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Quasi-periodic changes of galactic cosmic ray anisotropy and intensity

The 27-day variations of galactic cosmic ray (GCR) anisotropy and intensity are studied based on the neutron monitors data for the $A > 0$ and the $A < 0$ polarity periods of solar magnetic cycles (for the $A > 0$ polarity period of the solar magnetic cycle lines of the interplanetary magnetic field (IMF) are directed outward from the northern hemisphere, while for the $A < 0$ polarity period the opposite situation takes place). It is shown that the amplitudes of the 27-day variation of GCR anisotropy are greater in the $A > 0$ polarity period than in the $A < 0$ polarity period of the solar magnetic cycles being in good correlation with the similar changes of the amplitudes of the 27-day variation of GCR intensity. These changes in the amplitudes of the 27-day variations of galactic cosmic ray intensity and anisotropy are caused by the alternating radial component of the drift stream S_d of galactic cosmic rays in different polarity periods of the solar magnetic cycles. In the $A > 0$ polarity period the stream S_d is directed outward from the Sun, while in the $A < 0$ polarity period of the solar magnetic cycle the stream S_d has vice versa direction.

КВАЗІПЕРІОДИЧНІ ЗМІНИ АНІЗОТРОПІЇ ТА ІНТЕНСИВНОСТІ ГАЛАКТИЧНИХ КОСМІЧНИХ ПРОМЕНІВ, Іскра К., Гіль А., Модзелевська Р., Аланія М. В. — Досліджуються 27-добові варіації галактичних космічних променів (ГКП) за даними нейтронних моніторів світової мережі для позитивних ($A > 0$ — силові лінії міжпланетного магнітного поля виходять із північної півкулі Сонця) і негативних ($A < 0$ — силові лінії входять у північну півкулю Сонця) періодів магнітного циклу Сонця. Показано, що амплітуди 27-добових варіацій анізотропії більші для періоду $A > 0$, ніж для періоду $A < 0$, і знаходяться у тісній кореляції з подібними змінами амплітуд 27-добових варіацій інтенсивності ГКП. Вважається, що зміни амплітуд 27-добових варіацій інтенсивності та анізотропії пов'язані із змінами радіальної складової дрейфового потоку ГКП у різні періоди магнітного циклу Сонця. У період $A > 0$ дрейфовий потік напрямлений від Сонця, тоді як у період $A < 0$ поток напрямлений протилежно.

КВАЗИПЕРИОДИЧЕСКИЕ ИЗМЕНЕНИЯ АНИЗОТРОПИИ И ИНТЕНСИВНОСТИ ГАЛАКТИЧЕСКИХ КОСМИЧЕСКИХ ЛУЧЕЙ, Искра К., Гиль А., Модзелевска Р., Алания М. В. — Исследуются 27-дневные *вариации галактических космических лучей (ГКЛ) по данным нейтронных мониторов мировой сети для положительных (A > 0 — силовые линии межпланетного магнитного поля выходят из северного полушария Солнца) и отрицательных (A < 0 — силовые линии входят в северное полушарие Солнца) периодов магнитного цикла Солнца. Показано, что амплитуды 27-дневных вариаций анизотропии больше для периода A > 0, чем для периода A < 0, и находятся в хорошей корреляции с подобными изменениями амплитуд 27-дневных вариаций интенсивности ГКЛ. Полагается, что изменения амплитуд 27-дневных вариаций интенсивности и анизотропии связаны с изменяющейся радиальной компонентой дрейфового потока ГКЛ в разные периоды магнитного цикла Солнца. В период A > 0 дрейфовой поток направлен от Солнца, в то время как в период A < 0 поток направлен противоположно.*

