Indian J. Phys. **81** (8), 767-777 (2007)

Behaviour of cosmic ray daily variation and solar activity on anomalous days

Rajesh K Mishra[1*] and Rekha Agarwal Mishra[2]

[1]Computer and IT Section, Tropical Forest Research Institute, PO RFRC, Mandla Road, Jabalpur-482 021, Madhya Pradesh, India

[2]Department of Physics, Govt Model Science College (Autonomous), Jabalpur-482 001, Madhya Pradesh, India

E-mail rkm_30@yahoo com

Received 18 May 2006, accepted 1 August 2007

Abstract : A detailed study has been conducted 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 traine events (LAEs) in cosmic ray intensity for the period 1981-90 It has been observed that the phase of the diurnal anisotropy for majority of the LAE events significantly shift 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 LAE events The occurrence of LAE is dominant during solar activity minimum years The Frequency of occurrence of low amplitude events shows a very nominal correlation (–0 54) with sunspot numbers The amplitude as well as phase of diurnal anisotropy does not seem to depend on the annual average sunspot numbers during the periods of LAEs.

Keywords Cosmic ray, sunspot, solar activity, solar cycle and diurnal anisotropy

PACS Nos. 96 40.Kk, 96 40 –z, 96 40 cd

1. Introduction

Long-term variations of galactic cosmic rays were compared with the behaviour of various solar-activity indices and heliospheric parameters many times. A close relation of this parameter to the behaviour of cosmic rays in the past decades was substantiated theoretically [1,2] and proved experimentally [3–14].

The previous studies have established the existence as well as the characteristics of the first three harmonics of the daily variation of cosmic rays (diurnal, semi-diurnal and tri-diurnal) at neutron monitor energies [15,16]. The amplitudes and phases of all the three

*Corresponding Author

components usually show 11 and 22 yr variability associated with the variability of solar output [17,18]. The observational results for various harmonics (particularly at neutron monitor energies) have been compared among themselves as well as with various solar and geophysical parameters [19,20]. It was observed that the annual average amplitudes of first three harmonics are loosely correlated with each other, the lowest diurnal amplitudes observed during low sunspot activity period of 1995-96. Moreover, substantial increases during declining phase of the solar activity observed earlier, both for the second and third harmonics of the daily variation of cosmic rays [16,20]. However, the diurnal time of maximum (*i.e.* phase) has not been found to have any significant correlation with phase of either second or third harmonics. The amplitudes and phase of diurnal variation are found to be significantly smaller during low sunspot activity period [21,22]. It has also been reported that the phase of second harmonic shift to earlier hours during low sunspot activity periods as compared to that observed for the high sunspot activity period [23].

Long-term changes in diurnal anisotropy of cosmic rays has been studied by Ananth *et al* [24] 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^o 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* [25] 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 1965-90 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* [26] 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.

A number of high/low amplitude events have been studied and it was observed that the diurnal time of maximum consistently remains along the co-rotational direction for majority of the events or shift towards later/earlier hours [27–30]. Recently it is reported that the occurrence of LAE is dominant for the positively directed Bz component of interplanetary magnetic field (IMF) polarity [31].

A very few work [24,25] has been done in the past to find out the possible causes responsible to produce the low amplitude anisotropic wave trains and their solar cycle dependence. The purpose of this contribution is to consider at first some different aspects of the cosmic ray modulation during the period 1981-90 and to suggest tentative reasons for the occurrence of low amplitude events and their solar cycle dependence, which is a different approach from the earlier studies.

2. Data and analysis

2.1. Deep River super neutron monitor :

A full size super neutron monitor (NM 64 Type) consists of 18 counters in three independent units each containing 6 counters. This monitor have high counting rates $\approx$7,50,000 per hour at high and middle latitude [32]. The paraffin wax or polythene is used as reflector and moderator. The BF_3 counters used in the monitor assembly are the same, which are recommended for International Quiet Sun Year [33]. The temperature of experimental halls is maintained constant usually at 75° ± 5° F. The output pulse from each counter after proper amplification is fed to the amplifier-mixer in each unit separately, the output of which is counted and recorded for a pre-set duration. The whole operation is sequenced and processed by automatic data recording system.

