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Modulation of Cosmic Rays Along with Solar and Heliospheric Anomalies

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A study of the cosmic ray intensity data recorded with the ground-based neutron monitor at Deep River along with the associated interplanetary magnetic field and solar wind plasma parameter data during 1981—1994 was carried out by means of the Fourier analysis. Many days having abnormally high/low amplitudes for successive number of five or more days as compared to the annual average amplitude of diurnal anisotropy were selected as high/low-amplitude anisotropic wave train events (HAE/LAE). The results clearly indicate that the time of maximum of diurnal variation significantly remains in the 18-hr direction for the majority of the HAE/LAE cases. The phase of enhanced diurnal anisotropy shows a remarkable systematic shift towards later hours as compared to the co-rotational direction for some of the HAE cases, whereas it shows a remarkable systematic shift towards earlier hours for some of the LAE cases as compared to the co-rotational direction. The majority of the HAE/LAE events occurred when the disturbance storm time index D_{st} remains negative only. Significant deviations are seen in the cosmic ray intensity during the passage of interplanetary magnetic clouds for both HAE and LAE events. The high-speed solar wind streams (HSSWS) do not play any significant role in the occurrence of these types of events. The interplanetary disturbances (magnetic clouds) are also effective in producing cosmic ray decreases. The source responsible for these unusual anisotropic wave trains in cosmic rays is proposed.

INTRODUCTION

The transport of cosmic rays from the heliosphere edges to the vicinity of the Earth is greatly influenced by solar and heliospheric parameters. The long-term (solar cycle) variation of galactic cosmic ray (CR) intensity and its association with various solar, interplanetary and geophysical parameters revealed often contradictory results [8, 37, 36, 30, 12, 33, 34]. Many investigators [34, 36, 42] studied the relation between the solar activity parameters and the cosmic ray intensity. Balasubrahmanyan [5] found a relation between the cosmic ray intensity and the geomagnetic activity. In all cases hysteresis effect between the different parameters and the cosmic ray intensity is clearly manifested in the dependence of cosmic ray intensity on the magnitude of the above-mentioned parameters [29]. Xanthakis et al. [43] studied the cosmic ray modulation in the 20^{th} solar cycle and presented a more elaborated model. According to this model, the modulated cosmic ray intensity that was measured by the ground-based stations is equal to the galactic cosmic ray intensity (unmodulated) at a finite distance corrected by a few appropriate solar and terrestrial activity indices, which cause the disturbances in interplanetary space.

The systematic and significant deviations in the amplitude/phase of the diurnal/semi-diurnal anisotropy from the average values [41] are known to occur in connection with strong geomagnetic activity [27]. Rao et al. [38] 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. A number of high amplitude events was observed with a significant shift in the diurnal time of maximum to later or earlier hours [11].

Mavromichalaki [27] observed high-amplitude wave trains of cosmic ray intensity during June, July and August 1973. These events show 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 co-rotational direction or the anti-garden-hose direction. The diurnal anisotropy is well understood in terms of a convective-diffusive mechanism [9]. Mavromichalaki [24, 26] observed that the enhanced diurnal variation was caused by a source around 16 hr or by a sink at about 04 hr.

During the study of diurnal anisotropy of cosmic ray intensity observed over the period from 1970 to 1977 using the neutron monitor data of the Athens and Deep River stations, Mavromichalaki [25] found that the phase 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 observed that the behaviour of the diurnal phase was 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.

The average amplitude of diurnal and semi-diurnal anisotropy is found to be larger than normal one during the initial phase of the stream while it is smaller as compared to the normal one during the decreasing phase of the stream and phase is observed to remain almost constant [34], which means that the diurnal as well as semi-diurnal variation of galactic cosmic ray intensity may be influenced by solar polar coronal holes. The changes were observed as well in the amplitude and phase during the high-speed solar wind streams (HSSWS) coming from coronal holes [31, 14]. The diurnal variation might be influenced by the polarity of the magnetic field [35], so that the largest diurnal variation is observed during the days when the daily average magnetic field is directed outward from the Sun.

