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Dynamics in the arrival directions of galactic cosmic rays in the presence of large-scale solar wind disturbances

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To study the dynamics of the galactic cosmic ray distribution function in arrival directions to the Earth's magnetosphere in the presence of large–scale disturbances, a model has been developed based on the analysis of trajectory set of the relativistic protons in the interplanetary magnetic field with regard for the current sheet. Three types of particle trajectories have been revealed: 1) nonperturbed trajectories which are the trajectories of particles passed by a disturbance; 2) perturbed trajectories which are the trajectories of particles reflected as a result of the drift on the shock front; 3) trajectories of the particles associated with the disturbed region itself.

1. Introduction

Investigations of dynamics of cosmic ray (CR) intensity in the presence of large–scale disturbances of the solar wind is of considerable interest in connection with an opportunity to use results for forecasting of disturbance occurrence. The carried out investigations show that about 90% of major geomagnetic storms caused by large–scale solar wind disturbances, have clear precursor effects which can be used for forecasting [1]. It is important that propriety forecasting based on the characteristic behavior of CR intensity increases with increasing of the power geomagnetic storm [2]. Now for sufficiently large number of individual events the following precursor effects (see for example [2] and references therein) have been revealed: 1) CR pre–increase of intensity; 2) CR pre–decrease of intensity; 3) changes in 3–D anisotropy. The real method of forecasting with a sufficient propriety can be based on the adequate physical model describing the behavior of CR intensity in the presence of disturbance. The variant of model, in which the realistic spectrum of interplanetary magnetic field turbulence is taken into account, and practically real properties of the solar wind and disturbance are not taken into account, is developed by Ruffolo, etc. (see [3] and references therein). We offer the alternative variant of model in which real properties of the solar wind and disturbance are taken into account, and CR scatterings are completely ignored.

2. Model

The model is based on the analysis of set of CR trajectories coming to the Earth's magnetosphere from various directions. The Earth's magnetosphere is assumed as a sphere of radius $10R_E$, on its surface two angles define the direction of CR arrival: α is counted from an axis X; β – from YOX plane of the GSE coordinate system, where R_E is the radius of the Earth. CR trajectories in the interplanetary space are determined by a numerical integration back in time of the equations of relativistic proton motion with various energies in the given electromagnetic field of the quiet solar wind, and also in the presence of disturbance. The solar wind magnetic field is a Parker one, the speed of flow is constant, radial and equals to 400 km/s. The solar wind electric field is defined by a frozen–in condition. In the model the current sheet is taken into account which in the presented illustrative results is accepted as a plane lying in the solar equator plane. It is taken into account that the obliquity of the ecliptic is $7.25°$ relative to the solar equator plane. In calculations the disturbance is defined as a shock wave having a form of rotation paraboloid, the orientation of axis of symmetry of it is defined by two angles in the heliocentric coordinate system. The distribution of CR in the vicinity of the Earth

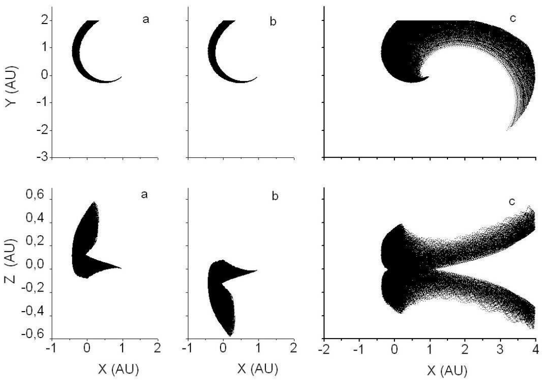

Figure 1. The projections of volume, occupied by CR trajectories coming to the Earth's magnetosphere from different directions, on the YOX plane (top pannels) and the ZOX plane (bottom pannels) of the GSE coordinate sysnem for $A > 0$ magnetic cycle of the Sun. Coordinates of the Earth are $(0, 0, 0)$, coordinates of the Sun are $(1, 0, 0.)$. Fig.1a – position of the Earth is the maximum northward removal with respect to the solar equator plane; Fig.1b – the same the Fig.1a but of southward removal; Fig.1c – the position of the Earth is in plane of solar equator.

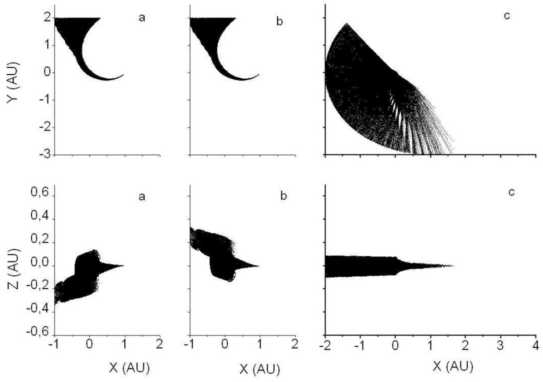

Figure 2. The same as in Fig.1. but the case for $A < 0$ magnetic cycles of the Sun.

is determined for several positions of the disturbance in the interplanetary space. CR, falling on the shock front from the region before the disturbance, either are reflected or penetrated into the region of disturbance. The electromagnetic field of internal volume of disturbance used for the calculation of particle drift on shock front is defined by Rankine-Hugoniot conditions.

