ON THE RELATIONSHIP OF THE ENERGY SPECTRUM INDEXES OF THE 11-YEAR VARIATION OF GALACTIC COSMIC RAYS AND THE INTERPLANETARY MAGNETIC FIELD STRENGTH FLUCTUATIONS

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ABSTRACT

Data of neutron super monitors and interplanetary magnetic field (IMF) have been used to find a relationship between the temporal changes of galactic cosmic rays (GCR) isotropic intensity variations energy spectrum index γ(δD/D(R) $\propto$ R$^{-\gamma}$, where R is the rigidity of GCR particles) and the exponent (of the power spectral density (PSD) of the IMF's strength fluctuations (PSD $\propto$ f$^{-\nu}$, where f is the frequency).

INTRODUCTION.

The 11-year variation of GCR is generally related with the similar variation of solar activity (SA) [1–5]. Up to present it is not well established which of parameters or group of parameters of SA and of the solar wind are responsible for the 11-year variation of GCR. To answer to this question it is necessary to estimate the separate contributions of each processes — convection, diffusion, drift and energy changes of GCR due to the interaction with the solar wind. However, all above mentioned processes are interconnected and an estimation of the roles of each separate processes contains some uncertainties. Regarding contributions of all above mentioned processes in the formation of the 11-year variation of GCR the special role is ascribed to the varying character of the diffusion from the minima to the maxima epochs of SA. It was noted [6–8] that the exponent γ of GCR isotropic intensity variations ($\delta D(R)/D(R) = AR^{-\gamma}$, where R is the GCR particle's rigidity and A is he power) could be considered as one of the important indices for the explanation of the 11-year variation of GCR for the energy more than 1 GeV.

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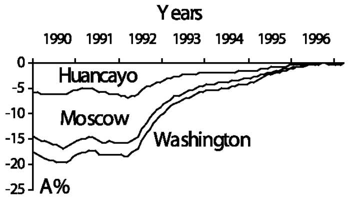

Fig.1a. Time profiles of the intensity of GCR for Moscow, Washington and Huancayo for 1989–1996

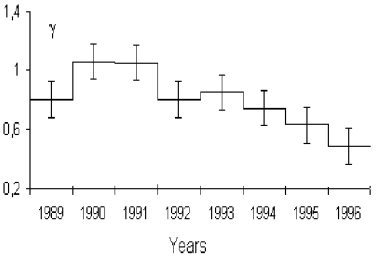

Fig.1b. Temporal changes of γ for period of 1989–1996

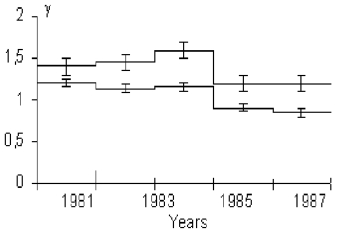

Fig.2. Temporal changes of γ for different effective energy range of GCR 1) $\approx$ 10–15 GV and 2) $\approx$ 20–25 GV for the period of 1981–1987

EXPERIMENTAL RESULTS AND DISCUSSION

Temporal changes of rigidity spectrum exponent γ of GCR.

The aim of this paper is to present more complete features of the temporal changes of the energy spectrum exponent γ of the GCR isotropic intensity variations separately for the periods of ascending and descending epochs of SA in different magnetic cycles (qA < 0 and the qA > 0). For this purpose the temporal changes (from year to year) of γ were calculated based on the neutron super monitors data using on the above mentioned expression $\delta D(R)/D(R) = AR^{-\gamma}$. Annual averages of the intensities maxima of GCR for the different minima epochs of SA were considered as the 100% level, henceforth called the reference point (RP) for each investigated period. The exponent γ was calculated for 5 ascending and 4 descending periods of SA by means of the annual averages of the neutron monitor data. In Figure 1a are presented the time profiles of the monthly averaged GCR intensity changes using different super neutron monitor data for the period of 1989–1996 (qA > 0, RP is 1997). One can see from these Figures 1b that there is a clear dependence of γ on the level of SA. For all the considered periods during solar maximum activity the energy spectrum of GCRs is soft ($\gamma \approx 1.2$–1.5), while during the minimum epochs the hardening of the energy spectrum ($\gamma \approx 0.4$–0.6) is observed for both qA>0 and qA<0 solar magnetic cycles during 1954–2000. Recently it was mentioned [6,8] that an establishment of the single valued relationship between γ and the parameter α representing the dependence of the diffusion coefficient K on rigidity R of GCR particles ($K \propto R^{\alpha}$) should be the major key in the understanding of the mechanism of the 11-year variation of GCR

On relationship of the parameters γ and α.

