Vol. 35 (2004) ACTA PHYSICA POLONICA B No 4

ON ROLES OF THE STOCHASTIC AND REGULAR HELIOSPHERIC MAGNETIC FIELDS IN DIFFERENT CLASSES OF GALACTIC COSMIC RAY VARIATIONS*

K. Iskra[a], M.V. Alania[a,b], A. Gil[a], R. Modzelewska[a] and M. Siluszyk[a]

[a]Institute of Mathematics and Physics, University of Podlasie
3 Maja 54, 08-110 Siedlce, Poland
[b]Institute of Geophysics, Georgian Academy of Sciences
Tbilisi, Georgia

(Received January 22, 2004; revised version received April 6, 2004)

Data of neutron monitors for different solar magnetic cycles have been used to study the role of the regular and stochastic components of the interplanetary magnetic field (IMF) on the diffusion propagation of galactic cosmic rays (GCR). Two classes of GCR variations are considered. The first one is the 11-year variation of GCR related with the similar periodic changes in solar activity and solar wind parameters; the second one is the quasi-periodic 27-day variation stipulated by the heliolongitudinal asymmetry of the electro-magnetic conditions (*e.g.* solar wind velocity and diffusion) in the inner heliosphere caused by the Sun's rotation. Transport equation of GCR particles has been numerically solved for two and three dimensional IMF including diffusion, convection, drift due to gradient and curvature of the regular IMF and the energy change of GCR particles because of interaction with the irregularities of solar wind. It is shown that a significant changes in the structure of the IMF's irregularities from the minima to the maxima epochs of solar activity reflecting in the dependences of the diffusion coefficient on the GCR particles' rigidity is one of the general reasons of the 11-year variation of GCR. The heliolongitudinal asymmetries of the solar wind velocity and diffusion processes in the inner heliosphere cause the GCR 27-day variation with the larger amplitude in the minima and near minima epochs of the $qA > 0$ solar magnetic cycle, than that in the $qA < 0$ cycles due to existence of the oppositely directed drift streams of GCR. An interpretation of this phenomenon has been proposed based on the modern theory of GCR propagation.

PACS numbers: 96.50.Ci, 96.40.Cd

* Presented at the XVI Marian Smoluchowski Symposium on Statistical Physics, Zakopane, Poland, September 6–11, 2003.

1. Introduction

IMF B can be represented as a sum of regular B_0 and stochastic δB components, $B = B_0 + \delta B$, average values of $\langle B \rangle = B_0$ and $\langle \delta B \rangle = 0$ [1]. In the maxima epochs of the 11-year cycle of solar activity the Sun's global magnetic field undergoes a reversal [2]. An interval between two successive minima epochs of solar activity is called the 11-year cycle of solar activity, while an interval between two successive maxima epochs with the definitely identified global magnetic field direction is called the positive ($qA > 0$) or the negative ($qA < 0$) part of the 22-year solar magnetic cycle, respectively. For $qA > 0$ solar magnetic cycle lines of the regular component B_0 of the IMF (global magnetic field of the Sun) are directed outward from the northern hemisphere, while for $qA < 0$ cycle an opposite situation (inward direction) occurs . Effect of drift due to gradient and curvature of the regular IMF causes various types of changes in different classes of GCR variations; namely: considerable changes of the time profile and level of GCR intensity (11-year variation of GCR) in different $qA > 0$ and $qA < 0$ solar magnetic cycles [3]; radial gradient of GCR for the $qA > 0$ cycles is much less than that in the $qA < 0$ cycles in the throughout of the heliosphere [4, 5]; the amplitude of the 27-day variation of GCR for the minima epochs is greater in the $qA > 0$ cycles than that in the $qA < 0$ cycles [6–12]; the phase of the diurnal variation of GCR is observed at the earlier hours in the $qA > 0$ cycles than that in the $qA < 0$ solar magnetic cycle [13–15]. Moreover, due to adiabatic focusing of particles in the regular spiral IMF an anisotropy of solar cosmic rays [16–18] is observed. A stochastic (random) component δB of the IMF plays an important role in the scattering (diffusion) of GCR in the interplanetary space. Particularly, according to the quasi linear approach (or two component model with 80% 2D fraction and 20% slab fraction) a parallel diffusion coefficient $K_{\|}$ of GCR of the rigidity $\geq$ (5–10) GV depends on the GCR particle's rigidity R, as $K_{\|} \propto R^q$, where $q = 2 - \nu$; ν is the exponent of the power spectral density (PSD) of the IMF fluctuations, PSD $\propto f^{-\nu}$ [19–21]. Various values of the exponent ν for the minima and maxima epochs of solar activity indicate that there takes place a rearrangement of the structure of the IMF's large scale irregularities. It causes different typeset of the diffusion of GCR *vs.* solar activity and is well pronounced in behavior of the power rigidity spectrum $\frac{\delta D(R)}{D_0(R)} \propto (\frac{R}{R_0})^{-\gamma}$ of GCR intensity variations. Here, $\delta D(R) = D_0(R) - D(R)$ is the change of the differential rigidity spectrum, $D_0(R)$ and $D(R)$ are the differential rigidity spectra of GCR for the minimum epoch of solar activity (accepted in the interim as an unmodulated one) and for any current period of solar activity, respectively. Generally $R_0 = 1$ GV, however, for the calculations of the rigidity spectrum by means of neutron monitors data, $R_0 = 10$ GV.

