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On the Energy Spectrum of the 27-Day Variation of the Galactic Cosmic Ray Intensity

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Abstract: We study the features of the rigidity power spectrum of the 27–day variation of the galactic cosmic ray (GCR) intensity by neutron monitors experimental data in the minima epoch for different polarity periods of solar magnetic cycles. We construct theoretical models based on the 3-D transport equation considering the heliolongitudinal changes of the interplanetary magnetic field (IMF) turbulence and the diffusion coefficient as the possible sources of the 27-day variation of the galactic cosmic rays intensity. We show that the expected amplitudes of the 27-day variation of the GCR intensity are not in an agreement with the neutron monitor experimental data when the heliolongitudinal asymmetries of the IMF turbulence and the diffusion coefficient are implanted in the Parker's transport equation; so, we confirm our previous results that only the existence of the heliolongitudinal asymmetry of he solar wind velocity stipulates the difference of the amplitudes of the 27-day variation of the GCR intensity in different polarity epochs due to the GCR particles drift. The expected amplitudes of the 27-day variation of the GCR intensity are greater for the 3 –D IMF (when the heliolatitudinal component of the IMF is assumed) than for the Parker's 2-D IMF.

Introduction

The changes of the amplitudes of the 27-day variation of the galactic cosmic rays intensity (A27 I) versus the A>0 and A<0 polarity periods of solar magnetic cycle were not studied at all up to recent period. Richardson et al. [1] found an evidence that the size of the recurrent cosmic ray modulations is ~ 50% larger during the A> 0 cycle than during the A<0 cycle. Alania et al. [2, 3], Gil and Alania [4], Vernova et al. [5], and Iskra et al. [6] have found that the amplitudes of A27 I calculated based on the theoretical modeling and neutron monitors data are greater in the A>0 periods than in A<0 polarity periods of the minima and near minima epoch of solar activity. Kota and Jokipii [7] demonstrated that the magnitude of the expected 26-day variation is larger in the A>0 than in A<0. Burger and Hitge [8] shown that the amplitude of the 26-day recurrent variation of proton intensity depends on the heliolatitudinal gradients of GCR with the tendency to be greater in the A>0 than in A<0 period. Our aim in this paper is to study the energy spectrum of the 27-day variation of the GCR intensity in different polarity epochs.

Experimental Data

The 27-day variation of the GCR intensity with the amplitudes greater than ~ 0.5% is stochastic, in general; it appears up in chance and disappears averagely during 4-6 rotations of the Sun [4]. However, even in the minima epoch of solar activity, especially for the A>0 polarity periods, there exists a background 27-day variation of the GCR intensity with the amplitudes less than 0.5% [4, 9]. It is of interest how the rigidity spectrum of the amplitudes of the generally background 27-day variation of the GCR intensity behaves in different polarity periods of solar minima epoch.

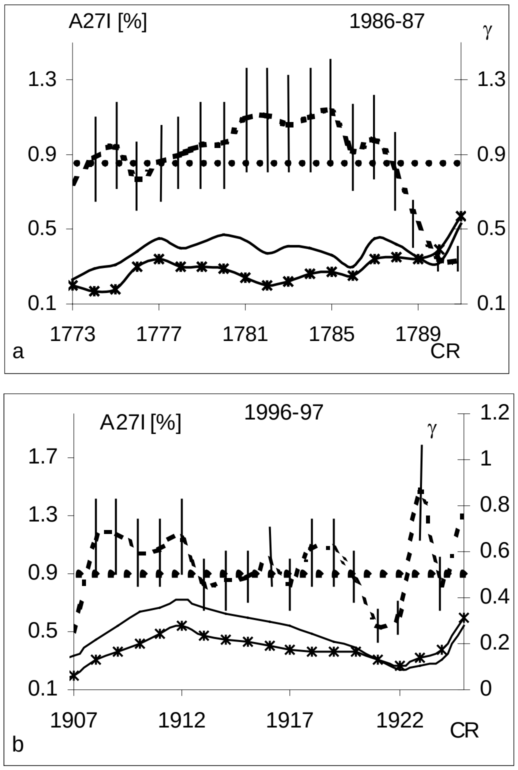


Figure 1ab: The temporal changes of the 27-day variation of the GCR intensity by Moscow (solid line), Hermanus (crossed line) neutron monitors data and changes of the rigidity spectrum exponent γ for the period of (Fig. 1a) 1986–1987 (A<0) and (Fig. 1b) 1996–1997 (A>0). The average value of $\gamma \approx 0.86$ for 1986-1987 (A<0) and $\gamma \approx 0.54$ for 1996-1997 (A>0) is plotted by doted straight lines.

