Features of the Galactic Cosmic Ray Anisotropy in Solar Cycle 24 and Solar Minima 23/24 and 24/25

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Abstract We study the role of the drift effect in the temporal changes of the anisotropy of galactic cosmic rays (GCRs) and the influence of the sector structure of the heliospheric magnetic field on it. We analyze the GCR anisotropy in Solar Cycle 24 and solar minimum 23/24 with negative polarity ($qA < 0$) for the period of 2007–2009 and near minimum 24/25 with positive polarity ($qA > 0$) in 2017–2018 using data of the global network of Neutron Monitors. We use the harmonic analysis method to calculate the radial and tangential components of the anisotropy of GCRs for different sectors ('+' corresponds to the positive and '-' to the negative directions) of the heliospheric magnetic field. We compare the analysis of GCR anisotropy using different evaluations of the mean GCRs rigidity related to Neutron Monitor observations. Then the radial and tangential components are used for characterizing the GCR modulation in the heliosphere. We show that in the solar minimum 23/24 in 2007–2009 when $qA < 0$, the drift effect is not visibly evident in the changes of the radial component, *i.e.* the drift effect is found to produce $\approx 4\%$ change in the radial component of the GCR anisotropy for 2007–2009. Hence the diffusion dominated model of GCR transport is more acceptable in 2007–2009. In turn, near the solar minimum 24/25 in 2017–2018 when $qA > 0$, the drift effect is evidently visible and produces $\approx 40\%$ change in the radial component of the GCR anisotropy for 2017–2018. So in the period of 2017–2018 a diffusion model with noticeably manifested drift is acceptable. The results of this work are in good agreement with the drift theory of GCR modulation, according to which, during negative (positive) polarity cycles, a drift stream of GCRs is directed toward (away from) the Sun, thus giving rise to a 22-year cycle variation of the radial GCR anisotropy.

Keywords Cosmic rays · Anisotropy · Solar Cycle · Diffusion · Neutron monitor · Heliospheric magnetic field

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1. Introduction

Galactic cosmic rays (GCRs) measured at Earth are modulated in the heliosphere by an expanding solar wind (SW). Modulation of GCRs is governed by the convection of SW, inward diffusion of GCRs on the irregularities of heliospheric magnetic field (HMF), drift on the regular HMF and adiabatic cooling of GCRs particles due to extension of SW. GCRs intensity detected near Earth contains the various long- and short-term quasi-periodic variations; see *e.g.* (Kudela and Sabbah, 2016; Chowdhury, Kudela, and Moon, 2016; Bazilevskaya *et al.*, 2014 and the references therein). The most prominent periodic variations are 22 years, 11 years, 27 days and solar diurnal variation (≈ 24 hours). On the background of the long-term solar modulation: 22 years and 11 years, connected with the global HMF and the solar activity (SA) cycle, respectively, the short-term modulation effects sporadic (*e.g.* Forbush decreases) and recurrent (≈ 27 days) also take place.

This paper focuses on an anisotropic part of GCRs flux, reflected in the solar diurnal variation (≈ 24 hours wave), being a consequence of the equilibrium state between inward diffusion of GCRs in the HMF in the heliosphere and outward convection by the SW. The mechanism of the solar diurnal anisotropy was developed by Ahluwalia and Dessler (1962), Krymsky (1964), and Parker (1964) based on the anisotropic diffusion-convection modulation theory of GCR transport in the heliosphere, and further developed by Gleeson and Axford (1967, 1968).

The anisotropy vector $\mathbf{A}$ is expressed in terms of the stream of GCRs and spatial density gradient, as (Gleeson, 1969):

$$\mathbf{A} = -\frac{3\mathbf{S}}{NV} = -\frac{3}{V}(\mathbf{K} \cdot \mathbf{G} - C\mathbf{U}) \quad (1)$$

where N is the GCRs density, $\mathbf{G} = \frac{\nabla N}{N}$ is the density gradient, $\mathbf{S}$ is the stream of GCRs, $\mathbf{K}$ is the diffusion tensor representing the diffusion and drift effects of GCRs, V and U are speeds of the GCRs particles and of the SW, respectively, C is the Compton–Getting factor.

The components of the free-space anisotropy vector $\mathbf{A} = [A_r, A_\theta, A_\phi]$ in spherical coordinates centered on the Sun are in the following form (Riker and Ahluwalia, 1987; Bieber and Chen, 1991; Alania *et al.*, 2001):

$$A_r^\pm = 3[CU - K_{rr}G_r^\pm \pm K_T G_\theta^\pm \sin \Psi + (K_{\parallel} - K_{\perp})G_\phi^\pm \sin \Psi \cos \Psi]/V \quad (2)$$

$$A_\theta^\pm = -3[\pm K_T G_r^\pm \sin \Psi + K_{\perp} G_\theta^\pm \pm K_T G_\phi^\pm \cos \Psi]/V \quad (3)$$

$$A_\phi^\pm = 3[(K_{\parallel} - K_{\perp})G_r^\pm \sin \Psi \cos \Psi \pm K_T G_\theta^\pm \cos \Psi - K_{\phi\phi}G_\phi^\pm]/V \quad (4)$$

where $K_{\perp}$, $K_{\parallel}$, and K_T are perpendicular, parallel and drift diffusion coefficients of GCRs, respectively; $G_r^\pm$, $G_\theta^\pm$ and $G_\phi^\pm$ are the radial, heliolatitudinal and heliolongitudinal gradients of GCRs; signs $(-)$ and $(+)$ correspond to the HMF lines toward (negative) and away (positive) from the northern hemisphere of the Sun; V and U are speeds of the GCRs particles and of the SW, respectively; Ψ is the angle between the HMF lines and the Earth–Sun line; $C = 1.5$ for GCRs sensitive to neutron monitors (NMs) energy.

