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East-West and Radial Anisotropy in Cosmic Ray Modulation

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Abstract

The cosmic ray (CR) data observed with the Deep River neutron monitoring station has been harmonically analyzed for the period 1964–95 to obtain the diurnal and semi-diurnal components of cosmic ray intensity on geomagnetically 60 quiet days. The annual diurnal anisotropy vectors have been resolved into two components: one along the 12-Hr direction, the radial anisotropy component; and the other along 18-Hr direction, east-west anisotropy component. It is observed that when the polarity of solar poloidal magnetic field (SPMF) in northern hemisphere (NH) is positive, the radial anisotropy component increases; whereas, the east-west anisotropy component decreases. This results in shifting the diurnal anisotropy vector towards earlier hours during the positive polarity epoch. During the negative polarity epoch, the east-west anisotropy component attains its maximum and the radial anisotropy component attains its minimum, which results in shifting the anisotropy vector gradually towards later hours. For semi-diurnal anisotropy, it is found that the magnitude of the 3-Hr component is larger than the 6-Hr component during the positive polarity epoch; which results in shifting the anisotropy vector towards earlier hours, but the same does not hold good for the negative polarity epoch i.e., the magnitude of 6-Hr component is not always found to be greater than the 3-Hr component.

Key Words: Cosmic rays, diurnal, semi-diurnal, anisotropy and solar poloidal magnetic field.

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1. Introduction

Various CR anisotropies are found to depend on the solar magnetic field orientation, which extends in the interplanetary space, embedded within by the solar wind, in turn affecting the polarity configuration of interplanetary magnetic field (IMF). The abrupt reversal of vectors for annual and semi-annual anisotropy is associated with the reversal of polarities of solar polar magnetic fields [1]. Studies of solar magnetic field have revealed that these fields change sign about every 11/22-year cycle, near the time of maximum solar activity [2]. The nature of the long-term variation in CR intensity is likely to depend upon the polarity of the SPMF [3]. The phase shift in CR solar diurnal variation following the heliomagnetic polarity reversal has been pointed out by many researchers [4–6]. Munakata et al. [7] pointed out a clear dependence of the three harmonics on the magnetic polarity of the heliosphere; whereas Ahluwalia and Fikani [8] denied the effect of polarity on semi-diurnal anisotropy parameters.

According to Hashim and Thambyahpillai [9] and Rao et al. [10], the enhanced diurnal variation of large amplitude events exhibits a maximum intensity in space around the anti-garden-hose direction at 0200 Hr, and a minimum intensity in space around the garden-hose direction at 0900 Hr. Mavromichalaki [11] noticed the large amplitude wave trains of cosmic ray intensity during June, July and August 1973. These events exhibit the same characteristics as the event of May, 1973. During these days the phase of the enhanced diurnal anisotropy is shifted to a point earlier then either the corotation direction or the anti-garden-hose direction. The diurnal anisotropy is well understood in terms of a convective-diffusive mechanism [12]. Mavromichalaki [13, 14] has observed that the enhanced diurnal variation was caused by a source around 1600 Hr or by a sink at about 0400 Hr. It was pointed out that this diurnal variation by the superposition of convection and field-aligned diffusion due to an enhanced density gradient of $\approx$8% AU^{-1}.

During the study of cosmic ray diurnal anisotropy observed over the period 1970–1977 using the neutron monitor data of Athens and Deep River stations, Mavromichalaki [15] 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 behavior 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.

1.1. Experimental data and analysis

Pressure corrected data of Deep River neutron-monitoring (NM) station (cutoff rigidity 1.02 GV; latitude 46.1° N; longitude 282.5° E; altitude 145 m) has been Fourier analyzed after applying trend corrections to obtain the first and second harmonics at ground for the period 1964–95. According to solar geophysical data, five quietest days are selected in a month; thus 60 quietest days in a year. These are called International Quiet Quiet days or QQ days. The study of diurnal and semi-diurnal variation has been performed on 60 QQ for the period 1964–95. The days with extraordinarily large amplitude, if any, have not been taken into consideration. Also all those days are discarded having more than three continuous hourly data missing.

