotropy, pointing to a correlation between the amplitude of the first three harmonics and D_{st}-index for the high amplitude anisotropic wave train events. However, no significant correlation between tri-diurnal phase and D_{st}-index was found, as the scattering is very large.

Fig. 3, *a—c* give the amplitudes (%) and phases (Hr) of diurnal, semi-diurnal and tri-diurnal anisotropies for all the LAE events with the variations in the associated values B_z of *z*-component of interplanetary magnetic field. It is observable from these plots that the amplitude of the diurnal anisotropy for positively directed IMF ($+B_z$) is significantly large for majority of the events; whereas, the amplitude remains significantly low for negatively directed IMF ($-B_z$) for most of the LAE events. The diurnal time of maximum for both positive and negative polarity of B_z has a tendency to shift towards earlier hours as compared to co-rotational value for all the LAE events, which is in good agreement with the earlier trends reported by Hashim and Bercovitch [11] and Kannanen et al. [15], for the period 1967—1968, i. e., 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 low and phase shifts to early hours as compared to co-rotational value. For semi-diurnal anisotropy the amplitude of semi-diurnal anisotropy is evenly aligned for both positive and negative polarity of IMF for all LAEs. Further, for tri-diurnal anisotropy the amplitude is evenly aligned for both positive and negative polarity of IMF for majority of the LAEs.

Fig. 3, *d—f* give the amplitudes (%) and phases (Hr) of diurnal, semi-diurnal and tri-diurnal anisotropies for HAEs with the variations in the associated values of B_z. It is quite apparent from these plots 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 towards and away polarity is higher and phase shifts towards earlier hours as compared to the co-rotational values for most of the HAEs, which is in partial agreement with the earlier findings [11, 15] for the period 1967—1968. In case of semi-diurnal anisotropy the amplitude is evenly aligned for both positive and negative polarity of IMF for all HAEs. Further, for tri-diurnal anisotropy the amplitude is evenly aligned both positive and negative polarity of IMF for most of the HAEs.

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 [22], which significantly differs from our findings; that is the occurrence of low as well as high amplitude anisotropic wave train events is independent of nature of IMF polarity. The trends we found in this study for LAE reveal that for both away and towards polarity days the time of maximum for diurnal anisotropy shifts towards earlier hours with an exception for one event; whereas, for HAE during both away and towards polarity days the diurnal time of maximum shifts towards earlier hours with an exception for one event.

Fig. 4 shows the frequency histogram of solar wind velocity for all HAEs/LAEs. It is quite observable from these plots that the majority of the HAE/LAE events have occurred when the solar wind velocity lies in the range from 400 to 500 km/s, i. e., being nearly average. Usually, the velocity of high-speed solar wind streams (HSSWSs) is 700 km/s [25]. Therefore, it may be deduced from these plots 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 solar wind velocity, which is in agreement with earlier findings [25] and significantly contradicts the earlier results reported

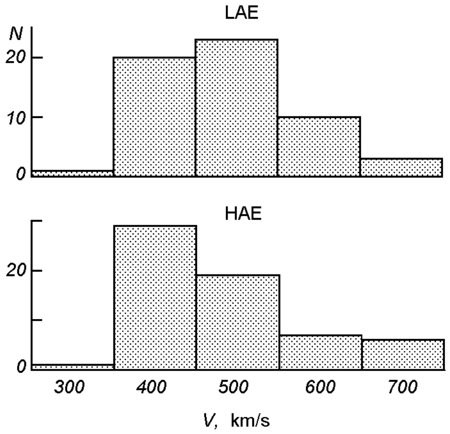

Fig. 4. The frequency histogram of the solar wind velocity for all LAEs and HAEs

by Iucci et al. [13] and Dorman et al. [8], that the solar diurnal amplitude is enhanced during the HSSWSs coming from coronal holes. According to Ahluwalia and Riker [4], 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 [25]. No significant difference was found between the variation of diurnal vectors in high-speed days and the days; when, the speed is normal. Recently Shrivastava [31] concluded that both the flare generated streams (FGS) and co-rotating streams (CS) produce short-term transient decreases in cosmic ray intensity for the period from 1991 to 1996; whereas medium range (5- to 6-day duration) solar wind streams are found to be more effective in producing cosmic ray transient decrease. On close inspection of both data on neutron monitor (NM) and muon telescope (MU), Munakata et al. [24] found that the modulation of the diurnal anisotropy by the high speed solar wind streams may occur through two different processes; one is that many already reported that with the development of the HSSWSs the diurnal waves are enhanced, and are observed by both NM and MU, and the other is that along with the decline in the HSSWSs the diurnal waves are again enhanced, and are rather observed by NM.

CONCLUSIONS

On the basis of our investigation the following conclusions are made:

1. The diurnal time of maximum is shifted to earlier hours as compared with the quiet day annual average for LAE; whereas it remains in the co-rotational direction as compared to the quiet day annual average for HAE for majority of the events.
2. The phase of semi-diurnal anisotropy for LAE shifts towards earlier hours as compared to the quiet day annual average for majority of the events; whereas, it has no definite trend in case of HAE. However the phase of tri-diurnal anisotropy for LAE as well as for HAE is shifted to later hours as compared to the quiet day annual average for majority of the events.
3. The occurrence of low and high amplitude anisotropic wave train events is independent of nature of IMF polarity. The diurnal time of maximum for both positive and negative polarity of B_z has a tendency to shift towards earlier hours as compared to co-rotational value for all the LAE events; whereas, it shifts towards earlier hours as compared to the co-rotational values for most of the HAEs.
4. The occurrence of LAE/HAE is dominant when the solar wind velocity is being nearly average. This reveals that HAE/LAE events are not caused either by the HSSWS or by the sources on the Sun which are responsible for producing the HSSWS such as polar coronal holes (PCH) etc. Thus, we may infer that HAEs/LAEs are weakly dependent on solar wind velocity.
5. First three harmonics of diurnal amplitude significantly correlates with D_{st}-index. Diurnal time of maximum shifts towards earlier hours for LAE; whereas, it remains in the co-rotational direction for HAE. The shift in phase towards earlier hours for LAE is independent of D_{st}-index.

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МІЖПЛАНЕТНІ ПЕРЕМІЩЕННЯ, ЩО ВИКЛИКАЮТЬ НЕЗВИЧАЙНІ АНІЗОТРОПНІ ХВИЛЬОВІ ПАКЕТИ В ІНТЕНСИВНОСТІ КОСМІЧНИХ ПРОМЕНІВ

Раджеш К. Мішра, Реха Агарвал Мішра

Розглядаються короткотривалі варіації інтенсивності космічних променів на інтервалі 1991—1994 рр. Досліджено виникнення великої кількості високо- і низькоамплітудних анізотропних хвильових пакетів. Вивчено кореляцію між цими незвичайними анізотропними явищами та параметрами плазми сонячного вітру і міжпланетного магнітного поля, щоб з'ясувати можливу причину появи названих явищ. Виявилось, що момент максимуму добової варіації показує помітний систематичний зсув у бік більш ранніх годин для низькоамплітудних явищ, а для високоамплітудних явищ момент максимуму зберігає напрямок на 18 год. Важливо також відмітити, що виникнення як низько-, так і високоамплітудних анізотропних хвильових пакетів не залежить від природи полярності міжпланетного магнітного поля.