The amplitude of the diurnal anisotropy is observed to be significantly large during three types of clouds [19], in comparison with the amplitude observed in geomagnetically quiet days [44]. The phase has also been observed to shift to earlier hours during these clouds in comparison to the phase in geomagnetically quiet days (QD). The behaviour of semi-diurnal anisotropy on LAE was studied by Jadhav et al. [15] on the basis of comparison of the average semi-diurnal amplitude for each event with 27-day or annual average semi-diurnal amplitude. They observed no significant difference between the two wave trains. The semi-diurnal amplitude is observed to be normal, which indicates that the diurnal and semi-diurnal anisotropies of daily variation are not related to each other for these LAE cases.

An attempt was made in this work to investigate a probable reason for the occurrence of these types of unusual events in CR intensity observed over the period from 1981 to 1994.

DATA ANALYSIS

The pressure corrected data from the Deep River neutron monitor NM (cut off rigidity = 1.02 GV, latitude = 46.1° N, longitude = 282.5° E, altitude = = 145 m) were subjected to the Fourier analysis for the period of 1981 to 1994 after applying the trend correction to have the amplitude (%) and phase (Hr) of the diurnal and semi-diurnal anisotropies of cosmic ray intensity for unusually low-amplitude events. The amplitude of the diurnal anisotropy on an annual average basis is found to be 0.4 %, which has been taken as reference line in order to select low-amplitude events.

The days having abnormally low amplitude for a successive number of five or more days were selected as low-amplitude anisotropic wave train events and having abnormally high amplitude for a successive number of five or more days were selected as high-amplitude anisotropic wave train events. The anisotropic wave train events are identified using the hourly plots of cosmic ray intensity recorded at the ground-based neutron monitoring station and 28 unusually low-amplitude wave train events and 37 high-amplitude anisotropic wave train events were selected during the period 1981—1994. Further, various features observed over the solar disk during the periods of events were studied as well.

Daily variation, sometimes the variation in cosmic ray intensity is not strictly periodic. Therefore it is required to subject the pressure corrected data to trend correction before analyzing the data for getting the harmonics of cosmic ray anisotropy using the Fourier technique. Thus if the number to be analyzed represents bihourly (or hourly) means of cosmic ray intensity, the mean for hour t_0 (0^{th} hour) will not, in general, be the same as the mean for hour t_{24} (or 24^{th} hour). This difference, on account of secular changes, in practice is allowed for by applying the correction known as trend correction, to each of the terms.

If y_0 is the value of the ordinate at $x = 0$ (0 hour) and y_{12} is the value of the ordinate at $x = 2\pi$ (24 hour) the trend corrected value for any hour is given by the equation:

$$\overline{y_k} = y_k - (\pm\delta_y k)/12\ ,$$

where $k = 0, 1, 2, \ldots$, y_k is uncorrected value, and $\pm\delta_y$ denotes secular changes, i.e., $\pm\delta_y = y_{12} - y_0$.

RESULTS AND DISCUSSION

Fig. 1, *a*, *b* gives the amplitude (%) and phase (hr) of diurnal anisotropy for high amplitude event at ground in local time (LT). It is quite apparent from Fig. 1, *a* that the diurnal amplitude is observed to remain significantly high and statistically, whereas the phase is found to shift towards earlier hours throughout the event. During these events a negative magnetic cloud without shock has been noticed on 25 September at 03 UT. Principal magnetic storms (PMS) on 7 February 1993 at 05 UT and on 8 February 1993 at 19 UT were observed during these events. However, for the HAE as depicted in Fig. 1, *b* the amplitude is observed to remain high and statistically constant, whereas the phase of diurnal anisotropy significantly remains in the co-rotational direction during the entire event. These results are in partial agreement with the earlier findings [20, 22] where it is noticed that in space the phase shifted towards later hours for some of the HAE, whereas it

