АСТРОФИЗИКА

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INTERPLANETARY MAGNETIC CLOUDS AND COSMIC RAY MODULATION

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We studied the cosmic ray intensity variation due to interplanetary magnetic clouds during an unusual class of low amplitude anisotropic wave train events. The low amplitude anisotropic wave train events in cosmic ray intensity has been identified using the data of ground based Deep River neutron monitor and studied during the period 1981-1994. Even though, the occurrence of low amplitude anisotropic wave trains does not depend on the onset of interplanetary magnetic clouds. But the possibility of occurrence of these events cannot be overlooked during the periods of interplanetary magnetic cloud events. It is observed that solar wind velocity remains higher (> 300) than normal and interplanetary magnetic field B remains lower than normal on the onset of interplanetary magnetic cloud during the passage of low amplitude wave trains. It is also noted that the proton density remains significantly low during high solar wind velocity, which is expected. The north south component of interplanetary magnetic field Bz turns southward prior to one day of the arrival of cloud and remains in the southward direction after the arrival of cloud. During these events the cosmic ray intensity is found to increase with the increase of solar wind velocity. The superposed epoch analysis of cosmic ray intensity for these events during the onset of interplanetary magnetic clouds reveals that the decrease in cosmic ray intensity start not at the onset of cloud but after few days. The cosmic ray intensity increases on arrival of the magnetic cloud and decreases gradually after the passage of the magnetic cloud.

Key words: *cosmic ray: interplanetary magnetic cloud*

1. *Introduction.* A number of low amplitude anisotropic wave train events have been observed with a significant shift in the diurnal time of maximum to co-rotational/ 1800 Hr direction or later hours ([1] and references therein). Agrawal and Bercovitch [2] have shown that the direction of the 22-year component is perpendicular to the diurnal anisotropy vector and is along the line 162° east of the Sun-Earth line; they have attributed the 11-year component to the variation of cut-off rigidity. A significant increase is observed in the amplitude of first three harmonics (diurnal/semi-diurnal/tri-diurnal) during the passage of high speed solar wind stream, whereas the direction of the anisotropy have no time variation characteristics associated with solar wind velocity and north south component of interplanetary magnetic field for three neutron monitoring stations located at different geomagnetic cutoff rigidities and altitudes [3].

Interplanetary magnetic clouds belong to one of the several classes of transient flows in the solar wind. Magnetic clouds as ideal force free objects (cylinders or spheres) are ejected near the Sun and followed beyond the

Earths orbit. It is found that the decrease in cosmic ray intensity, which are associated with magnetic cloud preceded by a shock, are very high and these decrease starts few days earlier than the arrival of cloud at Earth. From the study of the time profile of these decrease, it is found that the onset time of a Forbush type decrease produced by a shock associated cloud starts nearly at the time of arrival of the shock front at the Earth [4,5] and the recovery is almost complete with in a week. Forbush decreases associated with shock-associated cloud are caused by magnetic field variations associated with interplanetary disturbances [5].

Badruddin et al. [6] have reported a possible correlation between magnetic clouds and cosmic ray intensity decrease while Kudo et al. [7] have reported an increases in cosmic ray intensity that may be related to the geomagnetic D_{st} index and Iucci et al. [8] have found short term increase in CR intensity occurring inside the Forbush decrease, that possibly may be associated with magnetic clouds. Zhang and Burlaga [9] infer that the cosmic rays are mainly modulated by fluctuation rather than by drifting in the strong smooth field in the magnetic cloud.

Intense interplanetary magnetic fields are of basic importance to solar wind physics, magnetospheric physics and cosmic ray physics and play a crucial role in the modulation of galactic cosmic rays [10]. Barouch and Burlaga [11] found that the individual magnetic enhancements are generally associated with depressions in cosmic ray intensity and Barouch and Sari [12] have further demonstrated that these depressions are not related to turbulence or random motions in the field and only the large-scale features of interplanetary magnetic fields are important. However, Nishida [13] has emphasized the importance of scattering by turbulent magnetic field in producing the transient modulation.

