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ORIGINAL ARTICLE

Solar cycle and 27-day variations of the diurnal anisotropy of cosmic rays during the solar cycle 23

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Abstract The diurnal anisotropy of cosmic-ray intensity observed over the period 1997–2006, which coincides with the solar cycle 23, has been analyzed using cosmic ray data from Athens and Oulu neutron monitor stations. In this analysis it was observed that the time of the diurnal variation maximum shifted to earlier hours than the corotation direction from 1997 to 2000, where the polarity state of the magnetic field was positive ($qA > 0$) and to later hours from 2001 to 2006 where the polarity state was negative ($qA < 0$).

Moreover the 27-day variation of the cosmic-ray diurnal anisotropy in connection with the 27-day variation of the interplanetary magnetic field has been studied. In this study six groups of ten Bartel rotations each one have been analyzed (2232–2241, 2249–2258, 2275–2284, 2286–2295, 2328–2337, 2356–2365). It is remarkable that the 27-day variation of cosmic- ray intensity is characterized by the well known sector structure and it is well correlated with the B_{XY} component of the interplanetary magnetic field. These findings during the last solar cycle confirm once again the close relation of the diurnal variation of cosmic ray intensity and the interplanetary magnetic field.

Keywords Cosmic rays · Diurnal anisotropy · Neutron monitors · Convective-diffusive mechanism

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1 Introduction

The cosmic ray intensity variations observed near the Earth are an integral result of numerous solar and heliospheric phenomena, so it would be difficult to believe that any parameter alone can determine the behavior of cosmic-rays. Burlaga and Ness (1998) argue that it is ultimately the strong magnetic field and its associated fluctuations that produce the modulation of cosmic rays.

The solar diurnal variation of cosmic ray intensity shows a large day to day variability. This variability is a reflection of the continually changing conditions in the interplanetary space. The average characteristics of cosmic ray diurnal anisotropy are adequately explained by the corotational concept (Krymsky 1964; Parker 1964). This concept supports the average diurnal amplitude in space of 0.4 % along the 18 hrs (LT) direction, using the worldwide neutron monitor data. Rao (1972) showed that the maximum intensity of diurnal anisotropy has not only appeared in the direction of 18 hrs (LT), which is the nominal corotational phase (Mavromichalaki 1980; Kudela et al. 2008). Moreover, Ananth et al. (1993) and Kumar et al. (1998) concluded that the amplitude of the diurnal anisotropy is correlated with the solar cycle, while the direction of the anisotropy is not correlated and shows a systematic shift to earlier hours (Forbush 1967; 1969; Levy 1975; Okpala and Okeke 2011; Kumar et al. 2012).

The existence of a 27-day recurrence tendency in cosmic-ray intensity has been pointed out by many authors. At first Simpson et al. (1952) observing the neutron intensity at Climax in 1951 found the existence of a 27-day periodicity in the intensity from the direct measurements. Later, Mori et al. (1964) indicated that also the diurnal variation of cosmic-rays reveals a strong 27-day recurrence and gives a strong support for the persistence of the streaming pattern of solar corpuscles in the interplanetary space. Ryder and Fatton (1968) using Deep River cosmic-ray data for the period December 1963–February 1964 assumed that such a radial streaming exists that is a net motion of cosmic-ray particles away from the Sun at the leading edge of the sector, where the diurnal amplitude increases towards it at the trailing edge of it. Later Bussoletti and Iucci (1970) using also Deep River cosmic ray data in 1965 and 1966, years in which the solar activity is rising, pointed out that there is no steady streaming of cosmic-rays along the lines of the interplanetary magnetic field (IMF) at the edges of the magnetic sectors. These discontinuities seen in the amplitude of the diurnal wave at the sector's edge can be explained by diffusion phenomena of cosmic-rays and therefore transverse fluxes of particles which can occur through the lines of IMF. Several authors have studied the effects of the sector structure of the interplanetary magnetic field on the galactic cosmic ray anisotropy at solar minimum activity by using Worldwide Network neutron monitor data (Mavromichalaki 1981; Alania et al. 2003). They noticed that the magnitude of the galactic cosmic ray anisotropy vector is larger in the positive IMF sector and that the phase shifts towards early hours.

In this work the diurnal anisotropy of cosmic-ray intensity over the time period 1997–2006 covering the solar cycle 23, has been analyzed using cosmic ray data from Athens and Oulu neutron monitor stations located at the same longitude, but different latitudes that means different cut-off rigidities, in relation to the polarity state of the IMF. A clear 11-year variation in the amplitude and the phase of the annual diurnal vectors of the cosmic ray intensity is appeared. Moreover a detailed study of the diurnal time of maximum of cosmic ray anisotropy and the sector structure of the IMF on a 27-day basis has given interesting results.