The count for each section is recorded in punch paper tape and in electronic typewriter alongwith the time and pressure code. The data is therefore processed by electronic computer, where the tests are applied for parallel operation of the three sections. The parallelism check helps in identifying the malfunction of anyone or more counters for immediate correction. The data is usually recorded every five minutes and after proper atmospheric corrections, they are usually averaged for each hour, which forms the basic data for further analysis. The hourly intensity recorded is made available to the scientific community by World Data Center.

The pressure corrected data for the Deep River Neutron Monitor (cutoff rigidity 1.02 GV; latitude 46.1°N, longitude 282.5°E; altitude 145M) have been used for the period 1981-90. The long-term effect has been taken care of by applying trend correction [34]. The pressure corrected data of Deep River has been subjected to Fourier analysis for the period 1981-90 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.

3. 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 :

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

$$a_n = \frac{1}{12} \sum_{i=1}^{24} r_1 \cos nt$$

$$b_0 = \frac{1}{12} \sum_{i-1}^{24} r_1 \sin nt$$

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 $$\phi_n = \tan^{-1} | \, a_n$$

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

$$F(t) = a_1 \cos t + b_1 \sin t + a_2 \cos 2t + b_2 \sin 2t + a_3 \cos 3t$$

$$+ b_3 \sin 3t + a_4 \cos 4t + b_4 \cos 4t$$

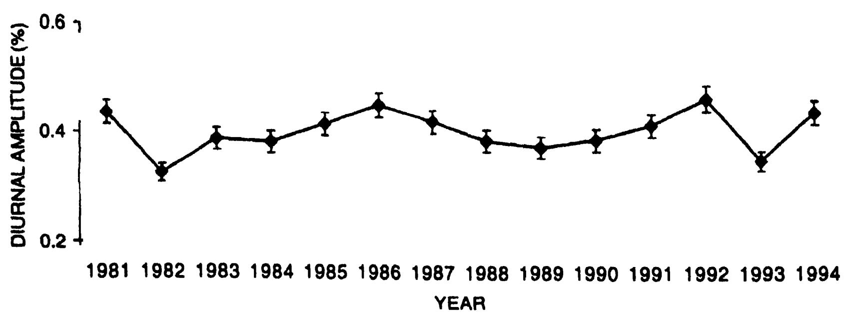

Figure 1. Annual average amplitude (%) of the diurnal anisotropy along with statistical error bar (I) for Deep River during 1981-90.

The theoretical predictions were found to be in good agreement experimentally at observed average diurnal variation characteristics [17,36-39], they observed average diurnal amplitude ≈ 0.4%. The amplitude of the diurnal variation at a high/middle latitude station has been found to be of the order of 0.3 to 0.4%, whereas the amplitudes of two higher harmonics is of the order of 0.02% and 0.08% respectively [40]. The amplitude of the diurnal anisotropy on an annual average basis is found to be 0.4% (Figure 1), which has been taken as a reference line to select LAEs.

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 diurnal anisotropy remains lower than 0.3% on each day of the event for at least five or more consecutive days.
- In the selection of events, special care has been taken, *i.e.* if there occurred any pre-Forbush decreases or post-Forbush decreases before or after the event or the event in recovery phase or declining phase, is not considered.

On the basis of above selection criteria, we have selected 15 low amplitude wave train events (*e.g.* see Figure 2) during the period 1981-90 as shown in Table 1.

