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Cosmic ray anisotropy depending on the current sheet in solar wind

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Abstract. Effects caused by the influence of the current sheet in solar wind are studied by using the Yakutsk underground muon telescope complex data. The anisotropy shows a dependence on the distance between the current sheet and the Earth. The anisotropy caused by symmetric heliolatitude density gradient of cosmic rays has also been revealed. Observed effects are interpreted in the framework of the diffusion - drift modulation mechanism.

1 Introduction

According to current concepts the heliospheric magnetic field is separated into hemispheres, with magnetic fields of the opposite polarity. Between them there is the current sheet which is deformed depending on the solar activity level. In the solar activity minimum the deformation of the current sheet decreases.

As the activity increases, the tilt angle of the current sheet gradually increases and in maximum the deformation reaches its maximum value at the same time the inversion of the general magnetic field of the Sun takes place. That is repeated in every 11 years (Potgieter, 1995).

The galactic cosmic ray modulation is caused by their convection from the side of the Sun, due to a supersonic solar wind, by a diffusion directed towards the Sun along the spiral interplanetary magnetic field and by adiabatic losses (Krymsky, 1964). However, for the last 10-15 years also the influence of the drift mechanism is being studied intensively (Kota and Jokipii, 1983). According to this mechanism, the galactic protons drift from the polar region towards the helioequator and they are removed along the wavy current sheet when the magnetic moment of the Sun is of the positive sign. After the change of the sign of the magnetic moment the particle drift velocity is directed towards the Sun. Such a mechanism qualitatively describes the temporal change of the density and anisotropy of the particle flux with the Hall's cycle (Krymsky et al., 2001).

However, the deformation effect of the current sheet in the cosmic ray anisotropy has been insufficiently studied.

2 Data Analysis

This paper consists of two parts. The first part is devoted to the study of the anisotropy depending on a distance of the Earth to a current sheet, the second part is to establish the reason of seasonal changes of the anisotropy. For the first part we have used data on the current sheet location during each Carrington's rotation of the Sun for $1982 - 1998$ (http://quake.stanford.edu/ wso/coronal.html). In order to find the distance up to the current sheet at the orbit of the Earth for every day the solar wind speed and the Earth's heliolatitude have been taken into account.

We have used the vertical ground and underground muon telescope data in Yakutsk at the depths of $7, 20, 60$ m w.e. for $1982 - 1984$, $1987 - 1988$, $1992 - 1994$, and $1997 - 1998$. To exclude the methodical errors, we have not used the data of muon telescopes during the solar activity minima when the deformation of the current sheet is insignificant and in the periods of the general magnetic solar field inversion when the deformation of the current sheet is more than $60°$ in heliolatitude in $1985 - 1986$, $1989 - 1991$, and $1995 - 1996$.

The data have been analyzed using the harmonic analysis for every day, the harmonics have been re-grouped depending on the Earth's distance up to the current sheet with a step of $10°$. In the end we have used the distribution of anisotropy vectors in the range of the current sheet deformation from $-60°$ to $+60°$. The angular distance, when the current sheet is northward of the Earth, we consider as positive. The anisotropy vectors are corrected for the influence of the geomagnetic field and from each vector the average vector has been subtracted. Then, each vector is expanded into two components: $A_6 - 6^h$ and $A_{12} - 12^h$. A_6 and A_{12} are found in two variants depending on the phase of solar