2 Data analysis

In order to examine the cosmic ray diurnal variation on a day-to-day basis in a statistically meaningful way hourly corrected for pressure cosmic ray data of the Athens (latitude 37.58° N, longitude 23.47° E, cut-off rigidity 8.53 GV, http://cosray.phys.uoa.gr/) and Oulu (latitude 65.05° N, longitude 25.47° E, cut-off rigidity 0.81 GV, http://cosmicrays.oulu.fi/) neutron monitor stations have been used. It is noted that the two stations are located at about the same geographic longitude and different latitude. Oulu is a near polar station, while Athens is a middle latitude one. Data analysis has been performed over the period of the years 1997–2006 covering the solar cycle 23 for the Oulu station and over the period 2000–2006 covering the maximum and descending phase of the same cycle for the Athens station, known that Athens station was started to work continuously from

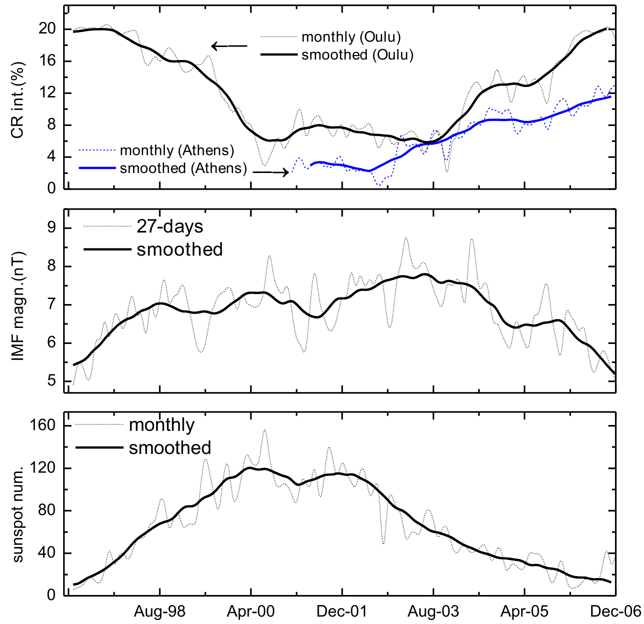

Fig. 1 Time profiles of the monthly and 12-month smoothed values of the cosmic ray intensity for Athens and Oulu neutron monitor stations (*upper panel*), of the IMF magnitude on a 27-day basis (*middle panel*) and of the monthly sunspot number (*lower panel*) for the time period 1997–2006 for Oulu station and 2000–2006 for Athens station

November 2000 (Mavromichalaki et al. 2001). Monthly corrected for pressure and 12-month smoothed cosmic ray intensity data obtained from these two stations are presented for the examined time period in Fig. 1 (upper panel). The cosmic ray intensity is normalized according to the relation

$$I\ (\%) = (I_i - I_{\min})/I_{\min} \times 100, \quad (1)$$

where I_i is the value of each hour and $I_{\min}$ the minimum value of the examined period for each station.

Moreover data of the IMF on a 27-days basis and of the sunspot number on monthly basis for the entire period 1997–2006 are obtained from the websites (http://omniweb.gsfc.nasa.gov/form/dx1.html) and (ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS/info.ssn), respectively. The corresponding time profiles of these parameters are presented in the middle and lower panels of Fig. 1. The solar cycle variation of the IMF and of the sunspot numbers and the inverse relation with the cosmic ray intensity is obvious in this figure (Forbush 1958).

The procedure for resolving the observed diurnal vectors of the cosmic ray anisotropy is the following. The amplitude and the hour of maximum of the observed diurnal anisotropy of Athens and Oulu neutron monitor stations are evaluated for each day of the above mentioned period. The cosmic ray data were normalized for each day according to Eq. (1) with respect to the mean value of each day. The annual mean vectors obtained from the averaged daily ones for the Athens and Oulu stations are presented on a harmonic dial in uni-

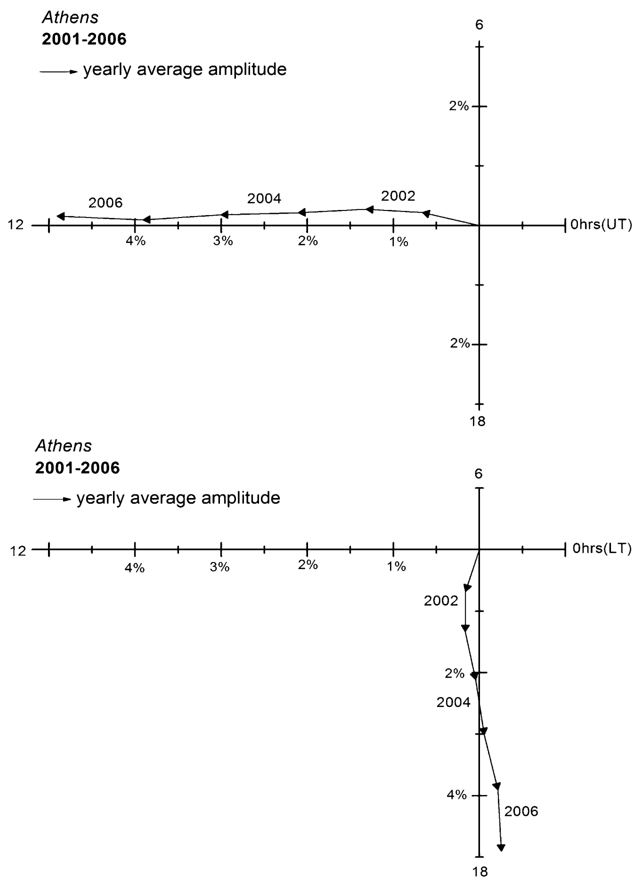

Fig. 2 Annual average diurnal vectors of cosmic ray intensity in space observed by the Athens neutron monitor station for the years 2001–2006

