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27-DAY VARIATIONS OF THE GALACTIC COSMIC RAY INTENSITY AND ANISOTROPY*

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We study the relationships of the 27-day variations of the galactic cosmic ray (GCR) intensity and anisotropy with the 27-day variations of the solar wind (SW) velocity, Wolf number (Rz) and interplanetary magnetic field (IMF) strength for different positive ($A>0$) and negative ($A<0$) polarity periods of the solar magnetic cycles based on the experimental data. We found that the long-lived active region of the longitudes (with life time more than 22 years) exists on the Sun. This phenomenon is clearly manifested for the $A>0$ period of the solar magnetic cycle. The stable long-lived active region of the longitudes on the Sun is the source of the 27-day variation of the SW velocity. The maximum of the phase distribution of the 27-day variation of the SW velocity *versus* the heliolongitudes is preceded by 170°–180° the maxima of the phases distributions of the 27-day variations of the GCR intensity and anisotropy for the $A>0$ polarity period. When comparing the theoretical calculations (obtained by the numerical solutions of the Parker's transport equation) with the experimental data we conclude that the 27-day variation of the solar wind velocity is the general source of the 27-day variations of the GCR intensity and anisotropy. The average amplitudes of the 27-day variations of the galactic cosmic ray anisotropy and intensity for the minima epochs of solar activity are larger in the $A>0$ period than in the $A<0$ period at the Earth orbit.

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1. Introduction

The change of the amplitudes of the 27-day variations of the GCR intensity and anisotropy *versus* the $A>0$ and the $A<0$ periods of solar magnetic cycle is one of the main phenomena related to the drift. Earlier, Richardson

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et al. [1] found clear evidence that the size of recurrent cosmic ray modulation is larger during the $A > 0$ period than during the $A < 0$ period of the solar magnetic cycle over two-year intervals around five solar minima. Kota and Jokipii [2] have shown that cosmic-ray ions should be more sensitive to any north–south asymmetry of the heliosphere in the $A > 0$ period of solar magnetic cycle based on the numerical solutions of the three-dimensional model of GCR transport. Recently, Burger and Hitge [3] developed a divergence free Fisk–Parker hybrid heliospheric magnetic field and numerically solved the three dimensional steady state Parker's transport equation. They found a linear relationship between the amplitudes of 26-day recurrent intensity variations of both protons and electrons and the latitudinal intensity gradient for both solar magnetic polarity periods. In [4–8] it was shown that the amplitudes of the 27-day variation of the GCR intensity, calculated by the experimental data and theoretical modeling, are larger for the $A > 0$ period than for the $A < 0$ period of solar magnetic cycle in the minima and near minima epoch of solar activity. The amplitudes of the 27-day variation of the GCR intensity calculated based on the neutron monitors data do not depend on the tilt angles of the heliospheric neutral sheet (HNS). In general the 27-day recurrence of the GCR anisotropy was studied less intensively [9,10]; a study of the 27-day recurrence of the GCR anisotropy *versus* the solar magnetic field polarity has been carried out only recently [11, 12]. In papers [11, 13] it was documented that the average amplitudes of the 27-day variation of the GCR anisotropy calculated by the neutron monitors data for the minima epochs of solar activity are larger in the $A > 0$ period than in the $A < 0$ period of the solar magnetic cycle. The solutions of the Parker's transport equation with the heliolongitudinal asymmetry of the SW velocity are in a good agreement with the experimental results, *i.e.* the heliolongitudinal asymmetry of the SW velocity can be considered as one of the general reasons of the 27-day variations of the GCR intensity and anisotropy. In this paper we study the relationships of the 27-day variations of the GCR intensity and anisotropy with the 27-day variations of the SW velocity, Rz and IMF strength for different $A > 0$ (1975–1977 and 1995–1997) and $A < 0$ (1965–1967 and 1985–1987) polarity periods of the solar magnetic cycles based on the experimental data. For comparison the results of modeling of the 27-day variations of the GCR intensity and anisotropy based on the Parker's transport equation, are presented.

