Calculated dynamics of the cosmic ray intensity pre-decrease in the 9 September 1992 event

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***Abstract*. Dynamics of the galactic cosmic ray intensity caused by their interactions with a shock front in the 9 September 1992 event has been determined by the method of particle trajectories. Corresponding variations of the cosmic ray intensity have been calculated for different stations of the world network of neutron monitors and muon telescopes of stations Nagoya and Sacashita by using viewing cones, sensitivity dependence from cosmic ray arrival direction and coupling coefficients. Comparison calculated results with observational data shows, in general, satisfactory consensus both on amplitude and in time. The method by particle trajectories can be used for investigation dynamics of the solar wind disturbances precursors in the cosmic rays.**

***Keywords*: Forbush decreases, kinetic model, precursors**

I. INTRODUCTION

Studies of cosmic rays (CRs) intensity dynamics at vicinity of interplanetary shock front is of a great interest in connection with the possibility to use the results for arrival prediction of an interplanetary disturbance to the Earth orbit and beginning of corresponding geomagnetic storm. At present for sufficiently large number of individual events predecrease and preincrease of CR intensity were revealed as precursors of disturbances. It was established that average time between the predecrease observation and arrival of the shock to the Earth orbit according to neutron monitors is 4 hours [1] and to muon telescopes is 8 hours [2].

Anisotropy of CR intensity arises at interaction of CRs with shock front. Different methods of forecast are based on the CR anisotropy observation. The common model of the description of CR intensity dynamics — formation of CR intensity anisotropy as a result of its interaction with shock front and subsequent propagation CRs to the Earth determined by kinetic equation of the Fokker–Planck form with pitch angular diffusion — is developed by Ruffolo et al [8].

Anisotropy of CR intensity, arising at their interaction with shock front on distance smaller than mean free path from front, basically, remains. According to determination of CR intensity gradients [6] and also to theoretical researches of charge particle propagation in solar wind with turbulence the CR mean free path with energies (10–30) GeV at vicinity of the Earth orbit is about (0.5–1)AU [7], where AU is astronomical unite. This value of the mean free path denotes that during an order 20 hours before disturbance arrival to the Earth dynamics of CR intensity anisotropy may be described without account scattering of CRs by irregular magnetic field.

Taking into account this simplification we have developed the kinetic model for description of CR dynamics at vicinity of a shock front. In given paper we compare calculated results with observation data of event 9 September 1992 year.

II. MODEL

CR distribution function is solution of Boltzmann equation. Without scattering the distribution function doesn't change along of the equation characteristics being the particle trajectories in the given electromagnetic field. In this case the calculation of the particle trajectory set determines the solution of Boltzmann equation.

At comparison of calculated results with observations it is necessary to take account viewing cone, coupling coefficients of a ground–based detector and angular distribution secondary particles in the Earth atmosphere. The viewing cone is defined by set of CR trajectories at the geomagnetic field which connect a detector with certain area of magnetosphere surface. The configuration and arrangement of this area depend on geographical coordinates of a detector, time of day, season, CR energy and direction of CR arrival to the detector. At computation of CR trajectories at geomagnetic field is used Tsyganenko model presented by 8-th harmonics for an epoch 2000. The trajectory calculations are carried out by Runge–Kutta method of the 4-th accuracy order. A negative step on time is used for computation of particle trajectory from a observation point to the magnetosphere surface.

Coupling coefficients take account of sensitivity of a detector to various CR energies. In case of a neutron monitor they are well–known coefficients of Quenby–Webber and in case of muon telescope they are coefficients for muon vertical intensity [9].

Ground–based detectors — neutron monitors and muon telescopes — record intensity of secondary particles — neutron and muons accordingly — generating at nuclear interactions primary CRs with atoms of the Earth atmosphere. The angular distribution of the secondary particles is defined by $\cos^{\alpha}\Theta$, where $\alpha = 6$ for neutrons and $\alpha = 2$ for muons. Here Θ is angle which is counted from vertical of the detector position.