The changes of ν *versus* solar activity are reflected in the behavior of the rigidity spectrum of the isotropic intensity variations of GCR. In the minima epochs the rigidity spectrum is hard ($\gamma \approx 0.5$), while in the maxima epochs the spectrum is soft ($\gamma \approx 1.2 - 1.5$) [15, 22–24]. This paper concerns theoretical and experimental studies of the roles of the regular and stochastic heliospheric magnetic fields on the formation of the 11-year and the 27-day variations of GCR in different $qA > 0$ and $qA < 0$ solar magnetic cycles.

2. 11-year variation of GCR

In Fig. 1 temporal changes of GCR intensity by Kiel neutron monitor data [25] and relative sunspot numbers [26] are presented. On the abscissa axis (bold-faced bars) the time intervals of the Sun's global magnetic field reversals are shown.

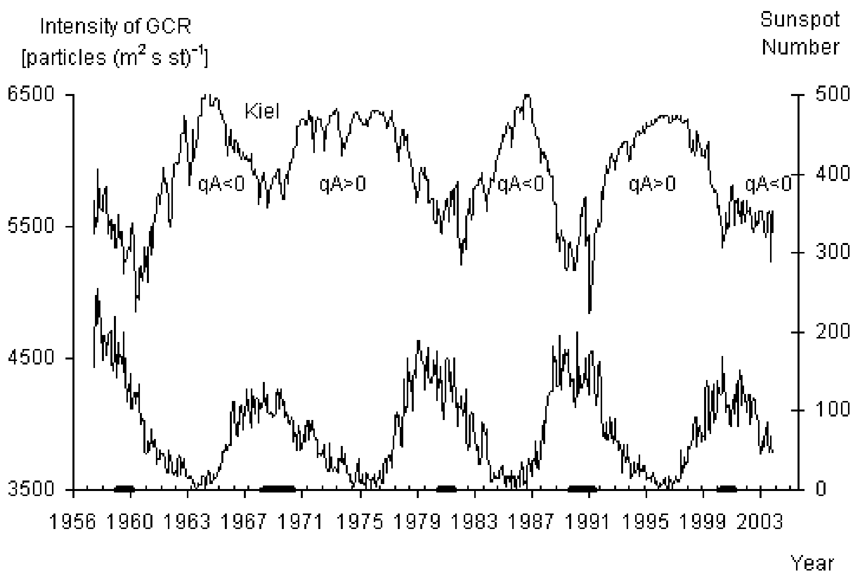

Fig. 1. Intensity of GCR for Kiel neutron monitor and sunspot number for the period 1957–2003 (bold-faced bars on the abscissa show time intervals of the global magnetic field reversals).

It is seen from this figure that in the minima epochs of solar activity the time profiles of the GCR intensity changes for different $qA > 0$ and $qA < 0$ solar magnetic cycles are remarkably distinct. For the $qA > 0$ cycles (1971–1978; 1992–1999) the time profiles of GCR intensity display plateau, while in the $qA < 0$ cycles (1960–1969; 1981–1989) sharp peaks [3] are noticeable.

At the same time in different $qA > 0$ and $qA < 0$ solar magnetic cycles the amplitudes of the 11-year variation of GCR differ from each other by less than $\leq 5\%$ (Fig. 1).

It is of interest to investigate the influences of the regular and stochastic IMF on the expected spatial distributions of density, radial and latitudinal gradients and rigidity spectrum of GCR variations for different $qA > 0$ and $qA < 0$ solar magnetic cycles based on the analyses of the theoretical calculations and neutron monitors experimental data. For this purpose Parker's transport equation has been used [27].

$$\frac{\partial N}{\partial t} = \nabla_i(K_{ij}\nabla_j N) - \nabla_i(U_i N) + \frac{R}{3}\frac{\partial N}{\partial R}(\nabla_i U_i)\,, \tag{1}$$

where N is a density in interplanetary space and R is rigidity of GCR particles. On the right side of the equation (1) the first term describes diffusion due to the symmetric part and drift due to the antisymmetric part of the anisotropic diffusion tensor K_{ij}, the second term describes convection and third one a change of the energy of GCR particles due to interaction with the irregularities of solar wind; U_i is the solar wind velocity and t is the time. The generalized anisotropic diffusion tensor K_{ij} of GCR has the following form [28, 29]:

$$\begin{aligned}
K_{rr} &= K_{\|}[\cos^2\delta\cos^2\psi + \alpha(\cos^2\delta\sin^2\psi + \sin^2\delta)]\,,\\
K_{r\theta} &= K_{\|}[sin\delta\cos\delta\cos^2\psi(1-\alpha) - \alpha_1\sin\psi]\,,\\
K_{r\phi} &= K_{\|}[sin\psi\cos\delta\cos\psi(\alpha-1) - \alpha_1\sin\delta\cos\psi]\,,\\
K_{\theta r} &= K_{\|}[\sin\delta\cos\delta\cos^2\psi(1-\alpha) + \alpha_1\sin\psi]\,,\\
K_{\theta\theta} &= K_{\|}[\sin^2\delta\cos^2\psi + \alpha(\sin^2\delta\sin^2\psi + \cos^2\delta)]\,,\\
K_{\theta\phi} &= K_{\|}[\sin\delta\sin\psi\cos\psi(\alpha-1) + \alpha_1\cos\delta\cos\psi]\,,\\
K_{\phi r} &= K_{\|}[\cos\delta\sin\psi\cos\psi(\alpha-1) + \alpha_1\sin\delta\cos\psi]\,,\\
K_{\phi\theta} &= K_{\|}[\sin\delta\sin\psi\cos\psi(\alpha-1) - \alpha_1\cos\delta\cos\psi]\,,\\
K_{\phi\phi} &= K_{\|}[\sin^2\psi + \alpha\cos^2\psi]\,.
\end{aligned} \tag{2}$$

