ON FEATURES OF THE DRIFT EFFECT IN ANISOTROPY OF GALACTIC COSMIC RAYS

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Abstract

Neutron monitors and interplanetary magnetic field data have been used to study the drift effect in the anisotropy of galactic cosmic rays for the solar activity minima epochs(1965,1976). Components of three dimensional anisotropy of galactic cosmic rays were calculated using the global survey method. It is shown that there are the differences between the amplitudes and between the phases of the anisotropy of galactic cosmic rays in the various sectors of the interplanetary magnetic field. Based on the above mentioned results the ratio $\alpha = K_{\perp}/ K_{\|}$ of the perpendicular $K_{\perp}$ and the parallel $K_{\|}$ diffusion coefficients of galactic cosmic rays has been calculated. This ratio ($\alpha \approx 0.35$) is 4-5 times greater than that obtained by in situ measurements in the interplanetary space ($\alpha \approx 0.05$-0.1) and widely used for the modeling of the propagation of galactic cosmic rays in the heliosphere.

1 . Introduction:

Investigation of the influence of the sector structure of the interplanetary magnetic field (IMF) on the anisotropy of galactic cosmic ray (GCR) up to day remains one of interesting tasks. First of all, the reliable manifestation of drift effect in anisotropy of GCR has the important significance for the theory of GCR modulation, according to which the drift must play an important role in the understanding of the features of GCR behavior in the heliosphere (Kota and Jokipii,l983). On the other hand, if the drift in the anisotropy of GCR successfully is manifested, that it can be used for calculations of the various parameters characterized solar wind and diffusion of GCR. The system of algebraic equations for the components of the anisotropy of GCR (Alania et al. ,1983,1987; Riker and Ahluwalia, 1987) has the following form:

$$A_\rho^{\pm} = 3[CU-K_{\rho\rho}G_\rho^{\pm} \pm K_{\blacklozenge}G_\theta^{\pm} \mathrm{Sin}\psi + (K_{:}-K_f)G_\varphi^{\pm} \mathrm{Sin}\psi\, \mathrm{Cos}\psi]/ V \qquad (1)$$
$$A_\theta^{\pm} = -3 [\pm K_{\blacklozenge}G_\rho^{\pm} \mathrm{Sin}\psi + K_f G_\theta^{\pm} \pm K_{\blacklozenge}G_\varphi^{\pm} \mathrm{Cos}\psi]/V \qquad (2)$$
$$A_\varphi^{\pm} = 3[(K_{:}-K_f)G_\rho^{\pm} \mathrm{Sin}\psi\, \mathrm{Cos}\psi \pm K_{\blacklozenge}G_\theta^{\pm} \mathrm{Cos}\psi -K_{\varphi\varphi} G_\varphi^{\pm}]/V \qquad (3)$$

Where, $K_{\blacklozenge}$, $K_{\perp}$ and $K_{:}$ are drift, perpendicular and parallel diffusion coefficients of GCR with respect to the interplanetary magnetic field lines, respectively. $G_\rho^{\pm}$, $G_\theta^{\pm}$ and $G_\varphi^{\pm}$ are radial, heliolatitudinal and heliolongitudinal gradients of GCR in the interplanetary space; ψ is an angle between the interplanetary magnetic field lines and the Earth-Sun line; U and V are the velocities of solar wind and cosmic ray particles, respectively. The Compton-Getting factor C is equal to ≈1.5 for GCR sensitive to neutron monitors. On the average, this anisotropy of GCR is about 0.3-0.4% according to neutron monitors data and a part of drift in it may reach 0,05-0,1%. (Alania, Djapiashvili, l978; Alania et al.,l983). It should be noticed about two types of drift in anisotropy of GCR. The first one stipulated by gradient and curvature of IMF, which can be clearly manifested in the average anisotropy for the different direction of the Sun's global magnetic field qA>0 (positive polarity in the Sun’s northern hemisphere ,1976) and qA<0 (negative polarity in the Sun’s northern hemisphere, 1965), when the role of the drift due to sector structure of IMF is insignificant because of the averaging for a long period. The second one can be caused by the existence of the spatial gradients of GCR and the sector structure of IMF, even when the gradient and curvature of the IMF in the range of 2-3 Larmor's radii of GCR can be neglected. For the reliable manifestation of the first type of drift in the anisotropy of GCR there is possible to average data for a long time of observation, which is good enough. At the same time, a single-valued manifestation of the second type of drift is a complicated problem on the background of the significant temporal changes of the solar wind parameters lasting the period comparing with the duration of the positive and negative sectors of IMF. So, in order to manifest the drift effect in anisotropy of GCR causing by sector structure of IMF we have to consider the minima epochs of solar activity. In this epochs the temporal changes of the solar wind parameters and the variations of cosmic rays associated with the Sun's rotation is minimum, while the sector structure of IMF is clearly manifested (Alania et al.,l987). In the paper (Alania et al.,l983) the system of equations (l)-(3) was used to calculate the various parameters characterized solar wind and diffusion of cosmic rays supposing the equality of the radial and transversal gradients $G_\rho^\pm$ and $G_\theta^\pm$ in different sectors of IMF for the minima epochs of solar activity. The components of anisotropy of GCR $A_\rho^\pm$ and $A_\varphi^\pm$ were calculated using harmonic analyses. Recently, the same problem was considered in (Ahluvalia, Dorman, 1997)