It can be seen from the system of Equations 2–4 that the GCR anisotropy (recorded by NMs on the Earth) must be due to diffusion, convection and drift of GCRs particles in the regular HMF of the interplanetary space. It is, on average, 0.3–0.4%. At the same time, the fraction of the particle drift effect can reach 0.05–0.1% of the average anisotropy (Alania *et al.*, 1983, 1987, 2001; Alania, Bochorishvili, and Iskra, 2003). It is necessary to distinguish two types of the drift effect in the GCR anisotropy. The first type, due to the

gradient and curvature of the HMF, can be identified in changes in the average anisotropy of GCRs in different periods of solar magnetic cycle $qA > 0$ and $qA < 0$ (for $qA > 0$, the HMF lines come out from the northern hemisphere of the Sun, and for $qA < 0$, they enter the northern hemisphere of the Sun). The second type of drift, due to the existence of local spatial gradients of the GCRs, is manifested in different sectors of the HMF. This component of drift is most notably linked to the heliospheric current sheet (HCS). The HCS is the surface where the polarity of the Sun's magnetic field changes from south to north and vice versa. The tilt angle (TA) is referred to the latitudinal extension (or waviness) of the HCS. We suppose that this drift effect can be manifested due to the sector structure of HMF for the minima epochs of SA, when the TA of the HCS is $< 10\text{--}15$ degrees, *i.e.* the Earth is located near the weakly wavy HCS. Revealing this type of drift may be difficult due to changes in SW speed and corotating interaction region (CIR) areas when the fast SW catches up slow SW (Richardson, 2018) disrupting the stability of the HMF sector structure. The absence of a significant azimuthal gradient in GCRs density when changing the HMF sign indicates a limited HCS thickness. This thickness should be many times smaller than the Larmor radius of GCRs particles with energy range of 1–10 GeV. If the width of the HCS were of the order of the Larmor radius or greater, then the Earth, moving in orbit around the Sun, would pass areas with isotropic and anisotropic diffusion and we would observe a significant azimuthal GCRs density gradient (Alania and Dzhapiashvili, 1979).

However, in order to detect the first type of the drift effect in GCR anisotropy, it is possible to average data over a long period of time (for example, over a period of ≈ 11 years). Whilst a clear identification of the second type of the drift effect is difficult on the background of changes in SW parameters for a short period of time comparable with the durations of the positive and negative sectors of the HMF.

Investigation of the role of the drift effect in the temporal changes of the anisotropy of GCRs is very important from the point of view of the GCRs particle transport theory in the heliosphere (*e.g.* Siluszyk, Wawrzynczak, and Alania, 2011; Siluszyk, Iskra, and Alania, 2015). On the one hand, it allows one to understand the behavior of GCRs particles transport in the heliosphere (Kota and Jokipii, 1983, 1998; Potgieter and Moraal, 1985; Burger and Potgieter, 1989; Potgieter, 1995; Alania *et al.*, 2001; Siluszyk *et al.*, 2018; Siluszyk, Iskra, and Alania, 2014; Iskra, Siluszyk, and Alania, 2015; Alania, Iskra, and Siluszyk, 2010; Iskra *et al.*, 2019). On the other hand, the clearly revealed drift effect in GCR anisotropy allows to estimate the various parameters characterizing the SW and the diffusion of GCRs (Alania, Bochorishvili, and Iskra, 2003).

Recently, Dubey, Kumar, and Dubey (2018) analyzed the GCRs diurnal phase during 1986–2017 and confirmed its Hale cycle dependence (≈ 22 years connected with solar magnetic cycle). Park *et al.* (2018) analyzed the diurnal variation comparing results of calculations for the pile-up method and harmonic analysis method. Oh, Yi, and Bieber (2010) found that the higher energy NMs contribute more to the 11 year phase variation of GCR anisotropy due to the diffusion process. Sabbah (2013) reported that the diurnal phase of higher energy NMs shifts towards earliest hours; this is connected with outward convection by SW, which increases the radial component of the daily variation more than the azimuthal component.

The aim of this work is to continue research on the role of the drift effect on temporary changes in GCR anisotropy. We analyze in detail the anisotropy behavior in Solar Cycle 24, especially during the solar minimum 23/24 in 2007–2009, when $qA < 0$ in comparison to the period 2017–2018 being near the solar minimum 24/25 when $qA > 0$. The most important issue is, based on anisotropy analysis, to determine the contribution of the drift effect in GCR modulation especially near solar minimum periods for Solar Cycle 24.

Table 1 Details of each NM and parameters used for calculations.

