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Semi-diurnal variation in cosmic ray intensity under different geomagnetic conditions

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A new concept of data analysis is attempted for studying the long/short term daily variations in cosmic ray (CR) intensity recorded with neutron monitors/meson telescopes. Fourier technique was applied on four different groups of days chosen according to their different geomagnetic conditions. The selected groups are 60 quietest days (60 QD), 120 quiet days (120 QD), continuous quiet days (CQD) and all days (AD) in a year. CQD is a new set of days selected on the basis of A_p and K_p values. These are the days when transient magnetic variations are supposed to be regular and smooth continuously for a span of at least three days. The criterion of selection is based upon the mathematical manipulation with A_p index. The data of Deep River neutron monitoring station are used for the period 1985—1995 to investigate, for a comparative study, the semi-diurnal anisotropy in CR intensity on 60 QD, 120 QD, CQD and AD. It is observed that 60 QD are most suitable to the anisotropic studies on short/long term basis. The time/spatial variations in the amplitude and phase of the semi-diurnal anisotropy become more pronounced for 60 QD for the period under investigation.

INTRODUCTION

Cosmic ray intensity exhibits a daily variation composed of a prominent diurnal component and also a semi-diurnal component of lesser amplitude. CR intensity observed on the ground is subject to the solar semi-diurnal variation of extraterrestrial origin [31]. The existence of CR anisotropy in the interplanetary medium is direct consequence of the modulation produced by the Sun. Studies of the solar semi-diurnal variation have been made by many authors [4, 16, 17] to obtain information on solar modulation in various conditions of heliosphere.

Ahluwalia [4] has found the semi-diurnal variation to be more prominent at equatorial locations. The dependence of the semi-diurnal variation on the median asymptotic latitude λ_m of viewing of the detector is given by $\cos^2\lambda_m$, independent of the primary rigidity [8]. Ables et al. [1] pointed out that the direction of maximum of the semi-diurnal component in free space is nearly perpendicular to the average direction of the interplanetary magnetic field (IMF). Agrawal [2] has reported some of the salient features of semi- and three-diurnal variations of CR. It has been found that the amplitude reduces roughly by a factor of 4 to 5 each time as one advances to higher harmonics when logarithmic scales are used to represent Fourier analysed average amplitude and phase. The mean amplitude of the semi-diurnal variation [36] associated with geomagnetically disturbed days is observed smaller than on geomagnetic quiet days. Further, on geomagnetic disturbed days the solar daily variation is only diurnal in character and semi-diurnal variation is significant only on geomagnetic quiet days. The low average amplitude of the semi-diurnal variation [4] on geomagnetically disturbed days compared with geomagnetically quiet days is primarily due to the large variability of the time of maximum of the semi-diurnal variation on disturbed days.

Agrawal [3] and Bieber and Evenson [12] have preferred to investigate the daily variation in CR intensity on long/short term basis performing the analysis for AD in a year, whereas Kumar et al. [24] have studied long/short term daily variation on geomagnetically 60 QD. Jadhav et al. [22] found that the semi-diurnal amplitude remains high during high amplitude anisotropic wave trains and contributes significantly on such days. Nigam et al. [30] have calculated the average value of amplitude and phase of semi-diurnal variation for positive sector group, negative sector group and mixed polarity group. Sabbah [35] calculated the diurnal variation for days with high, intermediate and low interplanetary magnetic field (IMF) magnitude. Thus, a question arises as to what type of days will be more suitable for performing long/short term analysis of CR intensity. Therefore, apart from AD and 60 QD, two more types of days, i. e., 120 QD and CQD, have been considered for the comparative studies of semi-diurnal anisotropy over a period of 11 years. An attempt was made to study the variational features of semi-diurnal time of maximum and its amplitude on different groups of days selected under different criteria depending on A_p values.