The existence of unusual magnetized clouds of plasma emitted by the active Sun was proposed by Morrison [14] as a cause of worldwide decreases in cosmic ray intensity lasting for days and correlated roughly with geomagnetic storms. Klien and Burlaga [15] have defined a magnetic cloud as a structure of radial dimension ~0.25 AU (at 1 AU) in which the magnetic field strength is higher than average and the field direction changes nearly monotonically from large southern (northern) to large northern (southern) directions. The field geometry in such a magnetic cloud is consistent with a magnetic loop [16]. Burlaga and Klein [17] have discussed two magnetic clouds one of which was associated with an unusual cosmic ray depression while no appreciable depressions in cosmic ray intensity was found in association with the other.

After the identification of magnetic clouds in interplanetary space [15,16,18], there have been studies to explore their effects on the propagation of cosmic rays. However, the studies have given contradictory results. Badruddin et al. [5,6] using the magnetic clouds have identified during the period 1967-1978 and Zhang and Burlaga [18], using the magnetic clouds observed during the period 1978-1982, have arrived at a similar conclusion that the turbulent sheath, between the upstream shock and the front boundary of magnetic clouds, is the main cause of cosmic ray variation rather than the magnetic cloud itself. On the other hand, Sanderson et al. [19,20] have suggested that the magnetic cloud, in fact, is as effective at causing a decrease as the post-shock turbulent region. They have also indicated that a magnetic cloud driving the shock is responsible for a Forbush decrease; the post shock turbulent region however has not played any crucial role in producing the decrease.

Earlier investigations indicated different mechanisms for the production of cosmic ray decreases. Hence, we need to determine the most appropriate physical mechanisms and the interplanetary configurations responsible for the cosmic ray decreases. In the present work we have identified an unusual class of low amplitude anisotropic wave trains. We investigate behaviour of cosmic ray intensity on the onset of interplanetary magnetic clouds during these events in order to understand the interplanetary mechanisms causing these events. For this we have performed the superposed epoch analysis using Deep River super neutron monitor data and the data of cloud observations at the Earth as the epoch day for these low amplitude events. Some individual events are studied for more specific investigation. The various interplanetary parameters associated with these magnetic clouds are then used to study the time profiles and other characteristics of low amplitude wave trains in cosmic ray intensity over the period 1981-1994.

2. *Data Analysis.*

Harmonic Analysis. Time dependent harmonic function $F(t)$ with 24 equidistant points in the interval from $t = 0$ to $t = 2\pi$ can be expressed in terms of Fourier series

$$F(t) = a_0 + \sum_{n=1}^{24} (a_n \cos(nt) + b_n \sin(nt)),$$

$$F(t) = a_0 + \sum_{n=1}^{24} r_n \cos(nt - \phi_n),$$

where a_0 is the mean value of $F(t)$ for the time interval from $t=0$ to 2π and a_n, b_n are the coefficients of n^{th} harmonics, which can be expressed as follows:

$$a_0 = \frac{1}{12}\sum_{i=1}^{24} r_i\,; \quad a_n = \frac{1}{12}\sum_{i=1}^{24} r_i \cos nt\,; \quad b_n = \frac{1}{12}\sum_{i=1}^{24} r_i \sin nt\,.$$

The amplitude r_n and phase ϕ_n of the n^{th} harmonic are expressed as

$$r_n = \left(a_n^2 + b_n^2\right)^{1/2}$$

and

$$\phi_n = \tan^{-1}\left[\frac{a_n}{b_n}\right]$$

The daily variation of the CR intensity can be adequately represented by the superposition of first, second, third and fourth harmonics as follows:

$F(t) = a_1 \cos t + b_1 \sin t + a_2 \cos 2t + b_2 \sin 2t + a_3 \cos 3t + b_3 \sin 3t + a_4 \cos 4t + b_4 \sin 4t$.