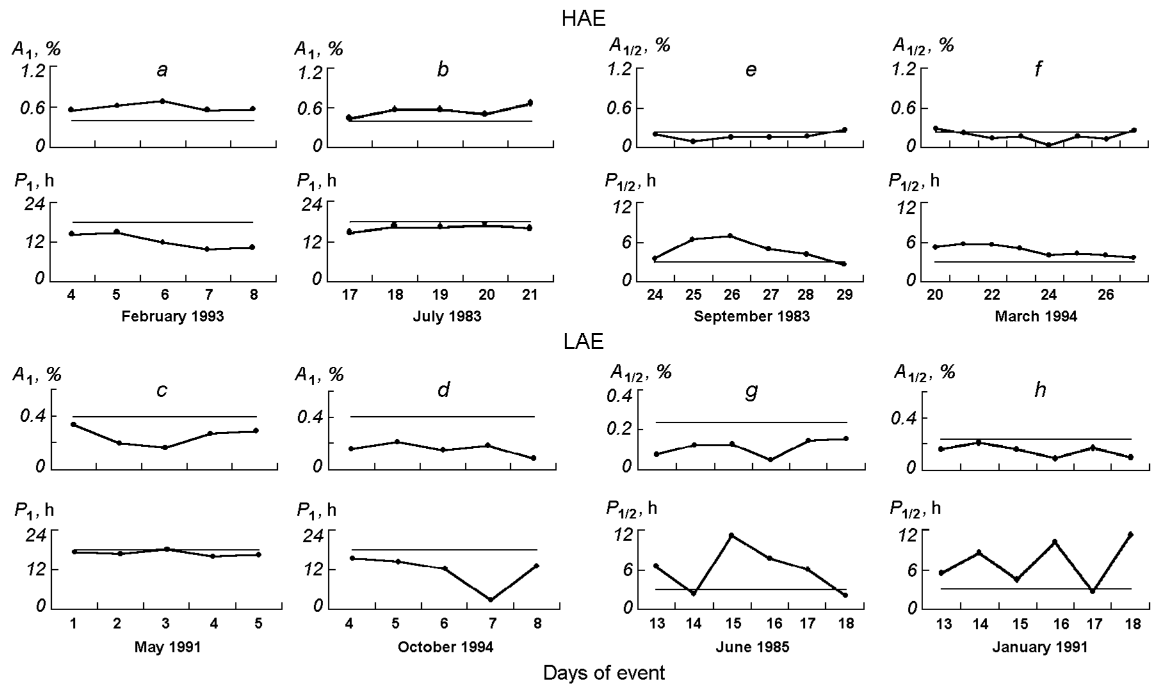

Fig. 1. Amplitude and phase of the diurnal (A_1, P_1) and semi-diurnal ($A_{1/2}$, $P_{1/2}$) anisotropy for HAE and LAE for severe periods

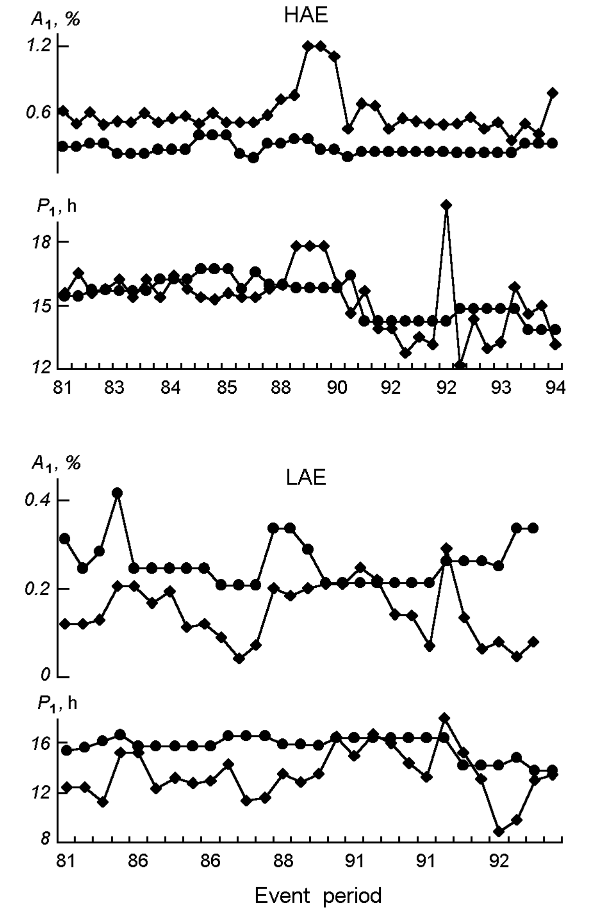

Fig. 2. Amplitude and phase of the diurnal anisotropy for each HAE and LAE (diamonds) along with quiet day annual average values (dots) during 1981—1994

remains in the 18 hr direction for the majority of the HAE events during the period 1981—1990. Principal magnetic storm on 8 September 1981 at 2141 was observed during these events.