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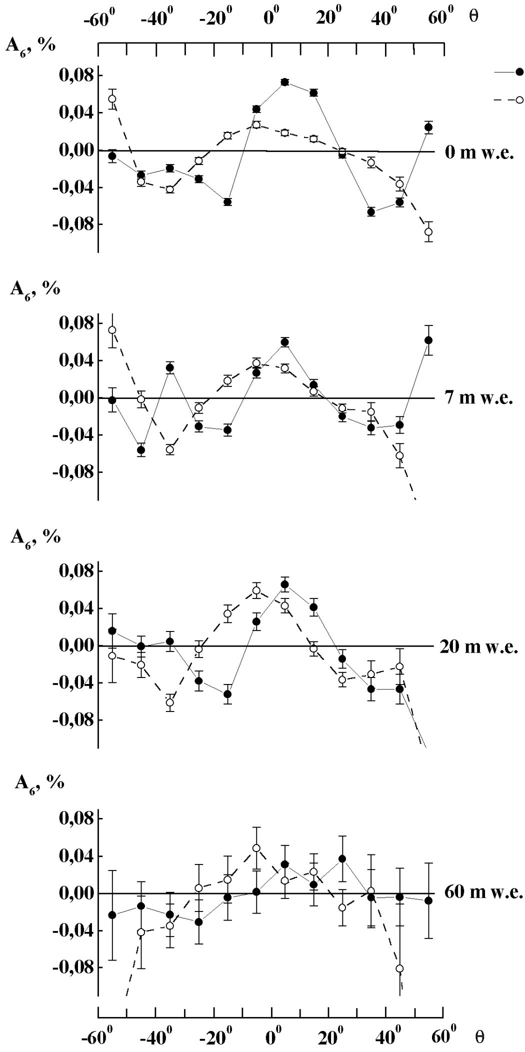

Fig. 1. Dependence of A_6-component on the angular distance of the Earth to a current sheet.

magnetic cycle.

It is seen from Fig.1 that near the current sheet the A_6 component has the maximum value, and it decreases as it moves away from the current sheet to one or another side i.e. the resulting anisotropy is minimum. Such a regularity ia observed at all underground levels. The amplitude of the A_6 anisotropy decreases insignificantly with the depth of registration that testifies about its hard energy spectrum. It is significant that the change of A_6 with a distance to the current sheet occurs independing on the phase of the magnetic solar cycle. The component A_0 doesn't depend on the location of the Earth relative to the current sheet (Fig. 2).

The second part of the analysis is devoted to the study of the dependence of cosmic ray anisotropy on the interplanetary magnetic field sign in the periods when the Earth is projected into the north and south heliolatitudes. In this case we have used cosmic ray diurnal variation data at the depth of 0, 20 and 60 m w.e. for $1981 - 1998$ and 7 m w.e. for $1982 - 1998$. At 0, 7 and 20 m w.e. we have used of the telescopes directed at 30° to the north and south relative to the zenith. As at the depth of 60 m w.e. the temperature effect is small, the data of the vertical telescope are used. It considerably increases the statistical accuracy in determination of the anisotropy. The hourly values are preliminary smoothed by a daily moving-average method. To exclude temperature contribution, we have used the differences of the southern and northern telescopes. We have also found the daily variations for days when the force lines of interplanetary magnetic field are directed to the Sun (-) and from the (+). Then these data are distributed by the southern (S) (January - April)and northern (S) (July - October) zones relative to the helioequator. The drift anisotropy of cosmic rays is defined as

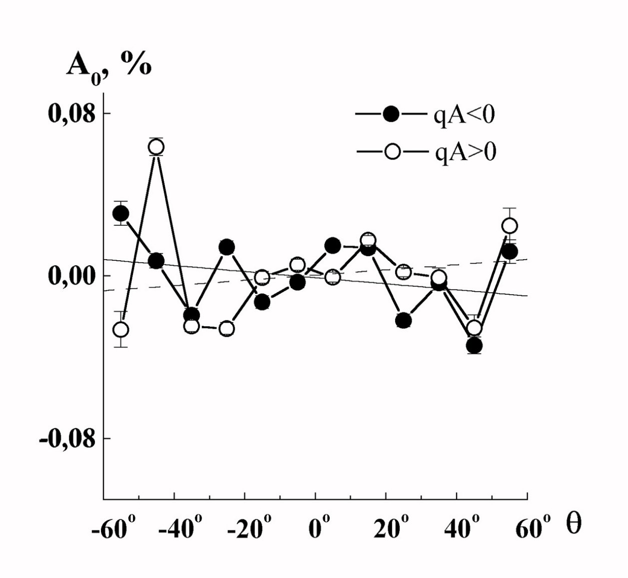

Fig. 2. Dependence of A_0-component on the angular distance of the Earth to a current sheet.