The expected (theoretical) variations $I_T(R)$ of the isotropic intensity of GCR (obtained, e.g., as a solution of Parker's diffusion- convection equation) is inversely proportional to the diffusion coefficient $K(I_T(R) \propto K^{-1})$. Additionally, the diffusion coefficient K is proportional to the particle's rigidity $R(K \propto R^{\alpha})$ and therefore $I_T(R) \propto R^{-\alpha}$ at least for the particles of GCR with the energy greater than 1 GV, [9–11]. In this case K is the isotropic diffusion coefficient of GCR. The parameter α depends on the IMF's structure[12] and changes over the range from 0 to 2, $(0 \leq \alpha \leq 2)$. Calculation of the energy spectrum from year to year during an 11-year period of SA by the expression $\delta D(R)/D(R) = AR^{-\gamma}$ means that the observed (based on the neutron monitors experimental data) GCR isotropic intensity variations $I_E(R)$ is proportional to the particle's rigidity R, i.e. $I_E(R) \propto R^{-\gamma}$. On the other hand the expected isotropic intensity variations $I_T(R)$ of GCR (as was mentioned above) is inversely proportional to the particle's rigidity R as, $I_T(R) \propto R^{-\alpha}$. It is reasonable to assume that the expected differential intensity $I_T(R)$ is related to the GCR isotropic intensity variations $I_E(R)$ (or to the differential energy spectrum $\delta D(R)/D(R)$) obtained using super neutron monitor data. Hence, R^{γ} is related with $\mathrm{R}^{\alpha}(R^{\gamma} \sim R^{\alpha})$. Thus, γ is related to the parameter α, i.e., $\gamma \sim \alpha$. If the relation γ and α is the case, then the quantity of $\gamma \approx 0.2$–0.6 (nearly to the lower value of $\alpha = 0$) corresponds to the scattering of GCR particles in the minima epochs of SA. The quantity of $\gamma \approx 1.1$–1.5 (nearly to the higher value of $\alpha = 2$) means that the scattering of GCR particles corresponds to the maxima epochs of SA.

On dependence of the parameter γ on rigidity R.

In the case of the existence of the direct relation between γ and α the considerable difference in the magnitude of γ corresponding to the various energy ranges must be noted. This kind of expected dependence of γ on the energy of GCR follows from the quasi linear theory (QLT) [9]. Particularly, it is uniquely seen from the dependence of the parameter α on the power energy spectrum exponent $\nu\alpha = 2-\nu$. [9–10]. Thus, the change of the magnitude of ν is responsible for the change of α, being the reason of the changes of γ for the energy range > 1GeV of GCR. As far $\gamma \propto \alpha$, one can write that $\gamma \propto 2 - \nu$. In particular, the expected energy spectrum exponent $\gamma_1 \sim 2 - \nu_1$, for the relatively higher effective energies, ($\sim$ 25–30) GeV must be greater than $\gamma_2 \sim 2 - \nu_2$ for the lower effective energies ($\sim$ 10–15) GeV, since ν_1 is less than ν_2 according to the QLT. In Figure 2 are presented some results of the calculation of γ for the different effective energy range of GCR using different groups of super neutron monitors. It is evident from Figure 2, that for the lower energies the average energy spectrum exponent γ_1 of GCR isotropic intensity variations equals ≈ 1.0 ($\gamma_1 \approx 1.0$) which is less than $\gamma_2 \approx 1.5$ for the relatively higher energies. The similar results are obtained for all

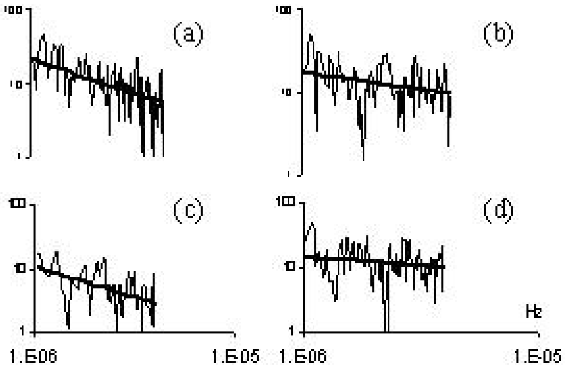

Fig. 3. PSD of components of the IMF for the periods of 1987 (fig. 3a and 3c) and 1990 (fig. 3b and 3d) vs frequency Hz. fig.3ab for By and fig.3cd for Bz components of IMF.

ascending and descending epochs of SA for the solar magnetic cycles qA $>$ 0 and qA $<$ 0 during the long period of 1954–2000 without any exceptions.

Changes of the exponent ν of the PSD of IMF irregularities.