Fig. 1, *c, d* gives the amplitude (%) and phase (hr) of diurnal anisotropy for one of the low-amplitude events at ground in local time (LT). As depicted in Fig. 1, *c*, the diurnal amplitude for low-amplitude events remains significantly low and constant, whereas the phase is consistently found to remain in co-rotational direction for the majority of the days of event. Two PMS, on 1 May 1991 at 01 UT and 2 May 1991 at 02 UT, were observed during these events. However, for the LAE plotted in Fig. 1, *d*, the diurnal amplitude significantly remains low and constant, whereas the time of maximum is found to shift towards earlier hours for the majority of the days of event. This is in good agreement with the earlier findings [21, 22] in space for LAE. A positive magnetic cloud without shock occurred on 20 April 1981 at 23 UT during these events. Five PMS, on 18 October 1992 at 12 UT, 19 October 1992 at 22 UT, 5 October 1994 at 08 UT, 6 October 1994 at 17 UT and 7 October 1994 at 13 UT, were observed. SSC has not been observed during these events.

Fig. 1, *e—h* gives the amplitude (%) and phase (hr) of semi-diurnal anisotropy for HAE/LAE at ground in LT. As depicted in Fig. 1, *e, f*, the amplitude of the semi-diurnal anisotropy for each HAE remains statistically the same, whereas the phase shifted to later hours throughout the period. Similar trends were also reported for the period 1981—1990 in space [20, 22]. Three PMS, on 20 March 1994 at 16 UT, 21 March 1994 at 02 55 UT and 25 March 1994 at 15 17 UT were observed during these events. The amplitude of the semi-diurnal anisotropy as shown in Fig. 1, *g, h* for LAE is observed to remain statistically the same for each event, whereas the time of maximum is found to shift to later hours. Similar trends were observed by Jadhav et al. [15] for the period 1966—1973 and Kumar and Chauhan [21] and Kumar et al. [22] in space for the period 1981—1990. A PMS on 21 December 1993 at 01 UT was observed during the event. We have rigorously studied all the HAE/LAE events during the period and noticed the same trends which were presented here for few events.

Fig. 2 illustrates the amplitude and phase of the diurnal anisotropy along with quiet days annual average values for all the HAE/LAE. It is observed that the amplitude of the diurnal anisotropy for the majority of the high-amplitude events is significantly larger than the quite day annual average values throughout the period and the phase of the diurnal anisotropy was shifted to earlier hours as compared to the quiet day annual average values for the majority of the events. This is in good agreement, for the amplitude but not for the phase, with earlier results [22] where the investigators noticed that diurnal amplitude remains significantly large but the diurnal time of maximum shifts towards later hours as compared to the quiet day annual average values in space for HAE.