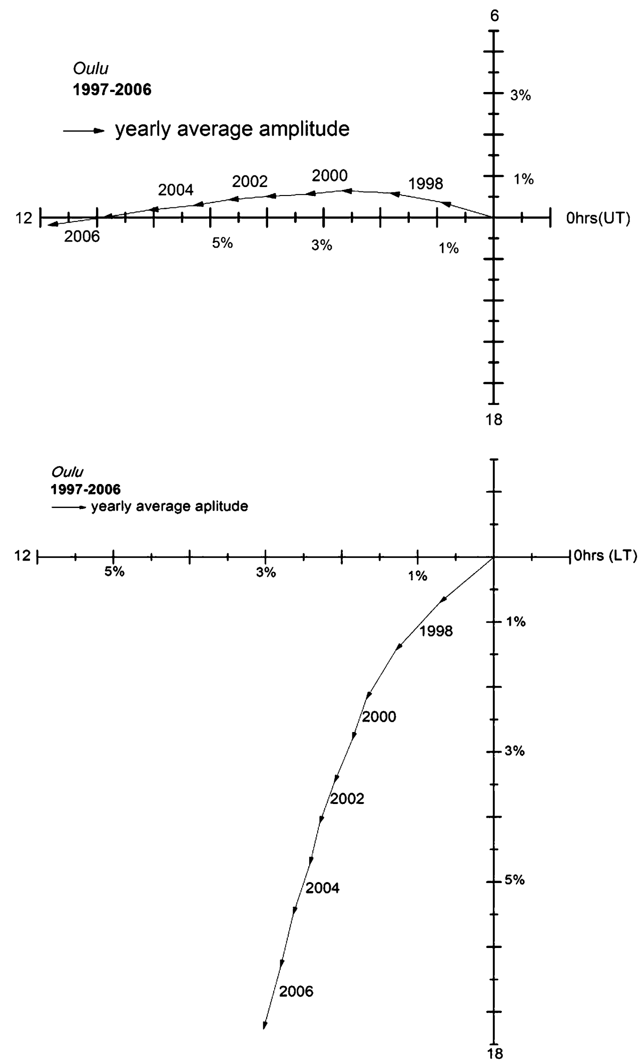

Fig. 3 Annual average diurnal vectors of cosmic ray intensity observed by the Oulu neutron monitor for the years 1997–2006

versal time (UT) in the upper panels of the Figs. 2 and 3 respectively, whereas the corresponding values of them with their statistical errors for both stations are given in Table 1. A phase shift to earlier hours than the 12:00 hrs (UT) with decreasing diurnal amplitude during the years 1997–1999, that is the period of the ascending phase of solar activity and a phase shift of it to later hours with increasing amplitude during the years 2004–2006 that is the period of the descending phase of solar activity, is observed. In the period 2000–2003 that is the time of solar cycle maximum characterized by a number of strong events, the diurnal amplitude remains in low values. It is noted that the same behavior is appeared in the annual diurnal vectors of the two stations for the declining phase 2001–2006. During the whole examined period for each station the mean annual diurnal amplitude is about 0.82 ± 0.02 % for the Athens station and 0.81 ± 0.02 % for the Oulu station, as it is expected from the corotational theory. The yearly mean error does not seem to be affected significantly from the dispersion of the diurnal vectors. Actually the mean times of maximum are 11.85 ± 0.05 UT and 12.16 ± 0.05 UT for Athens and Oulu stations respectively, being very close, as it was expected, due to about the same geographic longitude.

Moreover in order to derive the free space diurnal anisotropy vector, the Athens neutron monitor values have been corrected for geomagnetic bending according to the relation (Owens and Kash 1976),

$$\phi = \phi_1 + 2 + 4.4 \tag{2a}$$

and the corresponding ones of the Oulu station according to the relation

$$\phi = \phi_1 + 2 + 2.4 \tag{2b}$$

where ϕ is the hour of maximum intensity of diurnal variation in interplanetary space. The first term is the observed diurnal hour of maximum (UT), the second term changes it from universal time to local time (LT) and the third one gives the correction for geomagnetic bending, since Athens' asymptotic viewing cone is 66° west of its geographic longitude (Mavromichalaki 1989) and Oulu' asymptotic cone is

Table 1 Yearly values of the amplitude and the phase of the cosmic ray diurnal anisotropy for the two stations

