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Diurnal anisotropy of cosmic rays during intensive solar activity for the period 2001–2014

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HIGHLIGHTS

- The cosmic ray diurnal anisotropy is examined for two neutron monitors with the same longitude and different latitude.
- The diurnal amplitude seems to be varied with the different phases of the solar cycle for the examined time period 2001 to 2014.
- Changes of the diurnal anisotropy vectors are observed during extreme solar and cosmic ray events.

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ABSTRACT

The diurnal variation of cosmic ray intensity, based on the records of two neutron monitor stations at Athens (Greece) and Oulu (Finland) for the time period 2001 to 2014, is studied. This period covers the maximum and the descending phase of the solar cycle 23, the minimum of the solar cycles 23/24 and the ascending phase of the solar cycle 24.These two stations differ in their geographic latitude and magnetic threshold rigidity. The amplitude and phase of the diurnal anisotropy vectors have been calculated on annual and monthly basis.

From our analysis it is resulted that there is a different behaviour in the characteristics of the diurnal anisotropy during the different phases of the solar cycle, depended on the solar magnetic field polarity, but also during extreme events of solar activity, such as Ground Level Enhancements and cosmic ray events, such as Forbush decreases and magnetospheric events. These results may be useful to Space Weather forecasting and especially to Biomagnetic studies.

1. Introduction

Cosmic rays (CR) are particles at very high energies from extraterrestrial sources within or outside the Milky Way with high stability and isotropy in galactic scale. The intensity of galactic cosmic rays (GCR) recorded by ground based neutron monitors shows periodic and abrupt changes as the Sun and the interplanetary magnetic field (IMF) result in anisotropies and variations in both the energy spectrum and the intensity of CR as a function of space, time and energy called CR intensity modulation (Bieber et al., 2010).

The diurnal anisotropy of CR intensity is an anisotropic, short-term variation of local time with a periodicity of 24 hours due to the rotation of the Earth around its axis and consequently the rotation of cone detectors of CR, as shown in Fig. 1 (Pomerantz and Duggal, 1971; Ahluwalia, 1988). The diurnal variation is the result of complex phenomena involving the convection of GCR flux by the solar wind and the diffusion along the IMF, as discussed by the convective-diffusive theory (Sabbah, 2013), the asymmetry of the Earth's magnetosphere resulting in a daily variation of the local geomagnetic cut-off and the day-night difference in the atmospheric structure (Bieber et al., 2010). The characteristics of the diurnal variation (amplitude and phase) are also modulated by the latitude, the longitude and the altitude of the detectors location at Earth (Mailyan and Chilingarian, 2010).

The diurnal anisotropy depends on quite many parameters and its average annual features exhibit striking correlation with the 11-year solar cycle (SC), whereas the diurnal phase varies with a period of 22 years (one solar magnetic cycle) (Tiwari et al., 2012). The average amplitude of the diurnal anisotropy is 0.6%, as calculated by Forman and Gleeson, and in some cases may be as high as 1.5% (Forman and Gleeson, 1975). The solar diurnal variation of CR intensity shows a large day to day variability, which is a reflection of the continually changing conditions in the interplanetary space. The average characteristics of CR diurnal anisotropy are adequately explained by the corotational concept. This concept supports the average diurnal amplitude in space of 0.4% along the 18 h (LT) direction. The direction of the

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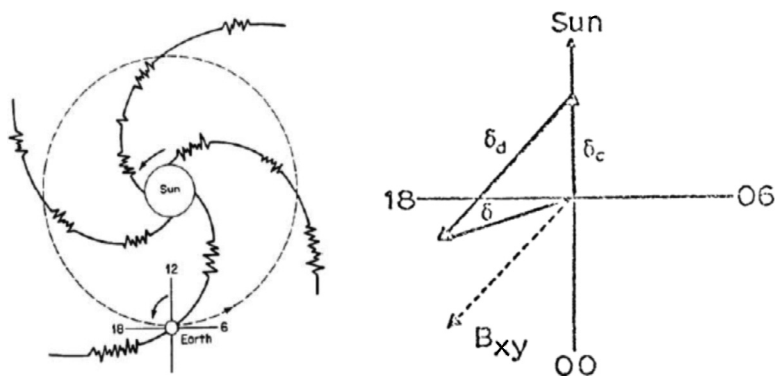

Fig. 1. Representation of the cosmic ray diurnal anisotropy model (left panel), and the convective-diffusion model of the diurnal variation of cosmic rays represented by the observed (δ), convective (δ_c) and diffusive (δ_d) anisotropy vectors and the IMF vector in the ecliptic plane (Bxy) for a typical day (right panel) (Mavromichalaki, 1989).

anisotropy is not correlated with the SC and shows a systematic shift towards early hours (Ananth et al., 1993; Kumar et al., 1990). The phase shift is found to be greater in stations with high cut-off rigidity. The diurnal variation during the ascending phase of the SC can also be explained in terms of the changes of the cut-off rigidity (Ahluwalia and Ericksen, 1971).