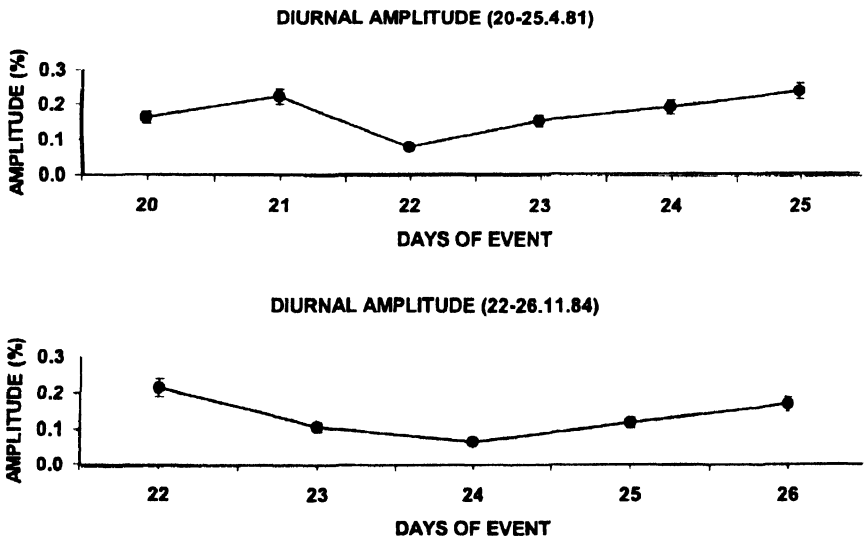

Figure 2. Amplitude (%) of the diurnal anisotropy along with statistical error bar (I) for LAE of 20-25 April 1981 and 22-26 November 1984.

4. Results and discussion

In the present study a systematic correlative analysis has been performed during the period 1981-90, using the average diurnal amplitude and phase of each LAE events of

Table 1. Low amplitude anisotropic wave train events during 1981-90

Event No.	Duration of event	Average diurnal amplitude (%)	Average diurnal phase (Hr)	Average sunspot number (Rz)	Freq of occurrence of days
1	20–25 4 1981	0 118	12 5	48 2	7
2.	17–21 4 1983	0 118	12.5	65	5
3	22–26 11 1984	0 127	11 3	45 4	5
4	13–18 6 1985	0 203	15 3	31	6
5.	12–19 4 1986	0 203	15 3	17 5	8
6	25–30 4 1986	0 167	12 4	32.8	6
7	10–17 6 1986	0 191	13 2	1	8
8.	27.9–12 10.1986	0 112	12 8	18 3	16
9	14–26 12 1986	0 119	13	7 5	13
10	19–25 1 1987	0 087	14 3	14 3	7
11	9–15 3 1987	0 04	11 4	7 9	7
12	7–14.5 1987	0 071	11 6	23 9	8
13	14–18 3 1988	0 198	13 6	78 6	5
14	13–21 4 1988	0 182	12 9	46 2	9
15	16–20 10 1990	0 198	13 6	81	5

cosmic rays for Deep River NM station against sunspot numbers. In cosmic ray modulation studies, sunspot numbers are generally used as a reliable solar parameter representing the variations in solar activity, besides many other solar activity parameter [41,42]. It is an established fact that the modulation of cosmic rays is due to the variations of the solar output in various forms. Threfore, it is necessary to perform correlative analysis between the anisotropic components of cosmic rays detected by ground based instruments continuously and the solar activity on a long-term basis to understood the solar output variability.

The amplitude (%) and phase (Hr) of the diurnal anisotropy for the LAE events along with the statistical error bars (I) and corresponding sunspot numbers (Rz) have been plotted in Figure 3. As depicted in Figure 3, it is quite apparent that the time of maximum (phase) of the diurnal anisotropy significantly shift towards earlier hours for all the LAE events as compared to the co-rotational (1800 Hr) direction, whereas the amplitude significantly deviates from lower to higher values as compared to the annual average amplitude (~0.4%). This is in partial agreement with the earlier findings [27,28], where they reported that the phase of the diurnal anisotropy remains in the co-rotational direction for majority of the LAEs and shift towards earlier hours for some of the LAEs.