2. Experimental data, methods and results

We use data of the worldwide network of neutron monitors, SW velocity, IMF strength and Rz for the $A > 0$ and $A < 0$ periods of solar magnetic cycles [14–16]. We analyze data for the minima and near minima epoch of solar activity as far as the disturbances in the interplanetary space are minimal and a direction of the Sun's global magnetic field is well established. Therefore, for this epoch the contribution of the drift effect of the GCR particles due to gradient and curvature of the regular IMF can be revealed reasonably purely in different classes of the GCR variations; this is especially important for the GCR variations with relatively small amplitudes, *e.g.* for the 27-day variations of the GCR intensity and anisotropy. The amplitudes and phases of the 27-day variations of the GCR intensity and anisotropy, SW velocity, IMF's strength and Rz for 1975–1977 and 1995–1997 ($A > 0$); for 1965–1967 and 1985–1987 ($A < 0$) were calculated by the harmonic analysis method for each Carrington rotation period (27-days). Our aim is to manifest the relationships of the 27-day variations of the GCR intensity and anisotropy with the 27-day variations of the SW velocity, Rz and strength of the IMF. For this purpose we analyze the distributions of the phases of the 27-day variations of the SW velocity, GCR intensity and anisotropy (Fig. 1(a)), and the IMF's strength and Rz (Fig. 1(b)) *versus* the heliolongitudes for the $A > 0$ periods (1975–1977 and 1995–1997). The distribution of the 27-day variation of the SW velocity has a sharply established maximum and for comparison has been also included in Fig. 1(b).

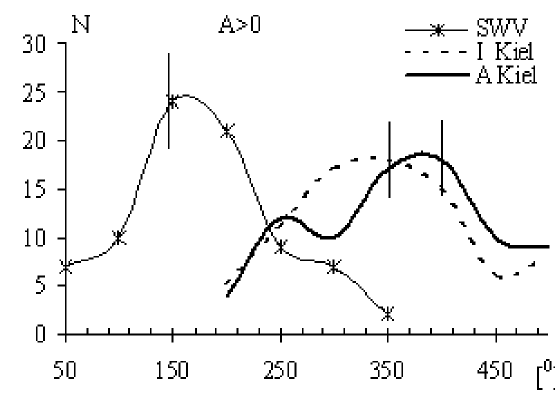

Fig. 1(a) The distributions of the phases of the 27-day variations of the SW velocity (SWV), GCR intensity (I Kiel) and anisotropy (A Kiel). On the ordinate axes is brought the frequency (N) of the given phases and on the horizontal axes — heliolongitudes in degrees [°] for the $A > 0$ polarity period of the solar magnetic cycle (1975–1977 and 1995–1997).

Figs. 2(a), 2(b) present similar frequencies obtained for the negative polarity periods ($A < 0$) years 1965–1967 and 1985–1987. For the $A > 0$ polarity periods data of all considered parameters (excluding Rz) consist of 6 years (~ 80 Carrington rotations). Daily Rz very often equals zero in the minima epochs and, because of that, from the consideration were excluded the Carrington rotations consisting ≥ 10 days with zero Rz; for these Carrington rotations the results of the harmonic analyses are not reliable. Accordingly, we have excluded from the consideration the data of 9 Carrington rotations for the $A > 0$ periods. In the $A < 0$ periods data of the strength of the IMF and SW velocity are absent for 1965–1967. Fig. 1(a) shows that the distributions of the phases of the 27-day variations of the SW velocity, GCR intensity and anisotropy have maxima. The maxima for the GCR intensity ($\sim 325°$ of the heliolongitudes) and anisotropy ($\sim 25°$ of the heliolongitudes) are basically opposite with respect to the maximum of the SW velocity ($\sim 175°$ of the heliolongitudes). The maximum of the phase distribution of the 27-day variation of the SW velocity *versus* the heliolongitudes is preceded by 170°–180° maxima of the phases distributions of the 27-day variations of the GCR intensity and anisotropy for the $A > 0$ polarity period.