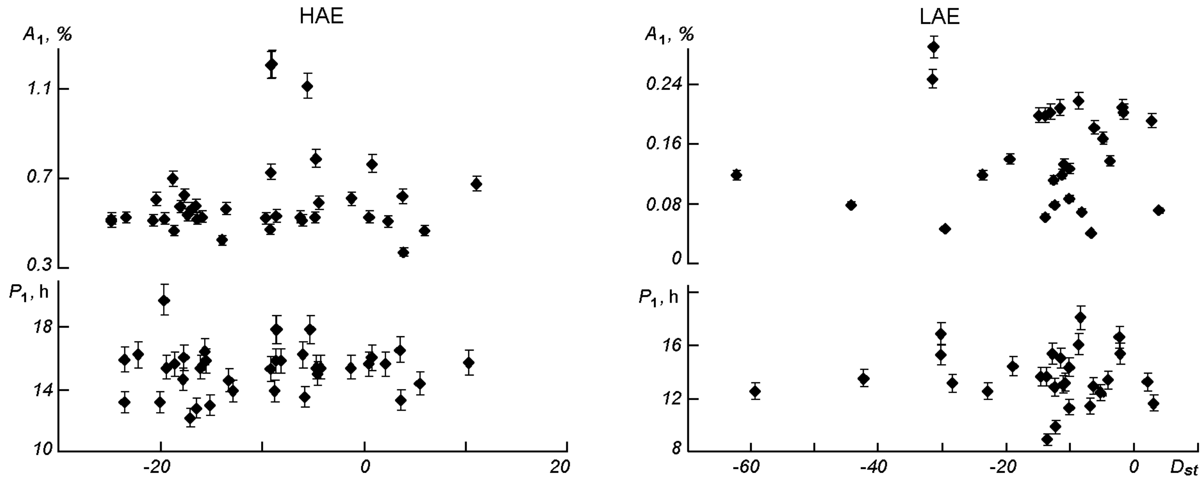

Fig. 3. Amplitude A_1 and phase P_1 of the diurnal anisotropy for each HAE and LAE along with the variation in associated value of D_{st}-index

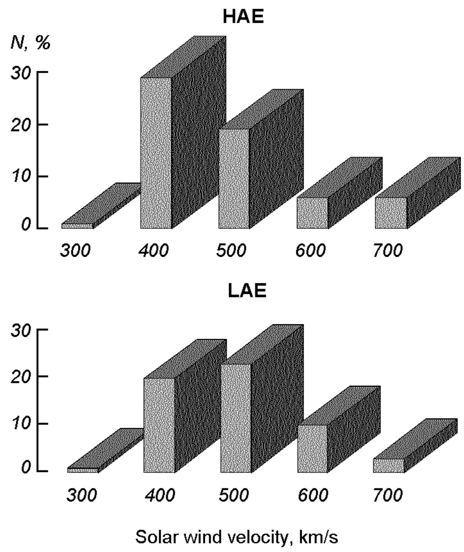

Fig. 4. Frequency histogram of solar wind velocity for all HAE and LAE during 1981—1994

However, the amplitude of the diurnal anisotropy for the majority of the LAE events as shown in Fig. 2 attains significantly lower values as compared to the quiet day annual average amplitude throughout the period 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 the majority of the LAEs confirming the earlier trends noticed by Kumar and Chauhan [21] and Kumar et al. [22] in space for the period from 1981 to 1990.

For individual HAE/LAE cases, the interplanetary magnetic field (IMF) and solar wind parameter (SWP) were studied as well. Fig. 3 gives the amplitude and time of maximum of the diurnal anisotropy for each HAE/LAE case along with the variation in the associated values of disturbance storm time index (D_{st}) and statistical error bars. The amplitude of diurnal anisotropy as shown in Fig. 3 (HAE) is found to be statistically constant for both positive and negative values of D_{st} index for the majority of the events. The amplitude of diurnal anisotropy for both polarities is higher ($\geq$ 0.5 %) and phase shifts towards earlier hours as compared to the co-rotational values (18 hr) for the majority of the HAE. It is also noteworthy that the majority of the HAE events (30) occurred when the D_{st} index remained negative only. Thus we can say that the occurrence of HAE events is dominant for negative polarity of D_{st} index. It is noticed 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—1968 [10, 17]. An enhanced mean amplitude of diurnal anisotropy correlates with positively directed sectors while the amplitude of the diurnal anisotropy seems to decrease during