Here $\delta = \arctan(B_\theta/B_r)$ and $\psi = \arctan(-B_\varphi/B_r)$ in spherical coordinate system (ρ, θ, ϕ) for $qA > 0$ solar magnetic cycle; δ is the angle between the magnetic field lines and radial direction in the meridian plane; $\alpha = \frac{K_\perp}{K_\|}$, $\alpha_1 = \frac{K_d}{K_\|}$, $K_\|$ and $K_\perp$ are parallel and perpendicular diffusion coefficients of GCR with respect to the regular IMF, respectively; K_d is drift diffusion coefficient. The ratio α is assumed as: $\alpha = (1+\omega^2\tau^2)^{-1}$, where $\omega\tau = 300H\lambda R^{-1}$; H is the strength of the IMF and λ — the transport free path of GCR particles. At the Earth's orbit $H = 5$ nT, $\lambda = 2\times10^{-12}$ cm. At the boundary region of the modulation a full isotropic diffusion is assumed, so that α tends to 1. The equation (1) in spherical 3D coordinate system (ρ, θ, ϕ) for the stationary case $\frac{\partial N}{\partial t} = 0$ can be written:

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

In equation (3) n is the relative density, ($n = N/N_0$; N_0 is density of GCR in the interstellar medium accepted as $N_0 \propto R^{-4.5}$ for the rigidities to which neutron monitors are sensitive); dimensionless distance $\rho = r/r_0$, where $r_0 = 100$ AU (AU — Astronomical Unit) is the size of the modulation region and r a distance from the Sun; $A_1, A_2, \ldots, A_{11}$ are the functions of ρ, θ, ϕ and R.

$$\begin{aligned}
A_1 &= \rho^2(\alpha \sin^2 \delta + \cos^2 \delta(\cos^2 \psi + \alpha \sin^2 \psi)) \,, \\
A_2 &= \rho \sin \theta (\sin^2 \delta((\alpha - 1)\sin^2 \psi + 1) + \alpha \cos^2 \delta) \,, \\
A_3 &= \frac{(\alpha - 1)\cos^2 \psi + 1}{\sin^2 \theta} \,, \\
A_4 &= \rho^3 (\sin \delta \cos \delta (1 - \alpha) \cos^2 \psi - \alpha_1 \sin \psi) \\
&\quad + \rho(\alpha_1 \sin \psi + \sin \delta \cos \delta (1 - \alpha) \cos^2 \psi) \,, \\
A_5 &= \frac{\sin \delta (\alpha - 1) \sin 2\psi}{\sin \theta} \,, \\
A_6 &= \frac{\rho^3}{\sin \theta} (\cos \delta (\alpha - 1) \sin \psi \cos \psi + \alpha_1 \sin \delta \cos \psi) \,, \\
A_7 &= -U\rho^2 + 2\rho(\cos^2 \delta \cos^2 \psi + \alpha \cos^2 \delta \sin^2 \psi + \alpha \sin^2 \delta) \\
&\quad + \rho \cot \theta (\alpha_1 \sin \psi + \sin \delta \cos \delta (1 - \alpha) \cos^2 \psi) \\
&\quad + (\alpha - 1) \sin 2\psi \cos^2 \delta \rho^2 \frac{U \Omega \sin \theta}{U^2 + \rho^2 \Omega^2 \sin^2 \theta} \\
&\quad + (\alpha_1 \cos \psi + (\alpha - 1) \sin 2\psi \frac{\sin 2\delta}{2}) \frac{U \Omega \rho^2 \cos \theta}{U^2 + \rho^2 \Omega^2 \sin^2 \theta} \\
&\quad + (\cos \delta (1 - \alpha) \cos 2\psi + \alpha_1 \sin \delta \sin \psi) \frac{0.2 U_0 \Omega \rho^2 \cos \phi}{U^2 + \rho^2 \Omega^2 \sin^2 \theta} \,,
\end{aligned}$$

$$\begin{aligned}
A_8 &= \frac{\sin 2\delta}{2}(1-\alpha)\cos^2\psi - \alpha_1 \sin\psi \\
&+((\alpha-1)\frac{\sin 2\delta}{2}\sin 2\psi - \alpha_1\cos\psi)\rho\frac{U\Omega\sin\theta}{U^2+\rho^2\Omega^2\sin^2\theta} \\
&+\cot\theta(\sin^2\delta\cos^2\psi + \alpha(\sin^2\delta\sin^2\psi + \cos^2\delta)) \\
&+\sin^2\delta(\alpha-1)\sin 2\psi\frac{U\Omega\rho\cos\theta}{U^2+\rho^2\Omega^2\sin^2\theta} \\
&+(1-\alpha)\sin\delta\cos 2\psi - \alpha_1\cos\delta\sin\psi)\frac{0.2U_0\Omega\rho\cos\phi}{U^2+\rho^2\Omega^2\sin^2\theta}\,, \\
A_9 &= \frac{1}{\sin\theta}(\cos\delta(\alpha-1)\frac{\sin 2\psi}{2} - \alpha_1\sin\delta\cos\psi) \\
&+(\cos\delta(\alpha-1)\cos 2\psi + \alpha_1\sin\delta\sin\psi)\frac{U\Omega\rho}{U^2+\rho^2\Omega^2\sin^2\theta} \\
&+\cot\theta(\sin\delta(\alpha-1)\cos 2\psi - \alpha_1\cos\delta\sin\psi)\frac{U\Omega\rho}{U^2+\rho^2\Omega^2\sin^2\theta} \\
&+(\alpha-1)\sin 2\psi\frac{0.2U_0\Omega\rho^2\cos\phi}{U^2+\rho^2\Omega^2\sin^2\theta}\,, \\
A_{10} &= \frac{8}{3}U\rho\,, \\
A_{11} &= \frac{2}{3}U\rho R\,.
\end{aligned}$$