Ballif et al. [10] correlated K_p and A_p with the mean fluctuations in amplitude of IMF, which in turn is related to diffusive component of convection-diffusion theory. A_p is also found to be related with solar wind velocity, which is related to convective component of convection-diffusion theory. The semi-diurnal variations are produced by the diffusion and convection of cosmic rays in the interplanetary space [26]. The amplitude of semi-diurnal variation is found to be proportional to the solar activity [19]. Ahluwalia [5], on the long term behaviour of the three harmonics of cosmic ray daily variation, showed that although a high degree of year to year variability exists, a trend with solar activity is evident. A significant semi-diurnal variation for the period 1953—1992 has been observed [8], although its amplitude and phase change from year to year.

EXPERIMENTAL DATA AND THEIR ANALYSIS

The pressure corrected data of Deep River Neutron Monitor (NM) (cutoff rigidity = 1.02 GV, latitude = = 46.1° N, longitude = 282.5° E, altitude = 145 m) has been subjected to Fourier analysis for the period 1985—1995 after applying the trend correction. A detailed comparative study of semi-diurnal anisotropy in CR intensity on four different groups of days selected under different criteria based on the values of A_p index has been performed over a period of one solar activity cycle (SAC). Thus, the data are analysed for four different phases of solar cycle, such as solar minimum activity period (1986), ascending phase of SAC (1988), solar maximum period (1991) and descending phase of SAC (1995). The days with extraordinarily large amplitude, if any, have not been taken into consideration. While performing the analysis of the data all those days are discarded having more than three continuous hourly data missing. For the purpose of study four groups of days are selected as follows:

(i) **All days**: This means all the 365/366 days in a year. The days are termed as AD.

Quiet days: Days on which the transient magnetic variations are regular and smooth, are said to be magnetically quiet or calm or Q days. The criterion of selection is based upon A_p and K_p values. There are two types of Q days:

(ii) **60 Quiet days**: According to solar geophysical data (SGD) five quietest days in a month are selected. These days are called the International quiet-quiet-days or QQ days. Thus, 60 Q days in a year; termed as 60 QD.

(iii) **120 Quiet days**: First ten Q days in a month. Thus, 120 Q days in a year; termed as 120 QD.

(iv) **Continuous quiet days**: 60/120 quiet days selected are discrete and scattered all over in a year's span of 365 days. In many cases the quiet days are preceded or followed by the days having larger values of geomagnetic disturbance index. Such days may be disturbed days. To avoid such days and to get a set of days having values of A_p index low continuously at least for three days, a group of days called continuous quiet days (CQD) is being selected [23].

RESULTS AND DISCUSSION

The values of amplitude (A, %) and phase (P, hrs) of the semi-diurnal anisotropy of CR intensity obtained on a day to day basis for 60 QD, 120 QD, CQD and AD in a year were plotted histographically for all the four phases of solar activity cycle (SAC), i. e., ascending phase of SAC, solar maximum period, descending phase of SAC and solar minimum. One of them is shown in Fig. 1, drawn for the year 1986 which corresponds to solar minima for the 22nd solar cycle. It is observed that during the year 1986 the prominent peak of the phase lies in the same interval of 03±01 hr for all the four groups of days. The sharpness of the prominent peak is maximum in case of 60 QD.

Considering the semi-diurnal amplitude for the year 1986, almost 80 % distribution is confined to a very narrow interval of 0.00—0.16 % for all the four groups of days but the height of the peak is maximum in case of 60 QD. As the level of the solar activity is low, the trend for the distribution of amplitude remains the same for all the four groups. It is observed that the general trend as shown by the distribution for the phase and amplitude for all the four types of days is quite comparable. The distribution in most cases is sharper in case of 60 QD,