In 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 earlier findings of Ahluwalia *et al* [28] for Deep River neutron monitor during the period 1980-87. The phase remains almost constant and high for the period 1988-89 *i.e.* close to solar activity maximum years and on 1990, *i.e.* during solar activity maximum. However, the phase 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 observe from the figure that the diurnal time of maximum does not show any correlation with the sunspot numbers

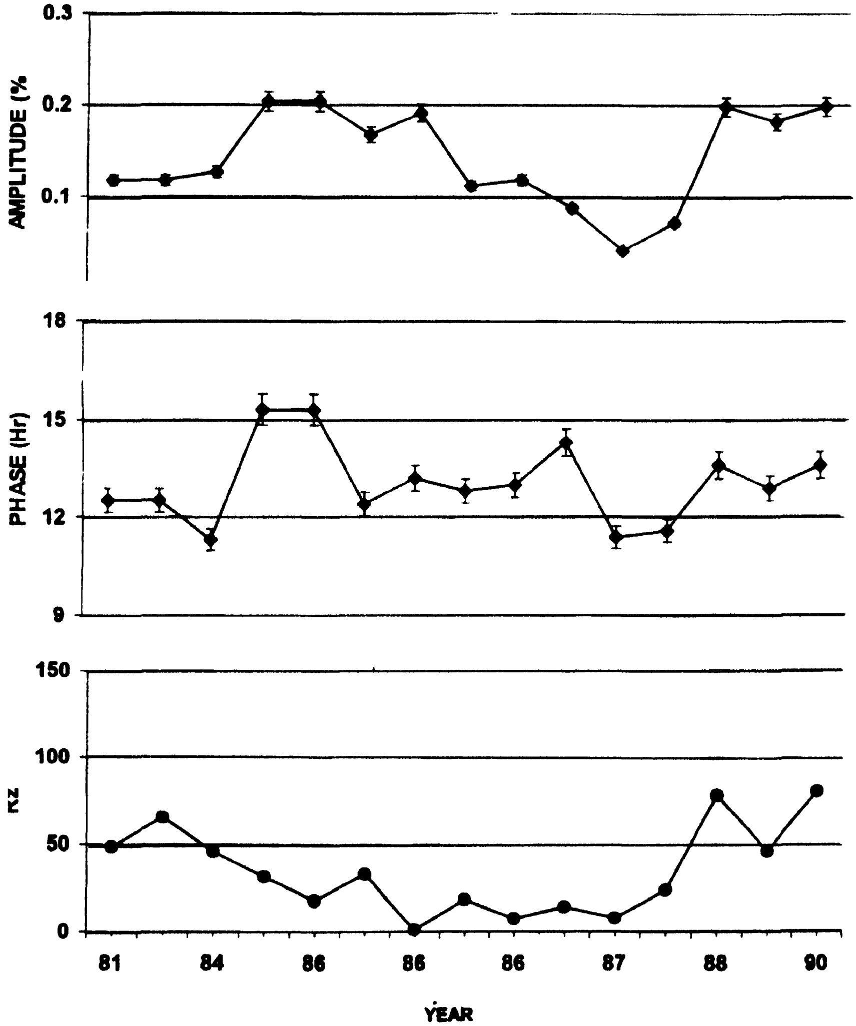

Figure 3. The long-term variation of cosmic-ray diurnal anisotropy amplitude (%) and the time of maximum (Hr) alongwith statistical error bar (I) for each LAE event is shown as a function of solar cycle represented by sunspot number (Rz) for the period 1981-90.

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* [24] 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.

The frequency distribution of low amplitude diurnal anisotropy days for each event during the period 1981-90 is plotted in Figure 4. In the same figure we have also plotted 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 1986-87 *i.e.* solar activity minimum 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 (Rz) and occurrence of LAEs, which is found to be –0.54. Thus one may conclude that LAEs are seems to be negatively correlated with sunspot numbers. However, the occurrence of LAE is dominant during solar activity minimum years.

