

COSMIC RAY DAILY VARIATION AND SOLAR ACTIVITY ON ANOMALOUS DAYS

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A study is carried out on the long-term changes in the diurnal anisotropy of cosmic rays using the ground based Deep River neutron monitor data during significantly low amplitude anisotropic wave train events in cosmic ray intensity for the period 1981-94. It has been observed that the phase of the diurnal anisotropy for majority of the low amplitude anisotropic wave train events significantly shifts towards earlier hours as compared to the co-rotational direction. The long-term behaviour of the amplitude of the diurnal anisotropy can be explained in terms of the occurrence of low amplitude anisotropic wave train events. The occurrence of these events is dominant during solar activity minimum years. The amplitude of the diurnal anisotropy is well correlated with the solar cycle but the direction of the anisotropy is not correlated with the solar cycle and shows a systematic shift to earlier hours.

Key words: cosmic ray, sunspot, solar activity, solar cycle and diurnal anisotropy.

1. INTRODUCTION

Cosmic ray daily variation (diurnal, semi-diurnal and tri-diurnal) arises from spatial anisotropies in interplanetary space. Ground-based detectors record these once everyday as their 'asymptotic cone of acceptance' sweeps through the direction containing the spatial anisotropy. The asymptotic cone of acceptance of a detector is the solid angle that contains all the asymptotic directions of approach of particles of various energies, which make a significant contribution to the counting rate of the detector. In addition to the diurnal component, the daily variation is composed of at least two more contributions of lesser amplitudes, *i.e.*, semi-diurnal and tri-diurnal components.

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. The results of power spectrum and harmonic analysis for different worldwide cosmic ray stations showed that the observed tri-diurnal variations are of extraterrestrial origin and arises from an ecliptic plane anisotropy in free space.

Solar diurnal variation of cosmic ray 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]. This concept supports mean diurnal amplitude in space of 0.4% along the 1800 Hr direction using the worldwide neutron monitor data. 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. McCracken *et al.* [17] first suggested the extension of this new concept from the solar cosmic events to the observed diurnal variation and the theoretical formulation was provided by Forman and Glesson [18]. On the basis of this mechanism the diurnal variation can be explained in terms of radial convection together with diffusion, which is mainly along the magnetic field line. The co-rotational concept is a special case of the convective-diffusive model with which we can explain the characteristics of the diurnal variation even on a day-to-day basis. 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]. Kane [15] showed that on a day-to-day basis the diffusion vector deviates from the interplanetary magnetic field (IMF) direction in the ecliptic plane by more than 30° on about 35% of the quiet days. Ananth *et al.* [1] comparing the diffusion vector with the magnetic field vector pointed out that this simple concept holds well on more than 80% of days. On the rest 20% of days the diurnal anisotropy characteristics seem to indicate the presence of a significant component of transverse diffusion current in addition to the normal convection and diffusion flow. Such days are found to be present in the form of trains of consecutive days and to be associated with abrupt changes in the interplanetary magnetic field direction. The value of the diffusion coefficients ratio K_{\perp}/K_{\parallel} which is normally about ≤ 0.05 for field aligned days, is found to be ~ 1.0 on non-field aligned days. It has been shown that on many days the interplanetary field seems to stick to the garden-hose direction, while the diffusion vector deviates significantly from the garden-hose direction and on some other days the reverse situation occurred [15]. Owens and Kash [16] by 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.

Using the neutron monitor data of Athens and Deep River stations over the period 1970–1977, 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 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 noticed that the behaviour of the diurnal time of maximum has been 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. It once again confirmed the field-aligned direction of the diffusive vector independently of the interplanetary magnetic field polarity. It is also noteworthy that the diurnal phase may follow in time the variation of the size of the polar coronal holes. All these are in agreement with the drift motions of cosmic-ray particles in the interplanetary magnetic field during this time period.

The 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. Further, the variability of the time of maximum of the anisotropy indicates that it is essentially composed of two components; one in the 1800 Hr (co-rotation) direction and the other, an additional component in the 1500 Hr direction (45° east of the S-N line) apparently caused by the reversal of the solar polar magnetic field. They also suggest that the direction of the anisotropy of low amplitude days contribute significantly to the long-term behaviour of the diurnal anisotropy as it produces an additional component of cosmic rays in the radial (1200 Hr) direction. 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. The slope of the power-spectrum density roughly characterized by power spectral index ‘n’ in the high frequency range 3.5×10^{-5} Hz to 8.3×10^{-4} Hz (time scales of 20 min to 8 Hr) is different for the two classes of events. 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 anisotropy during 1981-94 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 28 unusually low amplitude anisotropic wave train events (LAEs) during the period 1981-94. 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 anisotropy of cosmic ray intensity for LAE.