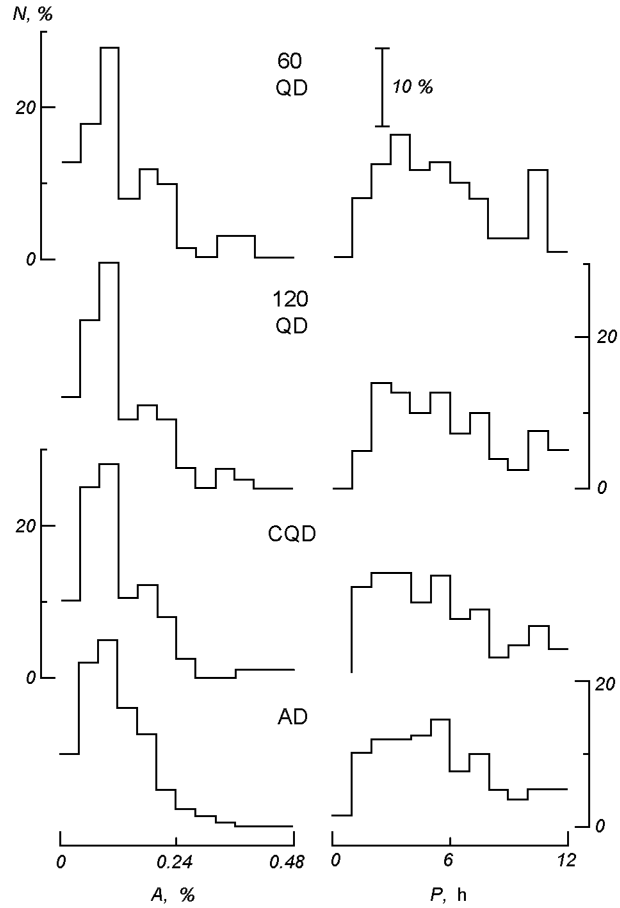

Fig. 1. The occurrence of days (N, %) plotted histographically for the amplitude (A, %) and phase (P, hrs) of the semi-diurnal anisotropy in CR intensity during 1986 for 60 QD (*a*), 120 QD (*b*), CQD (*c*) and AD (*d*)

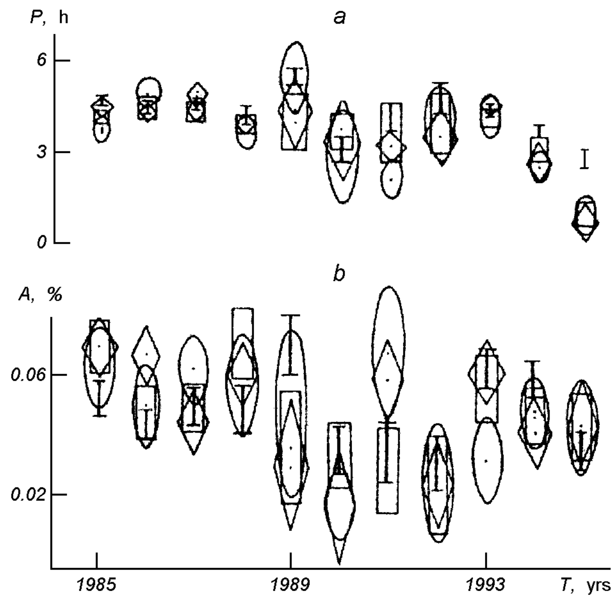

Fig. 2. The annual average values of phase P, hrs in LT (*a*) and amplitude A, % (*b*) at ground for the semi-diurnal anisotropy during the period 1985—1995 plotted for 60 QD (ellipses), 120 QD (crosses), CQD (diamonds) and AD (vertical bars). Height of the legend represents twice the error contained in the values