$$\boldsymbol{r}_{dr} = \frac{\boldsymbol{r}_{+} - \boldsymbol{r}_{-}}{2} \qquad (1)$$

The vectors $\boldsymbol{r}_{dr}$ corrected for the influence of the geomagnetic field and then averaged by all registration levels are presented in Fig. 3 for the positive and negative polarities of the magnetic moment of the Sun. Note that the weak dependence on the magnetic moment polarity is observed. Thereby, $\mid \boldsymbol{r}_{dr} \mid$ for the negative polarity is smaller than for the positive one. The clear dependence of $\boldsymbol{r}_{dr}$ on the Earth's location relative to the helioequator is observed. So, for the N-zone the diurnal variation is of the amplitude of $0,028 \pm 0,003\%$ and $t_{max} = 5,5 \pm 0,2^h$ and for the S-zone it is of amplitude of $0,056 \pm 0,003\%$ and $t_{max} = 15,5 \pm 0,1^h$ i.e. the vector $\boldsymbol{r}_{dr}$ changes along a line $3 \div 15^h$ that testified about its drift origin.

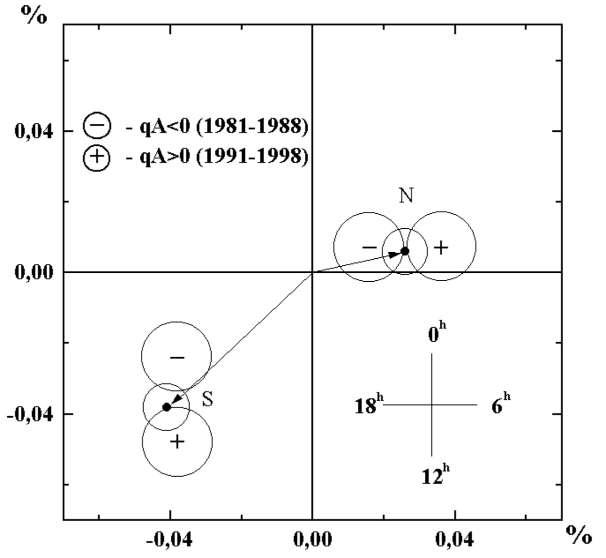

Fig. 3. The drift vector of cosmic ray anisotropy.

3 Discussion

The difference of the anisotropy observed in the fields of different sign testifies that there is a heliolatitudinal gradient of cosmic rays. Thereby, the gradient is directed to the opposite sides of the solar equator plane. The direction of the difference vector which is changed to the opposite one when the Earth passes from one to another heliospheric hemisphere testifies about it. If we suppose the solar wind speed $U_0 \approx 400\ km/s$ then the angle of Archimedes spiral (the deviation of the interplanetary magnetic field of the radial direction) will be $45°$. In this case the difference anisotropy vector which should be perpendicular to the cosmic ray gradient and also to the magnetic field vector will give the diurnal variation with $t_{max} = 3^h$ and 15^h LT in different hemisphere. The observed vector approximately corresponds to the above picture. The sign of vector shows that the minimum of cosmic ray intensity is observed near the heliospheric equator plane.

To estimate the value of the gradient and the difference anisotropy vector, consider the simplified model of cosmic ray modulation by the solar wind. Let's make the following simplification. Suppose, firstly, that the magnetic field in the region, where it is radial, doesn't depend on the heliolatitude and in the equatorial plane it changes the sign and that the solar wind speed u_0 is constant and everywhere is similar. Secondly, the transport coefficients (the transverse and antisymmetrical diffusion coefficient) are inversely proportional to the magnetic field intensity and they don't depend on coordinates evidently. At last, we shall consider the modulation in the far region where the field is practically azimuth. Namely this region makes the main contribution into modulation.