3. RESULTS AND DISCUSSION

The amplitude (%) and phase (Hr) of the diurnal anisotropy for the LAE events along with the corresponding sunspot numbers have been plotted in Figs. 1 (a, b). As depicted in Fig. 1 (a, b), it is quite apparent that the time of maximum (phase) of the diurnal anisotropy significantly shifts towards earlier

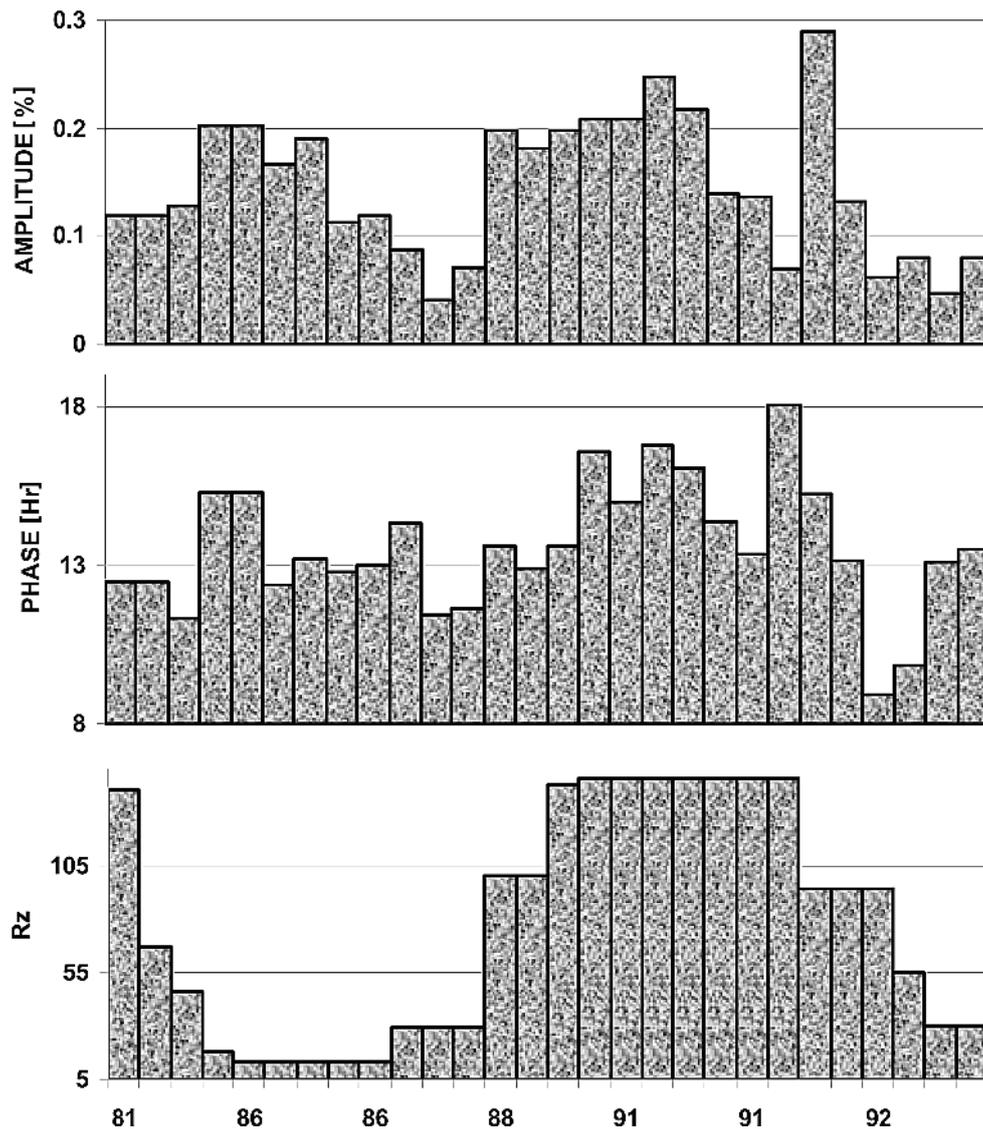


Fig. 1 – The long-term variation of cosmic-ray diurnal anisotropy amplitude (%) and the time of maximum (hr) for each LAE event is shown as a function of solar cycle represented by sunspot number (Rz) for the period 1981–1994.

hours for all the LAE events as compared to the co-rotational (18 Hr) direction, whereas the amplitude significantly deviates from lower to higher values as compared to the annual average amplitude. This is in partial agreement with the earlier findings [26, 27], where they reported that the phase of the diurnal anisotropy remains in the co-rotational direction for majority of the LAEs and shifts towards earlier hours for some of the LAEs.

It can be clearly seen from the figure that the amplitude of the diurnal anisotropy consistently remains constant (0.12%) during the period 1981-84. The distribution of amplitude shows two peaks during 1985 and 1986. There is a sharp decrease in the diurnal amplitude during the year 1986 and remains low during the solar activity minimum year 1987, which is in accordance with the findings of Ahluwalia *et al.* [28] for Deep River neutron monitor for the period 1980-87. It remains almost constant and high for the period 1988-89 close to solar activity maximum and solar activity maximum year 1990. It again falls to lower values during 1991 and gradually attains higher values during 1992. The amplitude falls to lower values during 1993-94. However it does not indicate a one-to-one correlation with the sunspot numbers. It is also evident from the figure that the diurnal amplitude remains high during solar activity minimum (1987) as well as solar activity maximum (1990). However, in case of HAE the diurnal amplitude consistently remains constant and the amplitude distribution shows a peak corresponding to sunspot maximum during the year 1989 close to the solar activity maximum year. Further we find from the figure that the diurnal time of maximum does not show any correlation with the sunspot numbers but indicates a shift towards earlier hours from the normal co-rotational/azimuthal direction during the entire period of event. These trends are found to be consistent with that of Kumar *et al.* [29] and Ananth *et al.* [23] and suggest that the amplitude of the diurnal anisotropy is correlated with the solar cycle but the direction of the anisotropy is not correlated with the solar cycle and shows a systematic shift to earlier hours.