It is well known, 2-dimensional axial symmetric case ($\frac{\partial n}{\partial\phi} = \frac{\partial^2 n}{\partial\phi^2} = 0$) is a good approximation for the 11-year variation of GCR as far as the role of the heliolongitudinal asymmetry of solar activity is negligible. For this case all terms in equation (3) containing $\frac{\partial n}{\partial\phi}$, $\frac{\partial^2 n}{\partial\phi\partial\theta}$, $\frac{\partial^2 n}{\partial\phi\partial\rho}$, $\frac{\partial^2 n}{\partial\phi^2}$ become 0 and they can be grouped in the form of:

$$A_1\frac{\partial^2 n}{\partial\rho^2} + A_2\frac{\partial^2 n}{\partial\theta^2} + A_4\frac{\partial^2 n}{\partial\rho\partial\theta} + A_7\frac{\partial n}{\partial\rho} + A_8\frac{\partial\, n}{\partial\theta} + A_{10}n + A_{11}\frac{\partial n}{\partial R} = 0\,. \quad (4)$$

This equation has been reduced to the linear algebraic system by the finite difference method. It was further solved numerically by the iteration method using a relaxation; an accuracy ε of the solution is equal to 5×10^{-6} ($\varepsilon = 5\times10^{-6}$).

In Fig. 2(a) and (b) are presented radial and heliolatitudinal dependences of the GCR density for the rigidity of 10 GV. In Fig. 2(a) are shown radial and in Fig. 2(b) heliolatitudinal dependences of the density of GCR for the $qA>0$ and the $qA<0$ solar magnetic cycles and for $qA=0$ case (in the

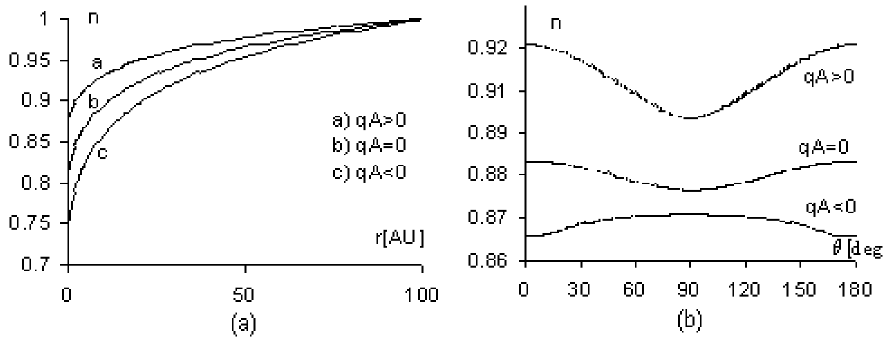

Fig. 2. (a) The density of GCR *versus* the distance from the Sun in equatorial region for rigidity R=10 GV: a) $qA > 0$ b) $qA = 0$ c) $qA < 0$. (b) The density of GCR *versus* the heliolatitude θ at 1 AU.

$qA = 0$ case the regular IMF is absent and diffusion of GCR is isotropic). It is seen from the figures that: (a) a density of GCR is higher for $qA > 0$ solar magnetic cycle (Fig. 2(a)) than that for the $qA < 0$ cycle; (b) a density for the $qA = 0$ case is less than that for the $qA > 0$ cycle, but it is greater for the $qA < 0$ cycle. The heliolatitudinal dependences of the GCR density have some peculiarities *versus* the $qA > 0$ and the $qA < 0$ solar magnetic cycles. Due to the spiral IMF diffusion coefficients (*e.g.* K_{rr}) of GCR are greater in the polar regions than that in the helioequatorial region (garden hose angle $\psi = 0$, for $\theta = 0°$ and $\theta = 180°$, and $\psi = 45°$ for $\theta = 90°$) for both the $qA > 0$ and $qA < 0$ cycles. So, densities of GCR are greater in the polar regions than those in the equatorial region (we call it 'the effect of the spiral IMF'). For $qA > 0$ cycle particles of GCR are drifting from the polar regions to the equatorial, while for the $qA < 0$ cycle the vice versa situation takes place. According to the above mentioned circumstances for the $qA > 0$ cycle the effects of drift and the spiral IMF coincide and a density of GCR is less in the helioequatorial region ($\theta = 90°$) than that in the polar regions ($\theta = 0°$ and $\theta = 180°$). For the $qA < 0$ cycle, depending on the magnitudes of these two oppositely directed effects, there could be observed different distributions of GCR density *versus* the heliolatitudes; *e.g.*, it is seen from the Fig. 2(b) that a density of GCR is smaller in polar regions of the Sun than that in the equatorial region. It means that in the considered model of GCR transport a magnitude of the drift effect is greater than that the magnitude of the oppositely directed effect of the spiral IMF at the Earth orbit. It is necessary to stress that in the various points of space the roles of drift and spiral IMF effects of GCR could be altered depending on the spatial and temporal changes of the parameters α and α_1.

