Relation of the equatorial component of the cosmic ray anisotropy to the parameters of interplanetary medium

Abunina M.[1], Abunin A.[1], Belov A.[1], Eroshenko E.[1], Oleneva V.[1], Yanke V.[1], Kryakunova O.[2]

(1) Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio wave propagation (IZMIRAN), Troitsk, Moscow, Russia (abunina@izmiran.ru)
(2) Institute of Ionosphere, Almaty, Kazakhstan

ABSTRACT

Variations of the cosmic ray vector anisotropy observed on Earth are closely related on the condition of near Earth interplanetary medium. The hourly characteristics of vector anisotropy obtained by the global survey method from the data of world wide neutron monitor network during 1957-2013 allow us to investigate connection of the cosmic ray anisotropy with the solar wind parameters. In the offered work relation of the equatorial component Axy of the cosmic ray anisotropy (rigidity 10 GV) to the solar wind velocity and density, to intensity of the interplanetary magnetic field and to the changes of cosmic ray density in which the spatial gradient of CR is revealed in interplanetary space, is studied. Characteristics of CR anisotropy for various combinations of the interplanetary parameters corresponding to various conditions of the interplanetary medium are compared. Opportunity to judge on condition of a solar wind by cosmic ray anisotropy is discussed.

INTRODUCTION

The local interplanetary parameters determine of the cosmic ray (CR) anisotropy: the IMF strength, direction and irregularity, solar wind velocity, and gradient of CR density. Accordingly to the convective-diffusion theory vector of the CR anisotropy $\vec{A}$ (the first spherical harmonic): $\vec{A} = \vec{A}_c + \vec{A}_d \approx C\vec{u} + \Lambda\vec{G}$, where Λ is the matrix of transport paths, $\vec{G}$ is a CR gradient. Convective component $\vec{A}_c$ is defined by local speed of the solar wind *V* (usually directed radially from the Sun) and by Compton-Getting factor *C*. Any component of matrix Λ is of the form $\lambda_i = k_i\rho$ where ρ is gyroradius of particles, which is in inverse proportion to the IMF strength, and coefficients k_i are defined by a degree of IMF irregularity.

We know which parameters determine the vector of anisotropy but these parameters are known not sufficiently. Although solar wind velocity and IMF characteristics are measured about half a century, but we may consider them as known by conventional (because the point for us and for cosmic rays means different things). For the CR point has a size of gyroradius (for the CR observable on the Earth this is 0.1 a.u. by order). Situation with other important parameters (IMF regularity and CR gradient) is much worse – they are not measured directly and there is no reliable way to determine these parameters for certain place and the moment. For all period of solar wind measurements (even since 1957) it was succeeded to obtain characteristics of vector anisotropy of CR. It allows one to make the statistical analysis of a relation of CR vector anisotropy characteristics with the measured parameters of a solar wind.

Main objectives of our work are to find out how the equatorial component Axy of vector anisotropy depends on key parameters of the interplanetary environment; to reveal distinctions of Axy in typical situations in the quiet and disturbed solar wind; to understand, in what measure data on Axy allow to judge about conditions in the interplanetary environment.

DATA AND METHODS

We used hourly characteristics of the CR with rigidity 10 GV calculated by Global Survey Method from the data of world wide NM network for the period from July 1957 to December 2013 (in total almost 500000 hours), and hourly values of the solar wind characteristics collected in OMNI Database (http://omniweb.gsfc.nasa.gov) starting from 1963.

RESULTS AND DISCUSSION

Equatorial component of vector anisotropy

We study here only equatorial component of the vector anisotropy Axy. Axy changes over a wide range: it is sometimes equal 0, in 56 years such happened 49 times, and once (in huge FD on October 29, 2003) Axy exceeded 10%. We will notice that Axy=0 doesn't mean lack of anisotropy as the North-South component of Az or higher harmonicas can significantly differ from 0 in these hours. The average size Axy=0.60%, median – 0.53%. 2/3 all Axy values are in rather narrow range of 0.25-0.91%. If to take narrow range of all parameters of a solar wind near mean values, then average Axy=0.53%, 2/3 of all values are within 0.24-0.80%.

It is well known that the direction of vector anisotropy depends on polarity of a solar dipole. But also vector size depends on it too. At approximately identical parameters of the interplanetary environment, but at various polarities the average size Axy will be various: 0.54% - at negative and 0.46% - at positive.