INTRODUCTION

The 27-day variations of the GCR intensity and anisotropy were studied by Dorman [9], Fan, et al. [10], Bazilevskaya and Charakhtchyan [8], Alania and Shatashvili [6], Naskidashvili and Shatashvili [15]. Richardson et al. [18] found that the recurrent cosmic ray modulation is ~ 50 % larger during the $A > 0$ polarity period than during the $A < 0$ polarity period of solar magnetic cycle. Kota and Jokipii [14] based on the numerical solution of the three-dimensional model of GCR transport showed that cosmic-ray ions should be more sensitive to any north-south asymmetry of the heliosphere in the $A > 0$ polarity period of solar magnetic cycle. Alania et al. [5, 7], Gil and Alania [11], Vernova et al. [20] found that the amplitudes of the 27-day variation of the GCR intensity are greater in the $A > 0$ polarity periods than in the $A < 0$ polarity periods of the minima and near-minima epochs of solar activity based on the neutron monitors experimental data and on the numerical solutions of the Parker's three-dimensional transport equation including the heliolongitudinal asymmetry of the solar wind velocity. The 27-day variation of GCR anisotropy has been studying less intensively up to day. The reliable manifestation of the 27-day variation of GCR anisotropy is not easy based on the relatively small amplitudes of the diurnal variations of the GCR intensity (≤ 0.3—0.4 %) which are undergone to the significant dispersions during the Sun's rotation period [6]. Alania et al. [4] found that the 27-day variation of GCR anisotropy observed in the minimum period of solar activity, in general, must be related with the drift of GCR particles in the well established 27-day changes of the sector structure of the IMF. A relation of the 27-day variations of GCR anisotropy with the $A > 0$ and the $A < 0$ polarity periods of solar magnetic cycles are not investigated up to present. The purpose of this paper is to study the features of the 27-day variation of GCR anisotropy in relation to the similar changes of GCR intensity for the $A > 0$ and the $A < 0$ polarity periods of the solar magnetic cycles.

EXPERIMENTAL DATA AND METHODS OF INVESTIGATION

The experimental data on neutron monitors and tilt angles of the heliospheric neutral sheet (HNS) were used to study the features of the temporal changes of the amplitudes of the 27-day variations of the GCR intensity and anisotropy versus the $A > 0$ and $A < 0$ solar magnetic cycles. The amplitudes of the 27-day variation of the GCR intensity were calculated by means of the daily data of the different neutron monitors using the harmonic analyses method. The amplitudes of the 27-day variation of the GCR anisotropy were found by two ways. In the first manner, there were calculated the radial A_r and tangential A_φ components of the solar daily variations by means of the hourly data of neutron monitors using the harmonic analyses method. After, using again the harmonic analyses method there were calculated the amplitudes $A_{r(27)}$ and $A_{\varphi(27)}$ of the 27-day variation of the radial A_r and the tangential A_φ components of the solar daily variations. Then, for each Carrington rotation of the Sun amplitude of the 27-day variation of the GCR anisotropy, A_{27A} was found as:

$$A_{27A} = \sqrt{A_{r(27)}^2 + A_{\varphi(27)}^2}.$$

In the second method, after finding the radial A_r and tangential A_φ components of the solar daily variations (as for the first case) the amplitudes A_d of the daily variations were calculated, as follows:

$$A_d = \sqrt{A_r^2 + A_\varphi^2}.$$

Then, the amplitudes of the 27-day variation of the anisotropy were calculated by means of the daily variations amplitudes A_d using the method of harmonic analyses. The comparison of the results obtained by two different methods shows that the superiority must be return to the first method. In this case the amplitudes of the 27-day variation of the GCR anisotropy A_{27A} are methodically correctly calculated as far the changes of the phase of the each daily anisotropy is taken into account for the determination of the 27-day variation of the GCR anisotropy.

Table 1 gives are presented the average amplitudes of the 27-day variation of the GCR intensity for the $A > 0$ (1975—1978 and 1995—1998) and for the $A < 0$ (1964—1967 and 1985—1988) polarity periods during the minima and near-minima epochs of solar activity based on the Kiel and Roma neutron monitors data. It is seen from Table 1 that the amplitudes of the 27-day variation of GCR intensity are greater in the $A > 0$ polarity periods than ones in the $A < 0$ polarity periods of the solar magnetic cycles [11, 12]. Table 2 lists

Table 1. Average amplitudes of the 27-day variation of GCR intensity

Station	Cut off rigidity in GV	Average amplitudes of the 27-day variation of GCR intensity for the $A > 0$ and $A < 0$ solar magnetic cycles, in %			
		1964–1967, $A < 0$	1975–1978, $A > 0$	1985–1988, $A < 0$	1995–1998, $A > 0$
Rome	6.32	0.18±0.01	0.36±0.02	0.21±0.01	0.29±0.02
Kiel	2.29	0.28±0.03	0.54±0.03	0.34±0.04	0.45±0.04

Table 2. Average amplitudes of the 27-day variation of GCR anisotropy

Station	Cut off rigidity in GV	Average amplitudes of the 27-day variation of GCR anisotropy for the $A > 0$ and $A < 0$ solar magnetic cycles, in %			
		1964–1967, $A < 0$	1975–1978, $A > 0$	1985–1988, $A < 0$	1995–1998, $A > 0$
Rome	6.32	0.045±0.001	0.086±0.001	0.033±0.001	0.064±0.001
Kiel	2.29	0.051±0.001	0.079±0.001	0.03±0.001	0.063±0.001