2. Result and Discussion

The annual diurnal anisotropy vectors, A_1 (%) obtained on 60 QD for Deep River NM have been resolved into two components, as depicted in Figure 1. One is along the 12-Hr direction i.e., the radial anisotropy component, A_{1R} (%); and the other is along the 18-Hr direction i.e., east-west anisotropy component, $A_{1\phi}$(%). The trend in the plots is very similar to that obtained by Sabbah [6] for the Deep River NM coupled with UMT located at Socorro. Prior to 1971, when the polarity of SPMF in NH is negative, the diurnal anisotropy vector, A_1 was almost constant at $\approx$16-Hr LT direction, with ϕ_1 at ground. After 1971, the radial anisotropy component increases sharply; whereas, east-west anisotropy component decreases gradually and attains its minimum in 1976. This results in shifting the diurnal anisotropy vector towards earlier hours during positive polarity epoch. During negative polarity epoch, the east-west anisotropy component attains its maximum in 1985 and the radial anisotropy component is minimum in 1987, which results in shifting the anisotropy vector gradually towards later hours. The east-west component has its lowest again in 1995 around solar activity minima; whereas, radial component has its highest which is responsible for the early hour shift of diurnal anisotropy vector. For the semi-diurnal anisotropy as depicted in Figure 2, it is found that the magnitude of the 3-Hr component is larger than the 6-Hr component during the positive polarity epoch, which results in shifting the anisotropy vector towards earlier hours; but the same does not hold good for the negative polarity epoch, i.e. the magnitude of the 6-Hr component is not always found to be greater than the 3-Hr component.

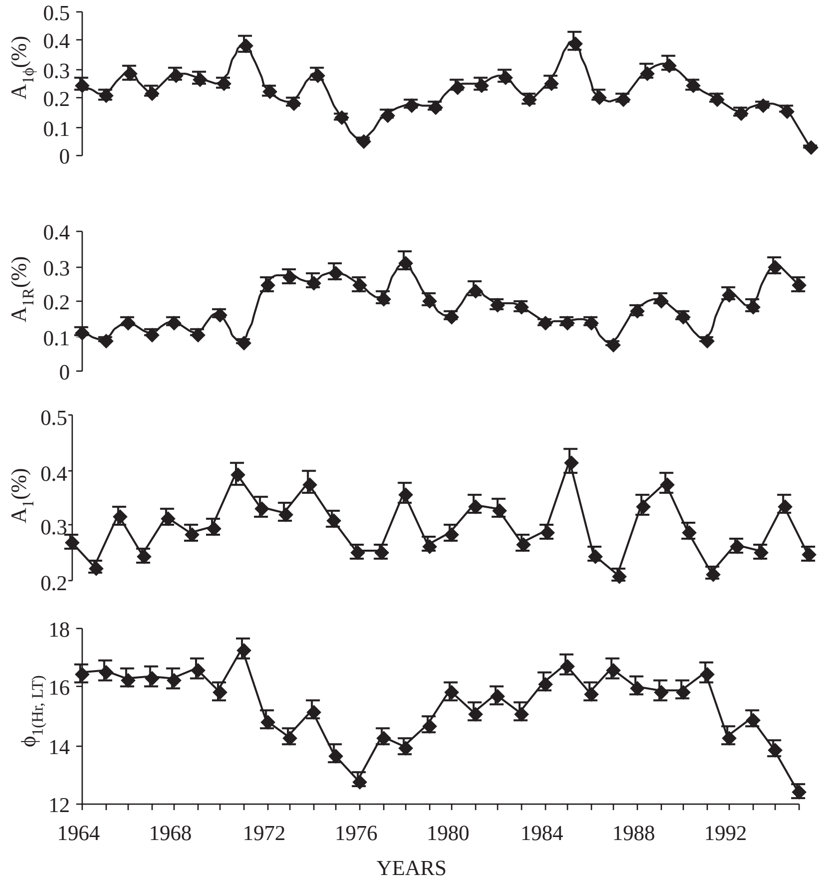

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Figure 1. The phase ϕ_1(Hr, LT), amplitude A_1(%), radial component A_{1R} (%) and east-west component $A_1\phi$ (%) at ground of the annual diurnal anisotropy in cosmic ray intensity on 60 QD plotted along with their respective errors (I) and SPMF polarity in NH and SH for the period 1964–95.