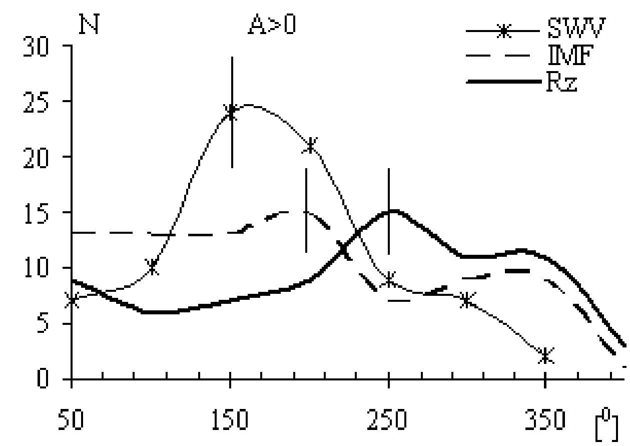

Fig. 1(b) The distributions of the phases of the 27-day variations of the SW velocity (SWV), Wolf number (Rz) and IMF stregth (IMF). On the ordinate axes is brought the frequency (N) of the given phases and on the horizontal axes — heliolongitudes in degrees [°] for the $A > 0$ polarity period of the solar magnetic cycle (1975–1977 and 1995–1997).

Fig. 1(b) shows that in the distributions of the phases of the 27-day variations of the IMF's strength and Rz cannot be resolved by any regular maxima (in scope of the existing statistics); these distributions are not in correlation with the phase distribution of the 27-day variation of the SW velocity.

Figs. 2(a) and 2(b) show that for the $A < 0$ period there are not any visible regularities. Besides, the statistics of the used data, for SW velocity and strength of the IMF, twice smaller than for analogous SW and IMF data in the $A > 0$ period. Nevertheless, the statistics for the GCR intensity and anisotropy are the same as for the $A > 0$ period ($\sim$80 Carrington rotations).

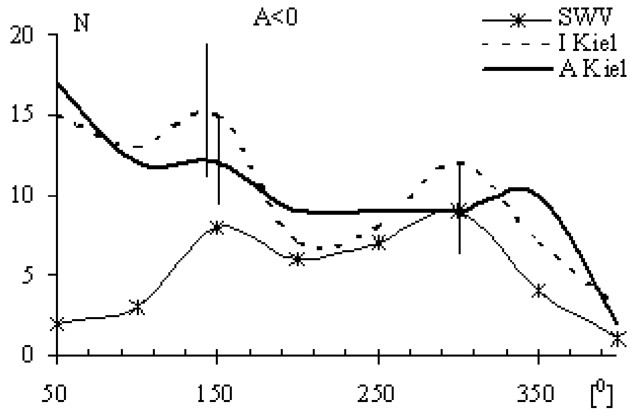

Fig. 2(a) The same parameters as in Fig. 1(a), for the $A < 0$ period of the solar magnetic cycle.

The scattered distributions of the phases of the 27-day variations of the GCR intensity and anisotropy (Fig. 2(a)) for the $A < 0$ polarity period suggest that the amplitudes of the 27-day variations of GCR intensity and anisotropy are greater in the $A > 0$ polarity period than in the $A < 0$ polarity period [11,13]. The phase distribution of the 27-day variation of the solar wind velocity (Fig. 1(a)) shows that the long-lived (with life-time more than 22 years) active region of the heliolongitudes exists on the Sun for the $A > 0$ polarity period of the solar magnetic cycle. The long-lived active region of the heliolongitudes is the source of the 27-day variation of the solar wind velocity, thus it can be considered as the general source of the 27-day variations of the GCR intensity and anisotropy.