NM station	Geo latitude $\lambda_{\text{geo}} [^\circ]$	Geo longitude $\Lambda_{\text{geo}} [^\circ]$	Asympt latitude $\lambda_{\text{asym}} [^\circ]$	Asympt longitude $\Lambda_{\text{asym}} [^\circ]$	R_c [GV]	CC min of SA	CC max of SA	CC intermediate	R_{ef} [GV]	R_m [GV]
Terre Adelie	-66.65	140.02	-66.22	163.25	0.00	0.361	0.505	0.4330	12	15
Nain	56.55	298.30	23.79	337.01	0.30	0.677	0.610	0.6435	12	15
Fort Smith	60.00	248.00	30.60	266.64	0.30	0.568	0.505	0.5365	12	15
Inuvik	68.35	226.28	43.37	238.43	0.30	0.568	0.505	0.5365	12	15
Thule	76.60	291.20	67.36	320.64	0.30	0.234	0.210	0.2220	12	15
Apatity	67.57	33.40	38.04	68.58	0.65	0.592	0.529	0.5605	13	16
Oulu	65.05	25.47	32.40	62.92	0.80	0.619	0.560	0.5895	13	16
Kerguelen	-49.35	70.25	-8.74	81.77	1.14	0.733	0.682	0.7075	13	15
Newark	39.70	284.30	-2.38	328.19	2.40	0.699	0.652	0.6755	14	17

This paper is organized as follows: in Section 1 we present a short introduction and description of anisotropy of GCRs. Section 2 introduces data and methods used to calculate the GCR anisotropy. In Section 3 we present experimental results and a discussion. Section 4 concludes the paper.

2. Data and Methods

We use the hourly data of GCRs intensity for NMs with geomagnetic cut-off rigidities $R_c < 5$ GV. For calculation of the GCR anisotropy we follow the procedure from (Modzelewska and Alania, 2018; Ahluwalia *et al.*, 2015). Details of the NMs and parameters used for calculations are presented in Table 1.

First for calculations of the daily radial A_r and tangential A_ϕ components of the diurnal variation of the GCRs intensity for each NM, we use the harmonic analysis method (*e.g.* Gubbins, 2004; Wolberg, 2006):

$$I(t) = \sum_{k=1}^{\infty} \left(A_r^k \cos \frac{2\pi kt}{T} + A_\phi^k \sin \frac{2\pi kt}{T} \right) = \sum_{k=1}^{\infty} A_k \sin \left(\frac{2\pi kt}{T} + \varphi_k \right) \quad (5)$$

where

$$A_r^k = \frac{1}{p} \sum_{i=1}^{2p} y_i \cos \frac{\pi ki}{p}, \quad A_\phi^k = \frac{1}{p} \sum_{i=1}^{2p} y_i \sin \frac{\pi ki}{p},$$

$$\varphi_k = \arctg \frac{A_\phi^k}{A_r^k}, \quad A_k = \sqrt{A_r^{2k} + A_\phi^{2k}},$$

where y_i designates the hourly GCRs intensity data, k is the consecutive harmonic of the Fourier extension. The daily radial A_r and tangential A_ϕ components of the diurnal variation of the GCRs intensity were calculated by means of normalized and detrended (excluding 25 hours trend) hourly data of the pressure corrected GCRs intensity as the first ($k = 1$, $2p = 24$ hours) harmonic of the Fourier extension.

We exclude from consideration the diurnal amplitudes $> 0.7\%$ as an anomalous events related to the transient disturbances in the interplanetary space, generally connected with Forbush decreases and we do not take into account HMF sectors with duration less than 4 days. The number of excluded days is less than 2–3% from the total number of days used for analysis.

Next, in order to find local components of diurnal variation we rotate the vector by geographic longitude Λ_{geo} of each NM station. Furthermore, we convert the radial A_r and tangential A_ϕ components of the GCRs diurnal variation into the radial A_r and azimuthal A_ϕ components of the GCR anisotropy into the heliosphere (free space), (for details see Modzelewska and Alania, 2018), dividing the diurnal components by coupling coefficients (CC). The CCs represent the ratio of the diurnal variation to the corresponding amplitude of the anisotropy of cosmic rays in the heliosphere (Dorman, 1963; Yasue, Sakakibara, and Nagashima, 1982).

The calculated components of the diurnal variation of the GCRs intensity are corrected due to influence of the Earth magnetic field (Dorman *et al.*, 1972; Dorman, 2009), taking into account the asymptotic cone of acceptance characteristic for each NM station (Shea, Smart, and Mc Cracken, 1965; Shea *et al.*, 1967) for the rigidity to which NMs respond. The asymptotic cones of acceptance for each NM station were calculated using the FORTRAN TJ2000 program developed by Shea *et al.* (1967). Geomagnetic field coefficients were taken for the epoch of 2015 of the International Geomagnetic Reference Field. It is done by the rotation of the corresponding angle, called geomagnetic bending (GB), $\varphi_{\text{GB}} = \Lambda_{\text{asym}} - \Lambda_{\text{geo}}$ characteristic for each NM station, Λ_{asym} and Λ_{geo} are the asymptotic and geographic longitude. The radial and the tangential components of the diurnal variation of the GCRs intensity corrected to the Earth's magnetic field influence are expressed (*e.g.* Ygbuhay, 2015):

$$A_r = a_r \cos(\varphi_{\text{GB}}) - a_\phi \sin(\varphi_{\text{GB}}) \quad (6)$$

$$A_\phi = a_r \sin(\varphi_{\text{GB}}) + a_\phi \cos(\varphi_{\text{GB}}) \quad (7)$$

$$\varphi_{\text{free space}} = \varphi_{\text{local phase}} + \varphi_{\text{GB}}. \quad (8)$$