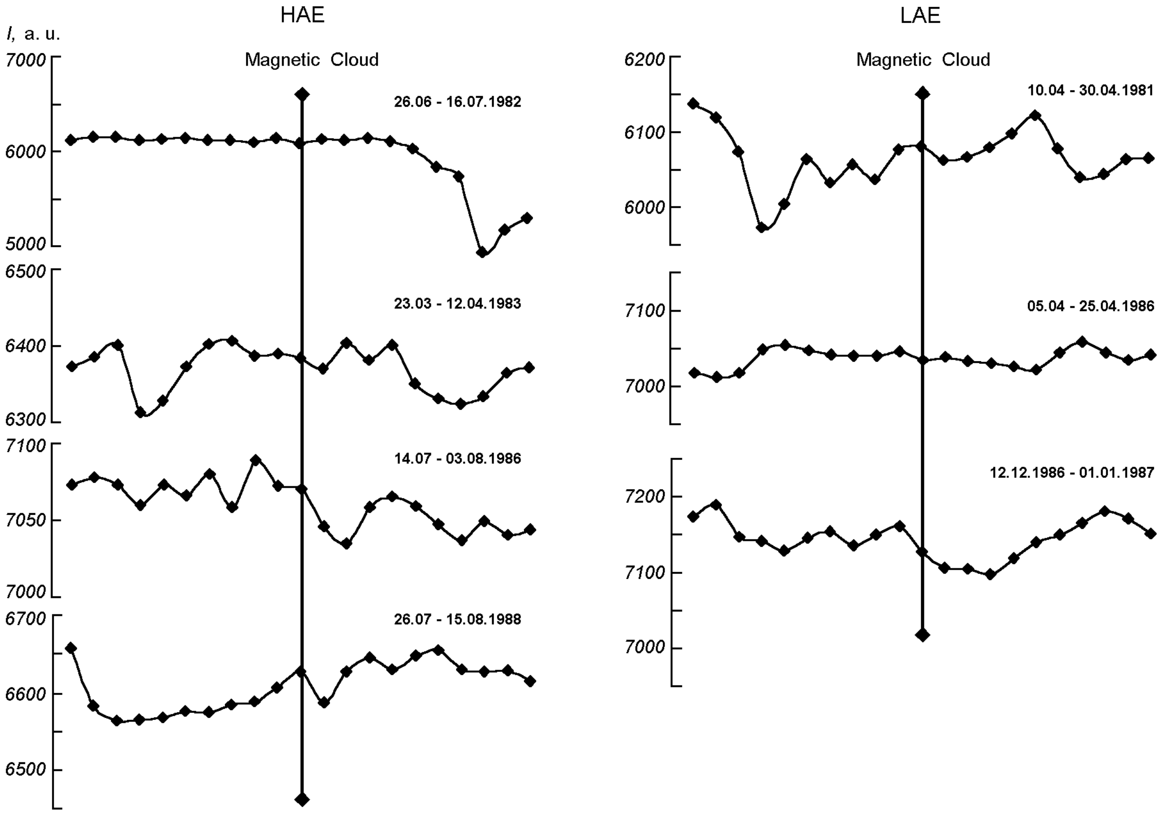

Fig. 5. Variations of cosmic ray intensity during HAE and LAE on the onset of interplanetary magnetic cloud events

sector boundaries [28]. Further for LAE events the amplitude of the diurnal anisotropy has no significant correlation with D_{st} index due to large scattering of points. The amplitude remains significantly low (~0.2 %) for the majority of the LAE events. The time of maximum of the diurnal anisotropy is significantly found to remain in a direction earlier than co-rotational direction (18 hr) for the majority of the HAE except for one event where it remains in co-rotational direction. It is also noteworthy that the majority of the LAE events (26) occurred when the D_{st} index remained negative only. Thus we can say that the occurrence of LAE events is dominant for negative polarity of the D_{st} index. Hashim and Bercovitch [10] as well as Kananen et al. [17] reported that 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 lower and phase shifts to early hours as compared to co-rotational value.

Fig. 4 illustrates the frequency histogram of solar wind velocity for each HAE/LAE. It is observable from these plots that the majority of the HAE/LAE events occurred when the solar wind velocity lay in the interval from 400 to 500 km/s, i.e., was nearly average. Usually, the velocity of high-speed solar wind streams is 700 km/s [31]. Therefore, one can infer from these figures 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 conclude that the HSSWS do not play an important role in the occurrence of the HAE/LAE, which is consistent with earlier findings [31] and inconsistent with the results obtained before that the solar diurnal amplitude is enhanced during the HSSWS coming from coronal holes [13, 7]. Ahluwalia and Riker

[2] found that the annual mean amplitude appears to have large values during the epoch of HSSWS. The amplitude of the diurnal anisotropy in free space is found to enhance by 0.15 % along 17—18 hr LT in HSSWS while it is diminished by 0.1 % along 17—18 hr LT, in low-speed solar wind streams [32]. Further, for HAE/LAE the second peak shown in the figures, where SWV lies in the range of 450—500 km/s, is attributed to the days when the polarity of IMF is not very well defined, i.e., they are either positive or negative or mixed polarity days. According to Ahluwalia and Riker [1], 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 [31]. No significant difference was found between the variation of diurnal vectors in the high-speed days and in the days when the speed is normal.

