Tensor anisotropy of cosmic rays by data of neutron monitors and muon telescopes

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Abstract. The long-term data of neutron monitors of the world-wide network have been processed using the global survey method. In addition to the symmetrical diurnal variation, the semidiurnal and antisymmetric diurnal variations reflecting the availability of tensor anisotropy have been stood out. Results are analyzed jointly with the data of muon component from the st. Nagoya for the time period 1971 to 2012 and physical mechanisms responsible for anisotropy are discussed.

Introduction

The intensity of galactic cosmic rays registered by ground-based detectors is isotropic in the first approximation. However, there are small deviations from the isotropy which are indicative of the presence of some directional motion of cosmic rays as a whole at each moment of time. This anisotropy is described by the first spherical harmonic by directions of particle motions and can be represented by a three-dimensional vector. Along with the vector anisotropy there exists an anisotropy of another kind which should be described by the second spherical harmonic by directions of particle motions. Five components of this anisotropy in the coordinate system with polar and azimuthal angles θ, ψ look like:

$$\Omega_1 = \sqrt{3}(cos^2\theta - 1/3)$$

$$\Omega_2 = sin2\theta cos\psi$$

$$\Omega_3 = sin2\theta sin\psi$$

$$\Omega_4 = sin^2\theta cos2\psi$$

$$\Omega_5 = sin^2\theta sin2\psi$$

One can represent the corresponding coefficients of decomposition $(a_2^0, a_2^1, b_2^1, a_2^2, b_2^2)$ in the form of five-dimensional vector of anisotropy $\vec{A}$. If we add the isotropic part to the distribution of intensity described by the second spherical harmonic we will gain one more geometrical form of anisotropy i.e. a triaxial ellipsoid. The ellipsoid orientation in relation to the coordinate system is described by three Eulers angles and the ellipsoid itself - by two eccentricities.At last, this anisotropy can be represented by a symmetrical matrix T with the given spur which also requires five independent components. As the system of angular coordinates changes, the components of matrix T also changes, that is it is a tensor. The mentioned triaxial ellipsoid is a surface which is described by the following equation:

$$\vec{\Omega}T^{-1}\vec{\Omega} = 1,$$

and is also termed as the second tensor ellipsoid.

A method of finding of the anisotropy

The cosmic ray intensity registered with a device, depends on a distribution of intensity by the solid angle $J(\Omega)$ and also on the directional pattern $R(\Omega)$:

$$I = \int J(\Omega)R(\Omega)d\Omega.$$

If we expand the directional pattern of device in spherical functions and take expansion coefficients belonging to the 2nd spherical harmonic $(x_2^0, x_2^1, y_2^1, x_2^2, y_2^2) \equiv \vec{R}$, we will obtain the contribution of tensor anisotropy into the intensity registered with a device:

$$\delta I = \vec{R} \cdot \vec{A}.$$

If there is a set of devices with the R_i vectors then the vector $\vec{A}$ can be found from the linear equation system by their indications δI_i.

The five-dimensional vector $\vec{R}$ termed as a receiving vector, should be determined in the coordinate system related to the rotating Earth where it conserves to be constant. At the same time the vector $\vec{A}$ arises owing to dynamic processes in the solar wind and should be determined in the coordinate system related to the Sun.

A transfer from one system to another is made by means of the matrix M of 5×5 dimensions. Generally the matrix arises as the effect of 3 sequential rotations around axes of coordinates corresponding to Eulerian angles. In order for both vectors $\vec{A}$ and $\vec{R}$ vectors to be transformed by the same matrix, it is necessary for the matrix to be orthogonal. It is achieved by that normalization of components Ω_i which is stated above. As in the expression for δI both vectors should be expressed in the unified coordinate system, at least, one of them will depend on the time of a day and consequently $\delta I(t)$ will contain an antisymmetric daily (a_2^1, b_2^1) and semidiurnal (a_2^2, b_2^2) variations. Corresponding components of a vector $\vec{A}$, can be found by indications of even one device if the anisotropy does not change within a day. If in the solar coordinate system the anisotropy is constant, then parametres of a daily variation will normally change during a year because the orientation of the Earths rotation axis changes.Thus, the slowly changing anisotropy can be found using a method of daily variations. In a case of prompt changes it must be determined by indications of the set of several devices. Such method of determination of anisotropy by the worldwide neutron monitor network has been realized in [1] and has been titled as a "method of global survey".