Finally, we correct the GCR anisotropy for the Compton–Getting (CG) effect, due to the Earth's orbital motion (Ahluwalia and Ericksen, 1970; Hall, Duldig, and Humble, 1996). The CG correction is a vector with amplitude $0.045 \cos \lambda_{\text{asym}}$ and phase 6 h, where λ_{asym} is the asymptotic latitude of each NM.

The GCRs intensity measured by ground-based NMs is based on the concept of an integrated GCR flux above the magnetic rigidity threshold that depends on the geomagnetic cut-off typical for each NM. In this case there arises the question of what the real energy is of the measurement. It is natural to introduce the “effective energy/rigidity” typical for a GCR detector, here NM. In the literature this term has different meanings: fixed energy/rigidity ≈ 10 GV for a NM, (Belov, 2000), median energy (Ahluwalia and Dorman, 1997; Jämsén *et al.*, 2007), maximum of the differential response function (McCracken *et al.*, 2004), or the integral effective energy (Alanko *et al.*, 2003). Unfortunately the above-mentioned effective energy concepts are not constant but are changing through the solar activity cycle. Recently, Gil *et al.* (2017) proposed a model of the effective energy in which the variability of the GCR flux at this energy is directly proportional to the detector's count rate, so that the percentage variability of the detector's count rate is equal to that of the GCR flux at this energy; for details see Asvestari *et al.* (2017).

In this paper we compare the analysis of the GCR anisotropy using this two approaches: the median rigidity R_m of NM response (Ahluwalia *et al.*, 2015; Ahluwalia and Fikani,

2007) and the effective rigidity R_{ef} characteristic for each NM proposed by (Gil *et al.*, 2017; Asvestari *et al.*, 2017).

3. Experimental Results and Discussion

Solar Cycle 24 was much less active than, for example, Solar Cycle 23, being rather similar to cycles at the beginning of the previous century. During this relatively weak cycle not many impulsive events happened on the Sun, but we could observe the prolonged solar minimum 23/24 with good established regular structure of the HMF. The current Solar Cycle 24 has now more or less finished its descending phase. At the beginning of 2018 ($\approx$ April), the Sun showed indications of the reverse magnetic polarity sunspot announcing Solar Cycle 25 (Phillips, 2018). The poleward reversed polarity sunspots suggest that a transition to Solar Cycle 25 is in progress and indicates that we may be in or near the minimum between Solar Cycles 24 and 25. So it is of special importance to study the features of the GCR anisotropy characteristics through the almost whole Solar Cycle 24 with special importance because of the comparison of the drift effect in GCR anisotropy during solar minimum 23/24 and near the solar minimum 24/25 with different polarity periods of solar magnetic cycle.

Here we present the time variation of the GCR anisotropy for Oulu NM (as an example) through almost the whole Solar Cycle 24, 2007–2018. We compare the values of the amplitude, phase, radial and azimuthal components of the GCR anisotropy using two approaches: median R_m (Ahluwalia *et al.*, 2015) and effective R_{ef} (Gil *et al.*, 2017) rigidity of response. The errors for annual values are estimated as the standard deviation from monthly data. The calculated results of the GCR anisotropy for effective and median rigidity are in good agreement, the difference is in the scope of the error bars. Figure 1 presents the time lines of the annual average of the amplitude (Figure 1a), phase (Figure 1b), radial (Figure 1c) and azimuthal (Figure 1d) components of the GCR anisotropy for 2007–2018. The amplitude of the GCR anisotropy displays the 11-year variation with systematic decrease of the values near the minima of SA (Figure 1a). The phase of the GCR anisotropy shows the undoubted indication of shifting towards earlier hours near the solar minimum 24/25 (Figure 1b). Figure 1c demonstrates the change of the A_r component from positive to negative values close the maximum of the solar cycle nearby to the reversal of the global HMF.

As far the differences of the GCR anisotropy parameters calculated for these two approaches: median and effective rigidity are rather negligible, we decided to use further in this paper only the GCR anisotropy using a recent R_{ef} methodology following Gil *et al.* (2017).

The aim of this work is to continue research on the role of the drift effect on temporary changes in GCR anisotropy. The most important issue is, based on the anisotropy analysis, to determine the contribution of the drift effect in the GCR modulation especially near solar minimum periods for Solar Cycle 24. For this purpose components A_r and A_ϕ of the anisotropy of GCRs were calculated using the harmonic analyses of hourly data of every separate NM for periods of two minima: solar minimum 23/24: 2007–2009, when $qA < 0$ and near solar minimum 24/25: 2017–2018, when $qA > 0$.