The shift of diurnal time maximum can be qualitatively understood in terms of the convective-diffusive mechanism (Forman and Gleeson, 1975), which relates the solar diurnal anisotropy of CR to the dynamics of the solar wind and of the IMF, either as an enhancement in the connective vector due to an increase in solar wind velocity accompanied by an increase in the value of diurnal anisotropy amplitude or as a decrease in the diffusive vector due to the increase in the value of K_{vert}/K_{horiz} accompanied by a decrease in diurnal anisotropy amplitude. If both of them operate simultaneously, the diurnal amplitude may remain constant (Agrawal and Singh, 1975; Mavromichalaki, 1980). The diffusive anisotropy vector δ_d for each day is obtained by vector subtraction of the convective anisotropy δ_c from the observed anisotropy δ according to the relation $\vec{\delta} = \vec{\delta}_c + \vec{\delta}_d$ (Fig. 1). Via this mechanism, the large variation observed in phases and amplitudes can be understood on a day-to-day basis. Periods of unusually large amplitude often occur in trains of several days and cannot be explained by the co rotational concept (Mavromichalaki, 1980).

The CR intensity variations observed near the Earth are an integral result of numerous solar and heliospheric phenomena. The strong magnetic field and its associated fluctuations are responsible for the modulation of CR (Burlaga and Ness, 1998). This modulation also includes other CR variations that affect the diurnal variation, such as Ground Level Enhancements (GLEs), Forbush decreases (Fds) and geomagnetic effects (GEs). The characteristics of the diurnal anisotropy during extreme solar and CR events show a remarkable variation.

In this work, the diurnal anisotropy of CR intensity recorded at the Athens and Oulu neutron monitor stations during the time period 2001–2014, is calculated. This time period covers different phases of the last SCs 23 and 24 over which it was shown that the CR diurnal anisotropy presents different features. The diurnal variation during extreme solar and CR events recorded at these two stations located at the same geographic longitude and different latitude is also studied for the first time.

2. Data analysis

In order to study the diurnal anisotropy of CR, hourly corrected for pressure and efficiency values of the CR intensity from the neutron monitor (NM) stations of the National and Kapodistrian University of Athens - ANEMOS (http://cosray.phys.uoa.gr/) and of the University of Oulu (http://cosmicrays.oulu.fi/) have been used. Both of them provide high-resolution data in real time to the internet in graphical and digital form. They are located at about the same geographic longitude, but in different latitudes having consequently different cut-off rigidities 8.53 GV and 0.81 GV, respectively. The characteristics of these NMs are given in Table 1.

Table 1
Characteristics of Athens and Oulu NM stations.

	Athens NM	Oulu NM
Type	Super 6NM-64	9NM-64
Geographic latitude	37.58° N	65.05° N
Geographic longitude	23.47° E	25.47° E
Altitude	260 m asl	15 m asl
Cut-off rigidity R_c	8.53 GV	0.81 GV

The intensity of cosmic radiation as measured by the Athens NM is lower than the one measured by the Oulu NM, due to the different geographic latitude and consequently threshold magnetic rigidity Rc of each station. Thus, while the Athens NM detects neutrons originating from the reaction of the molecules of the atmosphere with particles of cosmic radiation with Rc> 8.53 GV, the Oulu NM records neutrons with Rc> 0.81 GV. The difference in Rc results in detecting a wider energy spectrum in Athens (Agrawal and Mishra, 2008).

The examined time period 2001–2014 covers the maximum, the descending phase of the SC 23, the extended minimum of the SC 23/24 and the ascending phase of the SC 24. The diurnal vectors for each day (amplitude and time of maximum) of this period were calculated using Fourier analysis according to the equation

$$I_i = f(t_i) = I_{mean} + A'(\cos \omega t_i + \varphi) \quad (1)$$

where I_{mean} is the daily average of CR intensity, A' and φ are the amplitude and the phase of diurnal variation, respectively (Firoz, 2008).

Our data have been normalized according to the equation:

$$A = \frac{I - I_{mean}}{I_{mean}} 100(\%) \quad (2)$$

where I_{mean} is the average CR intensity for each day and A is the percentage variation of the amplitude of the diurnal anisotropy.

The calculated diurnal vectors for the above period are presented on a harmonic dial on monthly and annually basis in polar diagrams, an example of which is appeared in Fig. 3 (Mavromichalaki, 1989). In such diagrams the diurnal anisotropy is represented by a vector of length proportional to the amplitude and in the direction of the maximum intensity. This vector represents the anisotropy field. At the polar diagrams, the quantity A is illustrated as a function of the phase, i.e. the time of the day at