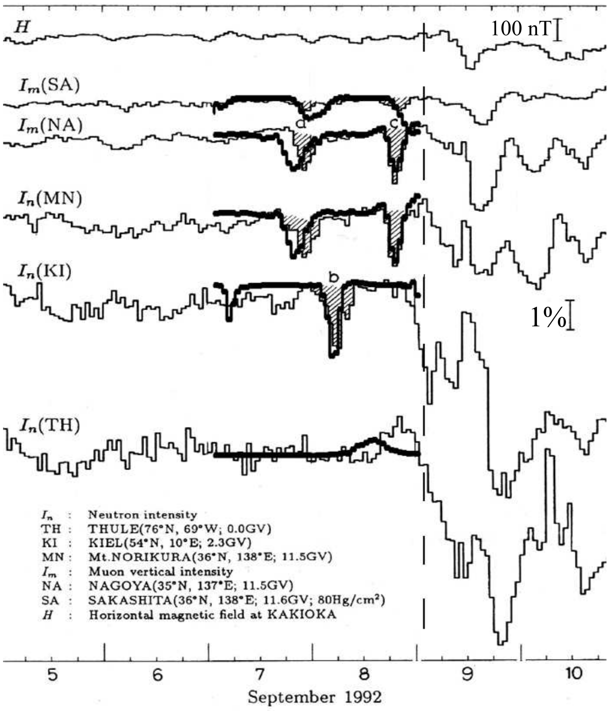

Fig. 1: Observed intensities of CRs by 5th ground-based detectors (thin curves): muon telescopes (I_m) and neutron monitors (I_n). Thick curves — calculated results. Vertical dashed line marks moment of shock arrival to the Earth orbit. The short-time decreases of CR intensities are produced by interaction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

For a variation of CR intensity observed by a ground–level detector it is possible to deduce the relation

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

$$= \frac{\int\limits_{\varepsilon_{min}} \int\limits_{\Omega} \Delta I_d(\varepsilon, \Theta, \phi) \cos^{\alpha+1}\Theta W(\varepsilon) d\varepsilon d\Omega}{\int\limits_{\varepsilon_{min}} \int\limits_{\Omega} \cos^{\alpha+1}\Theta W(\varepsilon) d\varepsilon d\Omega}$$

where J_0 is isotropic intensity of undisturbed galactic CRs; ΔI_d is the model variation of CR intensity; $d\Omega$ is differential of a solid angle; W are coupling coefficients; ε_{min} is cutoff energy caused by the geomagnetic field or a screen over the detector; Θ is vertical angle and ϕ is azimuth one. In case of a neutron monitor Θ is limited by $40°$ and in case of a muon telescope Θ is limited by $60°$. CR computed fluxes equal more than 85% of total fluxes for chosen values of limited angles in consequence of distribution of secondary particles in the Earth atmosphere.

At calculation of CR trajectories at interplanetary medium standard model of solar wind is used. Magnetic field of quiet solar wind is of Parker type with flow constant velocity being radial. Electric field of solar wind is defined by condition frozen–in. In model a neutral surface of interplanetary magnetic field dividing regions with different field direction is taken into account. Configuration of the neutral surface in interplanetary space is determined by the boundary position between regions of different polarity on the Sun surface. The model takes into account that the ecliptic plane is inclined by $7.25°$ relative to the solar equator plane.

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 azimuth symmetry; Θ is polar angle counted from an axis of azimuth symmetry, whose orientation relative to heliocentric equator 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 defining asymmetry of the shock shape.

It is known [4] that the boundary of disturbed region — Forbush decrease region (Fd) — is transparent for some particle groups (on used terminology — effect of a cone of losses). Probably depending on a gyro–phase and a pitch–angle with which particles come to the shock front some particle groups can to escape into interplanetary space, advancing the disturbance, and on the contrary, to come in Fd region from interplanetary medium. In this case the variation of CR intensity left the Fd region — predecrease of CR intensity — equals to Fd amplitude. Fd amplitude depends on CR energy. For the dependence account we use Fd spectrum [5]: $\Delta I_{Fd} = A(\varepsilon/10GeV)^{-\delta}$, where A is constant; ε is CR energy; δ is energy spectrum index, depending on turbulence level of solar wind magnetic field.The variation of CR intensity at trajectories intersected the shock front is defined by the Fd spectrum.

For variation of reflected CR intensity may be written

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

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 undisturbed galactic CRs; $\gamma = 2.77$ is spectrum index. As appears from relation the reflected particles provide preincrease of CR intensity since the momentum of reflected particles increases ($p > p_*$) and accordingly $\Delta I_{inc} > 0$. The variation of CR intensity at trajectories reflected from the shock front is defined by the change of particle momentum. The variation intensity at other CR trajectories is zero.

