Dynamics of the galactic cosmic ray intensity in presence of solar wind disturbances

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Abstract— **For studying of cosmic ray dynamics at presence of solar wind disturbances new method has been developed — method of relativistic particles trajectories. Model calculations quite satisfactory reproduce of cosmic rays intensity dynamics observed by ground-based detectors of the isolated event both on amplitude and in time. Calculations agree with general features of CRs intensity distribution on the Earth magnetosphere surface of events set too.**

I. INTRODUCTION

Studies of cosmic rays (CRs) intensity dynamics at presence of solar wind large-scale disturbances represent a great interest in connection with the possibility to use the results for occurrence prediction of an interplanetary disturbance at Earth orbit and corresponding geomagnetic storm. At present for sufficiently large number of individual events predecrease and preincrease of CRs intensity were revealed as precursors of disturbances. It was established that average time between the beginning of preincrease observation and arrival of an shock to Earth orbit according to neutron monitors equals 8 hours [1] and to muon telescopes equals 4 hours [2]. It is known that preincrease of CRs intensity proceeds within several hours before arrival of shock to Earth orbit, reaching a maximum at the moment of arrival (see, for example, [3]).

Anisotropy of CRs intensity arises at interaction of CRs with shock front. For particles moving outside in a direction from front after interaction were possible two variants of their prehistory: 1) the particles had been before shock front and ones reflected from it; 2) the particles had been behind front and ones crossed it.

For a variation of reflected CRs intensity may be written

$$\Delta I_{inc} \equiv (J(p) - J_0(p)/J_0(p) = (p/p_*)^{2+\gamma} - 1, \quad (1)$$

where $J = p^2 f$, f are intensity and distribution function of particles, p (p_*) is particle momentum after (before) interaction with front; $J_0 \sim p^{-\gamma}$ is intensity of the undisturbed galactic CRs; $\gamma = 2.77$ is spectrum index. As appears from relation the reflected particles provide preincrease of CRs intensity since the momentum of reflected particles increases ($p > p_*$) and accordingly $\Delta I_{inc} > 0$.

It is known (see, for example, [4]) that the boundary of disturbed region — Forbush decrease region (Fd) — is transparent for some particles groups (on used terminology — effect of a cone of losses). Probably depending on a phase and a pitch-angle with which particles get on the shock front some particles groups can to escape into interplanetary space, advancing the disturbance, and, on the contrary, to come to Fd region from interplanetary medium. In this case the variation of intensity of CRs left the Fd region — predecrease of CRs intensity — equals to Fd amplitude. Fd amplitude depends on CRs energy. For the dependence account we use Fd spectrum [5]: $\Delta I_{Fd} = A(\varepsilon/10\mathrm{GeV})^{-\delta}$, where A is arbitrary constant; ε is CRs energy; δ is energy spectrum index, depending on turbulence level of solar wind magnetic field. Anisotropy of CRs intensity, arising at their interaction with shock front, on distance of mean free path from front, basically, remains. According to determination of CRs intensity gradients [6] and also to theoretical researches of charged particles propagation in a solar wind with turbulence the CRs mean free path with energies (10 – 30) GeV at vicinity of Earth orbit equals about (0.5-1) AU [7], where AU is astronomical unit. This value of the mean free path denotes that during an order 20 hours before disturbance arrival into the Earth orbit, dynamics of CRs intensity anisotropy may be described by means of calculation of relativistic particles trajectories set in a regular electromagnetic field of a solar wind and disturbance. With the limits of the offered method influence of a turbulent magnetic field on variations of CRs intensity at their propagation from shock front to the Earth orbit can be took account by means of a phenomenological factor: $\exp(-L/\lambda)$, where L is length of a particle trajectory from front to the Earth orbit; λ is mean free path.

The similar model of the description of CRs intensity dynamics — formation of CRs intensity anisotropy as a result of interaction with shock front and subsequent propagation CRs though interplanetary medium — is developed by Ruffolo et al. [8]. Authors assume that effect of a turbulent magnetic field on propagation of CRs is essential. For the decision of the formulated problem they have accepted some simplifications as the dependence of the solution from pith-angle particles only and plane geometry of the shock front. In our opinion, these simplification may to deform the validity.

Our approach is based on the assumption that influence of the scatterings on dynamics of particles on distance smaller than mean free path from shock front is slight. The developed method of relativistic particles trajectories and its application for study of CRs intensity dynamics in the presence of solar wind disturbance is presented in given paper.