Trend Correction. The daily variation in CR intensity is not strictly periodic. Thus, if the number to be analysed represents bi-hourly (or hourly) means of CR 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, is allowed for in practice by applying a correction known as trend correction, to each of the terms.

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

$$\bar{y}_k = y_k - \frac{\pm\delta_y \times k}{12},$$

where $k = 0, 1, 2, 3, \ldots, 12$; y_k = uncorrected value; $\pm\delta_y$ = secular changes i.e. $\pm\delta_y = y_{12} - y_0$.

Mode of Analysis. The pressure-corrected data of the Deep River Neutron Monitor (NM) station (data from http://spidr.ngdc.noaa.gov/NeutronMonitor) has been subjected to Fourier analysis for the period 1981-1994 after detrending. While performing the analysis of the data, all those days discarded having more than three continuous hours of data missing.

Criteria for selection of events.

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 low-amplitude wave train events (LAE) have been selected on the basis of following criteria:

- Low-amplitude wave train events of continuous days have been selected when the amplitude of the diurnal anisotropy remains lower than 0.3% on each day of the event for at least five days.

- In the selection of these 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 the recovery phase or declining phase they are not considered.

On the basis of the above selection criteria we have selected 29 LAEs during the period 1981-1994. The main parameters of these events have been shown in Table 1. The hourly cosmic-ray intensity data for Deep

River NM station [Geog. Lat. 46°.10, Geog. Long. 282°.50, Vertical cut-off rigidity 1.02 (GV)] have been investigated in the present study. Figure 1 shows examples of low amplitude anisotropic wave trains. In the present study we have identified the interplanetary magnetic clouds using plots of hourly values of interplanetary parameters [21-25] to study the role of these clouds in LAE. The large Forbush decreases in cosmic-ray intensity, if any, have been excluded to avoid their influence. We have adopted the Chree analysis of superposed epoch to study the effect of interplanetary magnetic clouds on cosmic-ray intensity using the daily-average cosmic-ray intensity of the Deep River neutron monitor during LAE. Further, various features,

Table 1

LOW AMPLITUDE ANISOTROPIC WAVE TRAIN EVENTS ALONG WITH ASSOCIATED PARAMETERS

Event	Year	Month	Day		Diurnal	
No			Start	End	Amplitude	Phase
					(%)	(Hr)
1	1981	April	20	25	0.118	12.5
2	1983	April	17	21	0.118	12.5
3	1984	November	22	26	0.127	11.3
4	1985	June	13	18	0.203	15.3
5	1986	April	12	19	0.203	15.3
6	1986	April	25	30	0.167	12.4
7	1986	June	10	17	0.191	13.2
8	1986	September October	27	12	0.112	12.8
9	1986	December	14	26	0.119	13
10	1987	January	19	25	0.087	14.3
11	1987	March	9	15	0.04	11.4
12	1987	May	7	14	0.071	11.6
13	1988	March	14	18	0.198	13.6
14	1988	April	13	21	0.182	12.9
15	1990	October	16	20	0.198	13.6
16	1991	January	14	18	0.209	16.5
17	1991	January	19	23	0.208	15.0
18	1991	February	4	9	0.247	16.8
19	1991	May	1	5	0.218	16.0
20	1991	July	24	29	0.140	14.4
21	1991	September	11	16	0.137	13.3
22	1991	September	17	22	0.069	18.0
23	1991	December	4	8	0.068	14.6
24	1992	March	22	27	0.290	15.2
25	1992	October	17	23	0.132	13.1
26	1992	November	12	21	0.062	8.9
27	1993	December	21	25	0.079	9.8
28	1994	September	8	13	0.046	13.1
29	1994	October	4	8	0.079	13.5

which are observed over the solar disk (data from http://nssdc.gsfc.nasa.gov/omniweb) during the periods of events, have also been studied.