To find out a possible dependence of the amplitude, phase and occurrence of LAEs on sunspot activity, we have plotted the graph of amplitude, phase and frequency of occurrence of LAE as a function of annual average sunspot numbers along with regression line, R-

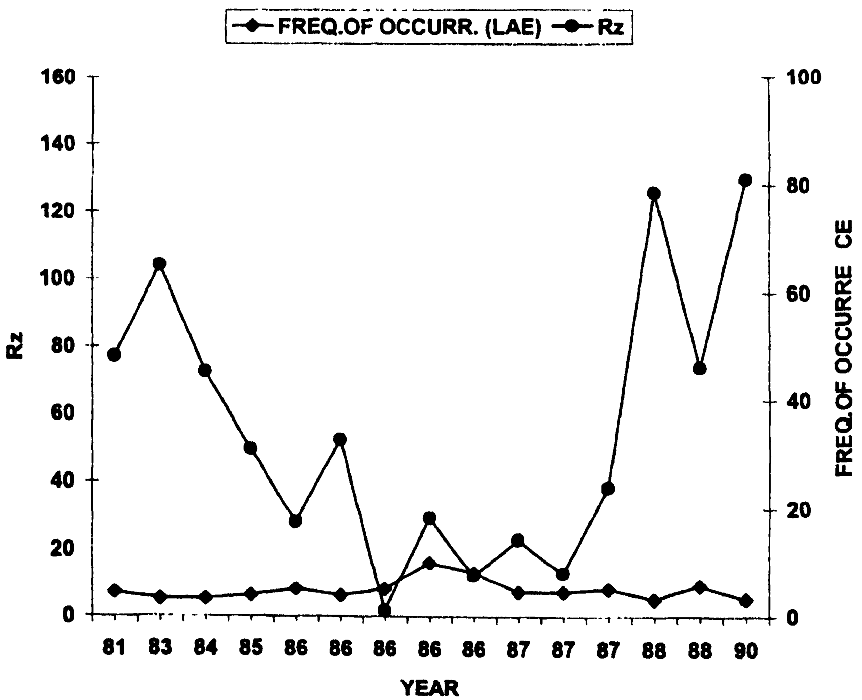

Figure 4. The solar cycle dependence of days with diurnal anisotropy for each LAE event for the period 1981-90.

squared value (The R-squared value, also known as the coefficient of determination, is an indicator that ranges in value from 0 to 1 and reveals how closely the estimated values for the trend line correspond to your actual data. A trend line is most reliable when its R-squared value is at or near 1) and correlation coefficient (*r*) and shown in Figure 5. It is clearly seen from the figure that the amplitude and phase of diurnal anisotropy does not show any correlation with annual average sunspot numbers due to large scattering of points of observation. Thus, we can say the amplitude as well as phase of diurnal anisotropy