The existence of interplanetary shock associated with magnetic clouds [6, 19] provided a new tool for the investigation of the physical process responsible for cosmic ray decreases. Many investigators [3, 4, 45], using the superposed epoch analysis technique for a number of events, demonstrated that the decreases are essentially produced by the turbulent sheath between the interplanetary shock and magnetic cloud. Sanderson et al. [39, 40], using the magnetic cloud data of Marsden et al. [23], showed clearly that magnetic clouds also produce cosmic ray decreases. They suggested that post-shock regions, tangential discontinuities and magnetic clouds are equally effective in producing cosmic ray decreases. Kahler and Reames [16], considering magnetic fields of different topology, suggested that the cosmic ray decreases could be produced by the passage of magnetic clouds with open field-line configuration as well. Using the methodology of Zhang and Burlaga [45] we identified some positive and negative magnetic clouds during these LAE/HAE events. The magnetic clouds were divided into two categories, namely, those associated with shocks and those not associated with shocks. During these LAE/HAE events few interplanetary magnetic clouds [40] were identified during the period 1981—1994. Some of them are negative clouds without shock and other are positive clouds with and without shock.

Fig. 5 give the cosmic ray intensity during these LAE/HAE events, during the arrival of cloud and preceding/succeeding period of the cloud. One can clearly see, that during HAE the cosmic ray intensity is found to remain constant (from 26 June to 16 July 1982) before and after the onset of the magnetic cloud. After few days of the magnetic cloud event the intensity decreases sharply. In the same figure (from 23 March to 12 April 1983), the cosmic ray intensity is found to increase gradually seven days prior to the magnetic cloud event and after the onset of the event it decreases gradually with some deviations. Significant deviations are observed in the cosmic ray intensity (from 14 July to 3 August 1986) before and after the onset of the magnetic cloud. As seen in the low panel of Fig. 5, the intensity increases sharply eight days prior to the magnetic cloud event and one day after the onset of the event it increases gradually with some deviations. Thus we can see that the cosmic ray intensity has significant deviations on the onset of magnetic cloud events during HAE.

As depicted in Fig. 5, for LAE events the cosmic ray intensity (from 10 to 30 April) increases gradually with some depressions seven days prior to the magnetic cloud event and after the onset of the event it increases gradually for five days; then it decreases sharply. As seen in the middle panel of the figure, (from 5 to 25 April 1986) the intensity seems to remain constant before and after few days of the magnetic cloud event. However it shows some deviations beyond these days. The intensity (from 12 December 1986 to 1 January 1987) decreases nine days prior to and three days after the magnetic cloud onset then it decreases sharply, as one can see in the low panel of Fig. 5. Thus we observed that significant deviations are also seen in the cosmic ray intensity during the passage of interplanetary magnetic clouds for LAE events.

Our findings are in good agreement with earlier ones reported by Yadav et al. [44]. These observations suggest that the cosmic ray decrease is essentially triggered by the passage of a magnetic cloud. Our observations agree with the observations of Sanderson et al. [39, 40] as well as of Kahler and Reames [16] that the magnetic clouds are also effective in producing cosmic ray decreases. Interplanetary disturbance (a magnetic

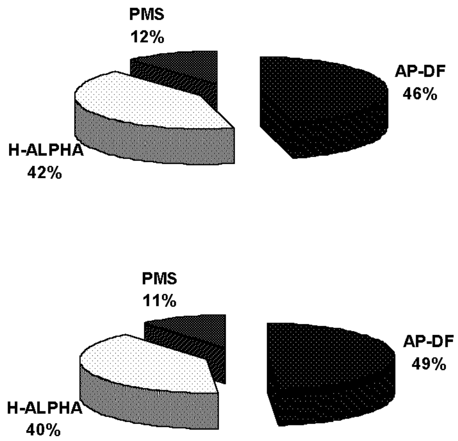

Fig. 6. Number of days (%) of HAE and LAE associated with H_α solar flares and/or AP-DF and/or PMS

cloud) is found to be a responsible factor in producing the decrease in cosmic ray intensity on short-term basis [18].