It should be make some remarks concerning the construction of vectors $\vec{R}_i$. The directional diagramme $R(\Omega)$ taken as a basis is constructed with the account of a geographical location of each device, its aperture, taking into account a direction of cosmic ray trajectories in the geomagnetic field which is different for particles of different energies with the account of a spectrum of anisotropy and coupling coefficients. The detailed results of such calculations are given in [2],[3],[4],[5],[6].

Mechanisms of tensor anisotropy

The most obvious mechanism of tensor anisotropy is a cosmic ray screening [7],[8],[1]. The interplanetary magnetic field formed by the solar wind can contain open magnetic tubes or the closed tubes in the form of magnetic loops. Those and others are diagrammatically depicted in

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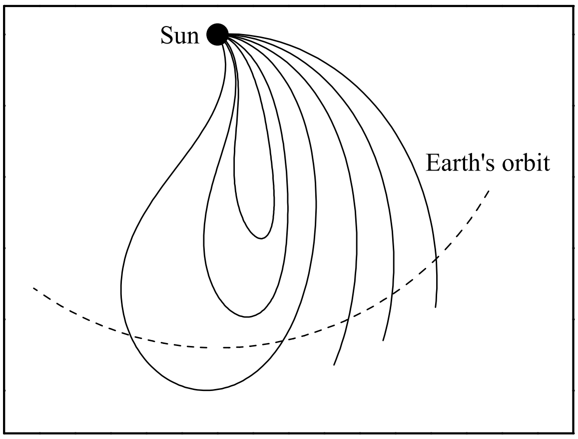

Figure 1. The geometry of magnetic tubes.

Fig.1. Loop-like tubes must form in a relatively narrow helio-latitudinal layer adjoining a plane of the solar equator, from whence the solar wind with lower velocity is emitted. The high-speed wind from higher helio-latitudes carries out open tubes. In each closed tube a deficit of particles moving along a magnetic field appears as the tube expands. A corresponding anisotropy in the system coordinate with the polar axis directed along the field will be depicted by a vector with the following components:

$$(a_2^0, 0, 0, 0, 0), \text{ where } a_2^0 < 0.$$

The physical reason of this effect is the magnetic shielding of particles: particle moving with small pitch-angles cannot penetrate into a tube.

Other mechanism is a shear flow in the inhomogeneous solar wind [9], [10].Cosmic ray scatterings on the moving magnetic inhomogeneities lead to the appearance of directional particle fluxes with the excess intensity

$$\delta I = (\gamma + 2)(\vec{u}\vec{v})/c^2$$

where $\gamma = 2.5$ is an index of cosmic ray spectrum, $\vec{u}, \vec{v}, c$ are velocities of the solar wind, particle and light, respectively. If there exists the shear of velocity, i.e. it is various in the adjacent tubes of flow, then a tensor anisotropy appears. Its parameters have been calculated. Let the velocity is directed along the axis x and depends on z as:

$$u_x(z) = gz, \text{ where } g = const$$

and the cosmic ray particles have the free path before scattering, equals to λ.

Let us introduce a polar coordinate system with the axis along z Then for the particles arriving at the observation point from the direction θ, ψ, we shall have the additional intensity

$$\delta I = \frac{\gamma + 2}{\lambda c^2} \int_0^\infty e^{-r/\lambda} (\vec{v}(\theta, \psi)\vec{u}(r, \theta, \psi)) dr$$

As the velocity $\vec{v}$ is directed along a position vector r, it is necessary for us to find a radial velocity component $\vec{u}$. It is equal to $u_r = u_x cos\psi sin\theta = grcos\theta sin\theta cos\psi$. Supposing $v = c$, we can find:

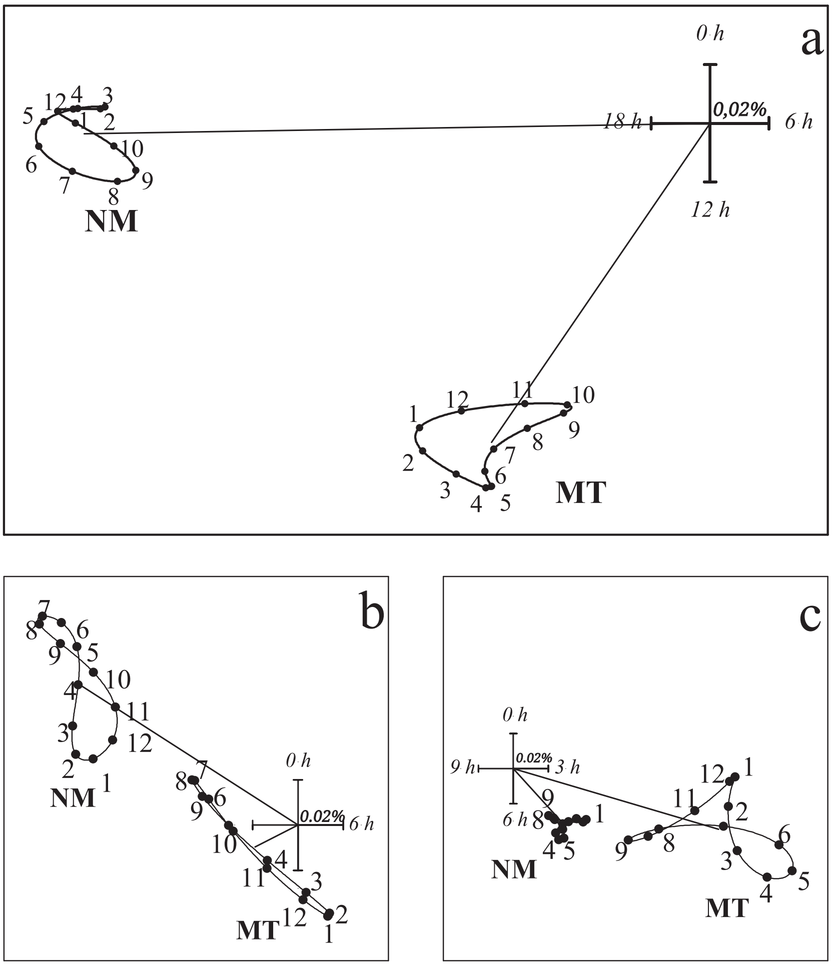

Figure 2. Annual course of the vector anisotropy (symmetric daily variation) (**a**) and tensor anisotropy components: antisymmetric daily variation (**b**), semidiurnal (**c**) by data of the multidirectional muon telescope of Nagoya (MT) and neutron monitor network (NM). Months are represented by numbers near the points on the curve. Error bars are not presented because of their small value.

$$\delta I = \frac{\gamma + 2}{2}\frac{\lambda g}{c} sin2\theta cos\psi$$

Thus, we have the tensor anisotropy with the following components:

$$\vec{A} = (0, a_2^1, 0, 0, 0);\ a_2^1 = \tfrac{\gamma+2}{2}\tfrac{\lambda g}{c}.$$

Tensor anisotropy in the neutron component

In [11] we obtained parameters of the antisymmetric daily and semidiurnal variations by data of muon telescopes at Yakutsk and Nagoya. The regular annual change of these parameters is caused by two possible reasons: the changes of orientation of the Earth's axis in the solar coordinate system and shift of the Earth in heliolatitude. These changes differ in phase and, consequently, can be divided in the observations. The main part of semidiurnal variation is