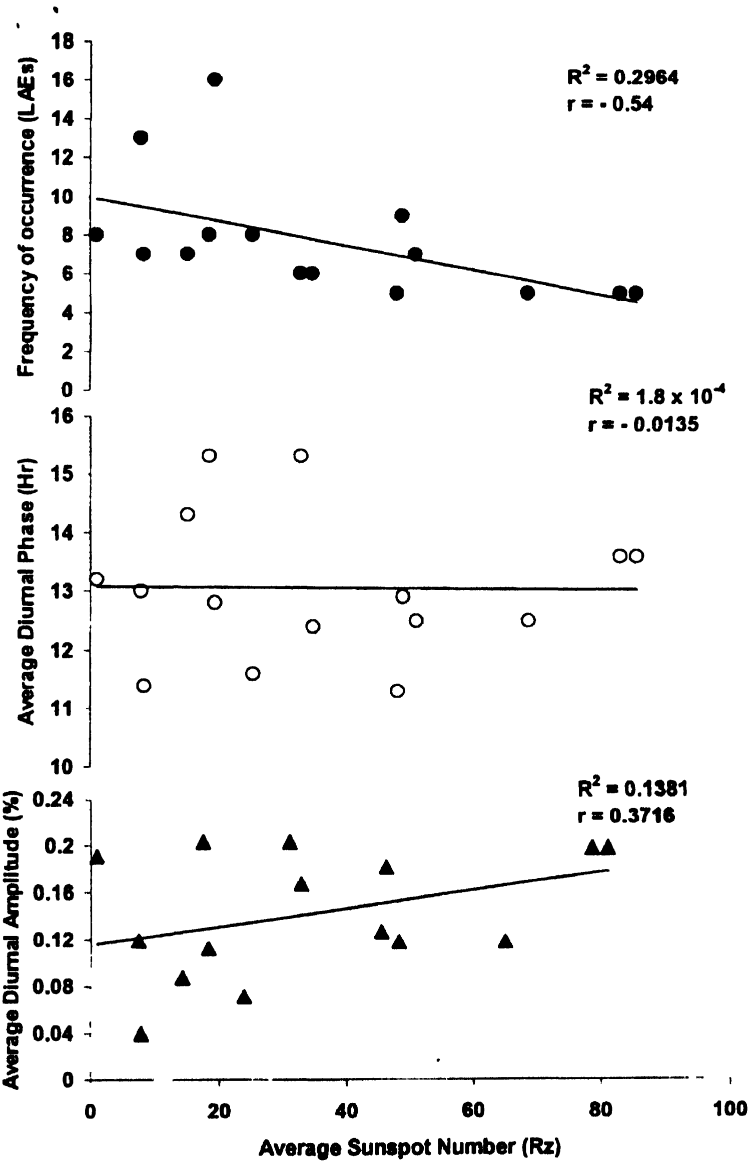

Figure 5. Frequency of occurrence, diurnal phase (Hr) and diurnal amplitude (%) of LAEs along with the variation in annual average sunspot numbers (Rz), regression line, R-squared value and correlation coefficient (*r*) during 1981-90.

does not seems to depend on the annual average sunspot numbers during the periods of LAEs. However, it is also noteworthy from the figure that the frequency of occurrence of LAEs seems to slightly decrease with the increase of sunspot numbers and shows a very nominal correlation of –0.54, which needs to be improved by studying a large data set in future.

5. Conclusions

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

1. 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 as compared to the co-rotational direction for all the LAEs.
2. The long-term behaviour of the amplitude of the diurnal anisotropy can be explained in terms of the occurrence of LAE events.
3. The occurrence of LAE is dominant during solar activity minimum years.
4. The frequency of occurrence of low amplitude events shows a very nominal correlation (–0.54) with sunspot numbers.
5. The amplitude as well as phase of diurnal anisotropy does not seem to depend on the annual average sunspot numbers during the periods of LAEs.

Acknowledgments

The authors are indebted to various experimental groups, in particular, Prof. Margret D Wilson, Prof. K Nagashima, Miss. Aoi Inoue and Prof. J H King for providing the data. We also acknowledge the use of NSSDC OMNI database and NGDC geophysical data.

References

[1] J R Jokipii and B T Thomas *Astrophys J* **243** 1115 (1981)

[2] J Kota and J R Jokipii *Astrophys J* **265** 573 (1983)

[3] J A Simpson *Recent Investigation of the Low Energy Cosmic and Solar Particle Radiations* Preprint N25, Vatican 323 (1963)

[4] I V Dorman and L I Dorman *On the nature of the lag of the cosmic ray intensity changes with respect to the solar activity changes, Cosmic rays. Articles* **N8** 100 (1967)

[5] E J Smith and B T Thomas *J Geophys. Res.* **91** A3 2933 (1986)

[6] W R Webber and J A Lockwood *J Geophys Res* **93** 8735 (1988)

[7] A V Belov, R T Gushchina and I V Sirotina *24th Int Cosmic ray Conf.* **4** 542 (1995)

[8] A V Belov, R T Gushchina and V G Yanke *Izv RAN Ser Phys* **63** N8 1606 (1999a)

[9] A V Belov, R T Gushchina and V G Yanke *26th Int Cosmic Ray Conf.* **7** 175 (1999b)