3. *Results and Discussion.* The existence of the interplanetary-shock-associated magnetic clouds [16,17] has provided a new tool for investigating

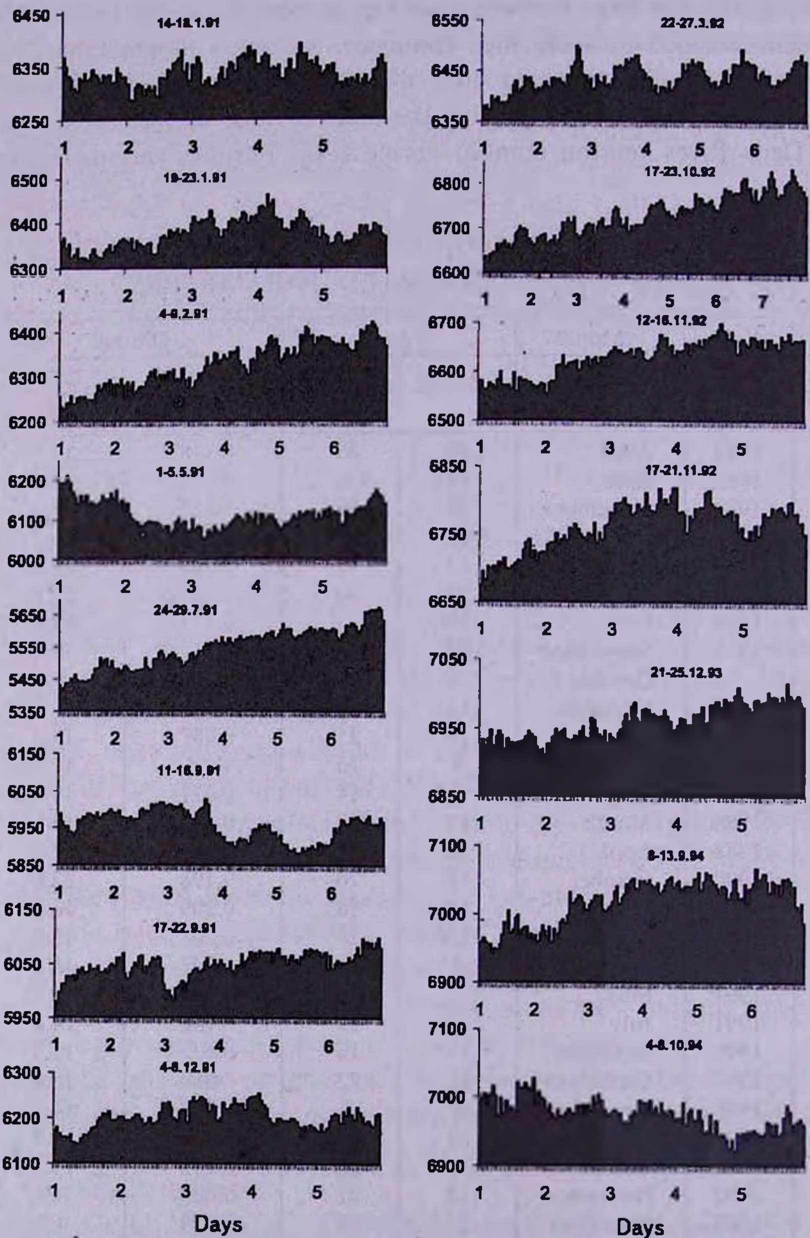

Fig.1. Cosmic Ray intensity records (Neutron Monitor count rates) at Deep River showing the occurrence of some low amplitude anisotropic wave trains.

the physical process responsible for cosmic-ray decreases. Many authors [5,18,26] using the superposed-epoch-analysis technique for a number of events have demonstrated that the turbulent sheath between the interplanetary shock and the magnetic cloud essentially produces the decreases. Sanderson et al. [19,20] using the magnetic cloud data of Marsden et al.