In Figures 2a, b, c are presented average GCR anisotropy vectors from following NMs: Apatity, Oulu, Newark, Thule, Fort Smith, Inuvik, Kerguelen, Terre Adelie and Nain (see Table 1) for different sectors of the HMF ('+' corresponds to the positive and '-' to the negative sectors) for the solar minimum 23/24 when $qA < 0$: 2007 (Figure 2a), 2008 (Figure 2b), and 2009 (Figure 2c). In 2007 data for Terre Adelie and Kerguelen NMs and in 2008 for Terre Adelie NM are not available.

Figure 1 Temporal changes of the annual average amplitude A (a), phase (b), radial A_r (c) and azimuthal A_ϕ (d) components of the GCR anisotropy by Oulu NM for the almost whole Solar Cycle 24, 2007–2018. Shadow area designates the solar maximum 2013–2014.

Figure 2 Harmonic diagram of the GCR anisotropy vectors for positive (+) and negative (−) sectors of HMF for solar minimum 23/24 when $qA < 0$: 2007 (a), 2008 (b) and 2009 (c). On the vertical and horizontal axes are the radial and azimuthal components, in %.

In Figures 3a, b are presented average vectors of the GCR anisotropy for different sectors of the HMF for the period near the solar minimum 24/25 when $qA > 0$: 2017 (Figure 3a) and 2018 (Figure 3b). Here we used data of the same NMs as in Figure 2.

Table 2 presents the radial and azimuthal components, magnitude of the GCR anisotropy and the phase relative to 18 h. The uncertainty of this data is estimated as the Poisson statistics using standard deviations for separate NMs divided by $\sqrt{n}$, where n is the number of NMs used in averaging for each period. As far as the drift stream is evidently pronounced

Figure 3 The same as in Figure 2 but near solar minimum 24/25 when $qA > 0$: 2017 (a) and 2018 (b).

in the radial component we present in Table 2 also the ratios of the absolute value of the radial component to the value of the magnitude of the GCR anisotropy vector. All quantities are for the different HMF sectors in 2007, 2008, 2009 and averaged values for 2007–2009, when $qA < 0$ and the same in 2017, 2018 and averaged for the period 2017–2018, when $qA > 0$.

From Figures 2a, b, c and Table 2, we can see that all vectors of the GCR anisotropy for both positive and negative sectors of HMF are slightly shifted towards later hours in relation to 18 hour for 2007–2009, when $qA < 0$. In 2007 the shifting is 24 min for the positive sectors and 3 min for the negative sectors, in 2008 – 14 min and 5 min all after 18 h, respectively. These values are very small and are in the scope of the error bars. In 2007 and 2008 the vectors of the GCR anisotropy for the positive sectors are shifted towards the later hours than the vector for the negative sectors. The ratios of the absolute value of the radial component to the value of the total anisotropy vector are $10.6 \pm 1.1\%$ and $1.3 \pm 0.8\%$ in 2007 for positive and negative sectors and $6.0 \pm 1.1\%$ and $2.3 \pm 1.2\%$ in 2008, respectively.

There is an unusual behavior of the vector of the GCR anisotropy in 2009. The vector of the GCR anisotropy for the positive sectors practically points to 18 hours (phase + 2 min before 18 h, phase – 2 min after 18 h). In 2009 the radial components of the anisotropy vectors for different sectors are almost zero ($A_r +$ is $-0.003 \pm 0.004\%$ towards 12 h and $A_r -$ is $0.003 \pm 0.004\%$ towards 24 h). The ratios of the absolute value of the radial component to the value of the total anisotropy vector in 2009 are $0.8 \pm 1.3\%$ and $1.0 \pm 1.3\%$ for positive and negative sectors, respectively. These quantities are practically the same within the error limits.

This means that in the above periods diffusion is responsible for the propagation of cosmic radiation in the heliosphere, while the drift of cosmic-ray particles due to the gradient and curvature is insignificant and in 2009 it hardly existed. One can see also that there are small differences between the amplitudes and phases of the GCR anisotropy vectors for different sectors of the HMF in 2008 and 2009. Moreover, the effect of drift in the anisotropy of GCRs due to the sector structure of the HMF during the minima epochs of SA is generally caused by the drift on the HCS and is mostly pronounced in the differences of azimuthal components between positive and negative sectors in 2007.

From Figures 3a, b and Table 2 one can see that all vectors of the GCR anisotropy for both positive and negative sectors of HMF are shifted towards earlier hours compared to 18 hour in 2017–2018, when $qA > 0$. In 2017 (Figure 3a) the magnitude of the vector of the GCR anisotropy for the negative sector of HMF is less ($A_- = 0.365 \pm 0.005\%$) than the magnitude of the vector for the positive sector ($A_+ = 0.429 \pm 0.004\%$). We have the reverse situation in 2018 (Figure 3b) ($A_+ = 0.324 \pm 0.005\%$), is less than ($A_- = 0.379 \pm 0.005\%$).

Table 2 The values of the radial and azimuthal components, magnitude of the GCR anisotropy, the phase relative to 18 h and the ratios of the absolute value of the radial component to the value of the magnitude of the GCR anisotropy vector for different HMF sectors in 2007, 2008, 2009 and averaged values for 2007–2009, when $qA < 0$ and the same in 2017, 2018 and averaged for the period 2017–2018, when $qA > 0$.