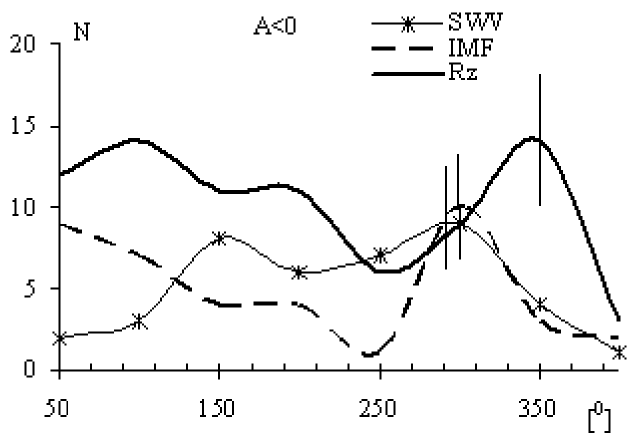

Fig. 2(b) The same parameters as in Fig. 1(b), for the $A < 0$ period of the solar magnetic cycle.

3. Theoretical modeling and discussion

To calculate the theoretically expected amplitudes of the 27-day variations of the GCR intensity and anisotropy the Parker's transport equation has been used [17]:

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

where f and R are the omnidirectional distribution function and rigidity of GCR particles, respectively. U_i is the solar wind velocity and t is time. Generalized anisotropic diffusion tensor K_{ij} of GCR for the three dimensional IMF is taken from [18]. For stationary case ($\partial f/\partial t = 0$) and in spherical coordinates (ρ, θ, φ) Eq. (1) takes the form:

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

where the coefficients $A_1, A_2, \ldots, A_{11}$ are the functions of (ρ,θ,φ) and R; $\rho = r/r_0$ is the dimensionless distance, r_0 the size of the modulation region and r distance from the Sun; $n = n_R/n_{0R}$ is the relative density of the GCR particles for the given rigidity R; $n_R = 4\pi R^2 f$ is the density in the interplanetary space; $n_{0R} = 4\pi R^2 f_0$ is the density and f_0 is the omnidirectional distribution function of GCR particles in the interstellar medium. The intensity I_0 of the GCR particles in the interstellar space ($I_0 = R^2 f_0$) is taken according to [19, 20] as

$$I_0 = \frac{21.1\,T^{-2.8}}{1 + 5.85\,T^{-1.22} + 1.18\,T^{-2.54}}\,,$$

where T is the kinetic energy of particles. The radius of the modulation region is equal to 100 AU. We assume that the stationary 27-day variation of the GCR intensity in the minima epochs of solar activity can be generally caused by the heliolongitudinal asymmetry of the solar wind velocity. In paper [8] we assumed that the solar wind velocity changes *versus* the heliolongitudes as, $U = U_0(1 + 0.2\sin\varphi)$. To exclude an intersection of the IMF lines this dependence takes place only up to the distance of ~ 7.5 AU. In this case heliolongitudinal asymmetry of the solar wind velocity is drastically cut from ~ 7.5 AU, and then $U = 400$ km/s throughout the heliosphere. In the present model to exclude the intersection of the IMF lines we assume that the heliolongitudinal asymmetry of the solar wind velocity is dumped gradually *versus* the radial distance up to 7.5 AU as

$$U = U_0\left(1 + 0.2\sin\varphi\; e^{\frac{\rho(0.01-\rho)}{0.001}}\right)\,. \tag{3}$$

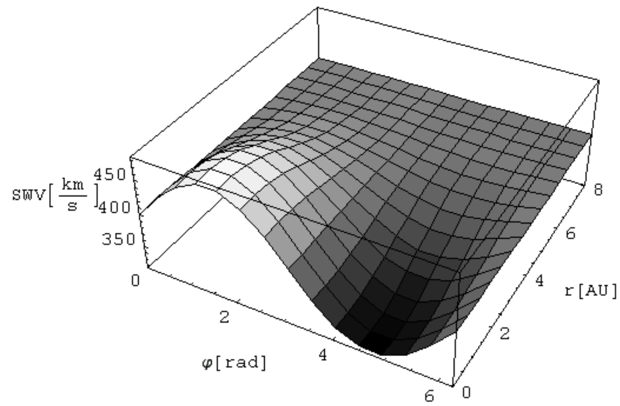

Fig. 3 The change of the solar wind velocity according to the expression (3) *versus* the heliolongitudes φ and the distance r.