[10] H Mavromichalaki, A Belehaki, X Rafios and I Tsagouri *Astrophysics and Space Science* **246** N1 7 (1996)

[11] H Mavromichalaki, A Belehaki and X Rafios *Astronomy and Astrophysics* **330** 764 (1998)

[12] G A Bazilevskaya and A K Svirzhevskaya *Space Sci. Rev.* **85** 431 (1998)

[13] K G McCracken and F B McDonald *27th Int Cosmic Ray Conf.* **9** 3753 (2001)

[14] I G Usoskin, K Mursula and G A Kovaltsov *27th Int. Cosmic Ray Conf.* **9** 3791 (2001)

[15] R M Sharma, S K Nigam, R L Singh and S P Agrawal *Indian J. Radio Space Phys.* **7** 210 (1978)

[16] S P Agrawal *J. Geophys. Res. (USA)* **86** 10115 (1981)

[17] U R Rao *Space Sci. Rev. (USA)* **12** 719 (1972)

[18] M A Pomerantz and S P Duggal *Space Sci. Rev. (USA)* **12** 75 (1971)

[19] D Venkatesan and Badruddin *Space Sci. Rev. (USA)* **52** 121 (1990)

[20] S P Agrawal *Space Sci. Rev. (USA)* **34** 127 (1983)

[21] S P Agrawal and R L Singh *Proc. Symp Solar Planetary Phys.* Physical Research Laboratory, Ahmedabad **2** 197 (1976)

[22] S Kumar, S K Shrivastava, S K Dubey, M K Riccharia and U Gulati *Indian J. Radio Space Phys.* **27** 236 (1998)

[23] C M Tiwari *Ph D Thesis* APS University, Rewa, India (2001)

[24] A G Ananth, D Venkatesan and S Pillai *Solar Phys.* **143** 187 (1993)

[25] A G. Ananth, K Kudela and D Venkatesan *Solar Phys.* **159** 191 (1995)

[26] D K Jadhav, M Shrivastava, A K Tiwari and P K Shrivastava *18th Int. Cosmic Ray Conf.*, Bangalore **3** 337 (1983)

[27] S Kumar and M L Chauhan *Indian J. Radio Space Phys.* **25** 106 (1996)

[28] S Kumar, M L Chauhan and S K Dubey *Solar Phys.* **176** 403 (1997)

[29] S Kumar, U Gulati and D Khare *21st Int. Cosmic Ray Conf.*, Adelaide **6** 330 (1990)

[30] R K Mishra *Ph D Thesis* Rani Durgawati University, Jabalpur, India (2006)

[31] S Kumar, R K Mishra, R A Mishra and S K Dubey *29th Int. Cosmic Ray Conf.*, Pune **2** 69 (2005)

[32] C J Hatton *Prog. Elem. Pat. and Cosmic Ray Phys., X.* North Holland Pub. **1** (1971)

[33] H Carmichael *Cosmic Ray, IQSY Instru. Manual,* 7 London (1964)

[34] R S Yadav and H Naqvi Tech. Note No. 1, Aligarh Muslim University, Aligarh, India (1973)

[35] H S Ahluwalia, I S Sabbah, J F Riker and M M Fikani *21st Int. Cosmic Ray Conf.*, Adelaide **6** 303 (1990)

[36] E N Parker *Planet. Space Sci.* **12** 735 (1964)

[37] W I Axford *Planet. Space Sci.* **13** 115 (1965a)

[38] W I Axford *Planet. Space Sci.* **13** 1301 (1965b)

[39] K G McCraken and U R Rao *9th Int. Cosmic Ray Conf.*, London **1** 213 (1965)

[40] M A Pomerantz *J. Geophys. Res.* **65** 3539 (1960)

[41] V K Mishra and D P Tiwari *Indian J. Radio Space Phys.* **32** 65 (2003)

[42] G S Lakhina and S Alex *Indian J. Radio Space Phys.* **31** 337 (2002)