Influence of a large-scale disturbance of the solar wind on the cosmic ray anisotropy dynamics

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Abstract. We have developed the calculation method of the cosmic ray intensity anisotropy dynamics near the solar wind disturbance. Possible variants of the dynamics for different conditions have been presented.

1. Introduction
The study of the dynamics of the cosmic ray (CR) intensity in the vicinity of large-scale solar wind disturbances can help to detect disturbance approaching to Earth. For many years mainly empiric rules of such research are created and refined. We have developed a kinetic method calculation, which allows to determine the CR dynamics with account of sufficiently realistic properties of the solar wind and disturbance. The method is based on the assumption that the CR dynamics is determined by regular electromagnetic field of the solar wind and disturbance. Comparison of calculations and measurements with the world network of neutron monitors and muon telescopes in the event of September 9, 1992 confirms the ability of the method to reproduce CR dynamics in real events [1]. In this paper we present the calculation method of the dynamics of the CR intensity anisotropy (CRIA) in the vicinity of interplanetary shock approaching to Earth.

2. Method
We assume that the CRIA vector in the Earth vicinity is defined for undisturbed conditions before arising of the disturbance in the interplanetary space. CRIA in the diffusion approximation can be written as

$$\vec{A} = -\frac{3}{v} \vec{k} \frac{\nabla f}{f} + \frac{(\gamma + 2)}{v} \vec{U},$$

where $f$ is the isotropic part of the distribution function of the CRs; $\vec{k}$ is the diffusion tensor; $\vec{U}, v$ are velocities of the solar wind and particle; $\gamma = 2.77$ is the spectral index of galactic CRs.

In the heliocentric spherical coordinate system for the Parker model of the solar wind in the case of axial symmetry of the spatial CR distribution and $k_\perp << k_\parallel$ components of CRIA have the form

$$A_r = -\frac{3}{v} k_\parallel \cos^2 \psi G_r + \frac{3}{v} k_\parallel \sin \psi \frac{\sin \psi}{r} G_\theta + (\gamma + 2) \frac{U}{c},$$
where \( G_r = \frac{\partial}{\partial r} \ln f \), \( G_{\theta} = \frac{\partial}{\partial \theta} \ln f \) are radial and latitudinal gradients of the relative CR intensity, \( k_{||} = \lambda v / 3 \) is parallel, \( k_H = k_{||} k/(1 + k^2) \) is Hall and \( k_{\perp} = k_{||} / (1 + k^2) \) is transverse components of the diffusion tensor; \( \omega = \lambda / \rho \) is coefficient taking into account the ratio between the components of the diffusion tensor; \( \omega, \rho, \lambda, \tau \) are gyrofrequency, the Larmor radius, length and the mean free time of a particle; \( \psi \) is the angle between the magnetic field and the Earth-Sun line.

For CRs with energy \( 15 \text{ GeV} \), which coincides with the particle effective energy recorded by neutron monitors it can be taken \( \lambda \sim r_e \) and \( \rho \sim 0.07 r_e \), where \( r_e = 1.5 \cdot 10^{13} \text{ cm} \) is astronomical unit and used the value of the magnetic field at the Earth’s orbit \( b_0 = 5 \cdot 10^{-5} \text{ Gs} \). In this case, \( k \sim 15 \).

From (1) for \( G_r \sim 1%/r_e \), \( G_{\theta} \sim 0.1%/\text{degree} \) it should be: 1) \(|A_r| < < |A_{\theta}|, |A_{\varphi}| \)

\[
A = \sqrt{A_{x}^2 + A_{y}^2 + A_{z}^2} \sim 1%, \quad \text{and } 3) \text{ the angle between the CRIA vector and the Earth-Sun line is } \sim 1.5\pi.
\]

The listed properties of the CRIA are in general agreement with the measurements [3].

For given CRIA values at the Earth’s orbit relations (1) are used to calculate the \( G_r, G_{\theta} \). We assume that \( G_r, G_{\theta}, k \) are not change at \( r < r_e \). In this case, relations (1) can be used to determine the components of CRIA at \( r < r_e \). The CRIA defines distribution of the CR intensity over the solid angle

\[
J = J_0(1 + A_x \sin \theta \cos \varphi + A_y \sin \theta \sin \varphi + A_z \cos \theta),
\]

where \( J, J_0 \) are intensity and isotropic part of the CR intensity, \( \theta \) is the polar angle counted from the axis of the \( \text{Z} \) GSE coordinate system; \( \varphi \) is the azimuthal angle counted from axis \( X \); \( A_x = -A_r, A_y = -A_{\varphi}, A_z = -A_{\theta} \) are components of the CRIA vector in the GSE coordinate system. The angular distribution of the CR intensity can be represented as a set of CR beams with decomposition of the total solid angle to the set of equal elements. The corresponding intensity of the CR beams is determined from the relation (2).