It is accepted that coefficient of the shock front transparency for CRs — classification of CRs on reflected particles from the shock front or intersected ones the shock front — is defined by result of the particle drift calculation along the shock front. Electromagnetic field in the region placed behind the front is determined by the Rankine–Hugoniot relations.

CR trajectories are the solutions of the relativistic particle movement equation system. They are carried out by Runge–Kutta method of the 4-th accuracy order. A negative step on time is used for computation of a particle trajectory from the magnetosphere surface.

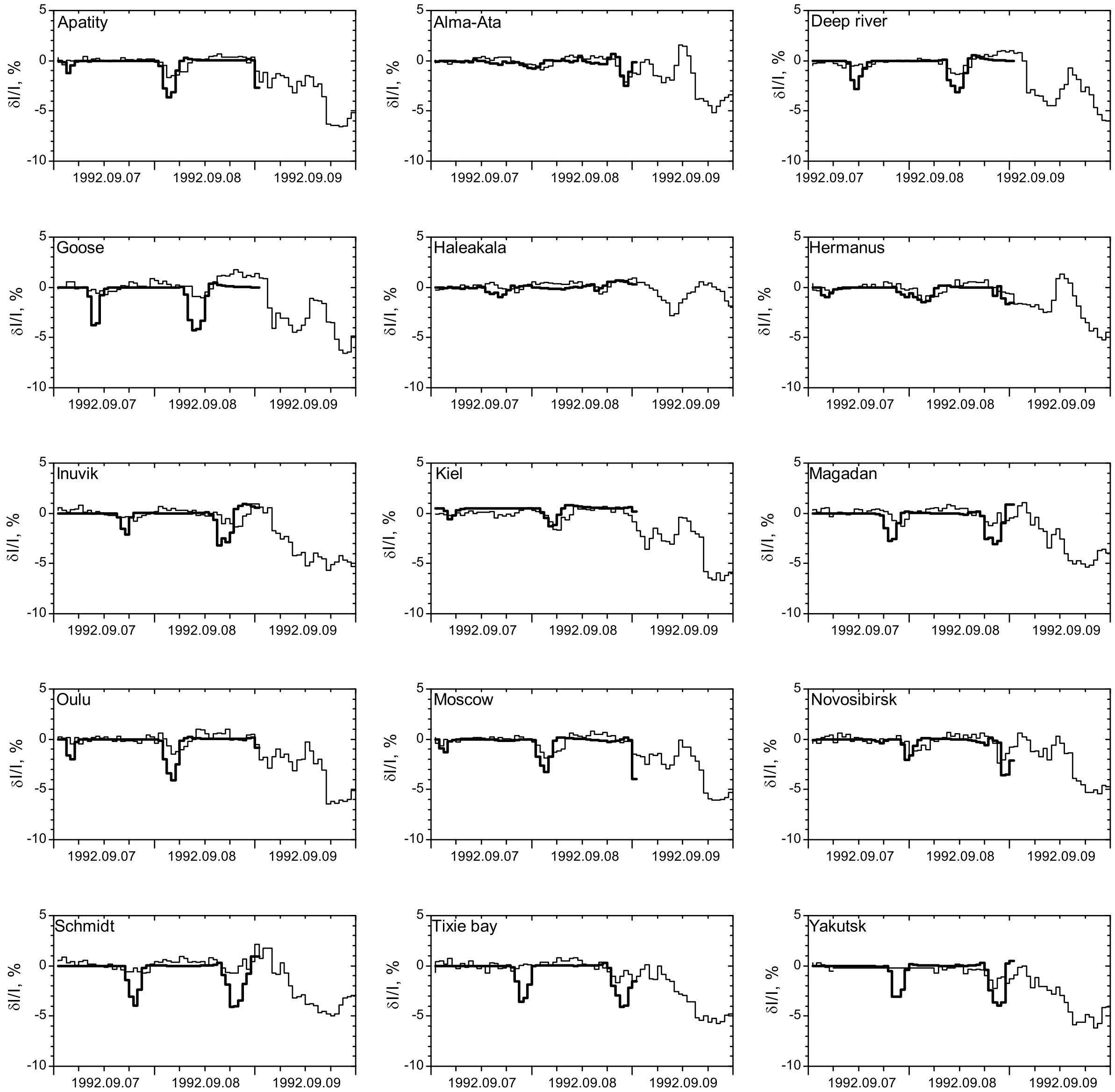

Fig. 2: CR intensity variation in event 9 September, 1992. Thin curves are observed data, thick curves are calculated result..

