The method of particle trajectories for description of a cosmic ray dynamics

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***Abstract*. The method of particle trajectories has been developed for calculation of the galactic cosmic ray intensity dynamics caused its interactions with front of a interplanetary shock. The method can be used when scatterings of the cosmic rays are weak. The method is based on calculation of a great number of relativistic proton trajectories in a given electromagnetic field of quiet solar wind or solar wind with disturbance. Detection probability of disturbance precursors has been estimated for different conditions. Calculated distribution precursor at the Earth magnetosphere surface and its modification at approach of disturbance to the Earth orbit is agreement, in general, with observational data.**

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

I. Introduction

Study of cosmic ray (CR) intensity dynamics with large-scale disturbance of solar wind is of a great interest in connection with the possibility to use the results for prediction of interplanetary disturbance arrival and beginning of corresponding geomagnetic storm. Investigations carried out according to the muon telescope data, show that 90% of high-power geomagnetic storms caused by solar wind large-scale disturbances, had obvious precursors [5]. It is important in this case that the probability of correct forecasting based on characteristic CR intensity behavior, increases with increasing geomagnetic storm power [2]. At present, the following precursors are revealed for a sufficiently great number of individual events (see, for example [2] and the references there): 1) preincrease of CR intensity, 2) predecrease of CR intensity, 3) change of three-dimensional anisotropy, 4) characteristic dynamics of CR intensity fluctuations.

However the precursors are detected not for all disturbances, and the conditions of the precursor formation are unknown up to now.

To solve this problem one have to develop an adequate physical model describing of CR intensity behavior at vicinity of a disturbance. Ruffolo et al. develop a common model of formation preincrease and predecrease of CR intensity [4]. According to their model CR distribution function is averaged on gyro–phase of particles. So CR anisotropy formed at its interactions with shock front depends on pitch–angle of particles only. Subsequent CR propagation from shock front to the Earth magnetosphere is governed by kinetic equation of the Fokker–Planck type with pitch–angular diffusion. Differences of our model consist in: 1) CR anisotropy forming at its interactions with shock front depends on both pitch–angle and gyro–phase of particles; 2) we suppose, that influence of scattering by irregular magnetic field on particle dynamics at distance smaller than mean free path is slight. So CR propagation at region placed before the shock front is determined mainly by regular electromagnetic field.

A comparison of the observation data with the model calculations will allow to reveal main factors of the CR intensity dynamics induced by a disturbance.

II. Model

CRs registered by ground-based detectors arrive to the Earth magnetosphere surface from different directions. CR travel for the distance of mean free path order is determined mainly by regular electromagnetic field of solar wind both in quiet conditions and with a disturbance. Great numbers of CR trajectories form a region in the Earth orbit vicinity. CR trajectories beginning from the Earth magnetosphere surface are calculated backward relative to time run by means of numerical integration of an equation system of relativistic proton movement.

The method of particle trajectories can be used for description of CR distribution in the interplanetary space with real properties. The presented results illustrating the influence of various factors on CR distribution in the Earth orbit vicinity are obtained within the scope of simplified model. Magnetic field of quiet solar wind is of Parker type, with constant flow velocity being radial and equals to 400 km/s. Electric field of solar wind is defined using a frozen condition. When particle trajectories calculating, a neutral surface of interplanetary magnetic field (IMF) 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. Within the bounds of the model, CR intensity dynamics detected on the Earth with a disturbance is caused by changes of regular electromagnetic field in the region occupied by particle trajectories. The disturbance is given in the shape of an ellipsoid of revolution whose symmetry axis orientation is defined by two angles in the heliocentric coordinate system. CR move velocity is much more than the disturbance propagation velocity.

Therefore the CR distribution is quasistationary, i.e. each own CR trajectory distribution at the Earth magnetosphere surface corresponds to specific position of the shock front. With a disturbance presence, trajectories of CR escaped from the disturbance region or reflected from a shock front appear at the Earth magnetosphere surface. At calculation particle drift at the shock front, electromagnetic field in the region behind the front is determined using the Rankine-Hugoniot relations. The trajectory computation is carried out by the Runge-Kutta method of the 4th accuracy order.