Year	$A_r + [\%]$	$A_r - [\%]$	$A_\phi + [\%]$	$A_\phi - [\%]$	$A + [\%]$	$A - [\%]$	$ A_r + / A + [\%]$	$ A_r - / A - [\%]$	phase + [h:mm]	phase - [h:mm]
2007	0.049 ± 0.005	0.007 ± 0.005	-0.462 ± 0.005	-0.563 ± 0.005	0.465 ± 0.004	0.568 ± 0.004	10.6 ± 1.1	1.3 ± 0.8	00:24	00:03
2008	0.025 ± 0.005	0.010 ± 0.005	-0.424 ± 0.005	-0.422 ± 0.005	0.425 ± 0.004	0.423 ± 0.004	6.0 ± 1.1	2.3 ± 1.2	00:14	00:05
2009	-0.003 ± 0.004	0.003 ± 0.004	-0.346 ± 0.005	-0.336 ± 0.004	0.346 ± 0.003	0.336 ± 0.003	0.8 ± 1.3	1.0 ± 1.3	-00:02	00:02
2007–2009	0.024 ± 0.005	0.007 ± 0.005	-0.411 ± 0.005	-0.442 ± 0.005	0.411 ± 0.004	0.442 ± 0.004	5.8 ± 2.0	1.5 ± 1.3	00:13	00:04
2017	-0.145 ± 0.005	-0.094 ± 0.007	-0.403 ± 0.004	-0.353 ± 0.007	0.429 ± 0.004	0.365 ± 0.005	33.8 ± 0.9	25.8 ± 1.7	-01:19	-01:00
2018	-0.153 ± 0.005	-0.217 ± 0.005	-0.265 ± 0.006	-0.310 ± 0.004	0.324 ± 0.005	0.379 ± 0.005	56.3 ± 1.1	57.5 ± 0.6	-02:17	-02:20
2017–2018	-0.164 ± 0.005	-0.156 ± 0.007	-0.336 ± 0.006	-0.331 ± 0.007	0.376 ± 0.005	0.366 ± 0.005	43.8 ± 0.4	42.5 ± 3.7	-01:44	-01:41

Figure 4 (a) Harmonic diagram of the average GCR anisotropy for positive (+) and negative (−) sectors of HMF for the periods 2007–2009 when $qA < 0$ and 2017–2018 when $qA > 0$; (b) harmonic diagram of the average over sectors the GCR anisotropy for 2007–2009 when $qA < 0$ and 2017–2018 when $qA > 0$ for the global HMF.

The anisotropy vector for the negative sector is shifted towards the later hours in 2017, at the same time we observe no significant difference in the phase for both sectors in 2018. The ratios of the absolute value of the radial component to the value of the total anisotropy vector are $33.8 \pm 0.9\%$ and $25.8 \pm 1.7\%$ in 2017 and in 2018 the ratios are even higher, being $56.3 \pm 1.1\%$ and $57.5 \pm 0.6\%$ for the positive and negative sectors, respectively. The ratios for various sectors in 2018 are practically the same within the error bars. The effect of drift in the anisotropy of GCRs due to the sector structure of the HMF is most pronounced in the differences of azimuthal components between positive and negative sectors in 2017 and 2018.

Figure 4a and Table 2 show the average GCR anisotropy vectors for different sectors of the HMF averaged over the periods 2007–2009, when $qA < 0$ and 2017–2018, when $qA > 0$. One can see that in 2007–2009 the magnitude of the vector for positive (+) sectors of HMF is a bit less ($A_+ = 0.411 \pm 0.004\%$) than the magnitude of the vector for the negative sectors ($A_- = 0.442 \pm 0.004\%$). Phases of the vectors A_+ and A_- are directed 13 min and 4 min, respectively, after 18 h in 2007–2009. Whereas in 2017–2018 there is no noticeable difference between positive and negative sectors; the magnitude of the anisotropy vectors is $\approx 0.37\%$ for both sectors, and the phase is shifted $\approx 1:40$ h before 18 h. The ratios of the absolute value of the radial component to the value of the total anisotropy vector are for the whole solar minimum 23/24 in 2007–2009 when $qA < 0$: $5.8 \pm 2.0\%$ and $1.5 \pm 1.3\%$ for (+) and (−) sectors, respectively and near the solar minimum 24/25 in 2017–2018 when $qA > 0$ the ratios are $43.8 \pm 0.4\%$ and $42.6 \pm 3.7\%$ for (+) and (−) sectors, respectively and practically are the same within the error bars.

Having calculated anisotropy vectors for different sectors, we average the vectors of the GCR anisotropy over different sectors but for the same directions of the global HMF. Figure 4b and Table 3 show, averaged over HMF sectors, the anisotropy vectors for different directions of the global HMF *i.e.* for 2007–2009, when $qA < 0$ and 2017–2018, when $qA > 0$.