Years	OULU NM			ATHN NM		
	A (%)	T_{max} (UT)	T_{max} (LT)	A (%)	T_{max} (UT)	T_{max} (LT)
1997	0.99 ± 0.02	10.57 ± 0.05	14.97 ± 0.05	–	–	–
1998	0.93 ± 0.02	11.05 ± 0.05	15.45 ± 0.05	–	–	–
1999	0.84 ± 0.02	11.77 ± 0.05	16.16 ± 0.05	–	–	–
2000	0.65 ± 0.02	12.52 ± 0.05	16.92 ± 0.05	–	–	–
2001	0.69 ± 0.02	12.29 ± 0.05	16.69 ± 0.05	0.69 ± 0.02	10.79 ± 0.05	17.11 ± 0.05
2002	0.66 ± 0.02	12.45 ± 0.05	16.85 ± 0.05	0.65 ± 0.02	11.69 ± 0.05	17.98 ± 0.05
2003	0.64 ± 0.02	12.84 ± 0.05	17.23 ± 0.05	0.79 ± 0.02	12.34 ± 0.05	18.59 ± 0.05
2004	0.79 ± 0.02	12.54 ± 0.05	16.94 ± 0.05	0.89 ± 0.02	12.15 ± 0.05	18.42 ± 0.05
2005	0.83 ± 0.02	12.84 ± 0.05	17.24 ± 0.05	0.91 ± 0.02	12.36 ± 0.05	18.67 ± 0.05
2006	0.98 ± 0.02	12.71 ± 0.05	17.11 ± 0.05	1.00 ± 0.02	11.78 ± 0.05	18.15 ± 0.05
1997–1999	0.92 ± 0.02	11.13 ± 0.05	15.52 ± 0.05			
2000–2003	0.66 ± 0.02	11.52 ± 0.05	16.92 ± 0.05	0.71 ± 0.02	11.61 ± 0.05	17.89 ± 0.05
2004–2006	0.86 ± 0.02	12.64 ± 0.05	17.09 ± 0.05	0.93 ± 0.02	12.09 ± 0.05	18.42 ± 0.05
1997–2006	0.81 ± 0.02	12.16 ± 0.05	16.51 ± 0.05	0.82 ± 0.02	11.85 ± 0.05	18.15 ± 0.05

about 40° west of the geographic latitude. By this way the diurnal vectors in free interplanetary space are calculated and the annual ones for the years 2001–2006 for Athens station and for the years 1996 to 2006 for Oulu station are presented in the lower panels of Figs. 2 and 3, respectively. The corresponding values of the diurnal anisotropy amplitudes and phases with their errors are illustrated in Table 1. A phase shift to earlier hours with decreasing amplitude for the years 1997–1999 that are in the ascending phase of the cycle 23 and a phase shift to later hours with increasing amplitude for the years 2004 to 2006 are observed for both stations. The time of maximum presents an about similar and constant behavior for both stations.

In order to examine the relation of the 27-day daily variation of the cosmic ray anisotropy with the well known sector structure of the IMF, daily values of the $\vec{B}_X$, $\vec{B}_Y$ and $\vec{B}_Z$ components of the IMF and the IMF polarity at the vicinity of the Earth as well, have been used covering the time period 1997–2006. Polarity determinations of the IMF have been carried out on a daily basis by utilizing the magnetic field data obtained from the OMNI data set (http://omniweb.gsfc.nasa.gov/html/polarity). Angles in the range 90–180° are denoted, typical away or positive polarity together with angles in the range 270–360°, typical toward or negative polarity. Moreover angles in either of the other two azimuthally quadrants are denoted. From the diagram and the table of this site the IMF sector polarity is determined for each Bartel rotation. The three components of the IMF $\vec{B}_X$, $\vec{B}_Y$, $\vec{B}_Z$ have been obtained from the spacecrafts Wind (1997–1999) and ACE (2000–2006) as well (http://omniweb.gsfc.nasa.gov/form/dx1.html). The amplitude and the direction of the diurnal vectors of cosmic ray intensity and the $\vec{B}_{XY}$ ecliptic component of the IMF obtained according to the relation $\vec{B}_{XY} = \sqrt{B_X^2 + B_Y^2}$ have been evaluated for each day of the examined period during the Bartel rotations from 2232 to 2365. Six groups of ten Bartel rotations have been analyzed in detail (No. 2232–2241 in time period 10/01/1997–06/10/1997, No. 2249–2258 in time period 14/04/1998–08/01/1999, No. 2275–2284 in time period 16/03/2000–10/12/2000, No. 2286–2295 in time period 07/01/2001–04/10/2001, No. 2328–2337 in time period 15/02/2004–10/11/2004, No. 2356–2365 in time period 12/03/2006–06/12/2006).

3 Results and discussion

From the calculated annual diurnal vectors of the cosmic ray anisotropy of the Athens and Oulu neutron monitor stations that are given in Figs. 2 and 3 respectively, we can outline significant results. A phase shift of the time of maximum to earlier hours with decreasing diurnal amplitude during the years 1997–1999, that is the period of the ascending phase of solar activity and a phase shift of this time to later hours with increasing amplitude during the years 2001–2006 that is the period of the descending phase of solar activity, is observed for both stations. In general, the mean annual diurnal amplitude is appeared to be greater in the polar station of Oulu, while the diurnal anisotropy is smaller in the middle latitude Athens station. The fact that the two stations are at the same longitude, is resulted to about the same diurnal phase towards the 12.00 hrs in UT. It is interesting to note that the mean annual amplitude of both stations vary with a period of 11-year solar activity cycle, as it is outlined from Figs. 2 and 3. Similar results have been reported also by Singh et al. (2011). They found systematic and significant differences in

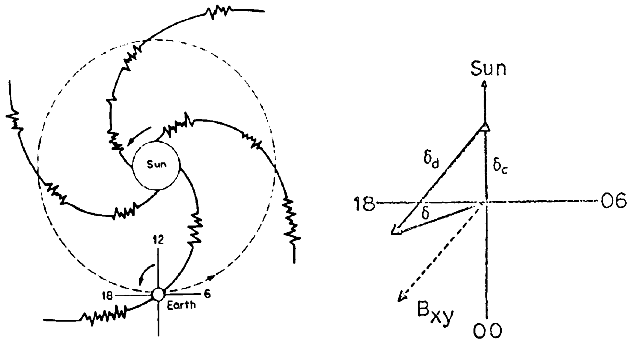

Fig. 4 A schematic presentation of the diurnal variation of cosmic ray particles. The combination of the outward solar wind convection and the inward diffusion parallel to the $B_{\chi\psi}$ of the magnetic field for a typical day is illustrated in the *right panel*