whereas some of the finer features of anisotropic variations are suppressed in AD. In some cases sharper peaks are also seen in case of CQD, as of sustained quiet conditions and small deviations on a day-to-day basis are suppressed. Fig. 2 shows the annual average values of semi-diurnal phase (hrs) in LT and amplitude (%) at ground during the period 1985—1995 for Deep River Neutron Monitor. In all cases the height of the legend represents twice the error contained in the values represented. The plots in Fig. 2, *a* show that the general trend shown by all the four types of days considered for analysis is quite comparable. However, some statistically significant deviations irrespective of the level of solar activity during some of the years are noticeable particularly on 60 QD, 120 QD or CQD, when compared with AD, which is more clearly observable during the year 1995. From the semi-diurnal amplitude plots shown in Fig. 1, *b*, it is observable that the general trend shown by all the groups of days considered for analysis, are same within the statistical errors. It is observable that during the year 1988 the value of semi-diurnal amplitude in case of 120 QD is statistically different from that obtained for AD. During the year 1991, the semi-diurnal amplitude is statistically slightly higher for 60 QD as compared to AD and 120 QD, whereas during 1993 the value of semi-diurnal amplitude is low in case of 60 QD. The statistical errors contained in the value of semi-diurnal amplitude for all four type of cases are observed to increase with the increase in the level of solar activity; however, during 1995, the error in case of 60 QD has slightly increased. During the entire period of investigation, statistical errors in case of AD have been observed to be low in comparison to 60 QD, 120 QD and CQD, which agrees well with the fact that the statistical errors for similar distributions decrease with increase in number of data.

The vector addition plots of semi-diurnal anisotropy for four different types of days for the period 1985—1995 are shown in Fig. 3. The general trend in the year to year variation of the phase of semi-diurnal anisotropy is almost alike consistently throughout the

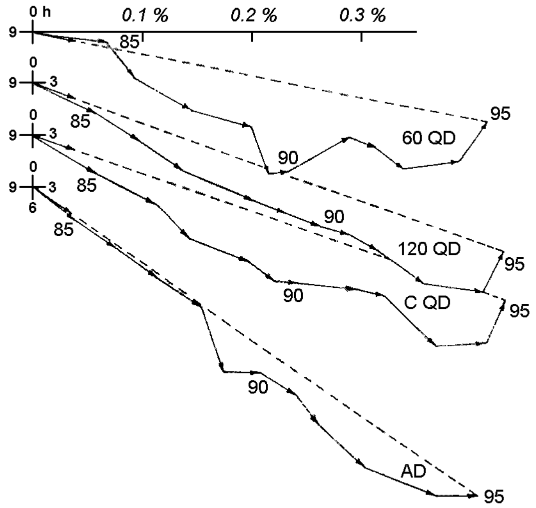

Fig. 3. Vector addition diagram of the semi-diurnal anisotropy for different types of days for the period 1985—1995

period under consideration. However, the phase of semi-diurnal anisotropy has shown a shift towards later hours during the year 1989, in case of 60 QD and AD and to some extent for CQD as well. This could be because of the abrupt increase in the average value of A_p index [2, 25, 37]. Further, the changes in the semi-diurnal anisotropy observable during the period 1992—1995 are most prominent in case of 60 QD, followed by CQD and 120 QD, whereas these changes are suppressed in AD. This could be either due to increased statistical error for different types of days during 1995 as compared to years 1993 and 1994. Furthermore, the phase has shown a significant shift to early hours, which is observable particularly on 60 QD followed by CQD and 120 QD as the solar activity approaches to its minimum level of SAC-23 during the year 1995. The phase of the semi-diurnal anisotropy has significantly shifted to earlier hour during 1990—1991 and 1995. The phase shifted to later hours during 1986. It is further observable that, during CR maximum of 1986, the polarity of SPMF is negative in NH, whereas it is positive during CR intensity maximum/solar activity minimum of 1995. Semi-diurnal variation has solar cycle dependence and it also depends on the polarity state of the polar magnetic field of the Sun, i. e. the variation changes its phase for the transition of the polarity state from positive to negative or vice versa, which occurs every epochs of the maximum solar activity [29]. According to the theoretical investigation by Munakata and Nagashima [26] the polarity dependence of the phase change has been interpreted as a result of the change of the CR density distribution in space caused by the difference of CR drift motion in the positive and negative polarity states. Nagashima and Fujimoto [28] pointed out that semi-diurnal harmonic vectors suddenly change their relative configuration from a proper type to another on the harmonic dial for the polarity reversal of the polar magnetic field of the Sun from positive to negative state. They pointed out the existence of polarity dependence in the rigidity spectrum of the semi-diurnal variation. The state is defined as positive when the magnetic field is away from the Sun at the north pole and toward the Sun at the south pole, while it is called negative when the polar magnetic fields are reversed. The spectrum of semi-diurnal is reported to be harder in negative state than that in the positive state.