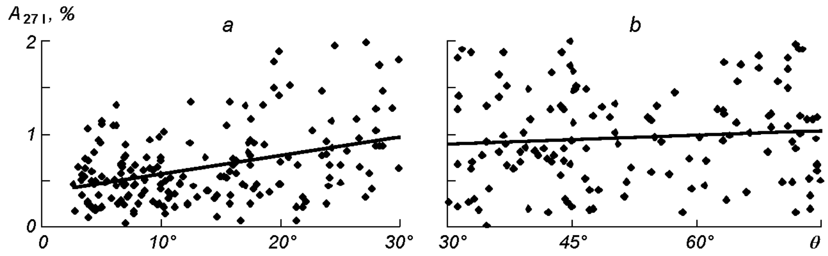

Fig. 1. Distribution of amplitudes of the 27-day variation of GCR intensity A_{27I} vs two ranges of the tilt angles θ of the HNS for Kiel neutron monitor data (approximation lines: *a* — $A_{27I} = 0.0201\theta + 0.377$; *b* — $A_{27I} = 0.0031\theta + 0.8074$)

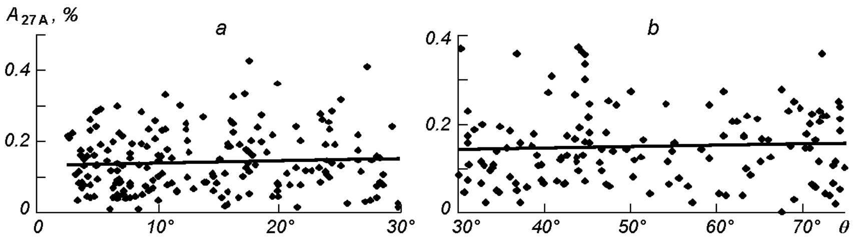

Fig. 2. Distribution of amplitudes of the 27-day variation of GCR anisotropy A_{27A} vs two ranges of the tilt angles θ of the HNS for Kiel neutron monitor data (approximation lines: *a* — $A_{27A} = 0.0008\theta + 0.1326$; *b* — $A_{27A} = 0.0003\theta + 0.1347$)

the average amplitudes of the 27-day variation of the GCR anisotropy for the $A > 0$ (1975—1978 and 1995—1998) and for the $A < 0$ (1964—1967 and 1985—1988) polarity periods of the minima epochs of solar activity based on the Kiel and Roma neutron monitors data. One can see from Table 2 that in just the same way as for the amplitudes of the 27-day variation of GCR intensity the amplitudes of the 27-day variation of GCR anisotropy are greater in the $A > 0$ cycles than those in the $A < 0$ polarity periods of the solar magnetic cycles. Figures 1 and 2 show the distributions of the amplitudes of the 27-day variations of GCR intensity and anisotropy versus the two ranges of the tilt angles. The first range (0—30°) corresponds to the solar activity minima and near-minima epochs of solar activity (Fig. 1, *a* and Fig. 2, *a*); the second range (31—80°) corresponds to the moderate, maxima and near-maxima epochs (Fig. 1, *b* and Fig. 2, *b*) of solar activity.

For the both ranges of the tilt angles there were excluded few solar Carrington rotations when the amplitudes of the 27-day variation of the GCR intensity were more than 1 % for minima and near-minima epoch and 2 % for maxima and near-maxima epoch caused by the Forbush effects. It is clear from Figures 1 and 2 that the amplitudes of the 27-day variations of GCR intensity and anisotropy do not show any remarkable dependences versus the tilt angles. Therefore, one can conclude that a topology of the HNS changing versus solar activity does not play any role in the creation of the 27-day variations of the GCR intensity and anisotropy.