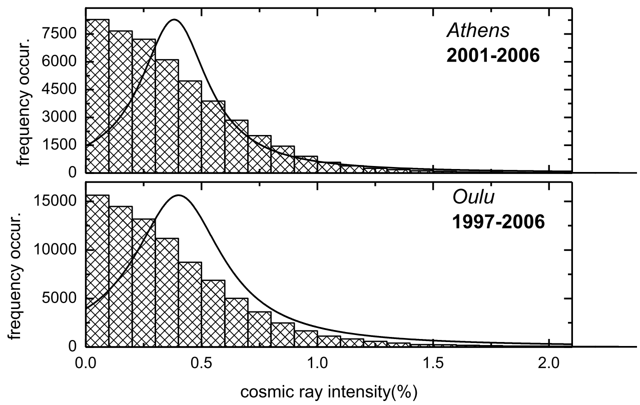

Fig. 5 Histograms Lorentz of the hourly cosmic ray intensity values normalized to the mean value of each day for the neutron monitor data of Athens and Oulu stations

the diurnal variation between the ascending and descending phases of the odd and even solar cycles.

On the other hand the Athens neutron monitor data shows that the time of maximum of the cosmic ray diurnal anisotropy in space is near to the corotational direction of 18 hrs (LT). This result was also pointed out in a previous work by Mavromichalaki (1989) examining the diurnal anisotropy of Athens and Deep River neutron monitor during the period 1970–1977, that is the declining phase of the solar cycle 20. This can be well explained by the mechanism of the diurnal variation presenting in Fig. 4, where the cosmic ray particles with the magnetic field are coming towards the direction of 18:00 hrs (LT) due to the Sun's rotation around its axis. According to Hall et al. (1996) the Earth's rotation causes the asymptotic cone of view of a detector to sweep through the anisotropy once a day. This, in a local time coordinate system, gives a rise to diurnal variation in count rate data with a time of maximum around 18:00 hrs (LT). The co rotational anisotropy is formed by a combination of outward solar wind convection (δ_c) and the inward diffusion (δ_d) parallel to the spiral magnetic field ($B_{\chi\psi}$ component), as it is presented for a typical day in the right panel of Fig. 4 (Mavromichalaki 1989).

Several theoretical models predict effects that depend on the polarity of the Sun's magnetic dipole. It is known that the solar magnetic field reverses at around of each solar maximum activity. According to Durant and Wilson (2003) during the solar cycle 23, the north solar reversal has been reported in February 2001 and the south polar reversal in September 2001. Another research supports that the north polar region field was reversed during the time period of June–September 2000, while the south was reversed during the period of May–August of 2001 (Dikpati et al. 2004). In this work results for Athens and Oulu neutron monitor stations that the amplitude and the time of maximum of diurnal variation shows a different behavior in the ascending and descending phases of solar cycle 23 that seems to be connected with the IMF polarity. In our case the field orientation was positive ($qA > 0$) for the period 1997–2000 and negative positive ($qA < 0$) for the period 2001–2006. In a previous work Mavromichalaki (1989) showed that the observed diurnal anisotropy in interplanetary space has shifted to earlier hours than the corotation direction from 1970 to 1976 where the IMF polarity was positive. Ahluwalia (1988) resulted that two components are present in the anisotropy during the positive IMF polarity. One of them is aligned with the E–W direction (corotation direction) at 18 hrs (LT) termed the E–W anisotropy and the other one is aligned in the direction radially outward from the Sun, called the radial anisotropy. The radial anisotropy vanishes during negative IMF polarity. The arrival direction is shifted from 18 hrs (LT) in the negative polarity state to 15 hrs (LT) in the positive polarity state, because of the radial anisotropy (Ahluwalia 1988). Histograms Lorentz of the frequency occurrence of the cosmic ray intensity values for the Athens and Oulu stations for the examined periods are illustrated in Fig. 5. The histogram Lorentz or Cauchy is a normal distribution applied to populations with long tail. In our case this histogram represents the distribution of the hourly values of the cosmic ray intensity normalized with respect to the mean value of each day. The mean daily anisotropy during the examined periods has been found to be about 0.80 % for the two stations that are consistent with the co rotational model. Forman's and Gleeson's model (1975) implied that the magnitude of the solar diurnal anisotropy is 0.6 % of the average isotropic background flux of cosmic rays that is in agreement with Parker (1964) and Axford (1965) theory.

