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Influence of Solar Activity on Low Amplitude Cosmic Ray Diurnal Anisotropy

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Abstract

A detailed study has been conducted on the occurrence of a large number of low amplitude events (LAE) of cosmic ray (CR) diurnal anisotropy during 1981–1994 as a function of solar activity. The low amplitude days with the time of maximum in the corotational/azimuthal direction do not indicate any significant correlation with solar activity. Our observations suggest that the direction of the anisotropy of LAE events contribute significantly to the long-term behaviour of the CR diurnal anisotropy. The occurrence of LAE is dominant during solar activity minimum years.

Key Words: Cosmic ray, sunspot, solar activity, solar cycle and diurnal anisotropy.

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1. Introduction

The solar activity presents many strange characteristic features from cycle to cycle and has been examined in detail from several workers. Forbush [1, 2] determined that the intensity of Galactic cosmic rays varies inversely with sunspot number. Forbush [2] was the first to point out the inverse correlation between cosmic ray intensity and solar activity in the 11-year variation, and has since been studied in detail by many workers [3, 4, 5]. These studies show that the time lag between cosmic ray intensity and solar activity varies from several to 12 months, depending on the solar cycle and on the activity index adopted [6, 7]. Xanthakis [8] has observed a time lag of one year between the cosmic ray intensity and the solar activity index for the 19^{th} solar cycle. Legrand and Simon [9] have pointed out that there are series of cycles with very high activity level (cycle 18, 19) as well as low activity (cycles 5, 6, 12 and 14). Xanthakis et al. [10] showed that the amplitude of solar modulation in the 20^{th} solar cycle was smaller than the corresponding one of the 19^{th} solar cycle.

The neutron monitor observations indicate that the anisotropy vector exhibits a significant variability in amplitude and time of maximum, when considered on a long-term basis. The studies of the long-term behaviour of diurnal anisotropy [11, 12, 13] have indicated that the anisotropy consists of two components, one related to the 22-year solar cycle and the other related to the 11-year solar activity (sunspot) cycle. Further, Agrawal and Bercovitch [11] have also 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.

Many authors have used the sunspot number or/and the flare activity in order to simulate the cosmic-ray intensity from the solar activity [14, 15]. An attempt was made to find out the most suitable index of the solar activity in order to reproduce to a certain degree the modulation of the cosmic ray intensity [16]. The contribution of more than one solar, interplanetary or geophysical parameter to the cosmic ray modulation process as solar flares, sunspot number, proton events, geomagnetic index etc. have also been reported [17]. Thus to examine the pattern of cosmic ray modulation with respect to the most suitable solar, interplanetary and geophysical parameters we can investigate the characteristic phenomena of the solar activity during a solar cycle.

The power spectral analysis of cosmic ray intensity [18, 19, 20] has indicated that the long-term changes in the power density are related to the solar activity cycle and this has been interpreted in terms of enhancement in the amplitude of the diurnal variation. Various authors have also described an anomalous behaviour of the cosmic ray intensity during the different solar cycles. This can be characterized by the abnormality of the modulation rigidity spectra of cosmic ray intensities [21], the softening of the spectra [22], the poor correlation of the cosmic ray intensity with the solar activity [23]. During the 21^{st} solar cycle a remarkably large time lag between cosmic ray minimum, which occurred in August 1982, and the sunspot maximum, which was in September 1979, has been reported for a first time [24]. The relationship of cosmic ray intensity with solar activity has been studied by a numerous workers [25, 26, 27, 28, 29].

Ahluwalia [30] suggested that the diurnal anisotropy is unidirectional during 1957–1970 having a maximum in the corotation direction (1800 Hr) and during 1971–1978 the anisotropy consists of two components: one in the corotation direction (1800 Hr); and the other in the radial 1200 Hr), similar to the to the concept proposed by Quenby and Hashim [31]. The average diurnal anisotropy vector has been explained as a consequence of the equilibrium established between the radial convection of the cosmic ray particles by solar wind and the inward diffusion of particles along the interplanetary magnetic fields due to the radial gradient [32, 33, 34]; the anisotropy is simply visualized as corotation of particles with the solar system magnetic fields [35, 36]. Further, a detailed analysis of diurnal anisotropy vectors on a long-term basis [37, 38, 39] and on a day-to-day basis [40] clearly indicates that a corotation theory derived by the convection-diffusion model is insufficient to understand the diurnal anisotropy characteristics and the systematic shifting of the average diurnal anisotropy to earlier hours envisages the need of an additional mechanism for explaining the long-term behaviour of diurnal anisotropy.