It is found that there exist clear 11/22-year variations of the solar daily variations (diurnal and semi-diurnal); the first is due to the variation of the solar activity while the second is due to the polarity of the solar magnetic cycle [16, 17]. The recovery from CR 11-year modulation follows two distinct repetitive patterns [18]; when the magnetic polarity of the Sun in the NH is negative, the recovery is completed in 5 to 8 years, but for the positive magnetic polarity epochs the recovery period is reduced to less than half as much [19]. The 22-year modulation consists of two discrete states, each corresponding respectively to parallel and anti-parallel states of the polarity of polar magnetic field of the Sun to the galactic magnetic field. When the polar magnetic field of the Sun is nearly parallel to the galactic magnetic field, they could easily connect with each other, so that the galactic cosmic rays could intrude more easily into the heliomagnetosphere along the magnetic lines of forces, as compared with those in the anti-parallel state of the magnetic fields [20].

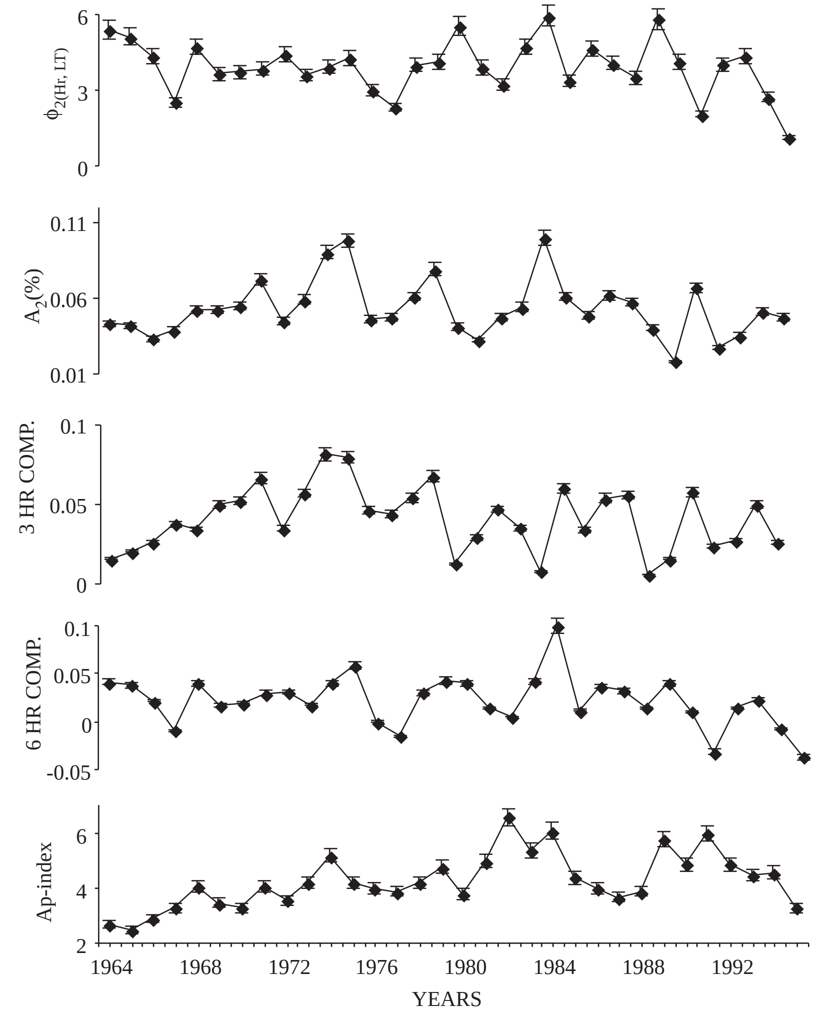

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Figure 2. The phase ϕ_2(Hr, LT), amplitude A$_2$(%), 6 Hr component, 3 Hr component Ap-index on 60 QD along with their respective errors (I) and polarity of SPMF in NH and SH, plotted for the period 1964–95.

According to the theoretical investigation by Munakata and Nagashima [21], the polarity dependence of the phase change has been interpreted as a result of the change in CR density distribution in space caused by the difference of CR drift motion in the positive and negative polarity states [22]. The steady state drift models predicts that the phase of the diurnal anisotropy responds significantly to a polarity change and shifts from ∼18-Hr LT in space for negative polarity epoch to ∼15-Hr LT in space during the positive polarity epoch [23]. Sign of the transverse particle density gradient changes with a change in the solar magnetic polarity. Its annual mean value is positive for positive polarity epoch and negative for negative polarity epoch [24].

The two components of the solar diurnal variation observed with two detectors characterized by linearly independent coupling functions have been used by Sabbah [5, 6] to estimate the free space anisotropy vector during the period 1968–95. The amplitude of the radial anisotropy shows ∼20-year magnetic cycle with the highest values around solar activity minima for positive polarity; whereas, the east-west anisotropy is minimum. Ahluwalia [25] resolved the annual mean diurnal anisotropy vector along the two rectangular components one is the east west