Moreover an analysis of the direction and amplitude of the diurnal anisotropy on a 27-day period shows a dependence upon the IMF sector polarity. The solar wind drags the solar magnetic field radially from the Sun and produces a thin magnetically neutral sheet. As the Sun rotates once every 27 days the neutral sheet corotates with it, passing the Earth. Since the neutral sheet is wavy, during a 27-day pe-

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
2249	-		+	+	+	+		+	+	+	-	-	-	-	-	-	-	+		-		-	-	-	-	-	-
2250	-	-	-	-		+	+	+	+	-	-	-	-	-	-	-	-	+	+		+	+		-	-	-	-
2251	-	-	-	-	+	+	+		+	+	+	-	-	-	-	-	-	+	+	+			+	+	+	-	-
2252	-	-			-	-	+	+	+	+	+	+	-		-	-	-	+	+	+	+	+	+				-
2253	+		+		+		+	+	+	+		+	+		-		+	+	+	+	-		+	+	+	+	+
2254		+	+	+	+		+		-	-	-	-	-	-	-		+	+	+	+	+	-	+	+	+	+	+
2255	+	+	+				+		-	-	-	-	-	-	+	+	+	+	+	+	+	-	-	-	+	+	
2256	+	+	+	+		+	+		-	-	-	-	-	+	+	+	+	+		+			-	-			-
2257		-	-	+	+		+	-	-		-	-	-	-	-	+	+	+	+	+	+	+	+	+	+	+	-
2258	-	-	-	-	-	+	+	+	+	+	+	+	+	+	+	+	+	-	+	+	+	+			-	-	-
+	3	3	5	4	5	5	9	5	6	5	3	3	2	2	3	4	6	9	8	9	6	4	4	4	5	4	2
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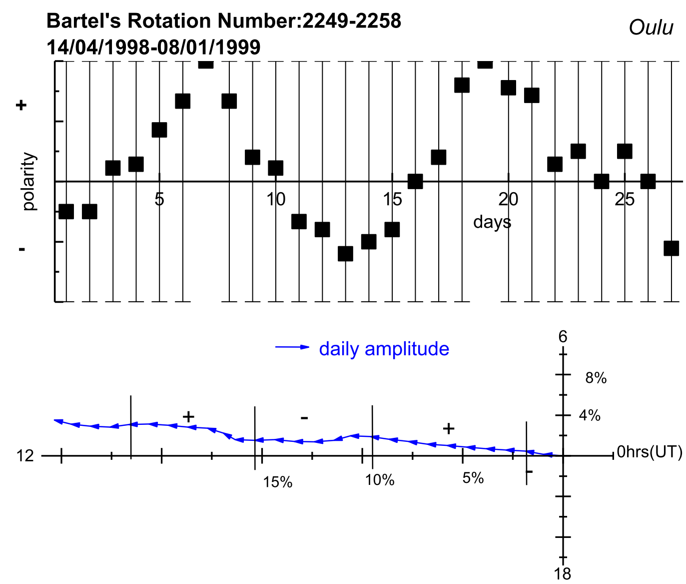

Fig. 6 Comparison between the daily average IMF polarity of every day of the 27-days for the Bartel rotations No. 2249–2258 covering the time period 14/04/1998–08/01/1999 (*upper* and *middle panels*) and the corresponding diurnal averaged for each 27-day amplitudes and phases of the cosmic ray intensity observed at the Oulu station. The four sector structure is obvious

riod the Earth will be alternatively above and below the neutral sheet (Hall et al. 1996).

The daily average IMF polarity of every day of the 27-days for the Bartel rotations No. 2249–2258 covering the time period 14/04/1998–08/01/1999 are presented in the upper and middle panels of Fig. 6, while the corresponding diurnal averaged for each 27-day amplitudes and phases of the cosmic ray intensity observed at the Oulu station are given in the lower panel of this figure and their values are appeared in Table 2. It is characterized that the four sector structure of the IMF is obvious in the direction of the diurnal variation of the examined period with two changes of negative to positive states and opposite. From this figure it is observable that for positive polarity of IMF the phase shifts to earlier hours and for negative polarity of IMF it shifts to later hours. Solar rotations 2232–2241 have been analyzed too and they have the same characteristics as discussed above. Analysis of the other groups of solar rotations 2275–2284, 2286–2295, 2328–2337, 2356–2365 during 2000–2006 does not show the sector structure so clearly due to peculiarities and extreme solar events of the declining phase of the solar cycle 23. Hashim and Bercovitch (1972) have calculated the average phases for the years 1967–1968 from the data of several stations and they concluded that the time of maximum occurs earlier in the case of positive polarity whereas it occurs later in the case of negative polarity. The B_Z component of interplanetary magnetic field (IMF) does not usually contribute to the solar modulation of cosmic rays, like the B_{XY} component, since the long-term average value of this component near the Earth is ∼0. However, Swinson (1981) and Swinson et al. (1981) have demonstrated that on occasions it can contribute to a field dependent anisotropy especially in the case of the extended trains of enhanced solar diurnal variation observed in 1974 (Mavromichalaki 1980). From the lower panel of Fig. 6 and Table 2, it is concluded that the diurnal anisotropy in a 27-day interval might be in close relation with the sector structure of the IMF. During this interval the amplitude and the phase of the diurnal anisotropy seems to be changed two times when the IMF is positive and two times when it is negative (Mavromichalaki 1981).