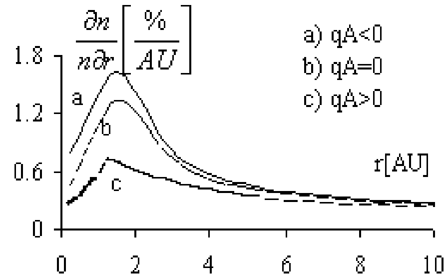

Fig. 3. The radial gradients of GCR *versus* the distance from the Sun at equatorial plane: (a) $qA > 0$, (b) $qA = 0$, (c) $qA < 0$.

In Fig. 3 the radial gradients of GCR for $qA > 0$, $qA < 0$ and $qA = 0$ cycles are presented. It can be seen from this figure that throughout the heliosphere the radial gradient is greater for the $qA < 0$ cycle than for the $qA > 0$ case.

To find a relationship between the GCR isotropic intensity variations rigidity spectrum exponent γ and the parameter q showing the dependence of the diffusion coefficient $K_\parallel$ on the GCR particle's rigidity R, ($K_\parallel \propto R^q$) a solution of the equation (4) has been carried out for $q = 0.0,\ 0.3,\ 0.5,\ 0.8,$ $1.0,\ 1.2,\ 1.5$. The dependences of the expected rigidity spectrum exponent γ of the variation of the density n of GCR ($\frac{\delta D(R)}{D_0(R)} \propto (\frac{R}{R_0})^{-\gamma}$) *versus* q are presented in Fig. 4. These dependences between γ and ν ($q = 2 - \nu$) can be approximated with the analytical forms for the $qA > 0$ and $qA < 0$ solar magnetic cycles:

$$\begin{aligned} \gamma(qA > 0) &= -1.12\nu + 2.22\,, \\ \gamma(qA < 0) &= -0.86\nu + 1.91\,. \end{aligned} \tag{5}$$

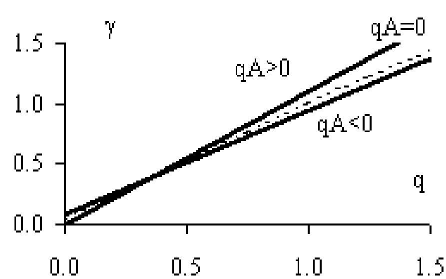

Fig. 4. Rigidity spectrum exponent γ *versus* the parameter q.

It is clear that there is not any remarkable difference (it is $\simeq 10\%$) between the γ $(qA > 0)$ and γ $(qA < 0)$ dependences on the exponents q or ν. Thus, rigidity spectrum index γ of the GCR isotropic intensity variations depends on the exponent ν of the PSD of IMF's fluctuations similarly for the $qA > 0$ and the $qA < 0$ solar magnetic cycles. For the purpose of further analysis the data of the IMF components B_x, B_y, B_z in the right handed (X, Y, Z) Cartesian coordinate system with Z axis along the Sun's rotational axis and X along the Sun–Earth line were used. From the point of view of diffusion of GCR, fluctuations of B_y and B_z components are of special interest. In Figs. 5(a), (b) and (c) a PSD of the B_y (the magnitude of the component of the IMF's strength perpendicular to the x direction in the helioequatorial plane) for the minima epochs of 1987 (Fig. 5(a)), 1996 (Fig. 5(c)) and for the maximum epoch of 1990 (Fig. 5(b)) of solar activity are presented. As can be inferred from these figures, within the range of frequencies 10^{-6}–4×10^{-6} Hz, the exponent $\nu_{\rm min}$ for the minima epochs is 1.01 (for 1987) and $\nu_{\rm min} = 0.74$ (for 1996). For the maximum epoch the exponent $\nu_{\rm max}$ is 0.43 (1990). By taking into account the obtained values for $\nu_{\rm min}$ and $\nu_{\rm max}$, a rigidity spectrum of the isotropic intensity variations of GCR according to

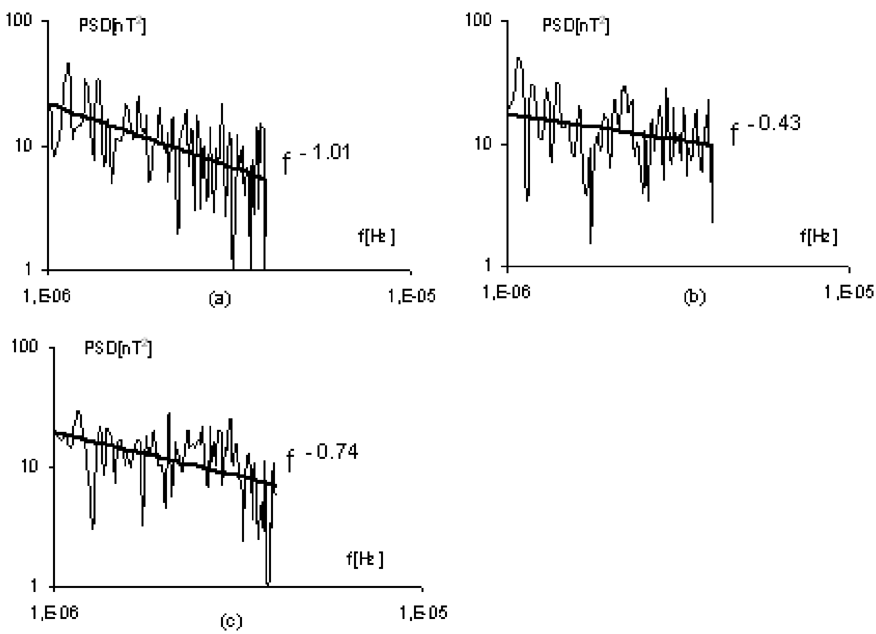

Fig. 5. PSD of the B_y component of the IMF *versus* the frequency Hz for the periods: (a) 1987, (b) 1990, (c) 1996.