III. RESULTS AND DISCUSSION

For calculation of CR intensity observed by a ground–based detector one give whole a solid angle of region from which secondary particles arrive to a detector. Directions of arrival to a detector of CRs with different energies are uniformly distributed within the solid angle. CR trajectories are computed from the detector up to the magnetosphere surface in the geomagnetic field. Then CR trajectories are calculated in the interplanetary space. We used following values of solar wind parameters according to 1–hours data of OMNI Database (http://omniweb.gsfc.nasa.gov): $B = 6$ nT is interplanetary magnetic field (IMF) strength at 1 AU; $w = 450$ km/s is quiet solar wind velocity before the shock front; $V_S = 625$ km/s is shock front velocity. At calculation neutral surface of the IMF aren't taken account. We know nothing about shape of the shock front. So we have accepted arbitrarily that the axis of azimuthal symmetry of the shock front is at ecliptic plane and is directed along line the Sun–Earth. For shape of the shock front it is accepted $b = 0.5$. It should be noted that computed results depend on these accepted assumptions amply slightly. As result of calculation CR trajectories are distributed on 3 groups: 1) reflected CRs from the shock front; 2) escaped CRs out of Fd region; 3) all other CRs. Every hour the area of the viewing cone at the magnetosphere surface defined relative to GSE system of coordinates turns due to the Earth rotation. The shock front moves and calculation of the CRs trajectories repeats.

CR intensity variation of 1-st group is defined by value of particle energy change at their interactions with shock front; one of 2-nd group — by Fd spectrum and one of

3-d group equals zero. It is accepted that Fd spectrum doesn't change within the shock travel and $\delta = 0.85$ in accordance with [5].

Fd amplitude has been fitted from comparison calculated Fd amplitudes with maximum values of ones observed by 5-th detectors at period when the Earth was inside the Fd region [4]. As a result it is obtained $A = 6.5\%$.

Computed results and observed data in event 9 September 1992 [10] are presented in fig. 1. The moment of shock arrival to the Earth is marked by vertical dashed line. As is seen in fig. 1 calculated results reproduce data observed by 3-d detectors (Norikura, Nagoya, Kiel) quite well both on amplitude and in time. Agreement between computation and observation by Sakashita muon telescope violates before the moment of shock arrival to the Earth. Calculation doesn't reproduce preincrease of CR intensity observed by Thule neutron monitor before the Fd beginning.

Precursors of the disturbance in event 9 September 1992 have been observed by the world net of the neutron monitors. Results of calculation and observations by 15-th neutron monitors (http://cr0.izmiran.rssi.ru) are presented in fig. 2. As is seen in fig. 2 detectors observed predecrease of CR intensity mainly within 8 September at different moments of the universal time. As is seen from comparison CR intensity decreases observed by different detectors are reproduced by calculation satisfactory well in time. Decreases amplitudes observed by some detectors are distinguished noticeably from calculated ones.

Detection long lasted pre–decrease which was observed by different neutron monitors on September 8 and twice (with one day interval) was observed by Japanese detectors on September 7 and 8 before the Fd on 9 September, 1992 are evidence of the fact, that the CR flux with decreased intensity are strongly localized in space and don't. change for a long time as the disturbance moves. Cross dimension of CR flux is smaller than the magnetosphere surface area.

Possible reasons of results distinction of computations and observations may be: 1) Fd spectrum parameters change at travel of shock front; 2) difference of IMF from Parker type which was appreciable within of event in accordance with data of OMNI Database.

Comparison results of computations and observations allows to formulate 3-e arguments about slight influence of the CR scattering: 1) agreement quality don't depend on time interval between arrival of shock front to the Earth and registration of predecrease; 2) well agreement for repeated predecreases observed by Norikura and Nagoya detectors; 3) at presence of scattering cross dimension of CR flux may be not smaller that the magnetosphere surface area owing to $R/R_m = 50 >> 1$. Here $R = 0.04$ AU is proton Larmor radius with energy $\varepsilon = 10$ GeV at the Earth orbit; $R_m = 20R_E$ is the magnetosphere radius, R_E is the Earth radius.

IV. CONCLUSION

The satisfactory consensus of the calculated results and observations of event 9 September 1992 testifies about adequacy of the developed model of CR intensity dynamics at vicinity of a shock front to real phenomenons. The model could be used for the decision of Space Weather problems.

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