Owens et al. (1980) have shown that the close correlation observed between the three dimensional cosmic-ray diurnal anisotropy and the IMF follows the mechanism $\vec{B} \times \vec{\nabla} \cdot n$ where $\vec{B}$ denotes the IMF and $\vec{\nabla} \cdot n$ stands for the cosmic-ray density gradient. They have proposed also that the component of the corotating cosmic ray gradient in the ecliptic plane gives arise to north-south anisotropy and the component of the corotating cosmic ray gradient perpendicular to the ecliptic gives rise to an anisotropy in the eclip-

Table 2 Mean cosmic ray anisotropy amplitude and phase for Oulu NM, as well as magnitude and phase of the B_{XY} vectors for each one of the 27-days of the Bartel's Rotations No. 2249–2258 (14/04/1998–08/01/1999)

Bartel's rotation day	A (%)	T (UT)	B_{XY} (nT)	T (UT) (hrs)	IMF polarity
1	0.984	11.30	8.91	9.00	–
2	0.987	10.40	8.46	11.40	–
3	0.987	11.50	8.60	9.10	+
4	0.991	11.40	7.69	9.20	+
5	0.992	11.20	6.64	13.50	+
6	0.995	11.20	6.29	12.50	+
7	0.997	11.40	8.28	13.80	+
8	1.000	10.70	9.63	12.10	+
9	1.000	11.00	8.41	9.50	+
10	0.998	10.60	8.25	10.80	+
11	0.997	11.70	6.79	7.90	–
12	0.997	14.30	6.95	16.10	–
13	0.999	12.70	10.20	11.20	–
14	0.998	11.80	7.53	7.00	–
15	0.996	11.10	7.87	7.80	–
16	0.997	12.40	7.93	11.00	–
17	0.997	11.60	7.50	9.70	+
18	0.994	8.40	8.63	13.00	+
19	0.992	9.50	10.08	11.40	+
20	0.995	11.50	11.67	9.40	+
21	0.992	11.10	11.12	10.90	+
22	0.988	11.40	8.23	10.90	+
23	0.993	12.30	8.80	11.80	+
24	0.992	13.20	7.91	10.40	–
25	0.986	11.60	8.99	12.90	–
26	0.987	11.00	9.42	9.20	–
27	0.991	9.90	10.31	11.70	–

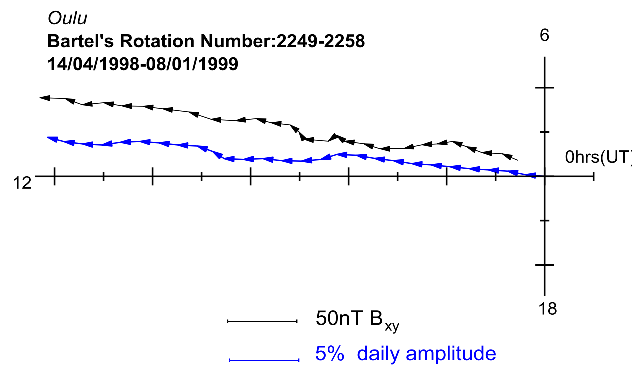

Fig. 7 Comparison between the diurnal average B_{XY} component of every day of the 27-day for the solar rotations 2249–2258 covering the time period 14/04/1998–08/01/1999 and the corresponding diurnal average amplitudes and phases of the cosmic ray intensity observed by the neutron monitor of Oulu

tic plane seen in the diurnal variation. Duggal et al. (1979) have shown that the particle gradient drift $\vec{B} \times \vec{\nabla} \cdot n$ may play the dominant role in producing the azimuthally 27-day wave. Bieber and Chen (1991) and Oh and Bieber (2010) have shown that the intensity of high-energy particles is controlled by the diffusion effect due to the magnitude of IMF. On the other hand, the intensity of low-energy particles is modulated by the drift effect due to the polarity of IMF. Thus, the amplitude of the diurnal anisotropy varies with a period of one sunspot cycle, while the phase varies with a period of two sunspot cycles. The principal axis of variation of the anisotropy is nearly aligned with the mean magnetic field (Bieber and Chen 1991; Chen and Bieber 1993). Taking nominal values for the parallel and perpendicular coefficients, they have found that the value of the radial gradient during epochs of negative solar magnetic polarity is persistently larger than during positive polarity epochs. It is concluded that drift theory provides a simple and natural explanation for the long term behavior of the cosmic ray diurnal anisotropy.

4 Conclusions

Using cosmic ray data from two neutron monitor stations located in the same longitude and different latitudes, Athens and Oulu, the diurnal cosmic ray anisotropy on annual, 27-day and day-to-day bases was studied and the following results are outlined:

1. The diurnal vectors of the time periods 1997–2006 and 2000–2006 for Oulu and Athens stations respectively, are estimated giving overall a mean daily amplitude around 0.40 % and a time of maximum around 12:00 hrs (UT). In the case of both stations correcting the diurnal vectors with the geomagnetic bending, the time of the maximum was found to be around the co rotational direction of 16–18 hrs (LT). It is justified from the fact that the diurnal anisotropy is a local time variation of cosmic rays presenting a maximum intensity around the 18 hrs (LT).
2. It is interesting to note that the annual diurnal anisotropy presents a clear 11-year variation during the solar cycle 23 that is characterized as a very active cycle. The diurnal amplitude is decreasing as we are along the ascending phase of the solar cycle (1997–2000), it presents rather constant values around the solar cycle maximum (2000–2002) and it is increasing in the declining phase (2003–2006). An analogous behavior is presented in the time of maximum that is shifted to earlier hours during the ascending phase, while it is shifted to later hours in the descending phase. It is resulted from the solar magnetic field polarity that is positive ($qA > 0$) in the ascending phase and negative ($qA < 0$) to the descending phase of this cycle. This shift on an average basis can be

qualitatively explained by the drift effect incorporated in diffusion-convection theory (Oh and Bieber 2010). Singh et al. (2011) examining data of neutron monitor stations, situated in different latitudes, found a significant diurnal phase shift to earlier hours in the ascending periods of odd solar cycles (21 and 23) in comparison to the diurnal phase in the ascending periods of even solar cycles (20 and 22). Recently Sabbah (2013) showed that there is dependence of the cosmic ray diurnal variation from the solar magnetic field polarity for all the time period 1953 to 2011.