Axy is conceptually close to the solar diurnal anisotropy which can be seen in data of any ground level detector like a diurnal wave, and practically, Axy is the amplitude of such a wave estimated for particles of 10 GV rigidity. Since 10 GV is close to the effective rigidity recorded at the majority NMs (with an exception of very low latitudinal ones) then, calculated Axy are close to the amplitudes of solar diurnal wave at high latitudinal (but not subpolar) NMs. Solar diurnal anisotropy is actively studied long ago (more than half a century), distinguishing, as a rule, a daily wave from of counting rate variations by means of the harmonic analysis. The obtained thus, solar diurnal anisotropy except similarity to Axy has also essential differences from it. Main preferences of Axy: 1) it is the characteristic of angular distribution of CR intensity which isn't connected with any detector; 2) it is hourly (not daily) characteristic. These differences give the chance of more detailed comparison of Axy with characteristics of the interplanetary environment.

Relation Axy to the solar wind velocity

Let us compare hourly values of Axy with solar wind velocity over the whole studied period – 316703 hours (fig. 1). If the reason of the CR anisotropy was only convection we would have simple linear growth of Axy with the wind velocity. But Figure 1 shows that for the wide velocity range, up to 750 km/s, a dependence of Axy(V) is practically absent. This is a direct consequence from convective-diffusion model of anisotropy. Dependence appears only under the highest velocities which follow the most significant interplanetary disturbances but all the same, dependence of Axy(V) remains to be weak (correlation coefficient for V>750 km/s is only 0.37). It is natural to suppose that in these hours the magnetic field may also be strengthened, and gradient of CR density is much higher as well than usual. Thus, the increase of Axy under large velocities may be determined not only by velocity. Parameters of the interplanetary environment are closely interrelated and to distinguish an influence of some one parameter on the anisotropy is difficult task. Apparently, is more perspective to consider at the same time an influence of two or several parameters. If to consider not only the size of speed of a solar wind, but also its dynamics (change of speed in an hour, dV = $(V_{k+1}-V_{k-1})/2$ where k is a number of hour), we will see stronger dependence and more interesting picture (fig. 2).

Follows from fig. 2 that dependence Axy on changes of speed of dV (more precisely, on abs(dV)) is stronger, than dependence on the speed. It thus that there is no straight line (expected from the theory) anisotropy relation to dV. In this case changes of a solar wind speed act as the indicator of a disturbance of the interplanetary environment.

Growth of speed is usually connected with interaction of streams of a wind, thus the probability of strengthening of IMF and appearance of considerable gradients of CR density is great in these places. Considerable and fast speed decrease, as the rule, is also observed in significantly disturbed solar wind. Fast change of speed of a solar wind is a sign of a perturbation of the interplanetary environment. Most likely, dependence of Axy(dV) is explained by it.

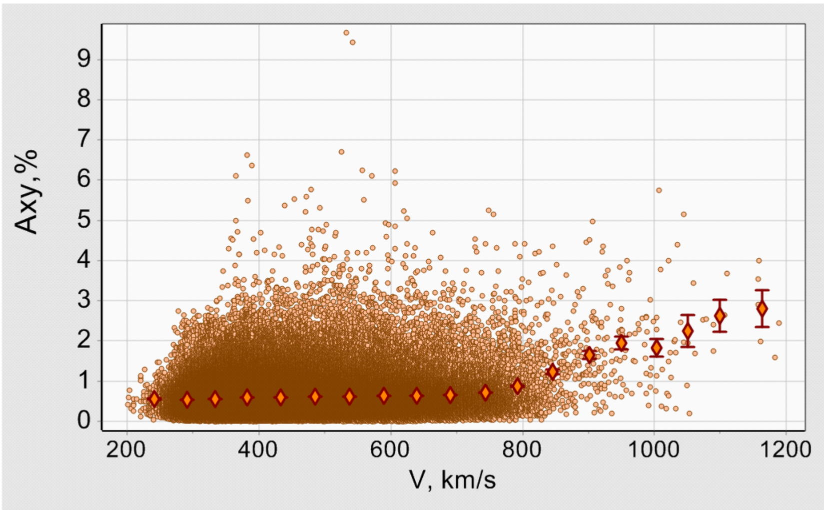

Figure 1. Axy versus to the solar wind velocity V. Circles show data for each hour, diamonds – Axy averaged by equal intervals of velocity.