THEORETICAL MODELING

In order to calculate the theoretically expected amplitude of the 27-day variations of GCR anisotropy, the Parker transport equation was used [16]:

$$\frac{\partial f}{\partial t} = \nabla_i(\kappa_{ij}\nabla_j f) - \nabla_i(U_i f) + \frac{1}{3R^2}\frac{\partial(fR^3)}{\partial R}(\nabla_i U_i), \tag{1}$$

where f and R are the omnidirectional distribution function and rigidity of GCR particles, respectively, U_i is the solar wind velocity and t denotes time. Generalized anisotropic diffusion tensor κ_{ij} of GCR for the three-dimensional interplanetary magnetic field (IMF) has the form [2, 3]:

$$\begin{aligned}
\kappa_{11} &= \kappa_{\|}[\cos^2\delta\cos^2\psi + \alpha(\cos^2\delta\sin^2\psi + \sin^2\delta)],\\
\kappa_{12} &= \kappa_{\|}[\sin\delta\cos\delta\cos^2\psi(1 - \alpha) - \alpha_1\sin\psi],\\
\kappa_{13} &= \kappa_{\|}[\sin\psi\cos\delta\cos\psi(\alpha - 1) - \alpha_1\sin\delta\cos\psi],\\
\kappa_{21} &= \kappa_{\|}[\sin\delta\cos\delta\cos^2\psi(1 - \alpha) + \alpha_1\sin\psi],\\
\kappa_{22} &= \kappa_{\|}[\sin^2\delta\cos^2\psi + \alpha(\sin^2\delta\sin^2\psi + \cos^2\delta)],\\
\kappa_{23} &= \kappa_{\|}[\sin\delta\sin\psi\cos\psi(\alpha - 1) + \alpha_1\cos\delta\cos\psi],\\
\kappa_{31} &= \kappa_{\|}[\cos\delta\sin\psi\cos\psi(\alpha - 1) + \alpha_1\sin\delta\cos\psi],\\
\kappa_{32} &= \kappa_{\|}[\sin\delta\sin\psi\cos\psi(\alpha - 1) - \alpha_1\cos\delta\cos\psi],\\
\kappa_{33} &= \kappa_{\|}[\sin^2\psi + \alpha\cos^2\psi],
\end{aligned} \tag{2}$$

where ψ is the angle between magnetic field lines and radial direction, $\psi = \arctan(-B_\varphi/B_r$, δ is the angle between magnetic field lines and radial direction in the meridian plane, $\delta = \arctan B_\theta/B_r$, in spherical coordinate system (r, θ, φ) for the $A > 0$ polarity period of the solar magnetic cycle; $\alpha = \kappa_\perp/\kappa_\|$, $\alpha_1 = \kappa_d/\kappa_\|$, where $\kappa_\|$, $\kappa_\perp$, κ_d are parallel, perpendicular and drift diffusion coefficients of GCR in the regular IMF, respectively. The Eq. (1) in spherical three-dimensional coordinate system (ρ, θ, φ) for stationary case $(\partial f/\partial t = 0)$ takes the form:

$$\begin{aligned}
&A_1\frac{\partial^2 n}{\partial\rho^2} + A_2\frac{\partial^2 n}{\partial\theta^2} + A_3\frac{\partial^2 n}{\partial\varphi^2} + A_4\frac{\partial^2 n}{\partial\rho\partial\theta} + A_5\frac{\partial^2 n}{\partial\theta\partial\varphi} +\\
&+A_6\frac{\partial^2 n}{\partial\rho\partial\varphi} + A_7\frac{\partial n}{\partial\rho} + A_8\frac{\partial n}{\partial\theta} + A_9\frac{\partial n}{\partial\varphi} + A_{10}n + A_{11}\frac{\partial n}{\partial R} = 0,
\end{aligned} \tag{3}$$

where $n = n_{\_R}/n_{0\_R}$ is the relative density of the GCR particles for the given rigidity R, $n_{\_R} = 4\pi R^2 f$ and $n_{0\_R} = 4\pi R^2 f_0$ are densities in the interplanetary space and in the interstellar medium, respectively; f_0 is the omnidirectional distribution function of GCR particles in the interstellar medium; $\rho = r/r_0$ is the dimensionless distance, r_0 denotes the size of the modulation region and r is a distance from the Sun; A_1, A_2, ..., A_{11} are the functions of ρ, θ, φ and R.

We consider a model of GCR diffusion in interplanetary space and assume that the stationary 27-day variation of GCR intensity in the minima epochs of solar activity is generally caused by the heliolongitudinal asymmetries of the solar wind velocity and diffusion coefficient. The solar wind velocity is altering as $U_0(1 + \eta\sin\varphi)$, where $\eta = 0.15$ and $U_0 = 400$ km/s throughout the heliosphere. The parallel diffusion coefficient $\kappa_\|$ changes versus the spatial