2. Experimental Data and Discussion:

In this paper, in contrast to our previous papers, in order to calculate the A_ρ, A_θ and A_φ components of anisotropy of GCR based on the neutron monitors data the global survey method (Belov et al., 1995) was used. The basic criterion for the selection of the data for the global survey method was the similar behavior of the diurnal variation of GCR in the different sectors of IMF obtained by the ordinary harmonic analysis, especially for the neutron monitor stations with the magnetic rigidities less than or equal 5 GV. In doing so, from any neutron monitors data , the days with the amplitudes more then 0.7% were excluded of the consideration. The data of the sector structure of the IMF was taken from the preprint (Mansurov's Catalog, 1984. Besides, for the calculations of A_ρ, A_θ and A_φ components of anisotropy were considered the positive and negative sectors of IMF with the duration greater then or equal four days. Hourly data of every separate neutron monitors for each year of 1965 and 1976 were averaged for all similar sectors of IMF and was obtained the hourly averaged daily waves for both sectors. Then using the global survey method the components A_ρ, A_θ and A_φ of the anisotropy of GCR were calculated. On the Figure 1a there are plotted the vector diagrams of the anisotropy of GCR in different sectors in percents ('+' corresponds to the positive sector and '-' to the negative sector of IMF for the period of 1965 and 1976).One can see that there are the significant differences between amplitudes and phases for different sectors of IMF in 1965 and 1976. At the same time the yearly averaged anisotropy (Fig.1b), for 1965 and 1976 (disregarding the positive and negative sectors of IMF) represents the changes of the anisotropy of GCR in various direction of the Sun's global magnetic field qA>0 (1976) and qA<0 (1965). This changes (Fig. 1b) are caused by the drift of GCR due to the gradient and curvature of the global IMF and is the general source of 22-years variation of the anisotropy of GCR measuring by neutron monitors. It is worth to remark that the changes of the phases of the anisotropy of GCR versus sequences of the changes of the direction of the IMF is similar in both cases, for the global magnetic field and for the sector structure of IMF. When the

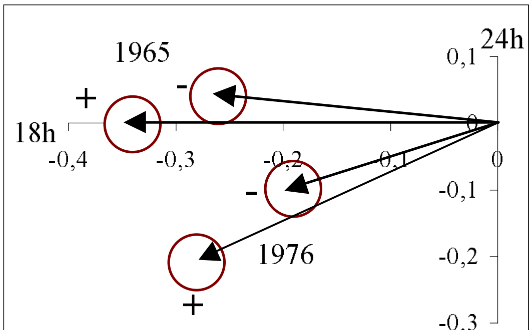

Fig. 1a

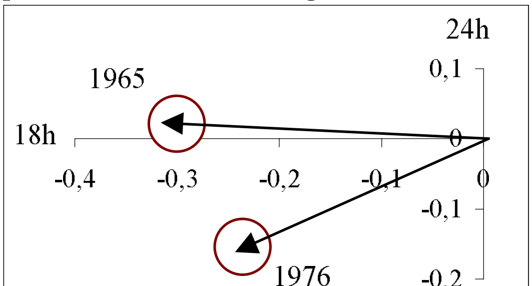

Fig. 1b

period of qA<0 is exchanged by the period of qA>0 the phase of averaged anisotropy is shifted to the earlier hours. This is similar for the sectors cases of IMF, when the negative sector of IMF has been exchanged by the positive sector. In the minima epochs of solar activity the variations of GCR connected with the Sun's rotation is very weakly pronounced, i.e. heliolongitudinal gradient $G_\varphi^\pm$ of GCR is very small. This gradient can practically be neglected when the average anisotropy or GCR for one year period, much greater than the Sun's rotation period (27 days) has been considered. Taking into account that the heliolongitudinal gradient $G_\varphi^\pm$ is equal to zero, $\alpha = K_\perp/K_{\|}$ and $\alpha_1 = K_\blacklozenge/K_{\|}$, the system of the equations (1)-(3), after the simple transformations can be reduced to:

$$A_\rho^\pm = 3K_{\|}[CU/K_{\|} - (\mathrm{Cos}^2\psi + \alpha\,\mathrm{Sin}^2\psi)G_\rho^\pm \pm \alpha_1 G_\theta^\pm\,\mathrm{Sin}\psi]/V \quad (4)$$
$$A_\theta^\pm = -3K_{\|}[\pm\,\alpha_1 G_\rho^\pm\,\mathrm{Sin}\psi + \alpha G_\theta^\pm]/V \quad (5)$$
$$A_\varphi^\pm = 3K_{\|}[(1-\alpha)G_\rho^\pm\,\mathrm{Sin}\psi\,\mathrm{Cos}\psi \pm \alpha_1 G_\theta^\pm\,\mathrm{Cos}\psi]/V \quad (6)$$

The system of the equations (4-6) can be rewritten:

$$A_r^+ + A_r^- = 3K_{\|}[-(\mathrm{Cos}^2\psi + \alpha\,\mathrm{Sin}^2\psi)(G_\rho^+ + G_\rho^-) + \alpha_1(G_\theta^+ - G_\theta^-)\,\mathrm{Sin}\psi]/V \quad (7)$$
$$A_r^+ - A_r^- = 3K_{\|}[-(\mathrm{Cos}^2\psi + \alpha\,\mathrm{Sin}^2\psi)(G_\rho^+ - G_\rho^-) + \alpha_1(G_\theta^+ + G_\theta^-)\,\mathrm{Sin}\psi]/V \quad (8)$$
$$A_\theta^+ + A_\theta^- = -3K_{\|}[\alpha_1(G_\rho^+ - G_\rho^-)\mathrm{Sin}\psi + \alpha(G_\theta^+ + G_\theta^-)]/V \quad (9)$$
$$A_\theta^+ - A_\theta^- = -3K_{\|}[\alpha_1(G_\rho^+ + G_\rho^-)\mathrm{Sin}\psi + \alpha(G_\theta^+ - G_\theta^-)]/V \quad (10)$$
$$A_\varphi^+ + A_\varphi^- = 3K_{\|}[(1-\alpha)(G_\rho^+ + G_\rho^-)\mathrm{Sin}\psi\,\mathrm{Cos}\psi + \alpha_1(G_\theta^+ - G_\theta^-)\mathrm{Cos}\psi]/V \quad (11)$$
$$A_\varphi^+ - A_\varphi^- = 3K_{\|}[(1-\alpha)(G_\rho^+ - G_\rho^-)\mathrm{Sin}\psi\,\mathrm{Cos}\psi + \alpha_1(G_\theta^+ + G_\theta^-)\mathrm{Cos}\psi]/V \quad (12)$$

Where, G_r^+, G_r^-, G_θ^+ and G_θ^- are radial and heliolatitudinal gradients of GCR in different sectors of IMF. As it was mentioned above, in order to calculate the components of anisotropy of GCR A_r^+, A_r^-, A_θ^+, A_θ^-, A_φ^+ and A_φ^- the data of neutron monitors was used. In the case of the solution of the system (7)-(12) it is very important to note that while the components A_r^+, A_r^-, A_φ^+ and A_φ^- of the anisotropy of GCR are reliable defined, with the components A_θ^+, A_θ^- of anisotropy there is some uncertainty. This uncertainty is connected with the possible existences of the north-south asymmetry and the heliolatitudinal gradient of GCR related to the long-lived asymmetry of the solar activity in the different hemispheres. For the reliable definition of the long-lived north-south asymmetry of GCR there is necessary a special investigation, which is beyond of our possibilities in this paper. Thus, only the components A_r^+, A_r^-, A_φ^+ and A_φ^- of the anisotropy of GCR can be used for the solution of the system of equations (7)-(12). In this cases, however, the number of unknowns is greater than the number of equations. So, it is necessary to make some assumptions to reduce the number of unknowns. Let us assume that the having the some name gradients (radial $G_\rho^\pm$ and heliolatitudinal $G_\theta^\pm$) are equal to each another in different sectors of IMF, i.e. $G_\rho^+ = G_\rho^-$ and $G_\theta^+ = G_\theta^-$. To the system of equations (7)-(12) one can add the equation, $U = \omega R_E / \mathrm{tg}\psi$ (Parker, 1963). where ω is the Sun's angular velocity and R_E is one astronomical unit. The system of equations (7)-(12) with above-mentioned assumptions can be rewritten as,