Summarizing, in the solar minimum 23/24 in 2007–2009 when $qA < 0$, the drift effect is not pronounced visibly in the changes of the A_r component being almost 0 ($A_r = 0.02 \pm 0.04\%$), determining the phase shifted 14 min after 18 h, *i.e.* for this solar minimum the diffusion dominated model of GCR transport is more acceptable in 2007–2009. In turn, near the solar minimum 24/25 in 2017–2018 when $qA > 0$, the radial component A_r is $-0.16 \pm 0.05\%$ and the phase is shifted 1:09 h prior 18 h. So, the drift effect is clearly

Table 3 The values of the radial and azimuthal components, average magnitude of the GCR anisotropy, the ratio of the absolute radial component to the average magnitude of the GCR anisotropy and the phase relative to 18 h for 2007–2009, when $qA < 0$ and the same for the period 2017–2018, when $qA > 0$ and for almost the whole Solar Cycle 24, 2007–2018.

Year	A_r [%]	A_ϕ [%]	A_{av} [%]	$ A_r /A_{av}$ [%]	phase [h:mm]
2007–2009	0.015 ± 0.036	-0.426 ± 0.038	0.427 ± 0.029	3.6 ± 2.4	00:14
2017–2018	-0.160 ± 0.053	-0.333 ± 0.049	0.370 ± 0.042	43.3 ± 11.6	−01:09
2007–2018	-0.012 ± 0.023	-0.422 ± 0.018	0.422 ± 0.015	2.8 ± 3.8	−00:06

Figure 5 Harmonic diagram of the average vector of the GCR anisotropy $A_{av}^{qA<0}$ for 2007–2009, $A_{av}^{qA>0}$ for 2017–2018 and A_{av} for the almost whole Solar Cycle 24 in 2007–2018 (dashed line). Figure 5 presents the drift anisotropy vectors A_{dr} for $qA < 0$ (blue) and A_{dr} for $qA > 0$ (red).

visible. So in the period of 2017–2018 the diffusion model with clearly manifest drift is acceptable. For the whole solar minimum 23/24 in 2007–2009 when $qA < 0$ the ratio of the absolute value of the radial component to the value of the total anisotropy vector is $3.6 \pm 2.4\%$, whereas near the solar minimum 24/25 in 2017–2018 when $qA > 0$ this ratio is $43.3 \pm 11.6\%$.

In Figure 5 are presented the average vector of the GCR anisotropy $A_{av}^{qA<0}$ for 2007–2009, $A_{av}^{qA>0}$ for 2017–2018 and A_{av} for almost the whole Solar Cycle 24 in 2007–2018 (dashed line). Figure 5 also presents the drift vectors A_{dr} for $qA < 0$ (blue) calculated as $(A_{av}^{qA<0} - A_{av})$ and A_{dr} for $qA > 0$ (red) calculated as $(A_{av}^{qA>0} - A_{av})$.

One can see that the drift anisotropy vector A_{dr} (red color in Figure 5) for the $qA > 0$ polarity is preferentially directed to the Sun (to the direction of 12 h in the harmonic diagram), and for the $qA < 0$ polarity the drift anisotropy vector A_{dr} (blue color in Figure 5) is directed out of the Sun. These empirical outcome are in good correspondence with the drift theory of modulation of GCRs (Jokipii, Levy, and Hubbard, 1977). Based on that theory in the $qA > 0$ cycle a drift stream of GCRs caused by the gradient and curvature of the HMF is preferentially coming from the polar regions to the helioequatorial region and is directed away from the Sun. For the $qA < 0$ cycle we have the opposite direction of the drift stream of GCRs.

Table 4 presents the radial and azimuthal components and magnitude of the drift GCR anisotropy vector A_{dr} and the ratios of the absolute value of the A_{dr}^r and A_{dr}^ϕ components to the total magnitude of A_{dr} for 2007–2009, when $qA < 0$ and 2017–2018, when $qA > 0$. In the solar minimum 23/24 in 2007–2009, when $qA < 0$, the ratio A_{dr}^r/A_{dr} is $\approx 99\%$. In turn, near the solar minimum 24/25 in 2017–2018 when $qA > 0$, the ratio A_{dr}^r/A_{dr} reaches $\approx 86\%$.

Table 4 The radial, azimuthal components and magnitude of the drift GCR anisotropy A_{dr} and the ratios of the absolute value of the components of A_{dr}^r and A_{dr}^ϕ to the total magnitude of A_{dr} for 2007–2009, when $qA < 0$ and 2017–2018, when $qA > 0$.

Year	A_{dr}^r [%]	$ A_{\text{dr}}^\phi $ [%]	A_{dr} [%]	$ A_{\text{dr}}^r /A_{\text{dr}}$ [%]	$ A_{\text{dr}}^\phi /A_{\text{dr}}$ [%]
2007–2009	0.027 ± 0.04	-0.004 ± 0.04	0.028 ± 0.04	98.9	14.7
2017–2018	-0.148 ± 0.05	0.089 ± 0.05	0.173 ± 0.05	85.7	51.5

Thus, the drift vectors A_{dr} of the GCR anisotropy (Figure 5) for $qA > 0$ and $qA < 0$ polarities basically contain the radial component, the contribution of A_{dr}^r in total A_{dr} is more than $\approx 86\%$ for $qA > 0$ and almost $\approx 99\%$ in $qA < 0$. The difference between anisotropy A for $qA > 0$ and $qA < 0$ polarities is produced by the drift of GCRs due to the curvature and gradient of the regular HMF and is the source of the long-term variation of the anisotropy A of GCRs (Forbush, 1969; Ahluwalia, 1988).