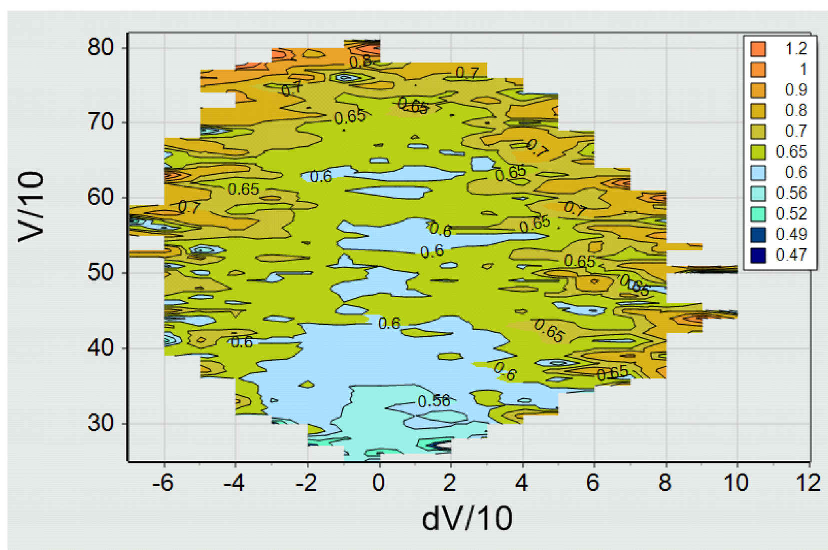

Figure 2. Relation Axy to the solar wind velocity V and its changes dV for one hour. Counter isolines correspond to equal values of Axy.

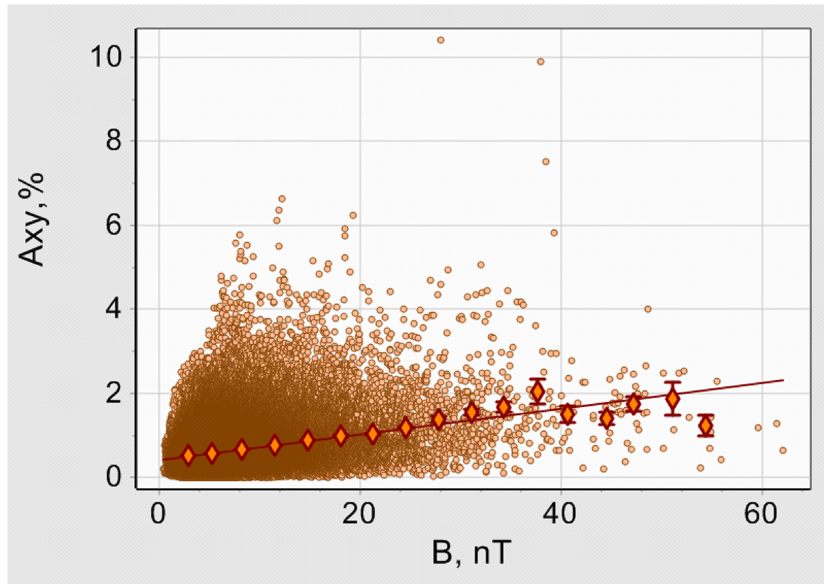

Figure 3. Dependence of Axy on the IMF strength B. Points are hourly values of Axy. Diamonds mean Axy averaged within the equal intervals of B.

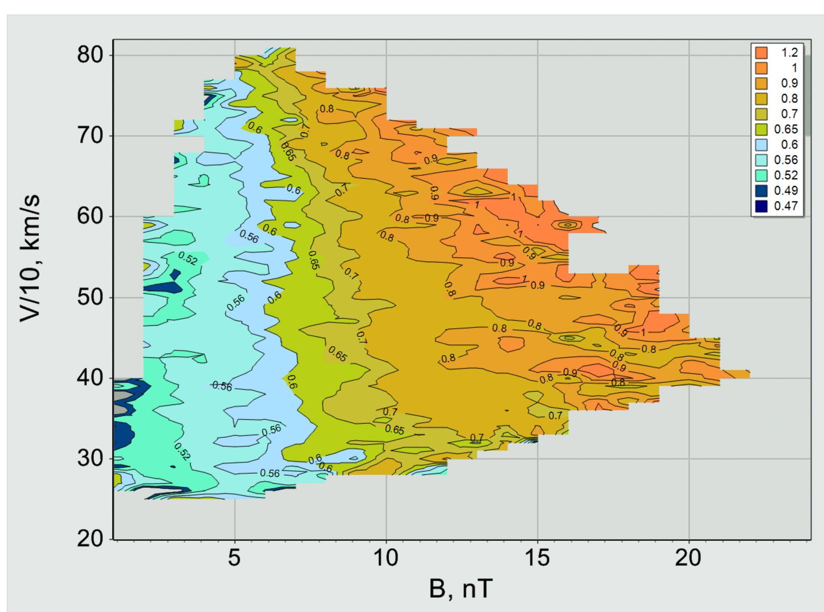

Figure 4. Connection of Axy with the solar wind velocity V and IMF strength B.