Since the above mentioned statement about the proportionality of the parameters γ and $2-\nu(\alpha=2-\nu)$ is valid, the changes of the exponent ν of the PSD of the IMF's irregularities ($PSD \propto f^{-\nu}$) in different epochs of SA based on in situ measurements in the interplanetary space must be noted. Particularly, ν must be less in maxima epochs of SA than in the minima epochs. In Figures 3abcd the examples of the changes of the PSD are presented in the range of frequencies $f=(10^{-6}-4.0\times10^{-6})$ Hz of the fluctuations of the $\mathrm{B_y}$ and $\mathrm{B_z}$ components of the IMF for the 1987 and 1990. The frequency range of $(10^{-6}-4\times10^{-6})$ Hz of the IMF's irregularities corresponds to the effective energy of $\sim$ (10–35) GeV of GCR to which super neutron monitors are sensitive [9]. It is seen from Figures 3a and 3b (for $\mathrm{B_y}$) that the exponent $\nu(v_{min}=1.01)$ is larger in the minimum period of 1987 (Fig.3a), than in the maximum period ($\mathrm{v_{max}}=0.43$) of 1990 (Fig.3b) the similar results are obtained for $\mathrm{B_z}$ component, namely $\mathrm{v_{min}}=0.97$ (Fig.3c) and $\mathrm{v_{max}}=0.27$ (Fig.3d). This result is ones more powerful argument for the confirmation of the clear relation between the parameters γ and α.

On the quantitative relation of the γ and α based on the modelling of GCR transport.

After establishing the relation between the parameters α and γ (as it was above mentioned), the natural enquiry is to find the range of this relationship, i.e. a quantitative dependence of the γ on the α. It is possible to establish this relationship based on the theoretical modelling of the transport of GCR, achiev-

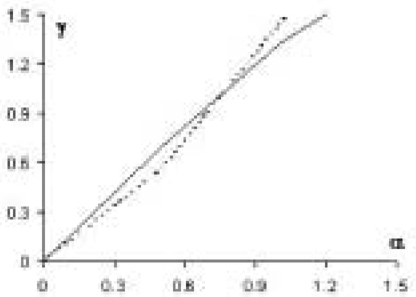

Fig. 4. A dependence between energy spectrum exponents γ and the parameter α (see text)

able by comparing the behaviour of the expected γ obtained from the solution of the GCR transport equation with the parameter α showing the dependence of the diffusion coefficient K on the rigidity of the GCR particles ($K \propto R^{\alpha}$). For this purpose the Parker's steady-state transport equation [11] has been numerically solved taking into account convection, diffusion, drift and energy changes of GCR due to the interaction with the solar wind [8]. To find a relationship between γ and α Parker's transport equation was solved for $\alpha = 0.0, 0.3, 0.5, 0.8, 1.0, 1.2, 1.5$. In Figure 4 is presented the dependence between the expected γ (calculated based on the solution of the transport equation by the expression $dn/dR = bR^{-\gamma}$, where n is relative intensity and b is the power of the energy spectrum) and the parameter α for qA>0 (dashed line) and qA<0 (solid line) solar magnetic cycles. It is seen from fig.4 that there is a clear relation between γ and α.

CONCLUSION

1. A reliable relationship between the energy spectrum exponent γ of the isotropic intensity variation of GCR and the exponent α (showing the diffusion coefficient's dependence on the rigidity of GCR particles) has been found.
2. One of the general reasons of the 11-year variation of GCR for the energy range more than 1 GeV is the radical changes of the large-scale structures of the IMF irregularities in the minima and maxima epochs of SA.
3. The temporal changes of γ must be considered as one of the important indices to explain the general wave of the 11-year cycle variation of GCR.

REFERENCES

1. Dorman L.I., Cosmic rays variations and space exploration, *Nauka*, Moscow,1963.
2. Alania M. V., Dorman I. L., The Spatial distribution of the density and stream of galactic cosmic rays, Tbilisi, *Mecniereba*, 1981. (In Russian)
3. le Roux J. A., and Potgieter M. S, *Astrophys. J.* 390, 1992.

4. Bazilevskaya G. A., and Svirzhevskaya A. E., *Space Science. Rev.*, 85, 431–521, 1998.
5. Belov A., Large scale modulation: view from the Earth, *Space Sci. Rev.*, 93, 79–104 , 2000.
6. Alania M.V., Iskra K., *Adv. Space Res.*, 16, 9, 241–244,1995.
7. Alania M.V., Stochastic variations of galactic cosmic rays, *Acta Phys. Polonica B*, 33, 4, 1149–1166, 2002.
8. Iskra K. Siłuszyk M and Alania M.V., *Proc. 27th Inter. Cosmic Ray Conf.*, 10, 4277–4280,, 2001.
9. Jokipii J. R., *Reviews of Geophysics and Space Physics*, 9, 21–87, 1971.
10. Toptygin I. N., Cosmic rays in interplanetary magnetic fields, *Reidel Publishing Company*, 1985.
11. Parker E. N., *Planet. Space. Sci.* 13, 9,1965.
12. Alania M. V., *Proc. of the Institute of Geophys. Georgian Academy of Sciences*, p. 5, Tbilisi, 1978.