Summarizing, in the solar minimum 23/24 in 2007–2009, when $qA < 0$, the drift effect is not pronounced visibly, the ratio $|A_r|/A_{\text{av}}$ is only $\approx 4\%$. Hence the diffusion dominated model of GCR transport is more acceptable in 2007–2009. In turn, near the solar minimum 24/25 in 2017–2018 when $qA > 0$, the drift effect is clearly visible and the ratio $|A_r|/A_{\text{av}}$ reaches $\approx 40\%$. So in the period of 2017–2018 the diffusion model with clearly manifest drift is acceptable. The above-mentioned statements are in agreement with other authors. According to (Moraal and Stoker, 2010; Mewaldt *et al.*, 2010) the solar minimum 23/24 was diffusion dominated with increasing of diffusion coefficient of GCRs particles in comparison to the previous solar minimum and consequently the drift effect was reduced. In 2007–2008 tilt angle was relatively large ($\approx 30^\circ$), so the drift effect might be reduced (maybe because of the weak HMF), consequently the latitudinal gradient is also smaller. At the same time coronal holes, CIRs and SW velocity were stable, so convection was strong. Due to the weak HMF diffusion was also enhanced. However, many characteristics of the heliospheric environment were not typical compared with earlier Solar Cycles, *e.g.* lower SW dynamic pressure and magnetic field strength, but high TA, together resulting in the extremely high GCRs intensities in 2009. Comparing Solar Cycles 23 and 24 it was observed (Dunzlaff *et al.*, 2008) lower effectiveness of the latitudinal transport in 2006–2009. Also (De Simone *et al.*, 2011) reported smaller negative latitudinal gradient in the $qA < 0$ polarity in Solar Cycle 24 comparing to previous $qA < 0$, but TA was rather high (*e.g.* Heber *et al.*, 2009), so the GCR modulation processes in the solar minimum 23/24, when $qA < 0$ maybe a consequence of large latitudinal extent of HCS (Potgieter and Ferreira, 2001; Heber *et al.*, 2009).

The results presented in this paper will be used in future work concerning the modeling of the transport of GCRs particles as the crucial parameters characterizing the solar modulation of GCRs by the SW in the heliosphere.

4. Conclusions

Using data from several neutron monitor stations of different magnetic rigidity cut-offs, we have studied the role of drift in the temporal variations of the GCR anisotropy and its influence on the sector structure of the heliospheric magnetic field. Using the harmonic analysis method, we have analyzed the GCR anisotropy in the $qA < 0$ solar minimum period

of 2007–2009 (Cycle 23/24) and near the $qA > 0$ minimum period of 2017–2018 (Cycle 24/25). Our main results can be summarized as follows:

- i) We have compared the analysis of the GCR anisotropy using the median R_m and effective R_{ef} rigidity of neutron monitor response. We have found that the differences of the GCR anisotropy parameters calculated for these two approaches: median and effective rigidity are rather negligible.
- ii) The global drift due to gradient and curvature of the heliospheric magnetic field is manifested in the radial component A_r of the anisotropy A of GCRs. For the $qA < 0$ cycle the A_r is directed away from the Sun, but for the $qA > 0$ magnetic cycle the A_r is directed to the Sun. This type of the drift effect is the source of the 22-year variation of the anisotropy of GCRs.
- iii) The drift effect due to the sector structure of the heliospheric magnetic field in the anisotropy A of GCRs (during the minima epochs of solar activity) is caused by the heliospheric current sheet and is visible in the azimuthal component of GCR anisotropy.
- iv) We have shown that in the solar minimum 23/24 in 2007–2009 when $qA < 0$, the drift effect is not pronounced visibly in the changes of the A_r component ($A_r \approx 0$), *i.e.* for this solar minimum the drift effect is only $\approx 4\%$. Hence the diffusion dominated model of GCR transport is more acceptable in 2007–2009. In turn, near the solar minimum 24/25 in 2017–2018 when $qA > 0$, the drift effect is clearly visible and reaches $\approx 40\%$. So in the period of 2017–2018 the diffusion model with clearly manifest drift is acceptable.

The following abbreviations are used in this manuscript:

Abbreviations

CC	Coupling coefficients
CG	Compton–Getting effect
CIR	Corotating Interaction Regions
GCRs	Galactic Cosmic Rays
HCS	Heliospheric Current Sheet
HMF	Heliospheric Magnetic Field
NM	Neutron Monitor
SA	Solar Activity
SW	Solar Wind
TA	Tilt Angle.

Disclosure of Potential Conflicts of Interest The authors declare that there are no conflicts of interest.

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The asymptotic cones of acceptance for each NM station were calculated using the FORTRAN TJ2000 program available at <http://ccmc.gsfc.nasa.gov/modelweb/sun/cutoff.html>.

Geomagnetic field coefficients were taken from <http://www.ngdc.noaa.gov/AGA/vmod/igrf.html>.

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