III. Result and Discussion

Variety of CR trajectories arriving to the Earth magnetosphere surface, forms regions of different shape depending on the IMF parameters and on the IMF neutral surface position. As a result of the Earth yearly travel around the Sun, or due to change of IMF neutral surface position in case when it is inclined relative to the solar equator plane, different regions of CR trajectories will be located in the Earth vicinity, and this, in turn, will cause different dynamics of CR distribution function, even though the disturbance is identical.

As a illustration let us determine trajectory region configuration for protons having 10 GeV energy and arriving to the Earth magnetosphere surface from different directions. The Earth magnetosphere is presented as a sphere of $20R_E$ radius (R_E is the radius of the Earth). Under the assumption that momentum of the particles arriving to the sphere surface is antiparallel to the radius, the trajectory on the sphere surface is defined by two angles of spherical coordinate system: Θ $(-90 < \Theta < 90)$ is latitude which is counted from XOY plane, and φ $(-180 < \varphi < 180)$ is longitude angle which is counted from positive direction of X-axis of the GSE coordinate system. The angle values of trajectories are given based on quasiuniform filling of the sphere surface. 5400 trajectories are calculated for each version.

Space distribution of CR trajectories is presented at the heliocentric equator system of coordinate with the center at the Sun. The XOY plane in this system is located in the solar equator plane. Coordinates of the Earth are as follows: $X_E = r_e\sqrt{1-\sin^2\varphi_E\sin^2\alpha_E}$, $Y_E = 0$, $Z_E = -r_e\sin\varphi_E\sin\alpha_E$, where $r_e = 1AU$; $\alpha_E = 7.25°$ is inclination angle of the ecliptic plane relative to the solar equator plane; $\varphi_E = 2\pi(N_d-340)/365$ is an angle taking into account the Earth location during its movement around the Sun. N_d is the ordinal day of year (DOY) number.

Projection of the Earth on the Sun surface intersects equator towards the south semisphere at 340 DOY (6 December). Length of trajectory is limited by the $1AU$ value being equal to an acceptable mean free path [1].

Fig. 1 shows trajectory region projections on coordinate planes of the heliocentric equator system. The results correspond to positive polarity of the solar magnetic dipole moment ($A > 0$ IMF radial component of the north semisphere of the Sun is positive) and location of the IMF neutral surface within the solar equator plane. The forms of region correspond to: a – maximum distance of the Earth northward from the solar equator ($N_d = 249$ DOY, 6 September); b – maximum distance of the Earth southward ($N_d = 65$ DOY, 6 March); c – Earth position coincides with the IMF neutral surface ($N_d = 157$ and 340 DOY, 6 June and 6 December). The projection shapes on the XOY plane are due to spiral configuration of IMF, and they reflect an essential influence of magnetic plugs on particle motion. The region with more powerful magnetic field from which particles are reflected according to the 1-st adiabatic invariant is designated with the ”magnetic plug” term.

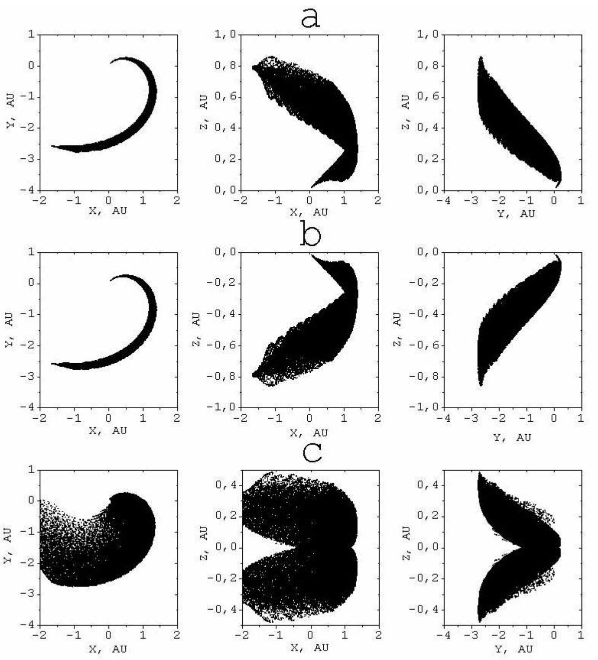

Fig. 1: Projections of CR trajectory region arriving to the Earth magnetosphere surface. Neutral surface of IMF places at the Sun equator plane. Polarity of the solar magnetic dipole moment is positive. Coordinates of the Earth relative to the heliospheric equator system are: panel a — $x = 0.992AU$, $y = 0.$, $z = 0.126AU$; panel b — $x = 0.992AU$, $y = 0.$, $z = -0.126AU$; $x = 1.AU$, $y = 0.$, $z = 0.AU$. — the Earth places at the neutral surface of the IMF.