We consider the minima epoch 1986-1987 (A<0) and 1996-1997 (A>0). In Figures 1ab are presented the changes of the amplitudes of the 27-day variation found by the harmonic analysis method by Moscow and Hermanus neutron monitors data for Carrington rotations 1773-1791 of periods 1986-1987 (A<0) and 1907-1925 of periods 1996-1997 (A>0), respectively. In these figures are presented the corresponding temporal changes of the rigidity spectra exponent γ (dashed lines) calculated using 9 neutron monitors for both periods.

The exponent γ of the power law rigidity spectrum $\frac{\delta D(R)}{D(R)} = \begin{cases} A R^{-\gamma} \; for \quad R \le R_{\max} \\ 0 \quad for \quad R > R_{\max} \end{cases}$ was calculated by means of the smoothed amplitudes of the 27-day variation of the GCR intensity for five Carrington rotations, assuming that $R_{max} \le 100$ GV (the upper limiting rigidity beyond which the 27-day variation of the GCR intensity vanishes) [10]. Figure 1a shows that for 1986-1987 (A<0) the rigidity spectrum is soft, average
$\gamma \approx 0.86$ for 17 Carrington rotations period, while for 1996-1997 (A>0) the rigidity spectrum is hard, average $\gamma \approx 0.54$ for 17 Carrington rotations. It seems that the energy spectrum is harder for the A>0 polarity period, than in A<0 polarity period of solar magnetic cycle. Possibly it is related with recently found peculiarities of the solar wind velocity; namely, the 27-day variation of the solar wind velocity is well established for the A>0 polarity period than for A<0 polarity period [11]. The more extended regular structure of the helio-longitudinal asymmetry of the solar wind velocity in positive A>0 epoch causes a modulation of the relatively higher energy particles of the GCR.

Theoretical Modeling

The theoretically expected amplitudes of the GCR 27-day variation were calculated using the transport equation [12]:

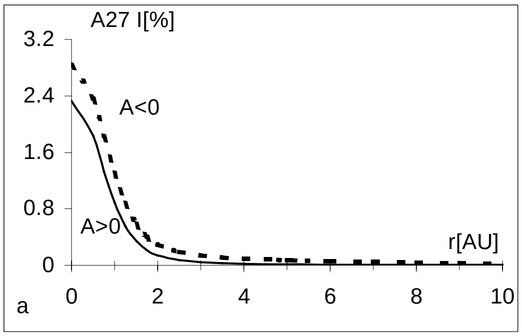
$$\nabla_i\left(\kappa_{ij}\nabla_j f\right) - \nabla_i\left(U_i f\right) + \frac{1}{3R^2}\frac{\partial\left(fR^3\right)}{\partial R}\left(\nabla_i U_i\right) = \frac{\partial f}{\partial t} \quad (1)$$

where f is the omnidirectional distribution function, R is the rigidity of GCR particles, U is the solar wind velocity and t - time. Generalized anisotropic diffusion tensor κ_{ij} of GCR for the 3-D IMF has the form [13, 14]:

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

$$\kappa_{31} = \kappa_{\|}\left[\cos\delta\sin\psi\cos\psi\left(\alpha-1\right)+\alpha_1\sin\delta\cos\psi\right]$$
$$\kappa_{32} = \kappa_{\|}\left[\sin\delta\sin\psi\cos\psi\left(\alpha-1\right)-\alpha_1\cos\delta\cos\psi\right]$$
$$\kappa_{33} = \kappa_{\|}\left[\sin^2\psi+\alpha\cos^2\psi\right]$$

where $\psi = arctg\frac{-B_\varphi}{B_r} = arctg\frac{\Omega r\sin\theta}{U}$, $\delta = arctg\frac{B_\theta}{B_r}$.



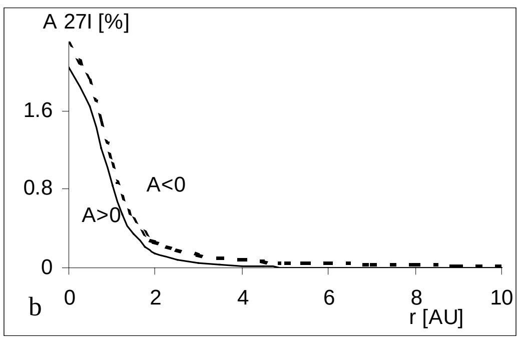


Figure 2ab: The radial changes of the amplitudes A27 I for the A > 0 (solid line) and A < 0 (dashed line) polarity periods of solar magnetic cycle for 2-D interplanetary magnetic field.