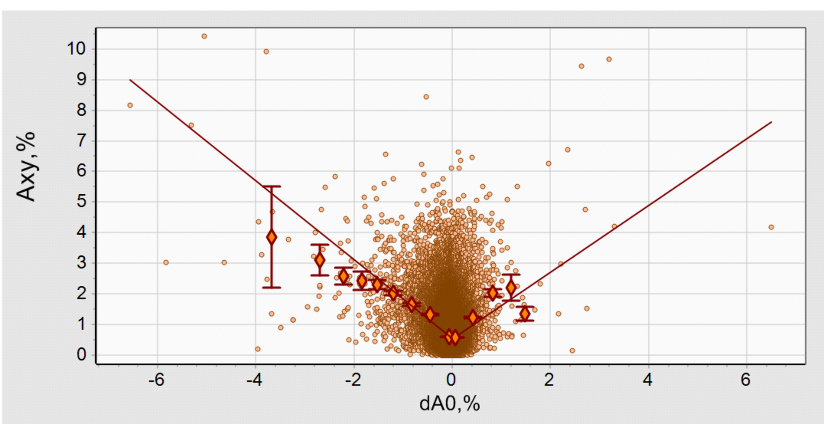

Figure 5. Relation of the Axy vector to the changes of CR density (dA0). Regression lines are obtained separately for positive and negative dA0.

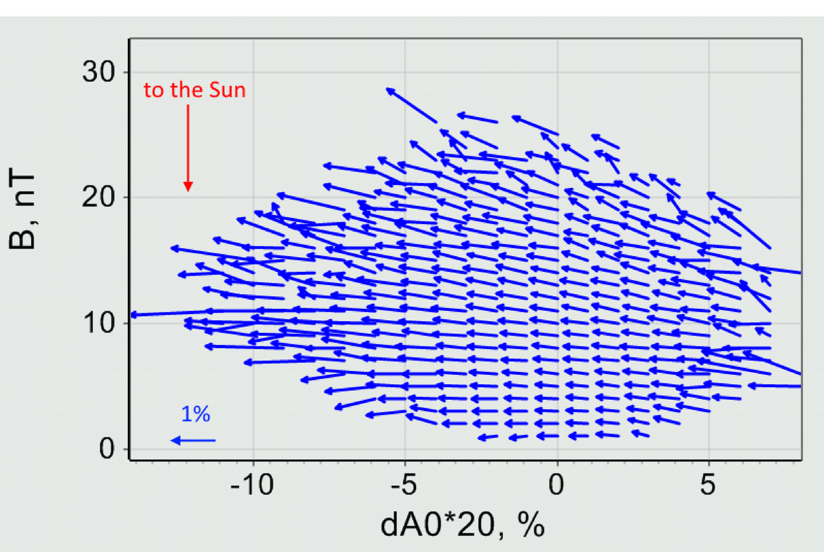

Figure 6. Connection $\overrightarrow{Axy}$ of with the changes of CR density dA0 and IMF intensity B.

Relation of Axy to the intensity of IMF strength

Such a relation has to be, but it is very difficult to receive it in pure form, it is even more difficult, than to search for correlation between Axy and a speed of a solar wind. If the high-speed and not disturbed solar wind can be imagined, the high IMF strength is always connected with interplanetary disturbances. Fig. 3 shows that relation of Axy(B) is weak (CC=0.26) though it is obviously stronger, than of Axy(V) relation. To very big values of IMF strength increase of Axy together with B is visible. And only at B ≈35-40 nT it stops.

In power representation of Axy(B) it looks like Axy $\propto$ $B^{0.28}$. If to remember that the magnetic field generally interferes of charged particle transfer and reduces anisotropy, at a gradient of g of CR density Axy $\propto$ ρg$\propto$ g/B. However the gradient, certainly, isn't constant, and correlates with intensity of a field. The stronger field, the more probable a big gradient is. From our result it follows that dependence of a gradient of CR on B is stronger than the linear.