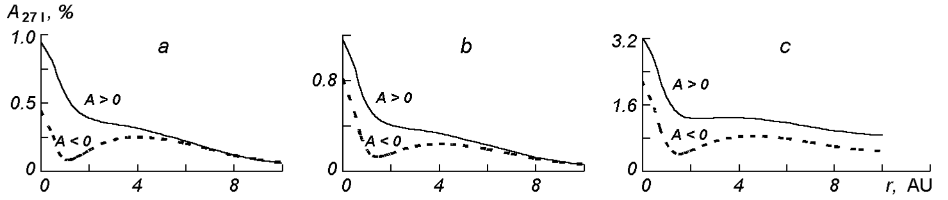

Fig. 3. Radial changes of amplitudes of the 27-day variation of GCR intensity obtained as solutions of equation (3) for different cases (see in text)

coordinates (ρ, θ, φ) and the rigidity R of GCR particles as $\kappa_{||} = \kappa_0\kappa(\rho)\kappa(\theta, \varphi)\kappa(R)$, where $\kappa_0 = \lambda_0 v/3 = 2\times10^{22}$ cm^2/s, $\kappa(\rho) = 1 + \alpha_0\rho$, $\alpha_0 = 50$, v is the velocity of GCR particles, $\kappa(\theta, \varphi) = 1 + \zeta\sin\varphi$, $\kappa(R) = (R/(1\text{GV}))^{0.5}$ and $\zeta = -0.15$. So, the parallel diffusion coefficient for the GCR particles of 10 GV rigidity equals, $\kappa_{||} = 10^{23}$ cm^2/s for $\varphi = 0$, $\theta = 90°$ and $\rho = 0.01$ (at the Earth's orbit). For $\eta = 0.15$ the Parker spiral lines of the IMF (corresponding to the solar wind velocities U_0 and $1.15U_0$) intersect at a radial distance of ~8 AU on the Sun's equatorial plane. Therefore, to exclude an intersection of the IMF lines, the dependence $U = U_0(1 + 0.15\sin\varphi)$ takes place only up to a distance of ~ 8 AU; then $U_0 = 400$ km/s remains throughout the heliosphere up to the boundary of modulation region [12]. This assumption must be considered as a minor destruction of the IMF in the negligibly small part of the whole heliosphere (0.05 %), which does not cause any changes neither of the strength nor of the numbers of the magnetic field lines. So, for the restricted at ~8 AU heliolongitudinal asymmetry of the solar wind velocity a condition for the IMF being the divergence free could be considered fulfilled in the whole heliosphere. The heliolongitudinal asymmetry of the solar wind velocity is disappeared from a distance of ~8 AU, and then $U_0 = 400$ km/s throughout the heliosphere up to the boundary of the modulation region. The flat HNS is considered as far according to our finding (Fig. 1, *a*, *b* and 2, *a*, *b*) the amplitudes of the 27-day variations of the GCR intensity and anisotropy do not depend on the tilt angles of the HNS. The neutral sheet drift was taken into account according to the boundary condition method [13]. Eq. (3) was reduced to the linear algebraic system of equations by finite difference scheme and then was numerically solved using the iteration method [17] for one rotation period of the Sun, i.e., for instant state of the heliosphere, when the distribution of the GCR density is determined by the time independent parameters included in Eq. (3). The normalized expected amplitudes of the 27-day variation of GCR intensity (for the 10 GV rigidity) obtained as the solutions of the Parker transport equation (3) with the heliolongitudinal asymmetry of solar wind velocity for different cases: a) the IMF is two-dimensional, $B_r \neq 0$, $B_\theta = 0$, $B_\varphi \neq 0$ (Fig. 3, *a*); b) the IMF is three-dimensional, $B_r \neq 0$, $B_\theta \neq 0$, $B_\varphi \neq 0$ (Fig. 3, *b*) and c) the IMF is two-dimensional $B_r \neq 0$, $B_\theta = 0$, $B_\varphi \neq 0$ (Fig. 3, *c*), but diffusion coefficient has the opposite phase of the heliolongitudinal asymmetry ($\zeta = -0.15$) with respect to the heliolongitudinal asymmetry of solar wind velocity. The solid line denotes the $A > 0$ polarity period of solar magnetic cycle and dashed line is for $A < 0$.