It is clearly seen from the figure that frequency of days with diurnal phase in the 1200 Hr direction significantly remains constant and the frequency of days with diurnal phase in the 1800 Hr direction show an increase during 1985-1986 and 1991. This clearly indicates that during 1981-1994, the change in the direction of the diurnal anisotropy vector has been caused by two kinds of flow of cosmic ray particles; one having a maximum in the 1200 Hr direction and another in the 1800 Hr direction. During 1985-86 and 1991 the phase shift of diurnal anisotropy has been caused by the streaming of particles in the 18 Hr direction and during the rest of the period, in addition to the 1200 Hr component, the presence of excess streaming in the 1200 Hr direction caused a shifting of the diurnal phase to earlier hours. Thus the anisotropy seems to be completely dominated by the two components one in the 1200 Hr and the other in the 1800 Hr direction.

The frequency distribution of low amplitude diurnal anisotropy days for the two solar cycles is shown in Fig. 2. In the same figure we have also shown the variation of sunspot numbers indicating the solar cycle. The figure clearly illustrates that the distribution of low amplitude days presents a very interesting picture. We observed that the occurrence of low amplitude days is dominant during 1985-86 close to solar activity minimum years showing peak during these years. The occurrence of LAE events is practically remains constant for rest of the period of solar activity. These observations clearly suggest that LAE events do contribute significantly to the long-term variation of time of maximum of diurnal anisotropy. We have calculated the correlation coefficient between sunspot numbers (R_z) and occurrence of LAEs, which is found to be -0.35 . Thus one may conclude that LAEs are seems to be weakly correlated sunspot numbers.

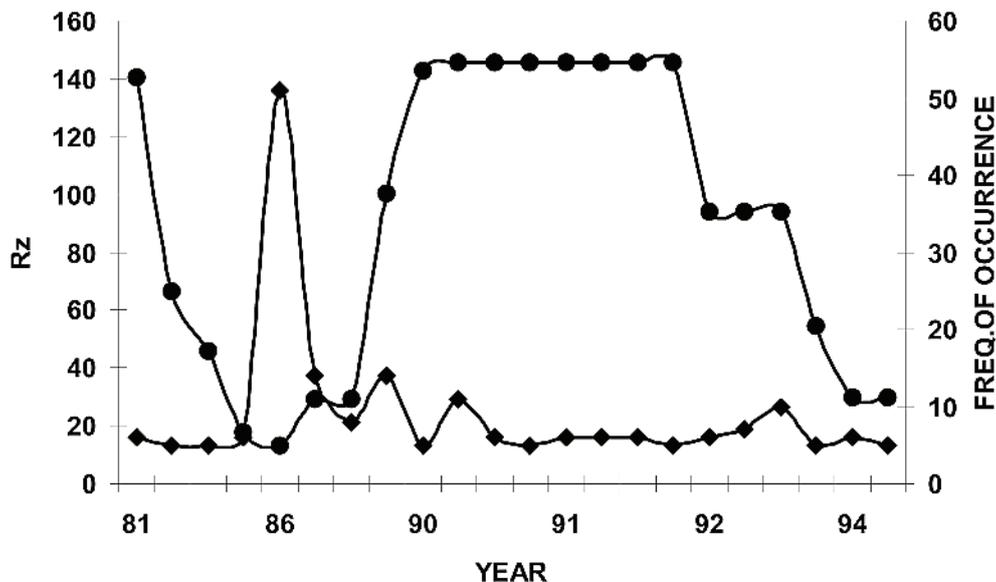


Fig. 2 – The solar cycle dependence of days with diurnal anisotropy for each low amplitude anisotropic wave train event for the period 1981–1994.

4. CONCLUSIONS

On the basis of the present investigation the following conclusions have emerged:

- The amplitude significantly deviates from the annual average values for diurnal anisotropy. The time of maximum of the diurnal anisotropy has shifted towards earlier hours for all the low amplitude anisotropic wave train events.

- The long-term behaviour of the amplitude of the diurnal anisotropy can be explained in terms of the occurrence of low amplitude events.
- The occurrence of low amplitude anisotropic wave train events is dominant during solar activity minimum years.
- The amplitude of the diurnal anisotropy is correlated with the solar cycle but the direction of the anisotropy is not correlated with the solar cycle and shows a systematic shift to earlier hours.
- The long-term behaviour of the time of maximum of the diurnal anisotropy vectors could be explained in terms of co-rotational (1800 Hr) component and 1200 Hr component.

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