the expression (5) in the minima epochs must be hard and in the maxima epochs — soft ($\gamma_{\min} < \gamma_{\max}$). To confirm the expectation concerned with the nature of the rigidity spectrum of the GCR isotropic intensity variations, the experimental data of neutron monitors for the 1957–2002, including more than four 11-year cycles of solar activity, were used. As an example in Fig. 6(a) temporal changes of the GCR intensity for Huancayo, Moscow and Washington neutron monitors for period of 1990–1997 are presented. The levels of intensities in 1997 are considered as 100%. A differential rigidity spectrum $\frac{\delta D(R)}{D_0(R)}$ of the isotropic intensity variations [30, 31] was calculated assuming that:

$$\frac{\delta D(R)}{D_0(R)} = \begin{cases} A(\frac{R}{R_0})^{-\gamma} & R \leq R_{\max}\,, \\ 0 & R > R_{\max}\,, \end{cases}$$

where $R_{\max}$ is the upper limit of the rigidity beyond which the variation of GCR intensity vanishes.

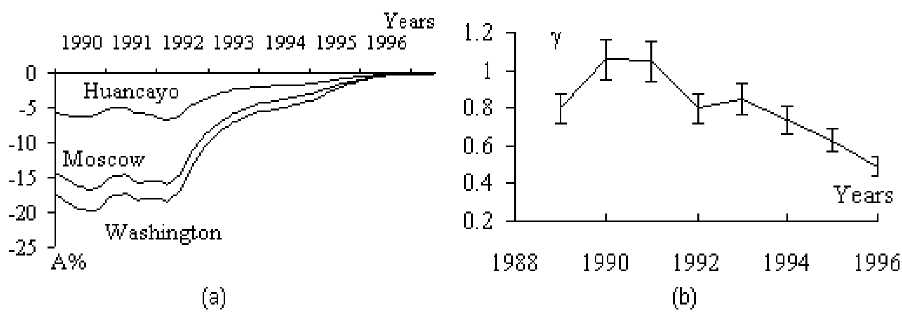

Fig. 6. (a) Time profiles of the intensity of GCR for Huancayo, Moscow and Washington neutron monitors for the period of 1990–1997. On the ordinate axis are presented the changes of the intensity in % with respect to 1997. (b) Temporal changes of the energy spectrum exponent γ of GCR isotropic intensity variations for the period of 1988–1996.

The results of calculation of γ are shown in Fig. 6(b). It is seen from this figure that in maximum epoch (1990–1991) of solar activity energy spectrum is soft ($\gamma_{\max} = 1.1$) and in the minimum epoch (1996) is hard ($\gamma_{\min} = 0.6$). Thus, from the experimental data it is obtained that $\gamma_{\min} < \gamma_{\max}$ as it is expected from the theoretical consideration based on the solutions of Parker's transport equation for different dependences of the parallel diffusion coefficient $K_{\parallel}$ on the GCR rigidity R ($K_{\parallel} \propto R^q$). Similar results are obtained for all ascending and descending epochs of solar activity for period of 1957–2003. These results show that the various character of diffusion in different epochs of solar activity is one of the important processes in the interplanetary space being responsible for the 11-year modulation of GCR.

3. 27-day variation of GCR

Parker's three dimensional (3D) transport equation (1) was used to describe the 27-day variation of GCR. In the 3D case an important problem is accounting the complicated (waviness) structure of the heliospheric neutral sheet (HNS) in the solution of the Parker's 3D equation [32–35].

In paper [6] it was found that there is not any remarkable relationship between the tilt angles of the HNS and the amplitudes of the 27-day variation of GCR for 1976–1998 period based on neutron monitors data. In this paper more detailed quantitative calculations were done for Climax, Kiel, Roma, Huancayo and Tokyo neutron monitors data for the period of 1976–2002. As an example in Fig. 7(a), (b) the distributions of the amplitudes of the 27-day variation of GCR by Kiel neutron super monitor data *versus* the tilt angles of the HNS for the $qA > 0$ (Fig. 7(a)) and the $qA < 0$ (Fig. 7(b)) solar magnetic cycles are presented. Solar rotations containing big Forbush decreases (about 20 solar rotations during May 1976–January 2002), *i.e.* that there were considered amplitudes of the 27-day variation $\leq 2\%$ at the Kiel station were excluded from the consideration.

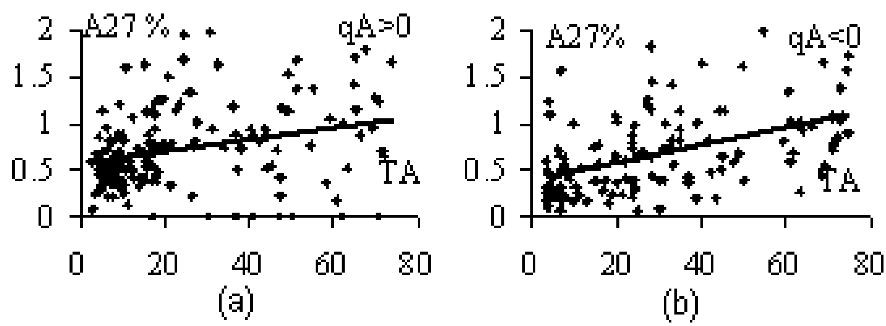

Fig. 7. Distribution of the amplitudes of the 27-day variation of GCR for Kiel neutron monitor *vs.* the tilt angles (TA) of the HNS; (a) for the $qA > 0$ and (b) for the $qA < 0$ solar magnetic cycles.