II. MODEL

CRs trajectories are the solutions of the relativistic particles movement equations system. The trajectories calculation is

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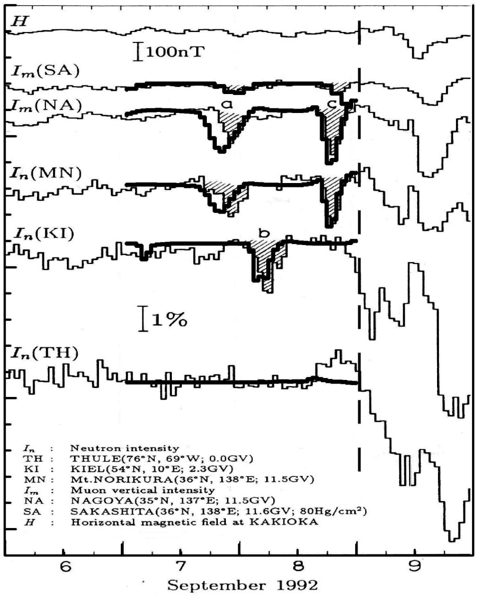

Fig. 1. Observed intensities of CRs by 5th ground-base detectors (thin curves): muon telescopes (I_m) and neutron monitors (I_n). Thick curves — calculation by the trajectories method. Vertical dashed line marks moment of shock arrival to the Earth orbit. The short-time decreases of CRs intensities are produced by interaction particles with shock front.

carried out by Runge-Kutta method of the 4-th accuracy order. A negative step on time is used for calculation of a particle trajectory from a observation point to a source. Magnetic field of quiet solar wind is of Parker type with flow constant velocity being radial and equals to 400 km/s. Electric field of solar wind is defined by condition frozen-in. At calculation of CRs trajectories is taken into account the neutral surface of interplanetary magnetic field dividing regions with different field direction. Configuration of the neutral surface at interplanetary space is determined by boundary position between regions of different polarity on the Sun surface.

At calculations the interplanetary shock has been accepted as a disturbance. Shock front has the form of a revolution ellipsoid $R_S = bR_{S,0}/(1 + (b - 1)\cos\Theta)$, where R_S, $R_{S,0}$ are radii at any point and on axis of disturbance azimuthal symmetry; Θ is polar angle counted from an axis of azimuthal symmetry, orientation of axis relative to heliocentric system of coordinates is defined by 2-th angles; $R_{S,0} = V_S t$; V_S is shock velocity; t is time; b is parameter determining asymmetry of the shock shape. At calculation a particle drift along the shock front electromagnetic field in the region placed behind the front is determined by the Rankine-Hugoniot relations.

At comparison of calculated results with observations it is necessary to consider viewing cone, sensitivity dependence from CRs arrival direction and coupling coefficients of a ground-based detector. The viewing cone is defined by set of CRs trajectories at the Earth magnetic field which connects certain area of magnetosphere surface to the detector. The configuration and arrangement of this area depend on geographical coordinates of the detector, time of day, CRs energy and direction of CRs arrival to the detector. At calculation of CRs trajectories in geomagnetic field is used Tsyganenko model presented by 8-th harmonics for an epoch 2000. Ground-based detectors — neutron monitors and muon telescopes — measure intensity of secondary particles — neutrons and muon accordingly — generating at nuclear interactions primary CRs with atoms of Earth atmosphere. Coupling coefficients consider sensitivity of a detector to various CRs energies.

For a variation of CRs intensity observed by a ground-based detector it is possible to deduce the relation

$$\Delta I = (J - J_0)/J_0 =$$

$$= \int\limits_{\varepsilon}\int\limits_{\Omega} \Delta I_d(\varepsilon, \Theta, \varphi)\cos^{\alpha+1}\Theta \cdot W(\varepsilon) d\Omega d\varepsilon,$$

where J_0 is isotropic intensity of undisturbed galactic CRs; $\Delta I_d(\varepsilon, \Theta, \varphi)$ is model differential variation of CRs intensity; α considers sensitivity of a detector to CRs arrival direction ($\alpha = 6$ in case of a neutron monitor and $\alpha = 2$ in case of a muon telescope); $d\Omega$ is differential of solid angle ($\Omega = 0.27$ is total solid angle in case of a neutron monitor, $\Omega = \pi$ is total solid angle in case of a muon telescope); $W(\varepsilon)$ are normalized coupling coefficients (in case of a neutron monitor they are well-known coefficients of Quenby–Webber and in case of ground-based telescope they are coefficients for muon vertical intensity [9]); $\varepsilon_{\min}$ is cutoff energy caused by the geomagnetic field or a screen over the detector; Θ is angle which is counted from vertical and φ is azimuth angle. As an example of real event we have used observations of event September, 9, 1992 by set of ground-based detectors [10]. We have not found values of solar wind parameters within time of the event in literature. So the values of model parameters have been chosen depending on best agreement between calculation and observations. It was accepted: shock velocity is constant and equals 650 km/s; $b = 0.5$; the axis of azimuthal symmetry of the shock front is at ecliptic plane and is rejected to the east on 10° from line the Sun–Earth; parameters of Fd: $\Delta I_0 = 12\%$, $\delta = 0.6$; the CRs mean free path equals 0.7 AU. It is possible to note weak dependence of calculation results on value of mean free path. It is necessary to notice that presented results have been obtained in the presence of a neutral surface of interplanetary magnetic field which the Earth has crossed during event. Otherwise the calculated amplitudes of serial predecreases of CRs intensity on measurements of the neutron monitor of station Norikura differ in 3 times. The relation of the predecreases amplitudes on measurements muon telescopes of stations Nagoya and Sakashita depends on poorly from presence of a neutral surface. It is explained from the fact that influence of a neutral surface on CRs trajectories decreases at increase of particles energy.