The number of days associated with H_α solar flare and/or active prominences-disappearing filaments (AP-DF) and/or principal magnetic storms (PMS) is plotted in Fig. 6, so as to make an attempt to investigate the probable source(s) of HAE/LAE in terms of various solar features observed over the solar disk during the period of occurrence of each HAE/LAE event. One can see from these plots that the majority of the days of HAE/LAE are associated with H_α solar flares or AP-DF. It is to be further noted that these trains of days of HAE/LAE are not associated with either any Forbush decrease or geomagnetic storm. Thus, the absence of geomagnetic disturbances during the days of HAE/LAE that we have examined shows that the Earth has not encountered the interplanetary transients caused by the various identified solar sources.

CONCLUSION

The following conclusions can be made on the basis of our findings.

- The results clearly indicate that the amplitude persists continually high/low for at least five or more days and the phase of the diurnal anisotropy remains in the co-rotational direction for the majority of the HAE/LAE. However, it shifts towards earlier hours for some of the HAE/LAE cases. This indicates that the sources responsible for HAE/LAE may be not the same.
- The amplitude of semi-diurnal anisotropy remains statistically invariant, whereas time of maximum (phase) shifted to later hours for both types of events.
- The amplitude of diurnal anisotropy remains significantly high for HAE and low for LAE, whereas the time of maximum shifts towards earlier hours for both type of events as compared to the quite day annual average values.
- The occurrence of HAE/LAE is dominant when solar wind velocity is average or moderate, which shows that these events are not caused by high-speed solar wind streams.
- The majority of the HAE/LAE events occurred when the disturbance storm time index D_{st} remained negative only.
- Significant deviations are seen in the cosmic ray intensity during the passage of interplanetary magnetic clouds for both HAE and LAE events. The magnetic clouds are also effective in causing cosmic ray decreases.
- Multiple solar features were observed over the solar disk for the majority of the cases during the period of study.

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МОДУЛЯЦІЯ КОСМІЧНИХ ПРОМЕНІВ, А ТАКОЖ СОНЯЧНИХ І ГЕЛІОСФЕРНИХ АНОМАЛІЙ

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Проведено Фур'є-аналіз даних про інтенсивність космічних променів, які були отримані з використанням наземного нейтронного монітора в Діп-Рівер, а також даних щодо параметрів міжпланетного магнітного поля й плазми сонячного вітру, здобуті протягом 1981—1994 рр. Багато днів, для послідовності яких з п'яти чи більше днів характерні ненормально високі чи низькі амплітуди, як порівняти із середньорічною амплітудою добової анізотропії, були вибрані як явища високо- чи низькоамплітудних анізотропічних хвильових пакетів. Наші результати чітко вказують на те, що момент максимуму добової варіації залишається, головним чином, у 18-годинному напрямку для більшості подій високо- чи низькоамплітудних анізотропічних хвильових пакетів. Фаза підвищеної добової анізотропії показує добре помітний систематичний зсув у бік пізніших годин, як порівняти з коротаційним напрямком, для деяких із подій високоамплітудних анізотропічних хвильових пакетів, а для деяких подій низькоамплітудних анізотропічних хвильових пакетів для неї характерний значний систематичний зсув у бік більш ранніх годин у порівнянні з коротаційним напрямком. Більша частина із розглянутих подій високо- чи низькоамплітудних анізотропічних хвильових пакетів відбулася тоді, коли часовий індекс збурювального шторму D_{st} залишався тільки негативним. Спостерігалися істотні відхилення в інтенсивності космічних променів під час проходження міжпланетних магнітних хмар для подій як високо-, так і низькоамплітудних анізотропічних хвильових пакетів. Високошвидкісні потоки сонячного вітру не відіграють суттєвої ролі у виникненні подій таких типів. Міжпланетні збурення (магнітні хмари) відіграють певну роль у зменшенні інтенсивності космічних променів. Запропоновано джерело описаних незвичайних анізотропічних хвильових пакетів у космічних променях.