By inspection of Fig. 7(a), (b)it can be seen that no notable dependence of the amplitudes of the 27-day variation of GCR on the tilt angles exists. A linear approximations of these dependences $(A27\%) = 0.006\theta + 0.57$ for the $qA > 0$ and $(A27\%) = 0.009\theta + 0.39$ for the $qA < 0$ are shown in Fig. 7(a), (b) (straight lines). It is seen that there is not any essential influence of the tilt angles on the amplitudes of the 27-day variation of GCR neither in the $qA > 0$ nor in the $qA < 0$ solar magnetic cycles for different levels of solar activity in accordance with former results [6]. The similar results with the various background levels of the amplitudes of the 27-day variation of GCR were obtained for all neutron monitors. Therefore, based on the above mentioned results the HNS can be considered as the principle plane in the modeling of the GCR 27-day variation. It is clear, that this assumption proven by the experimental data significantly simplifies the solution of the equation (3).The parallel diffusion coefficient changes as: $K_{\|} = K_0 K(r) K(r,\theta,\phi)$, where $K_0 = 2\times 10^{22}$ cm^{2}s^{-1} for the energy of 10 GeV, $K(r) = 1 + \alpha_0 r^{0.5}$. Parameters responsible for the 27-day variation of GCR have the following expressions: the heliolongitudinal asymmetry of the solar wind velocity U and diffusion coefficient $K(r,\theta,\phi)$ change as:

$$U = U_0(1 + 0.2\sin\phi) \quad \text{and} \quad K(r,\theta,\phi) = 1 + \xi\sin\phi\,. \tag{6}$$

Equation (3) was solved for two cases:

1. $U_0 = 400$ km/s in throughout of heliosphere,
2. U_0 changes *versus* heliolatitudes according to the Ulysses measurements,

$$U_0 = \begin{cases} 800 & 0 \le \theta \le 0.87\,, \\ 400(2 - 2.98\arctan(\theta - 0.87)) & 0.87 < \theta < 1.22\,, \\ 400 & 1.22 < \theta < 1.92\,, \\ 400(-4.74 + 7.1\arctan(\theta - 0.87)) & 1.92 < \theta < 2.27\,, \\ 800 & 2.27 \le \theta \le 3.14\,. \end{cases} \tag{7}$$

The IMF lines corresponding to the solar wind velocity $1.2\,U_0$ reaches to the IMF lines corresponding to the solar wind velocity U_0 at the radial distance of 7–8 AU. So, in order to exclude an intersection of the IMF lines in space the dependence of U on the heliolongitudinal angle ϕ (the expression (6)) takes place only up to the distance of 7 AU on the Sun's equatorial plane. This distance changes with the heliolatitudes according to the Parker's spiral rule of the IMF.

In the analysis a drift due to gradient and curvature of the regular IMF and a neutral sheet drift existing in the region determined by the Larmor radius of particles with respect to the helioequator [34, 35] were taken into account. In Fig. 8(a), (b), (c) radial changes of the amplitudes of the 27-day variation of GCR are presented. Fig. 8(a) corresponds to the case with neutral sheet drift existing in the region determined by the Larmor radius of particles with respect to the helioequator, changes of the solar wind velocity U_0 according to Ulysses measurements, and $\delta = 0$ (generalized tensor (2) for two dimensional IMF); Fig. 8(b) corresponds to the case of Fig. 8(a), but $\delta = 20^\circ$ (tensor (2) for three dimensional IMF). Fig. 8(c) corresponds to the case when $U_0 = 400$ km/s, $\delta = 0$ and $\xi = -0.1$ (solar wind velocity and diffusion coefficient are changing in the opposite phase).

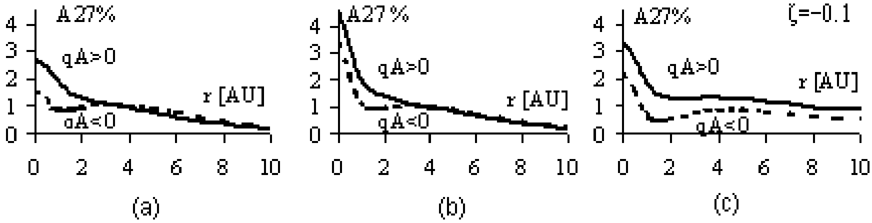

Fig. 8. Amplitudes of the 27-day variation of GCR with neutral sheet drift existing in the region determined by the Larmor radius of particles with respect to the helioequator, solid line $qA > 0$ and dashed line $qA < 0$; (a) $\delta = 0$, solar wind velocity U_0 according to Ulysses measurements; (b) $\delta = 20°$, solar wind velocity U_0 according to Ulysses measurements; (c) $\delta = 0$, U_0 const, $\xi = -0.1$ (see the text).