The expected amplitudes of the 27-day variation of GCR intensity A_{27I} for the both cases are greater for the $A > 0$ polarity period than for the $A < 0$

polarity period of solar magnetic cycle as it was found before [11]. This distinction is eliminated versus the distance (Fig. 3, *a*) due to the restriction of the heliolongitudinal asymmetry of the solar wind velocity stipulated in the GCR transport equation. However, when the unrestricted (versus the distance) diffusion coefficient is additionally included in the Eq. (3) the distinction between the amplitudes of the 27-day variation of GCR intensity for the $A > 0$ polarity period and for the $A < 0$ polarity period of solar magnetic cycle is kept far away from the Sun (Fig. 3, *c*). The expected amplitudes of the 27-day variation of GCR anisotropy A_{27A} were calculated for the first case, namely based on the solutions of the Eq. (3) for the Parker type IMF ($\delta = 0$ in the expression (2) for the tensor κ_{ij}) and for the heliolongitudinal asymmetry of the solar wind velocity, $U_0(1 + 0.15\sin\varphi)$ as follows:

$$A_{27A} = \sqrt{A_r^2 + A_\theta^2 + A_\varphi^2},$$

where

$$A_r^{\pm} = -\frac{3}{v}\,[CU_r - \kappa_{rr}\nabla_r^{\pm}n \pm \kappa_d\nabla_\theta^{\pm}n\sin\psi + (\kappa_{\parallel} - \kappa_{\perp})\nabla_\varphi^{\pm}n\sin\psi\cos\psi\,],$$

$$A_\theta^{\pm} = \frac{3}{v}\,[\pm\,\kappa_d\nabla_r^{\pm}n\sin\psi + \kappa_{\perp}\nabla_\theta^{\pm}n \pm \kappa_d\nabla_\varphi^{\pm}n\cos\psi\,], \qquad (4)$$

$$A_\varphi^{\pm} = -\frac{3}{v}\,[(\kappa_{\parallel} - \kappa_{\perp})\nabla_r^{\pm}n\sin\psi\cos\psi \pm \kappa_d\nabla_\theta^{\pm}n\cos\psi - \kappa_{\varphi\varphi}\nabla_\varphi^{\pm}n\,].$$

The signs «+» and «–» correspond to away and toward-polarities of IMF, respectively; $v \approx c$ is the cosmic ray particles velocity, $C \approx 1.5$ is the Compton-Getting factor, U is the solar wind velocity; $\nabla_r n = \frac{1}{n}\frac{\partial n}{\partial r}$, $\nabla_\theta n = \frac{1}{nr}\frac{\partial n}{\partial \theta}$, $\nabla_\varphi n = \frac{1}{nr\sin\theta}\frac{\partial n}{\partial \varphi}$ denote radial, heliolatitudinal and heliolongitudinal gradients, respectively [1, 19]. The radial changes of the expected A_{27A} for the $A > 0$ and $A < 0$ polarity periods are presented in Fig. 4. The A_{27A} at the Earth's orbit ($r = 1$ AU) is greater in the $A > 0$ polarity period than in $A < 0$ polarity period of solar magnetic cycle. It is in a good agreement with the similar changes of A_{27I}. Despite, the considered 3-dimensional model of GCR modulation is relatively simple, it satisfactorily describes the peculiarities of the 27-day variations of GCR intensity and anisotropy observed by neutron monitors in the $A > 0$ and $A < 0$ polarity periods of solar magnetic cycle for the minima and near-minima epochs of solar activity. We believe that the differences between the amplitudes of the 27-day variations of GCR intensity and anisotropy for the $A > 0$ and $A < 0$ polarity periods of solar magnetic cycles in different minima and near-minima epochs of solar activity are generally related with the heliolongitudinal asymmetry of the solar wind velocity.

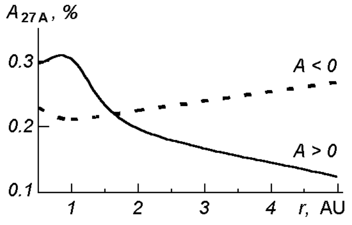

Fig. 4. Radial changes of amplitudes of the 27-day variation of GCR anisotropy

CONCLUSIONS

1. The amplitudes of the 27-day variations of GCR intensity and anisotropy do not depend on the tilt angles of the HNS throughout the 11-year cycle of solar activity.

2. The amplitudes of the 27-day variations of GCR anisotropy are greater in the minima and near-minima epochs for the positive period than those for the negative period of solar magnetic cycles according to the neutron monitors experimental data and the theoretical modeling based on the Parker transport equation. These results are in good correlation with the similar changes of the amplitudes of the 27-day variation of GCR intensity. A general motivation of these features is the direction alternating radial component of the drift stream S_d of GCR in different periods of solar magnetic cycles. In the positive period the stream S_d is directed outward from the Sun, while in negative period of solar magnetic cycle it has the opposite direction.

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