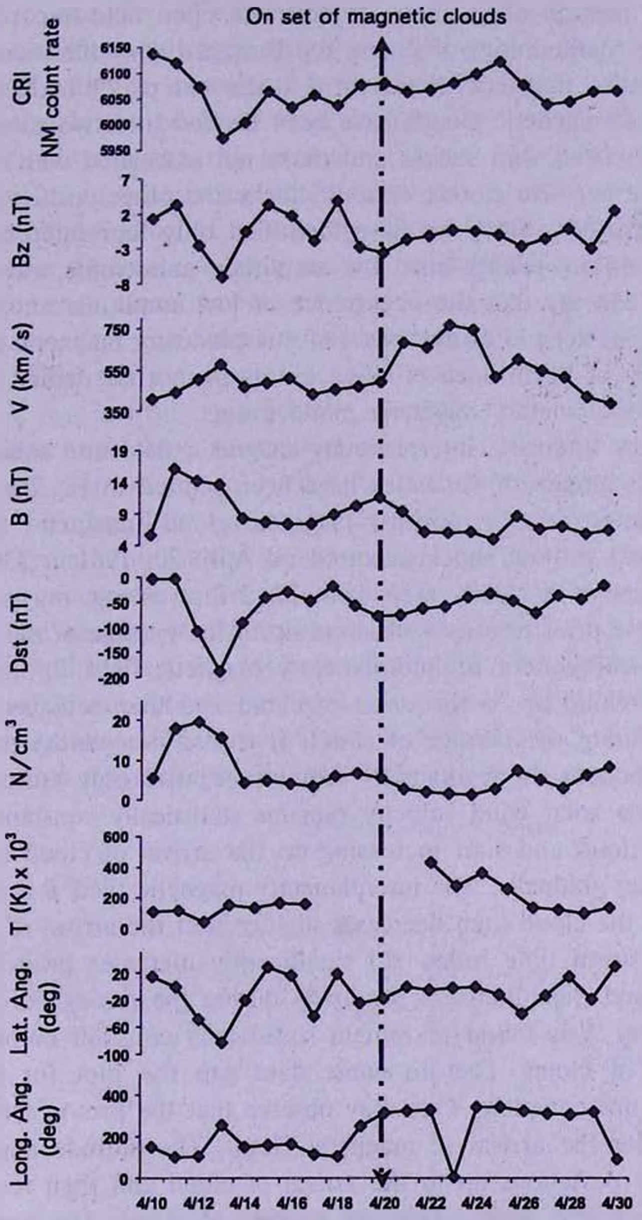

Fig.2. Daily variation of cosmic rays from -10 to +10 day for the magnetic cloud event of April 20, 1981 alongwith IMF (*Bz*), solar wind velocity (*V*), IMF (*B*), *Dst* index, proton density (*N*), proton temperatue (*T*), Latitude Angle and longitude Angle.

[27] have clearly shown that magnetic clouds also produce cosmic-ray decreases. They have suggested that post-shock regions, tangential discontinuities, and magnetic clouds are equally effective in producing cosmic-ray decreases. Kahler and Reames [28], considering magnetic fields of different topology, have suggested that the cosmic-ray decreases could also be produced by the passage of magnetic clouds with open field-line configurations. Using the methodology of Zhang and Burlaga [9] we have identified positive and negative magnetic clouds in 4 LAEs out of 29 LAEs during these events. These magnetic clouds have been divided into two categories, namely those associated with shocks and those not associated with shocks. Some of them are negative clouds without shocks and other positive clouds with and without shock. Since we have identified only four interplanetary magnetic clouds during twenty-nine low amplitude anisotropic wave train events. Thus we can say that the occurrence of low amplitude anisotropic wave trains does not depend on the onset of interplanetary magnetic clouds. But the possibility of occurrence of these events cannot be denied during the periods of interplanetary magnetic cloud events.