The region projections on XOZ and YOZ planes at panel a display distinction of proton motion in the IMF: polar angle of a proton radius-vector increases at approach towards the Sun and decreases at travel outward from the Sun in the positive radial component of the IMF. Polar angle is counted from the Sun rotation axis. Characteristic property of the proton motion is converse in the negative radial component of the IMF (see panel b).This explains the mirror symmetry of the projections on XOZ and YOZ planes in the panels a, b. When $A < 0$ the region projections on XOZ and YOZ planes are similar to the ones presented in panels

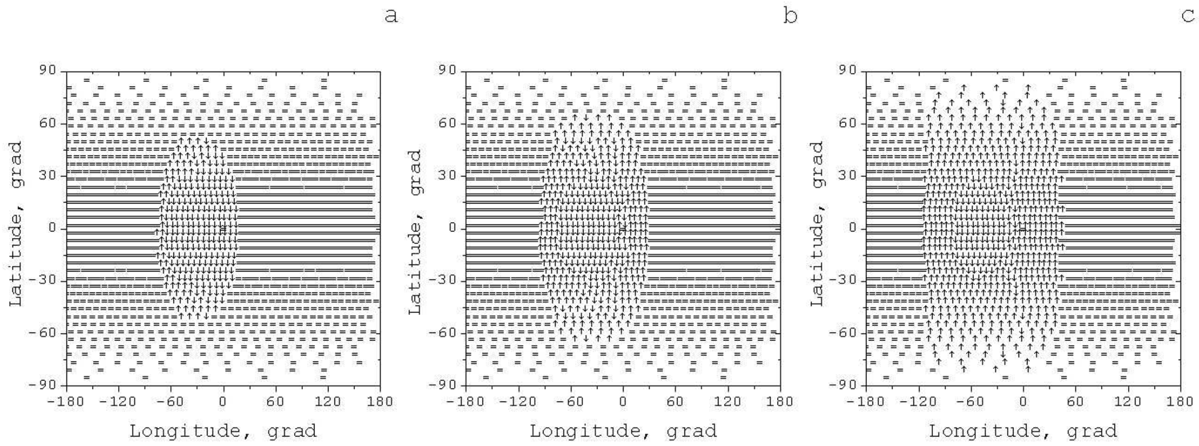

Fig. 2: CR trajectory distribution at the Earth magnetosphere surface for 3-th placements of the shock front: a) $R_S = 0.5AU$; b) $R_S = 0.7AU$; c) $R_S = 0.9AU$. Following denotations are used: $\downarrow$ — are CR trajectories escaped from Forbush–decrease region; $\uparrow$ — are CR trajectories reflected from shock front; $=$ — are all other CR trajectories.

a, b with the difference that the trajectory regions of the $0.3AU$ thickness are located in the neutral surface vicinity. This difference is caused by the fact that in this case CRs detected at the Earth magnetosphere surface cross the neutral surface.

The unique trajectories region appears at $N_d = 157, 340$ DOY and $A < 0$. Under such conditions, the particles move mainly along the neutral surface. As a result, the interplanetary space between the Sun and the Earth are filled by CRs slightly. Dimension of the region projection on Z-axis is of the proton Larmor-radius order.

The neutral surface is a plane at minimum of solar activity. At maximum of solar activity it inclines relative to the solar equator plane. The Earth intersects (twice) the boundary between the regions with different polarity of the IMF. At these moments dimension of the trajectory region essentially increases. Duration of the time interval consists of about 2 – 3 days.