We have to remember that together with IMF intensity other parameters of interplanetary environment are also changing (for example, solar wind velocity). Fig. 4 demonstrates the changes of Axy value under V and B variations.

At B=4÷6 nT close to average sizes, Axy almost doesn't change with changes of SW speed as showed also fig. 1-2. At the strengthened magnetic field the increased sizes of Axy are observed at all values of speed of a solar wind and Axy grows with increase in speed. At low speeds and the weaker field the size of Axy is lowered though at the lowest values of B the signs of some increase in Axy exist.

Connection with CR gradient

Gradient of CR density is the main reason of the CR anisotropy. Unfortunately, we don't know the CR gradient in a definite moment in a fixed point. However under certain circumstances changes of the CR density can give the information on CR gradient. In our work we use density variations (A0) of the CR with rigidity 10 GV, obtained by global survey method (GSM) together with characteristics of CR anisotropy. We consider that at hour k the CR density variation is dA0=$(A0_{k+1}-A0_{k-1})/2$. In some situations dA0 can give an information on components of a CR density gradient: about a radial component when passing ICME and about an azimuthal component in high-speed streams from the CHs.

In fig. 5 it is possible to see that there is some Axy dependence on an absolute value of dA0. For negative dA0 this communication looks more remarkable (correlation coefficient is 0.31), but this results is possible from the fact that there is much more significant negative dA0, than positive. Certainly, changes of CR density happen not in itself, and together with changes in a solar wind, with responding to them by a complicate way. One of the most essential characteristics to changes of CR density is IMF strength. In fig. 6 joint influence of these characteristics (B and dA0) on vector anisotropy of CR (on Axy) is shown.

To derive Figure 6 the whole area of changes was divided on the 1nTx0.05%/hrs cells and vector CR anisotropy was averaged in each cell. For small dA0 and normal IMF intensity a big number of hours was averaged in each cell (up to 2000). Under big changes of CR density and stronger IMF the number of hours was significantly less. The results are plotted only for the cells where a number of hours was ≥10. One can see that points with big value abs(dA0) under lower or normal IMF intensity (B) are absent in this picture. In Figure 6 not only magnitude of $\overrightarrow{Axy}$ but also its direction is shown. Fig. 6 shows that at little changes of the CR density and at the normal or a slightly strengthened IMF there is a zone of stable anisotropy where length and the direction of a vector $\overrightarrow{Axy}$ almost don't depend on dA0 and B. But if one of these values (or both) significantly differs from norm, the size Axy increases, and the direction of a vector $\overrightarrow{Axy}$ becomes unstable. In general, the direction to the west remains, but also deviations from it become considerable, and vectors from the Sun are observed more often than to the Sun. Such anisotropy isn't surely connected with observed changes of CR density, but, nevertheless, is defined by the CR gradient (first of all, radial) existing constantly, slowly changing and isn't proving itself in variations of CR density.

MAIN CONCLUSIONS

On the big volume of hourly experimental data covering almost entire period of solar wind measurements we studied the relation of the equatorial component of vector CR anisotropy with interplanetary characteristics, namely with the solar wind speed and its changes, with an interplanetary magnetic field strength, with changes of CR density.

Any measured or easily counted parameter of the interplanetary environment doesn't show close correlation with the size of CR vector anisotropy. However combinations of the parameters of the environment manifested of its disturbances are accompanied by increase of vector anisotropy. Most obviously increase of anisotropy is promoted by considerable changes of CR density and speed of a solar wind, and also strengthening of the IMF.

The size of vector anisotropy of CR almost doesn't depend on the speed of a solar wind as it was predicted by convectively-diffusive model of anisotropy.

Weak positive correlation of Axy with IMF strength B, apparently, testifies to stronger dependence on B for radial gradient of CR density.

Statistical relations of parameters of anisotropy to various conditions of the interplanetary environment give the information on degree of environment disturbance. The accounting of the size Axy (separately or together with variations of CR density) can change probability of the quiet or disturbed solar wind in tens and hundreds times.

Acknowledgements

The authors are thankful to colleagues of the world wide network of CR stations providing data of continue monitoring of neutron component: http://cr0.izmiran.ru/ThankYou/. We acknowledge also the NMDB database (www.nmdb.eu), founded under the European Union's FP7 program (contract no. 213007) for providing data from NM worldwide network.