along 18-Hr direction and the other is the radial component along 12-Hr direction. The amplitude of the radial anisotropy is zero till 1970 and increases sharply after polar field reversal of 1971. This analysis has been extended to diurnal and semi-diurnal anisotropy for the period 1964–95. The semi-diurnal anisotropy has been resolved along the two perpendicular components in the 3-Hr and 6-Hr directions.

Potgieter et al. [26] pointed out that during the periods when the northern hemispheric field points towards the Sun, positively charged particles will flow from the ecliptic towards the solar poles, leading to a decrease in intensities of positively charged particles observed near the Earth and hardening the primary spectra of particles to which neutron monitors respond. When the southern hemispheric field points towards the Sun, particles flow towards the ecliptic and near to the Earth intensities are increased and the spectra is softened. Nagashima and Fujimoto [3] pointed out the existence of polarity dependence in the rigidity spectrum of the semi-diurnal anisotropy. The semi-diurnal anisotropy vectors suddenly change their relative configuration from the usual direction to another for the polarity reversal of polar magnetic field of Sun from positive to negative state in NH. The state is defined as "positive" when the polar magnetic field is away from the Sun in northern hemisphere (NH) and towards the Sun in southern hemisphere (SH), while it is called "negative" when the polar magnetic fields are reversed. Duldig [27], using the data from the underground Mawson telescope for the period 1973–89, observed that the solar semi-diurnal variation is remarkably constant throughout the solar polarity reversal of cycle-21. Thus, confirming that the semi-diurnal anisotropy changes only at low rigidities with the solar polarity reversal but the higher rigidity spectrum remains constant [3]. On the contrary, Ahluwalia and Fikani [8] denied the effect at all primary rigidities. Munakata et al. [21] pointed out that during the 1970's and 1990's, when the magnetic polarity of the heliosphere is positive in NH, the phases of the first two harmonics are significantly shifted towards earlier hours than those during 1980's when the polarity of the heliosphere is negative in NH.

3. Conclusions

From the present analysis we may conclude that for the positive polarity epoch the radial anisotropy vector has higher amplitude as compared to east-west anisotropy vector, which results in shifting the phase towards earlier hour for the diurnal anisotropy vector whereas the same does not hold true for the semi-diurnal anisotropy.

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