The intensity I_0 of the GCR particles in the interstellar space is taken according to [15, 16] as:

$$I = \frac{21.1T^{-2.8}}{1+5.85T^{-1.22}+1.18T^{-2.54}} \quad (3)$$

where T is the particles kinetic energy. We solve the transport equation for 2-D: δ=0 in the Eq. (2) and 3-D IMF: δ in tensor is given as

$$\delta = \begin{cases} 20\sin^2(40\rho) & \rho \le 0.075 \\ 0 & \rho > 0.075 \end{cases} \quad (4)$$

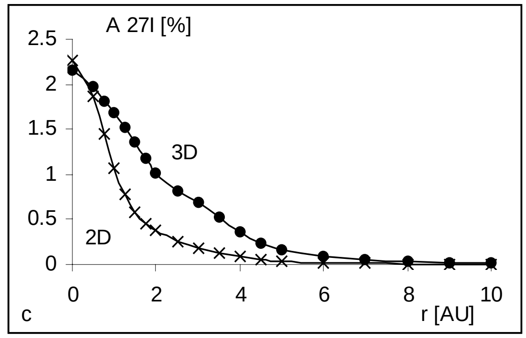


Figure 2c: The radial changes of the amplitudes A27I for 3-D IMF (doted line) and 2-D IMF (crossed line) in the A>0 polarity period of solar magnetic cycle.

The transport equation in the spherical 3-D coordinate system (ρ, θ, φ) for stationary case was reduced to the linear algebraic system of equations by finite difference scheme and then was numerically solved using the Gauss - Seidel 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. (1). In the model there is supposed that the heliolongitudinal changes of the turbulence of the IMF and the diffusion coefficient are the sources of the 27-day variation of the GCR intensity. It is assumed that the heliolongitudinal asymmetries of the diffusion coefficient and the IMF's turbulence are dumped gradually versus the radial distance up to ~7.5 AU [18]. The flat HNS is considered as far according to finding [19] that the amplitudes of the 27-day variation of the GCR intensity 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 [20]. Results of theoretical modeling are presented in the Figs. 2. Figure 2a presents results of mathematical modeling when heliolongitudinal asymmetry in the IMF turbulence is taken into account according to: $\kappa_{\|} = \kappa_0\kappa(\rho)\kappa(R)$, $\kappa(\rho) = (1+50\rho)$, $\kappa(R) = R^{\alpha_0(\rho,\varphi)}$,

$\alpha_0 = 0.5(1+0.2\sin\varphi\cdot e^{\rho(0.01-\rho)/0.001})$ and U=400km/s for 2-D interplanetary magnetic field. In Fig. 2b are presented results of modeling with heliolongitudinal asymmetry in the diffusion coefficient as follows: $\kappa_{\|} = \kappa_0 \kappa(\rho,\varphi)\kappa(R)$,

$$\kappa(\rho,\varphi) = (1+50\rho)(1+0.2\sin\varphi \cdot e^{\rho(0.01-\rho)/0.001})$$

and U=400km/s for 2-D interplanetary magnetic field.

It can be seen from Figs. 2a and b that the expected amplitudes are greater for the A<0 than for A>0 polarity which is in contrary to the experimental results [4]. In Fig. 2c are compared results of modeling for 2- and 3 –D IMF with heliolongitudinal asymmetry in the diffusion coefficient $\kappa_{\|} = \kappa_0 \kappa(\rho,\varphi)\kappa(R)$,

$$\kappa(\rho,\varphi) = (1+50\rho)(1+0.2\sin\varphi \cdot e^{\rho(0.01-\rho)/0.001})$$

and U=400km/s in the A>0 polarity period of solar magnetic cycle. Fig. 2c shows that the expected amplitudes are greater for the 3 –D interplanetary magnetic field than for the 2-D.

Conclusions

1. The rigidity spectrum of the 27-day variation of the galactic cosmic rays intensity is hard ($\gamma \approx 0.54$) for the A>0 polarity period, and is soft ($\gamma \approx 0.86$) for the A<0 polarity period of the minimum epoch of solar activity.

2. The expected amplitudes of the 27-day variation of the GCR intensity are not in an agreement with the neutron monitor experimental data when the heliolongitudinal asymmetries of the IMF turbulence and the diffusion coefficient are assumed in the Parker's transport equation.

3. The expected amplitudes of the 27-day variation of the GCR intensity are greater for the 3 –D IMF (when the heliolatitudinal component of the IMF is assumed) than for the Parker's 2-D IMF

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