A clear dependence of the three harmonics on the magnetic polarity of the heliosphere during the 1970's and 1990's when the magnetic polarity of the heliosphere is positive in NH has been pointed out by Munakata et al. [27]. The phases of the first three harmonics have significantly shifted towards earlier hours than those during 1980's when the polarity of heliosphere is negative in NH. Duldig [14], using the data from underground Mawson telescope for the period 1973—1989, observed that the solar semi-diurnal variation is remarkably constant throughout the solar polarity reversal of cycle-21. Thus, this confirms that the semi-diurnal anisotropy changes only at low rigidities with the solar polarity reversal but the higher rigidity spectrum remains constant [28]. Potgieter et al. [32] pointed out that during the periods when northern hemispheric field points towards the Sun, positively charged particles will flow from the ecliptic towards the solar poles, leading to 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 point towards the Sun, the particles flow towards the ecliptic and near the Earth intensities are increased and the spectra are softened.

The overall variation in the amplitude of semi-diurnal anisotropy for the period under consideration is comparable for different types of days. During the years 1989 and 1991, the semi-diurnal amplitude is observed to be high for different types of days except for 120 QD with the increase in the value of A_p index during the year. During the year 1990 the amplitude is observed to be reduced; where the value of the A_p index is relatively low. On the contrary, during the year 1995 where the average A_p index is further lowered, the amplitude is observed to be larger for different types of days. This brings out the fact that semi-diurnal amplitude although depends on the A_p index value, i. e., level of solar activity, however, this is not the only deciding factor. A_p bears a negative correlation with GCR intensity [6]. Bartels [11] considered A_p to be a measure of the geoeffectiveness of the solar corpuscular emissions (high speed solar wind stream HSSWS). The interaction between HSSWS and the Earth's magnetosphere transfers a vital information to the magnetosphere, which manifests itself in changing the geomagnetic activities as monitored by its geomagnetic indices A_p and a_a [38, 39]. A relationship exists between A_p, HSSWS and the southward component of IMF [13]. High speed solar wind streams occur during the descending phase of solar activity cycles 20, 21 near activity minima. High speed solar wind streams dominate the period 1982—1985 which includes the period when large values of semi-diurnal amplitude are observed. Ahluwalia and Fikani [8] have reported the appearance of HSSWS during the declining phases of SAC-20, 21, i. e., during the years 1973—1975 and 1982—1985. El-Borie et al. [15] observed the low values of solar semi-diurnal variation near the minimum solar activity 1986—1987 while large values are obtained near maximum solar activity 1990—1991. Large amplitudes of solar semi-diurnal variations are observed during declining phases of SAC. Fikani et al. [18] using the Deep River NM data for 1966—1988 observed a broad enhancement in the amplitude for the year 1973 through 1976. Iucci et al. [20, 21] with 33 well defined events of HSSWS found that the semi-diurnal amplitude depends on the Earth's position inside the stream. The present study performed on 60 QD leads to a high value of amplitude of semi-diurnal anisotropy during the year 1985.