This distribution is used as an initial conditions for the integration of the relativistic particle movement equation system. For calculation of the CR trajectories in the interplanetary medium standard model of the solar wind is used. Magnetic field of the quiet solar wind is of Parker’s type. The flow velocity is constant and radial. Electric field is defined by condition frozen-in. The equation system is solved by the Runge–Kutta method of 4-th accuracy order with negative time step (in more detail see [2]). As a result of computation the CR trajectories are divided into two types: 1) CRs have interacted with a shock front, 2) CRs haven’t interacted with one. It is accepted that the interplanetary shock is disturbance, which has form of a revolution ellipsoid \( R_S = R_{S,0}/(1 - (1 - b)\cos \psi) \). Here \( R_S, R_{S,0} = R_0 + V_S t \) are radii at any front point and at axis of axial symmetry. \( R_0 \) is initial radius of a shock front, \( V_S \) is speed of a shock front. Angle \( \psi \leq \psi_{\max} = \pi/4 \) is polar one, which is counted from axis symmetry, whose orientation is defined by two angles relative to the solar equatorial coordinate system. Index of the shape asymmetry is \( b = R_S(\pi/2)/R_{S,0} \). It is accepted that every shock front portion moves radially with constant speed.

The computation of the CR trajectories of first type is continued at the shock front. Electromagnetic field in region placed behind the front is determined by the Rankine–Hugoniot relations. Average field is used for calculation of any trajectory part behind the front. It is determined from fields placed at points of trajectory entrance and its exit from disturbed region. As a result of computation CR trajectories of first type are divided: 1) CRs were before the front and they reflected from the front; 2) CRs came across front.

Intensity of every CR beam is determined by the result of the CR trajectory calculations. The intensity of the particle beam passing by the shock front is conserved. The intensity of CRs, which came across the shock front (Forbush–decrease region), is given in the form \( J = J_0(1 - \Delta I) \), where \( \Delta I \) is the amplitude of the Forbush–decrease. The intensity of the CR beams reflected from the shock front is determined by...
Figure 1. Projections of the CRIA on the planes of the GSE – coordinate system: XOY projection are in the upper panels, XOZ projection are in the bottom panels. 1-st column represents total CRIA; 2-nd column represents the anisotropy, formed by the CRs reflected from the shock front only; 3-rd column represents CRIA formed by CRs which came across the shock front. The location of axies of the coordinate system and scale corresponding to 1% value are on the right side. Amplitude of the Forbush decrease equals 3%.

Figure 2. Same as the Fig. 1 for amplitude of the Forbush decrease 7%.

(2), in which an isotropic CR intensity

\[ J_0(r_1, \theta_1) = J_0(1 + (r_1 - r_e)G_r + (\theta_1 - \theta_e)G_\theta) \cdot (p/p_s)^{2+\gamma}, \]

where \( r_1, \theta_1, p_s \) are the position and the momentum of the particle beam in front of the shock front. The last multiplier takes into account change of the CR intensity due to change of the particle momentum at their move along the front and it is determined by the Liouville theorem. CRIA for point \( r_1, \theta_1, \varphi_1 \) is determined from the relations (1) for constant \( G_r, G_\theta, k \). The angles of CRs in (2) are determined by the components of the particle momentum.

The calculation defines the angular distribution of CR intensity at the Earth for any given time. Integrating the angular distribution of the CRs (2) with pre-multiplied by the corresponding trigonometric functions over the solid angle we obtain the CRIA components.

The results of illustrative calculations of the CRIA dynamics are shown in Figs. 1, 2. Each line-segment represents a projections of the CRIA on the planes of the GSE coordinate system. 52 values of
the CRIA through 1 hour are presented in the figures. The results presented in Figs. 1, 2 differ by the Forbush decrease amplitude only: Fig. 1 corresponds to the Forbush decrease 3%, Fig. 2 corresponds to the Forbush decrease 7%. It’s accepted that $A_x = 0$, $A_z = 0$, $A_y = -0.6%$ before the arising of disturbance in the interplanetary space. As seen in columns 2 and 3 in the Figs. 1, 2 CRs reflected from the shock front form $A_x < 0$, while the CRs come from within the Forbush decrease region form $A_x > 0$. The contribution of the CRs reflected from the shock front prevails for a few hours before shock front arriving to the Earth. The perpendicular component of the CRIA is arised when shock front approaches to the Earth. As can be seen from a comparison of the results shown in Figs. 1, 2 higher value of Forbush decrease corresponds to a greater CRIA value, that will be used for production of the arriving forecasting of the solar wind disturbances to the Earth. In general, the results of model calculations correspond to the measurements [3].

3. Conclusions
The developed method for calculating the dynamics of the anisotropy of CR intensity generally corresponds to the measurements. The analysis of the calculation can be used to determine the properties of solar wind and disturbances by measurements of the anisotropy of CR intensity with ground-based detectors, as well as making forecasting of arriving disturbances to the Earth.

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