The concept of the trajectory region of CRs arriving to the Earth magnetosphere surface can be used for searching precursors of solar wind large-scale disturbances and for estimation of their detection chance depending on interplanetary space conditions. It is obvious that dynamics of CR intensity detected with ground level detectors can only take place in case when the disturbance intersects the CR trajectory region. From the foregoing results, one can conclude that the best chance to detect a disturbance precursor is during the Earth location near the IMF neutral surface either situated in the solar equator plane at $A > 0$, or inclined relative to the solar equator plane. The least chance to detect a disturbance precursor is during the Earth location beside IMF neutral surface situated in solar equator plane at $A < 0$. At a period when the Earth is located far from the neutral surface, the chance of disturbance CR precursor detection depends on the disturbance angular width. At a small angular width, the precursors of western and central disturbances can be detected with large probability, while the ones of eastern disturbances can be detected just before the disturbance arrival to the Earth orbit. At a large angular width, the precursors can be detected for all the time of the disturbance travel.

Fig. 2 shows dynamics of CR trajectories at the Earth magnetosphere surface for three positions of interplanetary shock wave: $R_S = 0.3AU$; $R_S = 0.6AU$; $R_S = 0.9AU$. The shape of the shock front used in the calculations is as follows: $R_S = bR_{S,0}/(1 + (b - 1)\cos\Theta)$, where R_S is radius of the shock wave; $R_{S,0} = V_S t; V_S = 900$ km/s is shock velocity; t is time; $b = 0.5$ is a parameter defining asymmetry of the shock wave configuration; angle Θ is counted from the axis of disturbance azimuthal symmetry, which is directed along of axis X of the heliocentric coordinate system.

At drawing Fig. 2 the following notations are used: $\downarrow$ — are trajectories of CRs moving from the Sun after their shock front intersection; $\uparrow$ — are CR trajectories traveling from the Sun after their reflection from the shock front; $=$ — are other CR trajectories. The symbols, especially in the vicinity of latitudes $-90°$ and $90°$ are distributed non-uniformly. Visible non-uniformity arises when uniform filling the sphere surface with the symbols is designed on plane. For variation of CRs reflected from the shock front one can set up a ratio $\Delta I = (J - J_0)/J_0 = (p/p_*)^{2+\gamma} - 1$, where $J = p^2 f$ is CR intensity per unit of a solid angle; f is distribution function; $p(p_*)$ is particle momentum after (before) interaction with front; $J_0 \sim p^{-\gamma}$ is intensity of undisturbed CRs; $\gamma = 2.77$ is index of galactic CR spectrum. In consequence with ratio reflected CRs provide preincrease of the intensity, because particle energies increase $(p > p_*)$ when ones reflect from the shock front moving out from the Sun.

As is seen at fig. 2 pre-increase of CR intensity is on the dayside of the Earth magnetosphere surface ($-90^{\circ} < longitude < 30^{\circ}$), that is agreed with observations [3]. Calculated properties of preincrease are following: 1) duration of the phenomenon is about some hours; 2) effect maximum equals some percent and occurs at moment of arrival the shock front to the Earth; 3) amplitude of effect is directly proportional to the shock front velocity and it is reciprocal to the solar wind velocity. Noted results correspond to observations [3].

The CRs intersected the shock front ensure intensity predecrease because their trajectories are connected with the decreased intensity region, namely, with the region of Forbush-decrease. As it can be seen at fig. 2 these CR trajectories have a small pith-angle and they are on the dayside of the Earth magnetosphere surface as it is observed usually [7]. Detection long lasted predecrease which twice (with one day interval) was observed by Japanese detectors on September 7 and 8, 1992 in the morning (4.5 - 7.5 LT) before the Forbush - decrease on September 9, 1992 [6] are evidence of the fact that the CR trajectories for the predecrease are strongly localized in space. They do not change for a long time as the disturbance propagates, which is fully conformed to the model. According to fig. /reffig2 the areas occupied by preincrease and predecrease of CR intensity are overlapped. Extension, mainly, of reflected CR area consists of dynamics of phenomenon.

IV. Conclusion

Calculations within the model have revealed a strong influence of the IMF neutral surface on CR trajectories which (the influence) make difficult to detect the disturbance precursors at some positions of the Earth. The concept of CR trajectory region can be used to estimate the chance to detect disturbance precursors depending on the conditions in interplanetary space. The calculated properties of preincreases and predecreases are in general agreement with the observations.

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