The amplitude of the semi-diurnal variation depends upon the primary rigidity [31, 34, 40]. The variational spectrum applicable to semi-diurnal anisotropy may be represented by a double power law, with exponents γ_1 for a range of primary rigidities $R \le R_p$ and γ_2 for $R > R_p$, R_p being the peak rigidity. Ahluwalia [8] found $\gamma_1 = 0.7\pm0.3$ and $\gamma_2 = -0.4\pm0.2$. The upper cut-off rigidity, R_c applicable to semi-diurnal anisotropy has higher values near solar activity maxima and low values around solar activity minima. During the epoch when the solar wind speed is high (1982—1985) the value of the upper cut-off rigidity is also high. A close correspondence exists between the magnitude of IMF and the value of R_c and the peak rigidity, R_p. Both exhibit the solar as well as the hale cycle variation.

Pransky et al. [33], using ionization chamber data for the period 1954—1989, obtained results of decrease in amplitude during 1964, 1976 and 1986, i. e., the years of minimum solar activity. They also noticed the decrease in amplitude during magnetic field inversion of the Sun. Further, it is suggested that the decrease in amplitude during solar activity minimum can be explained by decrease in regular component of the IMF intensity. The reason for decrease in amplitude during magnetic field inversion has been thought to be due to increase of IMF irregularities originated from solar polar coronal holes. On the contrary, Ahluwalia and Fikani [7], using the muon telescope data for the period 1966—1988, observed increase in the amplitude after the epochs of SPMF reversal. The amplitudes are also observed to be smaller when the solar activity is low, which is in agreement with the findings of Pransky et al. [33]. According to Ahluwalia and Fikani [9], the polarity of IMF has no effect on the semi-diurnal anisotropy parameters (amplitude as well as direction) at all primary rigidities.

The amplitude of the semi-diurnal variation depends on the azimuthal direction of arrival of the particles incident at an angle of 45° to the zenith, whereas it is three times larger for the particles coming from south than for those coming from north [16, 17].

CONCLUSION

On the basis of the vigorous analysis of the CR intensity data, the following conclusions are derived:

1. It is concluded that 60 QD are better suited for long/short term studies of semi-diurnal anisotropy. The distribution of phase and amplitude on 60 QD are more regular and some of the variations are observed more clearly.
2. Significant semi-diurnal variation is observed for the entire period of study although its amplitude and phase change from one year to the next.
3. The amplitude of semi-diurnal anisotropy decreases during minimum solar activity and is high during the occurrence of HSSWS.

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ПІВДОБОВА ВАРІАЦІЯ ІНТЕНСИВНОСТІ КОСМІЧНИХ ПРОМЕНІВ У РІЗНИХ ГЕОМАГНІТНИХ УМОВАХ

Реха Агарвал Мішра, Раджеш К. Мішра

Застосовано нову концепцію аналізу даних до вивчення довго- та короткочасних добових варіацій інтенсивності космічних променів (КП), зареєстрованих за допомогою нейтронних моніторів і мезонних телескопів. До чотирьох різних груп діб, вибраних відповідно до різних геомагнітних умов, застосовано метод Фур'є. Вибрано такі групи: 60 найспокійніших діб (60 НД), 120 спокійних діб (120 СД), безперервні спокійні доби (БСД) та всі доби (ВД) року. Група БСД являє собою новий ряд діб, вибраних на основі величин A_p та K_p. Це такі доби, протягом яких змінні магнітні варіації, як припускається, є постійними і плавними безперервно для проміжку принаймні у три доби. Критерій вибору оснований на математичних маніпуляціях з індексом A_p. Щоб дослідити (для порівняльного вивчення) півдобову анізотропію інтенсивності космічних променів у групах 60 НД, 120 СД, БСД і ВД, використано дані нейтронного монітора станції Діп Рівер (Deep River) за період 1985—1995 рр. Виявлено, що група 60 НД найбільше підходить для дослідження анізотропії на основі довго- та короткочасових членів. Для досліджуваного проміжку часові та просторові варіації амплітуди й фази для півдобової анізотропії більше проявляються в групі 60 НД.