Xanthakis et al. [41] have studied the cosmic ray intensity records in the 20^{th} and 21^{st} solar cycle of five ground based neutron monitor stations for the time interval 1964–1985 using the method of analysing into trigonometric series and the method of power spectrum analysis. They noticed that cosmic ray intensities exhibit different time evolutions in the 20^{th} and 21^{st} solar cycles. They observed two kinds of periodicity in the data. The first one includes occurrences at periods greater than two years, as the ones of 10.41, 8.41 and 5.50 yr, which differ very little in amplitude from station to station but are similar in phase and the second one includes periodicities smaller than two years (24, 12, 8 and 6 months) which are similar in all stations but appeared in variable time intervals.

An attempt has been made by Mavromichalaki et al. [42] to reproduce the long-term cosmic ray modulation for the 21^{st} solar cycle taking into account the influence of the number of sunspots, solar flares ($\geq$1 B), solar wind streams and the geomagnetic index Ap. For this study monthly cosmic ray data from nine worldwide neutron monitor stations for the period 1975–1985 have been analysed. The empirical formula, which has been used to compute the long-term cosmic ray variations, follows the observations fairly well. They pointed out that the residuals in the cosmic ray intensity between that observed and that calculated by this empirical formula exhibit a still remaining short-term variation in all stations of 2.7 and 3.7 months. Mavromivhalaki et al. [43] determined systematic differences in the overall shapes of successive 11-year modulation cycles (1946–1995) and similarities in the shapes of alternate 11-year cycles seem to be related to the 22-year magnetic cycle and to the polarity reversals of the polar magnetic field of the Sun. They suggest that the 11-year modulation of the cosmic ray intensity has been modulated by some disturbances with the 22-year periodicity through the three solar cycles (1965–1994). The sunspot number has no ability to produce such a 22-year variation [44].

A Study of the cosmic ray intensity power spectrum using the Climax neutron monitor data in the frequency range from 10^{-9} Hz to 10^{-7} Hz (which corresponds to periodicities from 11 years to a few months) during the period 1953–1996 was carried out [45] by means of the successive approximations method of analysis and was compared against the power spectrum and the maximum entropy methods. They noticed that, in the cosmic ray intensity time series at the Neutron Monitor energies over four solar cycles, two groups of fluctuations were appeared: the long term peaks and the short term peaks with a limit of the period of 20 months (1.70 year) between them. This transit limit was also reported by Kudela et al. [46], in an analysis of cosmic ray time series from Calgary and Deep River stations for the time span 1965–1984. This fact indicates that the large-scale cosmic ray variations are caused from different physical mechanisms from those of short scale ones. The sunspot number, which is the most common tracer of solar activity, is not the only manifestation for solar induced effects in the interplanetary medium including the cosmic ray variations [47]. The flare related parameters are also indicators of this modulation. This means, once again, that the investigation of cosmic ray variations provide a unique tool to derive information about the pattern of the interplanetary magnetic field and its flow as well as to determine the temporal and spatial evolution of their configurations.

The purpose of this work is to investigate the solar cycle dependence of the diurnal anisotropy vectors over the period 1981–1994 and tried to interpret the behaviour of the diurnal anisotropy of the LAE events in terms of the distribution and characteristics of the diurnal vectors.

1.1. Data analysis

The pressure-corrected data of Deep River Neutron monitor NM (cut off rigidity = 1.02 GV, Latitude = 46.1 °N, Longitude = 282.5 °E, Altitude = 145 m) has been subjected to Fourier analysis for the period 1981–94, after applying the trend correction to have the amplitude (%) and phase (hr) of the diurnal anisotropy 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 have been selected as low amplitude anisotropic wave train events. The anisotropic wave train events are identified using the hourly plots of cosmic ray intensity recorded at ground based neutron monitoring station and selected twenty eight unusually low amplitude wave train events during the period 1981–94. The average values of sunspot numbers (R_z) for each corresponding LAE event have been used in the present analysis.