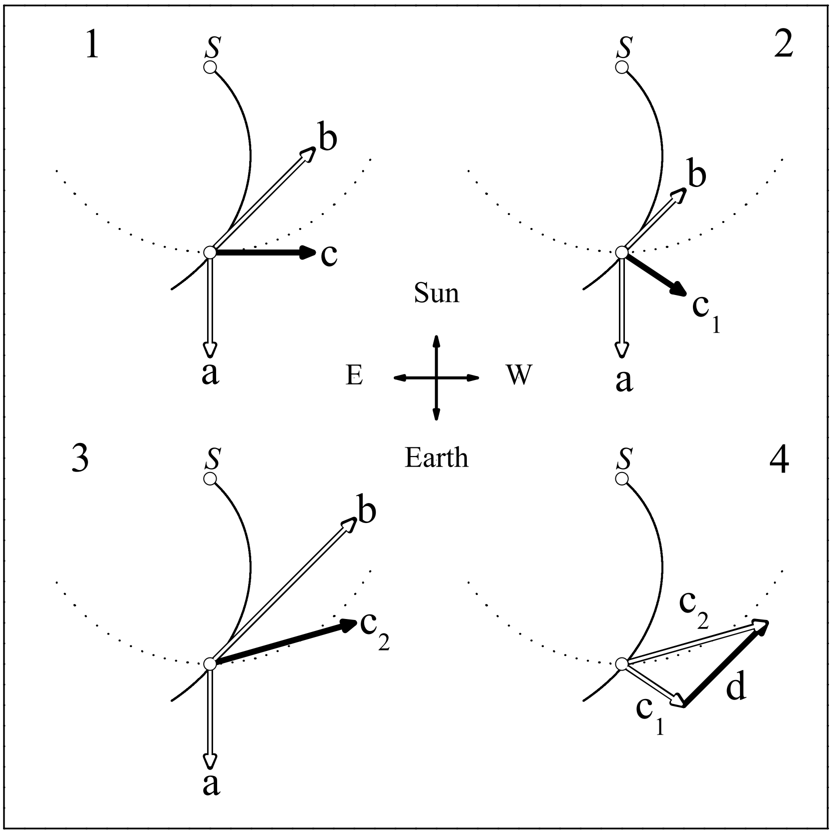

Figure 3. Balance of convective (**a**) and diffusive (**b**) currents and their local disturbance. 1 is the correct balance, 2,3 are the deficit and excess of diffusive current, 4 is the difference of currents (**d**) indicating to the occurrence of current gradient along the magnetic field. **c**, $\mathbf{c_1}$, $\mathbf{c_2}$ are the resultant currents for each case. The dotted curve indicates to the Earth's rotation orbit. The solid curve is the field lines of the interplanetary magnetic field.

created by the screening mechanism, and antisymmetric daily is mainly by the shear flow. It turned out that the extremum of heliolatitudinal changes falls on the $\approx 4.5°$ heliolatitude, but not on the equator. The known fact of southward shift of a low-latitudinal layer in the solar wind [12] confirms it.

Here the results of treatment of observations registered by the worldwide neutron monitor network are given. Figure 2 presents results on the 24 and 12 hour dials. The changes of parameters during a year are shown. The data are smoothed by the 1st and 2nd harmonics (annual and semi-annual variation).

At the same Figure the results of muon measurements from [11] are shown. The general correspondence of those and other data with the account of the fact that the mean particle energies making a contribution into the neutron intensity are considerably lower than in muons is observed. Because the tensor anisotropy spectrum increases with the energy, the neutron component reveals variations which are smaller in value than in the muons. The noticeable difference is revealed in the annual average antisymmetric variation which are considerably higher in the neutrons. Let us discuss the nature of this effect. The above described tensor anisotropy mechanism caused by the solar wind shear flow is the example of more general phenomenon. The tensor anisotropy will occur every time when there is a current gradient of cosmic rays. The reason of this gradient can be not only the shear flow but also any conditions creating the solar wind inhomogeneity, for example, the presence of magnetic mirrors. In [13] the effect of decrease of cosmic rays in a zone of interaction of prompt and slow solar wind streams, caused by the occurrence of magnetic mirror, was considered. Such interaction occurs in the vicinity of neutral sheet of the interplanetary magnetic field. From this it follows that in this field the radial removal of cosmic rays and deficit of compensating diffusive current along the field should prevail. At the boundaries of interaction zone the excess diffusive current which is required for the balance of cosmic rays, on the contrary, should be observed.

The current of cosmic rays creating the ordinary (vector) anisotropy arises as a result of balance of the convective and diffusive currents (**a** and **b** in Figure 3). When the balance is broken, for example, owing to heliolatitudinal differences, it remains unchangeable only on the average. It corresponds to the situation depicted in 2nd and 3rd parts of Figure. The arising current gradient (4th part of Figure) as the north-southern current asymmetry corresponds to the direction of the interplanetary magnetic field. The mentioned effect, apparently, is a reason of annual average of antisymmetric daily variation in the neutron component.

Conclusions

The tensor anisotropy by neutron monitor observations corresponds, as a whole, to the anisotropy observed in the muon component if we take into account the distinction in the energy of particles. However, the annual average vector of antisymmetric daily variation has appeared to be unexpectedly major. In the work it is shown that this property can be understood as the result of interaction of prompt and slow solar wind streams under conditions that its structures are southward shifted. In this case the known mechanism of the tensor anisotropy which is associated with the shear flow of the wind has been generalized.

Acknowledgments

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