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High amplitude anisotropic wave trains in cosmic rays

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A B S T R A C T

In the present study the occurrence of an unusual class of high amplitude anisotropic wave trains in the cosmic ray neutron intensity, which is distinctly different from the average diurnal variation as well as from other recognized types of high amplitude anisotropic wave trains are noted and the directional distribution in the interplanetary space determined. The major objective of this paper is to study the first three harmonics of high amplitude anisotropic wave trains of cosmic ray intensity over the period 1981–1994 for Deep River Neutron Monitoring station.

The significant characteristics of these events are that the high amplitude wave trains show a maximum intensity of diurnal component in a direction earlier than 1800 h/co-rotational direction. It is noticed that these events are weakly dependent on high-speed solar wind streams or by the sources on the Sun responsible for producing these streams such as polar coronal holes. However, the possibility of occurrence of these events during high-speed solar wind streams cannot be denied. The occurrence of high amplitude events is dominant for positive polarity of B_z. Majority of the HAEs have occurred when D_{st}-index remains negative and A_p-index remains $\leqslant 18\,\mathrm{nT}$.

All the three harmonics of HAEs except the amplitude of second harmonic do not show any significant correlation associated with D_{st} and A_p-index. The corotating streams produce significant deviations in cosmic ray intensity as well as in solar wind speed during high amplitude anisotropic wave train events.

1. Introduction

The existence of high and low amplitude anisotropic wave trains have been revealed through the long-term study of cosmic ray intensity. Periods of unusually large amplitude often occur in trains of several days. Cosmic ray (CR) variations observed near the Earth are the integral result of numerous solar and heliospheric phenomena. An existence of relation between solar wind magnetic field and long-term CR variations at neutron monitor energies seems to be apparent [1]. Many workers in the past studied the characteristics of the CR daily variation [e.g. 2,3 and reference therein].

The nature of the long-term variation in CR intensity is likely to depend upon the polarity of the solar poloidal magnetic field [4], the cumulative effect of Forbush decreases [5] and other forms of interplanetary perturbations linked with the solar activity. Researchers have also attempted to derive a relationship between the mean daily CR variation and the level of solar and geomagnetic activity [3,6 and references therein]. Ballif et al. [7] correlated the K_p and A_p with the mean fluctuations in amplitude of interplanetary magnetic field (IMF), which in turn is related to diffusive component of convection–diffusion theory. The geomagnetic activity index, A_p was also found to be associated with the solar wind speed, V [7]; which is related to convective component of convection–diffusion theory. On the other hand, the CR intensity exhibits a daily variation composed of a prominent diurnal component and also a semi-diurnal component of lesser amplitude.

The occurrence of high amplitude anisotropic wave train events (HAEs) has been observed to be dominant during the declining phase of solar activity period; the interplanetary sources causing diurnal variation on quiet days and the ones for HAEs seem to be different when investigated with solar wind speed even at 99% level of statistical confidence [8].

The consecutive days having abnormally high or low amplitudes in daily variation of CR have been reported several times earlier with explanation of sources and sinks in anti-garden-hose and garden-hose directions [9]. The existence of high and low amplitude anisotropic wave trains have been revealed through the long-term study of CR intensity. Periods of unusually large amplitude often occur in trains of several days. The average characteristics of CR diurnal anisotropy are adequately explained by the co-rotational concept [10–12]. This concept supports the mean

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diurnal amplitude in space of 0.4% along the 1800 h direction using the worldwide neutron monitor data. However, the observed day-to-day variation both in amplitude and time of maximum, and the abnormally large amplitudes or abnormally low amplitudes of consecutive days, cannot be explained in co-rotational terms. Moreover, the maximum intensity of diurnal anisotropy has not appeared in the direction of 1800 h, which is the nominal co-rotational phase [6].

The average daily variation of CR intensity generally consists of diurnal variation, semi-diurnal variation and tri-diurnal variation. The amplitude of the diurnal variation at a high/middle latitude station has been found to be of the order of 0.3–0.4%, whereas the amplitudes of two higher harmonics is of the order of 0.02% and 0.08%, respectively [13]. The average characteristics have also been found to vary with solar cycle, where the variation is much larger at higher energies. A number of investigators have reported the short-term characteristics of the daily variation, where they have selected continually occurring days of high and low amplitudes of diurnal variation [14]. These results have pointed out significant departures in the time of maximum as well as their association with higher harmonics.

Many workers [9,15,16] 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 has provided by Forman and Gleeson [18]. Several workers have attempted to find the possible origin of the 'large amplitude wave trains' of cosmic ray neutron intensity to develop a suitable realistic theoretical model, which can explain the diurnal anisotropy in individual days.

Hashim and Thambyahpillai [19] and Rao et al. [9] have shown that the enhanced diurnal variation of large amplitude events exhibits a maximum intensity in space around the anti-garden-hose direction (2100 h) and a minimum intensity in space around the garden-hose direction (0900 h). Kane [20] and Bussoletti [21] have noticed that quite often an enhanced intensity is presented along the co-rotational direction and it is not correlated with the garden-hose direction. The diurnal anisotropy is well understood in terms of a convective–diffusive mechanism [18]. Mavromichalaki [22] has observed that the enhanced diurnal variation was caused by a source around 1600 h or by a sink at about 0400 h. It was pointed out that this diurnal variation caused by the superposition of convection and field-aligned diffusion due to an enhanced density gradient of $\approx 8\%\,\mathrm{AU}^{-1}$.

The B_z component of IMF does not usually contribute to the solar modulation of CR since the long-term average of this component near the Earth is ~ 0. However, Swinson et al. [23] have demonstrated that on occasions it can contribute to a field dependent anisotropy especially to the extended trains of enhanced solar diurnal variation observed in 1974. They contend that this enhancement resulted from the constructive interference of the regular solar diurnal variation, $B_y \times \nabla N_y$ streaming.

2. Data treatment

2.1. 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 nth harmonics, which can be expressed as follows:

$$a_0 = \frac{1}{12} \sum_{i=1}^{24} r_i$$

$$a_n = \frac{1}{12} \sum_{i=1}^{24} r_i \cos nt$$

$$b_n = \frac{1}{12} \sum_{i=1}^{24} r_i \sin nt$$

The amplitude r_n and phase ϕ_n of the nth harmonic are expressed as

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

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:

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

2.1.1. Trend correction

The daily variation in CR intensity is not strictly periodic. Thus, if the number to be analyzed represents bi-hourly (or hourly) means of CR intensity, the mean for hour t_0 (0th hour) will not, in general be the same as the mean for hour t_{24} (or 24th 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 $x = 0$ (0th hour) and y_{12} is the value of the ordinate at $x = 2\pi$ (24th 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, and $\pm\delta_y =$ secular changes i.e. $\pm\delta_y = y_{12} - y_0$.

2.2. Mode of analysis

The pressure corrected data of Deep River Neutron Monitor (NM) station has been subjected to Fourier analysis for the period 1981–1994 after applying the trend correction. While performing the analysis of the data all those days are discarded having more than three continuous hourly data missing.

2.3. 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 High amplitude wave train events have been selected on the basis of the following criteria:

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