2. Results and Discussion

The long term variation of the amplitude (%) and time of maximum (hr) of the diurnal anisotropy for each LAE event is plotted for 1981–1994 and shown in Figure 1, along with the corresponding sunspot numbers. 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. [48] 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 [49]. 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 corotational/azimuthal direction during the entire period of event. The time of maximum for diurnal anisotropy also does not shows any correlation with the sunspot numbers but indicates a significant shift towards earlier hours from the normal corotational/18 Hr direction for the HAE [49]. These trends are found to be consistent with that of Kumar et al. [50] and Ananth et al. [51] 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.

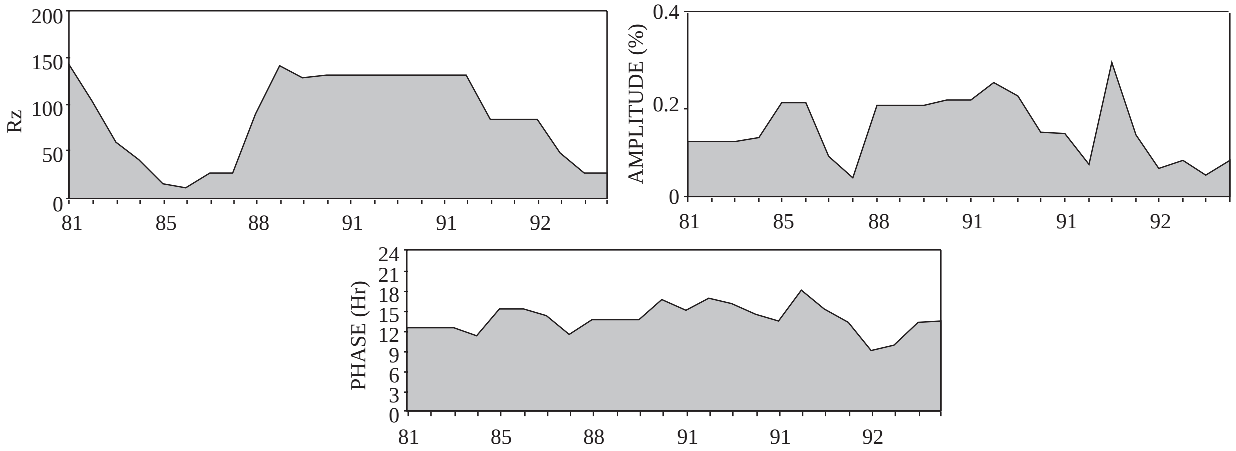

Figure 1. The long-term variation of cosmic-ray diurnal anisotropy amplitude (%) and the time of maximum (hr) for each LAE event is shown as a function of solar cycle represented by sunspot number (Rz) for the period 1981–1994.

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 12 hr component, the presence of excess streaming in the 12 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; whereas in case of HAE it is completely dominated by the15 hr and 18 hr component [49].

The frequency distribution of low amplitude diurnal anisotropy days for the two solar cycles is shown in Figure 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. However, the occurrence of HAE is dominant during 1985 close to solar activity minimum year and 1990 solar maximum year [49]. These observations clearly suggest that LAE events do contribute significantly to the long-term variation of time of maximum of diurnal anisotropy.

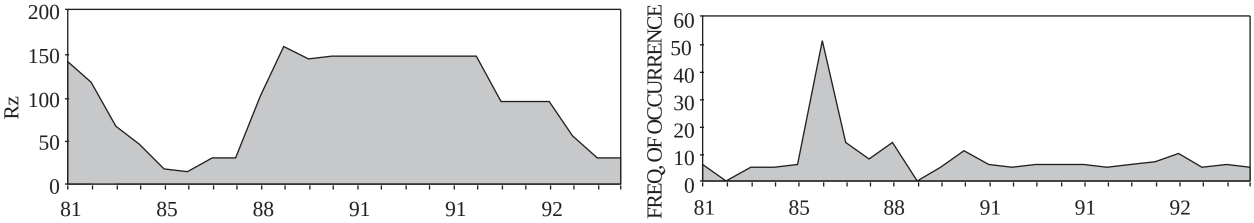

Figure 2. The solar cycle dependence of days with diurnal anisotropy for each LAE event for the period 1981–1994.

3. Conclusions

From the above analysis and observations we may conclude the following:

The long-term behaviour of the amplitude of the diurnal anisotropy can be explained in terms of the occurrence of LAE events.

The occurrence of LAE 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 corotational (1800 Hr) component and 1200 Hr component.

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