Because the total modulation depth is small for the high energy particles, we can use with a high accuracy the linear approach by the solar wind speed (Krymsky et al., 1981), i.e. to represent the distribution function f as a sum of undisturbed $f_0 \sim p^{-(\gamma-2)}$ and varied f_1 parts. In this case in the transfer equation of cosmic rays the terms with the solar wind speed doesn't contain f_1. With regard to the above remarks, the equation is of a form:

$$\frac{1}{r^2}\frac{\partial}{\partial r}(r^2\kappa_\perp\frac{\partial f_1}{\partial r}) + \frac{1}{r_2\sin\theta}\frac{\partial}{\partial\theta}(\sin\theta\kappa_\perp\frac{\partial f_1}{\partial\theta}) - -u_r\frac{\partial f_1}{\partial r} - \frac{u_\theta}{r}\frac{\partial f_1}{\partial\theta} = \frac{b}{r} \qquad (2)$$

Here $b = 2(\gamma+2)\frac{u_0 f_0}{3}$, $\kappa_\perp = \kappa_0\frac{r}{r_0\sin\theta}$, $r_0 = const$, $u_r = u_{dr}\delta(\theta-\pi/2)$, $u_\theta = u_{dr}\frac{Sign(\pi/2-\theta)}{\sin\theta}$.

The drift velocity u_{dr} is obtained as the result of differentiation of the antisymmetrical part of diffusion tensor (Krymsky et al., 1981). The values κ_0 and u_{dr} are considered as independent parameters.

If we assume that the heliosphere boundary (heliopause) is sufficiently distant and we neglect by its influence, then we can find the r - independent solution of equation. In this case the equation is simplified:

$$\frac{\kappa_0}{r_0}\frac{\partial^2 f_1}{\partial\psi^2} + u_{dr}\frac{\partial f_1}{\partial\mid\psi\mid} = b\cos\psi, \qquad (3)$$

where $\psi = \pi/2 - \theta$ is heliolatitude.

The solution is obtained by means of twice integration:

$$f_1 = \frac{br_0}{\kappa_0(4k^2+1)}(2k\sin\mid\psi\mid + e^{-2k|\psi|} - -\cos\psi) + const. \qquad (4)$$

The integration constant is chosen in such a way so that $f_1 = 0$ at $\mid\psi\mid = \pi/2$. Parameter $k = \frac{u_{dr}r_0}{2\kappa_0}$.

If we consider that the particles diffuse because of isotropic scatterings which occur with them in the regular magnetic field, then the transport coefficients κ_0 and u_{dr} are found to be related with each other (Krymsky et al., 1981). In this case, the introduced above constant k is a ratio of the particle gyrofrequency to the scattering frequency.

The transport coefficients are expressed through this constant as follows:

$$\kappa_0 = V\frac{pc}{eH_0}\cdot\frac{k}{3(k^2+1)} \qquad (5)$$

$$u_{dr} = V\frac{pc}{eH_0 r_0}\cdot\frac{2k^2}{3(k^2+1)} \qquad (6)$$

Here p, V - the momentum and velocity of particle, respectively, e is the electronic charge, H_0 is the azimuth component of magnetic field in the solar equator plane at a distance r_0 of the Sun.

For the heliolatitudinal gradient we have the expression:

$$\frac{\partial f}{\partial\mid\psi\mid} = b_1\frac{2k}{4k^2+1}(\sin\mid\psi\mid + +2k\cos\psi - 2ke^{-2k|\psi|}). \qquad (7)$$

The constant

$$b_1 = (\gamma + 2)\frac{k^2+1}{k^2}\frac{u_0}{V}\frac{eH_0r_0}{pc}f_0. \tag{8}$$

The gradient disappears at $\psi = 0$ and increases symmetrically to both sides of the equator plane.