The cosmic ray intensity, interplanetary magnetic field and solar wind plasma parameters alongwith *Dst* index have been plotted in Fig.2 to show an example of interplanetary positive magnetic cloud (magnetic field is directed northward) without shock occurred on April 20, 1981 at 2300 UT during these events. It is clearly seen from Fig.2 that cosmic ray intensity is found to increase prior to arrival of cloud up to the passage of the cloud. The north south component of interplanetary magnetic field Bz increases prior to onset of cloud up to the onset of cloud and then remains statistically constant during the passage of cloud. It is also noteworthy that the north south component Bz significantly remains negative only during passage of cloud. The solar wind velocity remains statistically constant prior to the arrival of cloud and start increasing on the arrival of cloud for few days then decreases gradually. The interplanetary magnetic filed B is slightly increases prior to the cloud then decreases slightly after the arrival of cloud. The disturbance storm time index *Dst* significantly increases prior to the arrival of cloud and then increases gradually during the passage of cloud. The proton density N is found to remain statistically constant before and after the arrival of cloud. Due to some data gap the plot for proton temperature T is not complete. One may observe that the proton temperature decreases after the arrival of magnetic cloud. The latitude angle increases with some deviations up to the arrival of cloud and then found to remain constant for few days during the passage of cloud. The longitude angle increase few days prior to the onset of cloud up to 2 days after the cloud then significantly decreases for one day and then remains constant for few days. We can see from the plot that solar wind velocity remains higher (>300) than normal and interplanetary magnetic field B remains lower than normal during this period. It is also evident that the proton density remains significantly low during high solar wind velocity, which is expected. The north south component of interplanetary magnetic field Bz turns southward prior to one day of the arrival of cloud and remains in the southward direction after the arrival of cloud. The cosmic ray intensity is found to increase with the increase of solar wind velocity.

To study the effect of these interplanetary magnetic clouds on cosmic ray intensity during the passage of LAEs, we have adopted the Chree analysis of superposed epoch for days -10 to +10 and plotted in Fig.3 as a percent deviation of cosmic ray intensity data alongwith statistical error bars I for Deep River neutron monitor during the period 1981-94. Deviation for each event is obtained from the overall average of 21 days. Epoch day (zero day) correspond to the starting days of interplanetary magnetic cloud. One can see from Fig.3 that on the onset of magnetic cloud the cosmic ray intensity significantly increases from -10 days to -7 day then decreases with some fluctuations up to -1 day. The cosmic ray intensity increases from -1 day to +2 day. It starts decreasing gradually from +2 day up to +10 day. Thus we can see from this plot that decrease in cosmic ray intensity start not at the onset of cloud but after 2 days. The cosmic ray intensity increases on arrival of the magnetic cloud and decreases gradually after the passage of the magnetic cloud. This is in good agreement with earlier findings reported by Yadav et al. [29]. These observations suggest that the cosmic-ray decrease during LAEs is essentially triggered by the passage of a magnetic cloud. Sanderson et al. [19,20] and Kahler and Reames [28] found that magnetic clouds are effective in producing cosmic-ray decreases.

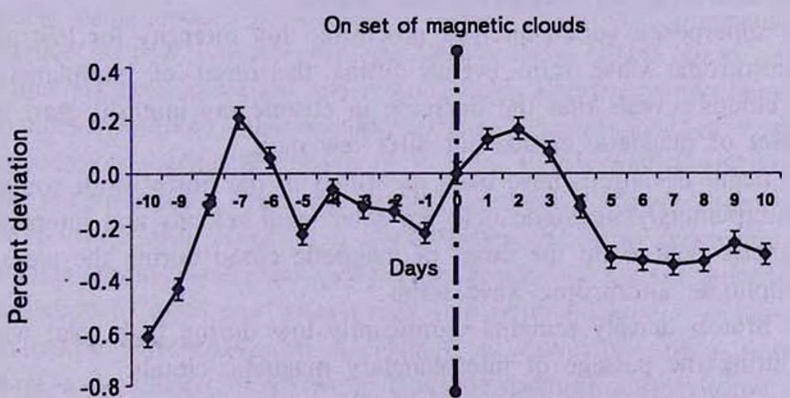

Fig.3. Superposed epoch results of cosmic Ray intensity at Deep River NM station due to interplanetary magnetic clouds alongwith statistical error bars (I) during low amplitude anisotropic wave trains.