The change of the solar wind velocity *versus* the heliolongitudes and distance is presented in Fig. 3. The parallel diffusion coefficient $K_\parallel$ changes *versus* the spatial coordinates (ρ, θ, φ) and rigidity R of GCR particles as, $K_\parallel = K_0 K(\rho) K(\varphi) K(R) \approx 2 \times 10^{22}\,\mathrm{cm}^2/\mathrm{s}$, where $K_0 = \lambda_0 v/3$, $K(\rho) = 1 + \alpha_0\rho$, $\alpha_0 = 50$, v is the velocity of GCR particles, $K(R) = (R/1\mathrm{GV})^{0.5}$. So, the parallel diffusion coefficient for the GCR particles of 10 GV rigidity equals, $K_\parallel \approx 10^{23}\,\mathrm{cm}^2/\mathrm{s}$ for $\varphi = 0$, $\theta = 90^\circ$ and $\rho = 0.01$ (at the Earth orbit).

The ratios of α and α_1 of the perpendicular and drift diffusion coefficients $K_\perp$ and K_d to the parallel diffusion coefficient $K_\parallel$ are: $\alpha = K_\perp/K_\parallel = (1 + \omega^2\tau^2)^{-1}$ and $\alpha_1 = K_d/K_\parallel = \omega\tau(1 + \omega^2\tau^2)^{-1}$. We assume that $\alpha \approx 0.1$ ($\omega\tau \approx 3$) at the Earth orbit. The transport free path λ_0 for the GCR particles of the rigidity $R = 10\,\mathrm{GV}$ and for the strength $H = 5\,\mathrm{nT}$ of the IMF, (at the Earth's orbit) is found from the expression $\omega\tau = 300\,\mathrm{H}\ \lambda_0 R^{-1}$ ($\lambda_0 \approx 2 \times 10^{12}\,\mathrm{cm}$).

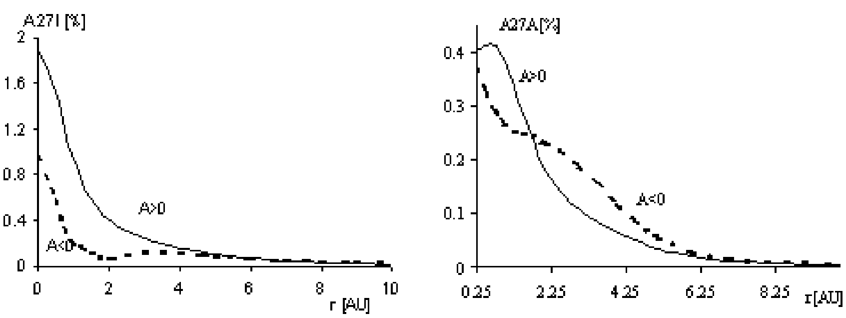

Fig. 4 The changes of A27I (a) and A27A (b) *versus* radial distance for $A > 0$ (solid line) and $A < 0$ (dashed line).

The flat HNS is considered so far according to our finding [11] that the amplitudes of the 27-day variations of the GCR intensity and anisotropy noticeably do not depend on the tilt angles of the HNS. The neutral sheet drift was taken into account according to the boundary condition method [21] and was compared with the velocity field method [22,23]. It was found that there are not any valuable differences between the results obtained based on the above mentioned two methods [8]. Eq. (2) was reduced to the linear algebraic system of equations by finite difference scheme and then was numerically solved using the iteration method [24] for one rotation period of the Sun, *i.e.* for the instant state of the heliosphere, when the distribution of the GCR density is determined by the time independent parameters included in Eq. (2). The normalized expected amplitudes of the 27-day variation of the GCR intensity (for the 10 GV rigidity), obtained as the solutions of the Parker's transport Eq. (2), are presented in Fig. 4(a) for the $A > 0$ (solid line) and the $A < 0$ (dashed line) periods of solar magnetic cycle *versus* the radial distance from the Sun. The solutions correspond to the Parker's type IMF. The expected amplitudes of the 27-day variation of the GCR intensity (A27I) are greater for the $A > 0$ period than for the $A < 0$ period of solar magnetic cycle as it was found before [6]. The distinction is eliminated *versus* the distance due to the dumping of the heliolongitudinal asymmetry of the solar wind velocity stipulated in the GCR transport equation. The 27-day variation of the GCR anisotropy is genetically related with the similar changes of the GCR intensity. The expected amplitudes of the 27-day variation of the GCR anisotropy (A27A) were calculated based on the solutions of the Eq. (2) for the Parker's type IMF and for the heliolongitudinal asymmetry of the solar wind velocity (Eq. (3)) as follows:

$$(\mathrm{A27A}) = \sqrt{A_{\mathrm{r}}^2 + A_\theta^2 + A_\varphi^2}\,,$$

where

$$\begin{aligned}
A_r^{\pm} &= -\frac{3}{v}[CU_r - K_{rr}\nabla_r^{\pm} n \pm K_d \nabla_\theta^{\pm} n \sin\psi + (K_\parallel - K_\perp)\nabla_\varphi^{\pm} n \sin\psi\cos\psi]\,,\\
A_\theta^{\pm} &= \frac{3}{v}[\pm K_d \nabla_r^{\pm} n \sin\psi + K_\perp \nabla_\theta^{\pm} n \pm K_d \nabla_\varphi^{\pm} n \cos\psi]\,,\\
A_\varphi^{\pm} &= -\frac{3}{v}\left[(K_\parallel - K_\perp)\nabla_r^{\pm} n \sin\psi\cos\psi \pm K_d \nabla_\theta^{\pm} n \cos\psi - K_{\varphi\varphi}\nabla_\varphi^{\pm} n\right]\,. \qquad (4)
\end{aligned}$$

The signs $\pm$ correspond to away ("$+$") and toward ("$-$") polarities of the Sun's global magnetic field, 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; $\nabla_r n = (1/n)\,\partial n/\partial r$, $\nabla_\theta n = (1/(nr))\,\partial n/\partial\theta$, $\nabla_\varphi n = (1/(nr\sin\theta))\,\partial n/\partial\varphi$ are radial, heliolatitudinal and helilongitudinal gradients, respectively [17,25,26]. The radial changes of the expected A27A for the $A > 0$ and $A < 0$ periods are presented in Fig. 4(b).

The A27A at the Earth orbit ($r = 1\,\mathrm{AU}$) are greater in the $A > 0$ period than in the $A < 0$ period of solar magnetic cycle. However, this relationship is violated for the distance $> 2\,\mathrm{AU}$. These complicated phenomena are generally related to the heliolongitudinal asymmetry of the solar wind velocity and with the specific distributions of the spatial gradients of the GCR density.

4. Conclusion

1. The phase distribution of the 27-day variation of the solar wind velocity shows that the long-lived (with life time more than 22 years) active region of the heliolongitudes exists on the Sun for the $A > 0$ polarity period of the solar magnetic cycle. The stable long-lived active region of the heliolongitudes is the source of the 27-day variation of the solar wind velocity, thus it becomes the general source of the 27-day variations of the GCR intensity and anisotropy caused by the drift.

2. The maxima for the GCR intensity and anisotropy are basically opposite with respect to the maximum of the SW velocity. The maximum of the phase distribution of the 27-day variation of the SW velocity *versus* the heliolongitudes is preceded with 170°–180° maxima of the phase distributions of the 27-day variations of the GCR intensity and anisotropy for the $A > 0$ polarity period.

3. Solutions of the Parker's transport equation for stationary case show that the A27I and A27A at the Earth orbit are greater in the $A > 0$ period than in the $A < 0$ period of the solar magnetic cycle. This phenomenon is related to the heliolongitudinal asymmetry of the solar wind velocity.

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