The anisotropy vector $\boldsymbol{A}$ in the regular field $\boldsymbol{H}$ depending on the field sign, with the availability of the gradient $\nabla f/f_0$ is determined by the expression (Krymsky et al., 1981):

$$\boldsymbol{A} = \left[\frac{\nabla f}{f_0} \times \frac{\boldsymbol{H}}{H}\right] \cdot \frac{k^2}{k^2+1} \cdot \rho, \tag{9}$$

where $\rho = pc/eH$ is the particle gyroradius. Substituting the expression of the heliolatitudinal gradient into (9) we have:

$$A = (\gamma + 2)\frac{2k}{4k^2+1}\frac{u_0}{V}\frac{H_\varphi}{H}(\sin \mid \psi \mid + \\ +2k\cos\psi - 2ke^{-2k|\psi|}). \tag{10}$$

Here $r = r_0$, H_φ/H is a ratio of the azimuth component to the total vector of the field, which is defined by the solar wind speed u_0. Besides of u_0, the anisotropy depends only on the parameter k characterizing ”laminarity” of the interplanetary magnetic field. It is necessary to underline, if k doesn't depend on p, then the anisotropy has ”flat” energy spectrum, its value is constant in some range of momenta. For $\psi = 7°$, $\gamma = 2.5$, $u_0 = 400 km/s$, $H_\varphi/H \approx 1/\sqrt{2}$ we have $A(k)$ presented in Table 1.

Table 1. The expected amplitude of the anisotropy with the availability of the gradient directed to the opposite sides of the solar equator plane at different phases of the solar magnetic cycle.

	k	0.2	0.4	0.6	0.8	1.0
$A, \%$	$'' + ''$	0.020	0.039	0.057	0.075	0.091
	$'' - ''$	0.021	0.043	0.066	0.091	0.117

Signs ± correspond to different polarities of the general magnetic field of the Sun. The transition from $+$ to $-$ is made by means of the change of the sign of k in formula (10) for A and the change of the sign of the whole expression.

The comparison of these values with results of Fig. 3 shows that by the order of magnitude they are consistent with each other. In theoretical calculations a number of effects which can distort the results have not been taken into account, namely, oscillations of the neutral surface around the mean value during a solar rotation and also the influence of the radial gradient of cosmic rays.

As to the dependence of the anisotropy of the Earth's distance up to the current sheet, its reason is probably the sheet of low-speed solar wind is flanking on the neutral surface of magnetic field. In this sheet the anisotropy must be lower than in the surrounding wind.

If we denote the velocity of the Sun's rotation projected on the Earth's orbit as $u_* = 400\ km/s$, then according to (Krymsky et al., 1981) the anisotropy will be:

$$A = A_{max}\frac{k^2}{k^2+1+(\frac{u_*}{u})^2}. \tag{11}$$

We take the speed of slow wind $u_1 = 350\ km/s$, and of fast wind $u_2 = 600\ km/s$. The difference in values of the anisotropy in the fast and slow wind depending on k is given in Table 2.

Table 2. The expected amplitude of the anisotropy under deformation of the interplanetary magnetic field current sheet.

k	0.4	0.6	0.8	1.0
$\Delta A, \%$	0.020	0.038	0.053	0.063

From Fig. 1 and Table 2 it is seen that observed differences are of the same order of magnitude at $k \simeq 0.6 \div 0.8$.

4 Conclusion

Observations of the anisotropy provide a possibility to estimate the relative contribution of the turbulent and regular magnetic fields in the heliosphere. For cosmic ray particles registered with the muon telescopes in Yakutsk the characteristic spatial scales of the turbulent field, influencing on the anisotropy, is $(0.1 \div 0.5)r$, where r is the distance of the Sun. From the above analysis it follows that in the periods of high solar activity the turbulent field becomes dominant - the scattering mean free path of particles doesn't exceed their gyroradius in the regular field.

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