Interplanetary disturbances (Magnetic cloud) are found to be the responsible factor in producing the decrease in cosmic-ray intensity on a short-term basis [30]. Mishra et al. [31] concluded from their analysis that magnetic clouds in association with SSC events produce large decreases in cosmic-ray intensity start not on the onset of cloud but after 2 days.

The decrease occurs in cosmic-ray intensity associated with clouds preceded by shocks not at the arrival time of the clouds but earlier. The onset of these decreases as observed on the Earth is almost coincident with the shock arrival at the Earth. A turbulent sheath of ambient plasma in which there may be large fluctuations in both the strength and direction of the magnetic field follow the shocks. This in turn is followed by the mass ejecta, which is driving the shock. The shock and associated ejecta both are important in determining the time profile of the decrease. The field magnitude and the speed of this modulating region both seem to be related to the magnitude of cosmic-ray decreases.

Previously [32] studied a number of low amplitude anisotropic wave train events over the years 1965-1990 using the data of Calgary and Deep River neutron monitor. They have selected the low amplitude days in which the diurnal amplitude is $<0.2\%$ for three (or more) consecutive days. The reported that low amplitude events are inversely correlated with solar activity and that the enhanced and low amplitude anisotropic wave train events are produced by different types of interplanetary magnetic field distributions.

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

- Even though, the occurrence of low amplitude anisotropic wave trains does not depend on the onset of interplanetary magnetic clouds. But the possibility of occurrence of these events cannot be overlooked during the periods of interplanetary magnetic cloud events.
- The superposed epoch analysis of cosmic ray intensity for low amplitude anisotropic wave train events during the onset of interplanetary magnetic clouds reveals that the decrease in cosmic ray intensity start not at the onset of magnetic clouds but after few days.
- Significant deviations have been identified in the north south component of interplanetary magnetic field Bz, solar wind velocity and interplanetary magnetic field B on the onset of magnetic cloud during the passage of low amplitude anisotropic wave trains.
- The proton density remains significantly low during high solar wind velocity during the passage of interplanetary magnetic clouds.

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МЕЖПЛАНЕТНЫЕ МАГНИТНЫЕ ОБЛАКА И МОДУЛЯЦИЯ КОСМИЧЕСКИХ ЛУЧЕЙ

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Мы изучали изменение интенсивности космического луча, обусловленного межпланетными магнитными облаками, в необычном классе анизотропного волнового цуга событий низкой амплитуды. Указанное изменение было выявлено благодаря данным, полученным в результате мониторинга нейтронов на наземной станции Deep River и изученным в период времени 1981-1994гг. Хотя сами по себе анизотропные волновые цуги событий низкой амплитуды не зависят от появления межпланетных магнитных облаков, однако возможностью возникновения этих событий нельзя пренебрегать при наступлении событий таких облаков. Согласно наблюдениям, если при прохождении цуга волн малой амплитуды появляются межпланетные магнитные облака, то скорость солнечного ветра остается выше своего нормального значения (> 300), а межпланетное магнитное поле B - ниже нормального значения. Было также замечено, что, при высокой скорости солнечного ветра плотность протонов, как и ожидалось, остается значительно низкой. Северо-южный компонент межпланетного магнитного поля Bz за день до достижения облака имеет южное направление и сохраняет его по достижении облака. Было найдено, что в течение этих событий с увеличением скорости солнечного ветра интенсивность космического луча растет. Временной анализ интенсивности космического луча для указанных событий позволил выявить, что уменьшение интенсивности наступает не при появлении магнитных облаков, а несколько дней спустя. При достижении облака интенсивность луча растет, а после прохождения через него постепенно убывает.

Ключевые слова: *космические лучи: межпланетное магнитное поле*

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