It is seen from these figures that for all cases the amplitudes of the 27-day variation of GCR are greater for the $qA > 0$ cycle than for the $qA < 0$ solar magnetic cycle. Neutron monitors measurements were used in order to compare these theoretical results with the experimental data for different $qA > 0$ and $qA < 0$ solar magnetic cycles. Using the harmonic analysis method the amplitudes of the 27-day variation for each Carrington rotations of two minima epochs of solar activity, 1975–1977 ($qA > 0$) and 1985–1987 ($qA < 0$) were found.

Station	Cut off rigidity in GV	Average amplitudes of 27-day variations of GCR for different qA>0 and qA<0 magnetic cycles, in %		Ratio of amplitudes of 27-day variations of GCR for different qA>0 and qA<0 magnetic cycles for 1975-77/1985-87
		1975-77 qA>0	1985-87 qA<0	
Climax	3.03	0.56 ± 0.05	0.39 ± 0.04	1.44 ± 0.31
Huancayo	13.45	0.26 ± 0.01	0.21 ± 0.04	1.23 ± 0.32
Roma	6.32	0.36 ± 0.02	0.21 ± 0.01	1.71 ± 0.19
Kiel	2.29	0.54 ± 0.03	0.34 ± 0.04	1.59 ± 0.31
Tokyo	11.61	0.29 ± 0.02	0.21 ± 0.03	1.38 ± 0.34

Results of calculations for different neutron monitors data are shown in the table. It is seen from this table that the amplitudes of the 27-day variation of GCR are greater for the $qA > 0$ than that for the $qA < 0$ solar magnetic cycle, in a good qualitative agreement with the theoretical expectations obtained based on the solution of the Parker's transport equation. The obtained theoretical and experimental results can be explained as follows. For the $qA > 0$ period of solar magnetic cycle, stream of drift $S_{\mathrm{dr1}} = V_{\mathrm{dr}} n_1$, where n_1 is the GCR particles' density involved in the drift, and V_{dr} is the drift velocity; in this case the drift velocity V_{dr} is parallel to the solar wind velocity in the equatorial region. An existence of the heliolongitudinal asymmetry of the solar wind, $U = U_0(1 + \alpha \sin\phi)$ leads to the appearance of the stream $S_c^{(+)}$ of the convection $S_c^{(+)} = U_0(1 + \alpha \sin\phi)(n_0 + S_{\mathrm{dr1}}/V_{\mathrm{dr}})$, where $(n_0 + S_{\mathrm{dr1}}/V_{\mathrm{dr}})$ is density of GCR particles corresponding to the $qA > 0$ cycle. Analogically, for the $qA < 0$ solar magnetic cycle a drift stream is $S_{\mathrm{dr2}} = -V_{\mathrm{dr}} n_2$, where n_2 is the GCR particles' density involved in the drift. In this case the drift velocity V_{dr} is directed oppositely to the solar wind velocity in the equatorial region. So, for $qA < 0$ cycle there appears a stream of the convection $S_c^{(-)} = U_0(1 + \alpha \sin\phi)(n_0 - S_{\mathrm{dr2}}/V_{\mathrm{dr}})$; $(n_0 - S_{\mathrm{dr2}}/V_{\mathrm{dr}})$ is a density of GCR particles corresponding to the $qA < 0$ cycle. Considering the difference between $S_c^{(+)}$ and $S_c^{(-)}$, one obtains

$$
\begin{aligned}
S_c^{(+)} - S_c^{(-)} &= U_0(1 + \alpha \sin\phi)\left[\left(n_0 + \frac{S_{\mathrm{dr1}}}{V_{\mathrm{dr}}}\right) - \left(n_0 - \frac{S_{\mathrm{dr2}}}{V_{\mathrm{dr}}}\right)\right] \\
&= U_0(1 + \alpha \sin\phi)\frac{S_{\mathrm{dr1}} + S_{\mathrm{dr2}}}{V_{\mathrm{dr}}} > 0
\end{aligned}
$$

so, $S_c^{(+)} > S_c^{(-)}$. This difference between various streams in the $qA > 0$ and $qA < 0$ solar magnetic cycle can be considered as a source of the various amplitudes of the 27-day variation of GCR. In particular, the amplitude of the 27-day variation of GCR in the $qA > 0$ cycle is greater than that in $qA < 0$ solar magnetic cycle.

4. Conclusions

1. According to the temporal changes of the exponent of the power spectral density of the IMF strength fluctuations throughout the 11-year cycle of solar activity a theoretical standing can be formulated: The energy spectrum of GCR isotropic intensity variations in the minima epochs of solar activity must be hard, while in the maxima epochs it must be soft. The above mentioned conception is based on the neutron super monitors data for more than four 11-year cycles of solar activity (1957-2000). One of the essential reasons responsible for the 11-year variation of GCR is a significant rearrangement of the power spectral density of the IMF's strength fluctuations; it causes a significant change of GCR diffusion from the minima to the maxima epochs

of solar activity. Particularly, a distribution of the power spectral density of the IMF's fluctuations is much steeper in the minima epochs than that in the maxima epochs of solar activity in the range of the frequencies 1×10^{-6}– 4×10^{-6} Hz.

2. The amplitude of the 27-day variation of GCR in the minima epochs of solar activity for the $qA > 0$ cycle is larger than that in the $qA < 0$ solar magnetic cycle. It is due to the oppositely directed drift streams and the existence of the heliolongitudinal asymmetry of the solar wind velocity and diffusion processes in the inner heliosphere.

The authors wish to thank the referee for useful comments and suggestions and Ms A. Wawrzynczak for her help in preparing this paper.

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