III. RESULTS AND DISCUSSION

Observation of CRs intensity within of event September, 9, 1992 by neutron monitors (I_n) and muon telescopes (I_m) [10] are presented in fig. 1 by thin curves. The moment of shock arrival to Earth orbit is marked by vertical dashed line. The

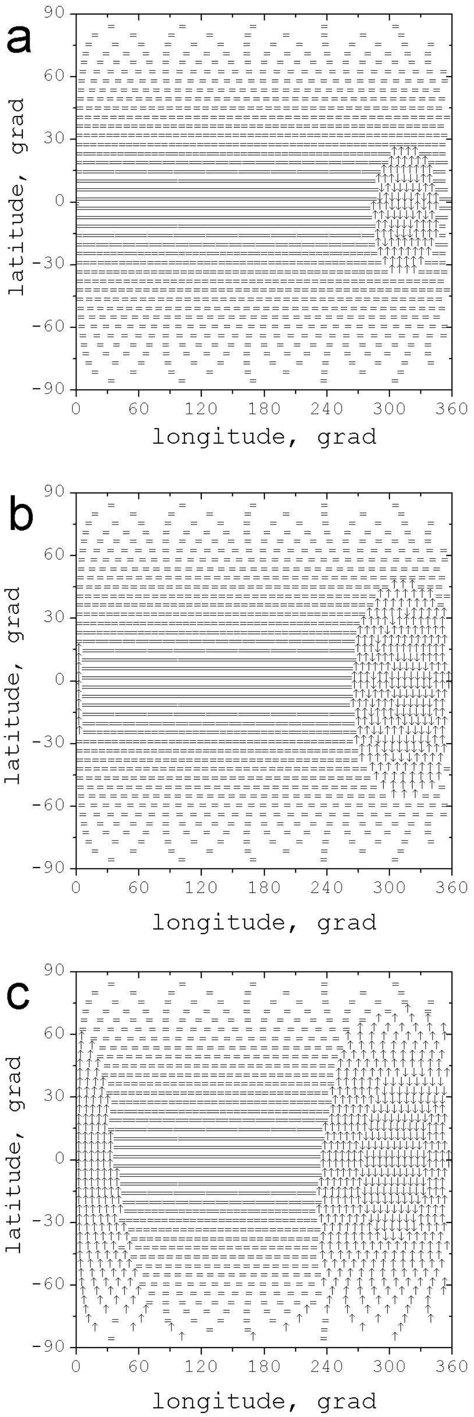

Fig. 2. Distribution of CRs trajectories at the Earth magnetosphere surface at 3-d positions of shock: a) $R_S = 0.5AU$; b) $R_S = 0.7AU$; c) $R_S = 0.9AU$. Used notations are: = – trajectories of undisturbed CRs; ↑ – trajectories of reflected CRs; ↓ – trajectories of escaped CRs;

short-time decreases of intensity are produced by interaction of CRs with shock front. As is seen in fig. 1 calculated results presented by thick curves reproduce observations of all set of CRs intensity both on amplitude and in time quite satisfactory.

It is possible to note one discrepancy: calculated CRs intensity variation on measurements of Thule monitor must absent. Feature of this detector is that it is at high latitude and has a narrow viewing cone. At calculation the disturbed CRs trajectories distribute, as a rule, at low and middle latitudes of the magnetosphere surface. The reason of occurence of CRs intensity preincrease at Thule latitude is not clear now.

We have determined distributions of CRs trajectories at the magnetosphere surface and their change in process of the shock approach to the Earth orbit for various sets of free parameters of the problem. Characteristic distribution for 3-d positions of shock is presented in fig. 2, where "a" corresponds to $R_S = 0.5AU$, "b" – $R_S = 0.7AU$, "c" – $R_S = 0.9AU$. Used notations are: symbols ↑ mark reflected particles; ↓ – escaped particles; = – undisturbed CRs. A point of the Earth magnetosphere surface is defined by two angles relative of GSE coordinate system: latitude is counted from the Earth equator, longitude is counted from X axis.

As is seen in fig. 2 a,b,c: 1) reflected particles trajectories distribute essentially on day-side of the magnetosphere surface that agree with observations (see, for example, [3]); 2) escaped CRs with small pith-angles (latitude $\sim 0^\circ$ and longitude $\sim 315^\circ$)arrive at the beginning of a event. Pitch-angles of arriving CRs trajectories increase at approach of the shock to the Earth orbit, that agree with observations too (see, [4]).

IV. CONCLUSION

The satisfactory consensus of calculated results and observations both set of events and of isolated event testifies to suitability of the method of relativistic particles trajectories for the description of CRs intensity dynamics in the presence of a large-scale disturbance of solar wind and its perspective for the decision of Space weather problems.

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