$$A_r^+ - A_r^- = 6K_{\|}\,\alpha_1 G_\theta\,\mathrm{Sin}\psi/V \quad (13)$$
$$A_r^+ + A_r^- = 6K_{\|}[CU/K_{\|} - (\mathrm{Cos}^2\psi + \alpha\,\mathrm{Sin}^2\psi)G_\rho]/V \quad (14)$$
$$A_\varphi^+ + A_\varphi^- = 6K_{\|}(1-\alpha)G_\rho\,\mathrm{Sin}\psi\,\mathrm{Cos}\psi/V \quad (15)$$
$$A_\varphi^+ - A_\varphi^- = 6K_{\|}\,\alpha_1 G_\theta\,\mathrm{Cos}\psi/V \quad (16)$$
$$U = \omega R_E/\mathrm{tg}\psi \quad (17)$$

the system of equations (13) –(17) was solved using the values of the components A_r^+ , A_r^-, A_φ^+ and A_φ^- of the anisotropy of GCR for 1976 ($A_r^+ = -0{,}20\%$, $A_r^- = -0{,}11\%$, $A_\varphi^+ = -0{,}28\%$ and $A_\varphi^- = -0{,}19\%$, Figure 1a). There were found that the angle ψ between the lines of IMF and the Sun-Earth line equals $\approx 46^o$ and the solar wind velocity U is equal to ≈ 420 km/s. According to the measurements (King, 1979) the average velocity of solar wind in 1976 near the Earth's orbit was ≈ 450 km/s, i.e. there is a good agreement between the direct measurements and the calculations based on the anisotropy of GCR. Besides, the ratio of the perpendicular and the parallel diffusion coefficients with respect to the IMF($\alpha=K_\perp/K_\parallel$) was calculated. It is equal to ≈0.33±0.05. This value of α is 4-5 times greater then the value of α=0.05-0.1 calculated by the in situ measurements of the IMF strength fluctuation in interplanetary space and widely used for the modeling of cosmic ray propagation (e.g., Kota and Jokipii,l983; Podgieter and Le Roux,l994). The excessive value of α obtained according to our calculations is possibly connected with the our assumption that having the same name gradients (radial $G_\rho^\pm$ and heliolatitudinal $G_\theta^\pm$) are equal to each another in different sectors of IMF. At the same time one can not help noting that according to the study of the anisotropy of GGR in the large energy range using the measurements on the different levels of the Jakutsk's underground station (Kuzmin, et a1.,1975), the α is much greater, as $\alpha \geq 0.6$. It is obvious that this magnitude of α is remarkably large by comparison with that (α =0.05-0.1), which is widely accepted. So, the problem of the definition of the magnitude of α versus the energy of cosmic ray particles and the level of solar activity remains up to day. From the system of equations (13)-(16) there were calculated too: the ratio of the drift coefficient $K_\blacklozenge$ and the parallel coefficient $K_:$ of diffusion $\alpha_1 \approx 0.47 \pm 0.05$; the products of the parallel diffusion coefficient and the radial gradient, $K_:$ x G_r=7.2| $10^9 sm^2/s$ %/AU, and the product of the parallel diffusion coefficient and the heliolatitudinal gradient, $K_:$| G_θ=1.4| 10^9 sm^2/s %/AU. Taking into account the results of the direct measurements of the radial gradient at the Earth's orbit, $G_r \approx 2\%$/AU for the energy of 2-5GeV, (Webber and Lockwood, l985) one can obtain, $K_:$ =4| 10^{22} sm^2/s and G_θ=0.4%/AU. The similar results were obtained in (Alania ,et al., l 983) for the period of 1965, based on the data of a few neutron monitor stations using the simple harmonic analysis. Unfortunately, our results are very averaged one. We could not solve the system of equations (8)-(12) and find the spatial gradients G_r^+, G_r^-, G_θ^+ and G_θ^- in different sectors of IMF, because of the uncertainties with the north-south asymmetries of GCR.

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