3. On 27-day basis of the Bartel rotations 2232–2365, we observed that the time of maximum shifts also towards to earlier hours for positive polarity of the IMF and towards later hours for negative polarity. The four sectors structure of the IMF is appeared during the Bartel rotation period of all the groups we have examined (Fig. 6).
4. Moreover the diurnal time of maximum of cosmic ray intensity on the 27-day variation follows the behavior of the ecliptic component B_{XY} of the IMF (Fig. 7). This fact on an average basis can be qualitatively understood in terms of simple convection-diffusion theory.

Concluding we can say that a further study on the diurnal cosmic ray anisotropy recorded at different neutron monitors located at different locations on the Earth and during extreme events of cosmic ray activity will help for a better understanding of the diurnal variation mechanism at different energies of primary cosmic rays.

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References

Ahluwalia, H.S.: Planet. Space Sci. **36**, 1451 (1988)
Alania, M.V., Bochorishvili, T.V., Iskara, K.: Sol. Syst. Res. **37**, 519 (2003)
Ananth, A.G., Venkatesan, D., Pillai, S.: Sol. Phys. **143**, 187 (1993)
Axford, W.I.: Planet. Space Sci. **13**, 115 (1965)
Bieber, J.W., Chen, J.: Astrophys. J. **372**, 301 (1991)
Burlaga, L.F., Ness, N.F.: J. Geophys. Res. **103**, 29719 (1998)
Bussoletti, E., Iucci, N.: Space Plasma Lab., Univ. of Rome LPS-70-12 (1970)
Chen, J., Bieber, J.W.: Astrophys. J. **405**, 375 (1993)
Dikpati, M., de Toma, G., Gilman, P.A., Arge, C.N., White, O.R.: Astrophys. J. **601**, 1136 (2004)
Duggal, S.P., Tolba, M.F., Pomerantz, A., Owens, A.J.: J. Geophys. Res. **84**, 6653 (1979)
Durant, C.J., Wilson, P.R.: Sol. Phys. **214**, 23 (2003)
Forbush, S.E.: J. Geophys. Res. **63**, 651 (1958)
Forbush, S.E.: J. Geophys. Res. **72**, 4937 (1967)
Forbush, S.E.: J. Geophys. Res. **74**(795), 3451 (1969)
Forman, M.A., Gleeson, L.J.: Astrophys. Space Sci. **32**, 77 (1975)
Hall, D.L., Duldig, M.L., Humble, J.E.: Space Sci. Rev. **78**, 401 (1996)
Hashim, A., Bercovitch, N.: Planet. Space Sci. **20**, 791 (1972)
Krymsky, G.F.: Geomagn. Aeron. **4**, 763 (1964)
Kudela, K., Langer, R., Firoz, K.: In: Proc. 21st ECRS (2008), paper 4.15
Kumar, S., et al.: Indian J. Radio Space Phys. **27**, 150 (1998)
Kumar, A.T., Singh, A., Agrawal, S.P.: Sol. Phys. **279**, 253 (2012)
Levy, H.: In: Proc. 14th ICRC, vol. 4, p. 1215 (1975)
Mavromichalaki, H.: Astrophys. Space Sci. **71**, 101 (1980)
Mavromichalaki, H.: In: Proc. 17th ICRC, vol. 10, p. 183 (1981)
Mavromichalaki, H.: Earth Moon Planets **47**, 61 (1989)
Mavromichalaki, H., Sarlanis, C., Souvatzoglou, G., Tatsis, S., Belov, A., Eroshenko, E., Yanke, V., Pchelkin: In: Proc. 27 ICRC 2001, p. 4099 (2001)
Mori, S., et al.: Rep. Ionos. Space Res. Jpn. **18**, 275 (1964)
Oh, S.Y., Bieber, J.W.: Sol. Phys. **262**, 199 (2010)
Okpala, K.C., Okeke, F.N.: Astropart. Phys. **34**, 878 (2011)
Owens, A.J., Kash, M.M.: J. Geophys. Res. **81**, 3471 (1976)
Owens, A.J., Duggsl, P., Pomerantz, A., Tolba, M.F.: Astrophys. J. **236**, 1012 (1980)
Parker, E.N.: Planet. Space Sci. **12**, 735 (1964)
Rao, U.R.: Space Sci. Rev. **12**, 719 (1972)
Ryder, P., Fatton, C.J.: Can. J. Phys. **46**, S999 (1968)
Sabbah, I.: J. Geophys. Res. **118**, 4739 (2013)
Simpson, J.A., et al.: Phys. Rev. **85**, 336 (1952)
Singh, A., Kumar, A.T., Agrawal, S.P.: In: Proc. 32nd ICRC 2011, vol. 6, p. 120 (2011)
Swinson, D.B.: Bull. Am. Astron. Soc. **12**, 8845 (1981)
Swinson, D.B., Saito, T., Mori, S.: J. Geophys. Res. **86**, 8845 (1981)