3. Results and discussion

The trajectory projections of CR with energy 10 GeV coming to the Earth's magnetosphere from different directions on the YOX plane (top panels) and ZOX plane (bottom ones) of the GSE coordinate system are presented in Figure 1 and Figure 2. The direction of particle arrival is defined by two angles whose values are chosen reasoning from the quasi–even distribution on a sphere surface. About 5500 trajectories have been determined for each variant. The results of presented in Figure 1 and Figure 2 correspond to $A > 0$ and $A < 0$ magnetic cycles of the Sun at which IMF field lines in the northern hemisphere are directed from the Sun or to the Sun, respectively. Letter designations in Figures correspond to different positions of the Earth relative the solar equator plane: Figure 1a and Figure 2a are the maximum northward removal; Figure 1b and Figure 2b are a maximum southward removal; Figure 1c and Figure 2c are a solar equator plane. As is seen from Figure 1a,b and Figure 2a,b CR arriving to the Earth's magnetosphere from different directions during these time moments occupy the volume in the interplanetary space whose projection on the YOX plane corresponds to the magnetic tube. The form of volume reflects the resulting CR movement in the IMF: CR arrive from outside of the Earth's orbit and come back after the reflection from a magnetic plug remaining in the same magnetic tube. The resulting movement of CR depends on the IMF direction: the relativistic protons moving to the Sun are also shifted towards the South Pole of the Sun and the same ones moving from the Sun are shifted towards the North Pole of the Sun in the IMF whose lines are directed from the Sun. Resulting movement of CR reverse in the IMF with an opposite direction. At $A > 0$ the projection of volume on the ZOX plane (the bottom panels Figure 1a,b) is caused by the touching (weak) effect of the current sheet located at $Z = 0$ on the shift of proton trajectories. The current sheet has a stronger effect on the shift of CR trajectories at the sign change of the solar magnetic cycle ($A < 0$) because in this case protons cross the current sheet completely (compare in Figure 1a,b and Figure 2a,b respectively). The strongest effect of the current sheet on the shift of CR trajectories at those moments of time when the Earth is near it (Figure 1c and Figure 2c). At $A > 0$ the projection of volume occupied by CR on the YOX plane is a tube as before, but of significantly larger sizes, and the projection on the ZOX plane consists of two parts located specularly relative to the current sheet (Figure 1c). In this case the protons come to the solar equator plane along the bottom part and they come back along the top one. At $A < 0$ CR mainly drift along the current sheet and as a result of this fact there are comparatively only a few CR between the Earth's orbit and the Sun. The volume occupied by CR has a little size (of the order of Larmor radius of a proton) along the Z axis (see Figure 2c). It is obviously that dynamics of CR intensity anisotropy can occur only in that case when a disturbance crosses the volume occupied by CR. From the results presented in Figure 1 and Figure 2 one can conclude that the most chances of registration of a disturbance precursor are realized during the location of the Earth near the current sheet lying in the solar equator plane at $A > 0$ magnetic cycle of the Sun. The least chances are realized at the same time at $A < 0$. The probability of registration of a disturbance precursor depends on the angular width of disturbance when the location of the Earth is far from the current sheet: a precursor of western disturbances can be registered in a high advance at a small angular width; a precursor of central and east disturbances practically can be registered just before the arrival of disturbance to the Earth's orbit; at a large angular width a precursor will be registered during the whole time of the movement of disturbance. CR trajectories — protons with energy 10 GeV — on the sphere of directions of their arrival to the Earth's magnetosphere are presented in Figure 3a,b,c for three positions of central disturbance in the interplanetary space: Figure 3a corresponds to $R_S = 0.1$ AU; Figure 3b – $R_S = 0.5$ AU; Figure 3c – $R_S = 0.9$ AU. It is accepted that each part of shock front moves with a constant radial velocity and equals to 1000 km/s. The relation of longitudinal size of the disturbance to the transversal one is accepted as 2 : 1. The following designations are used in the design of Figure: the empty area is occupied by CR trajectories going to the Sun from the external region relative to the Earth's orbit; the area marked by round dark blue symbols is occupied by CR trajectories going from the Sun and reflected from the magnetic plug; the area marked by red crosses is occupied by CR trajectories going from the Sun and reflected from the disturbance shock front; the area marked by black triangles is occupied by CR trajectories going from the Sun and coming from the internal region of the disturbance after crossing of the shock front. As is seen from Figure 3 the dynamics of CR trajectories marked on the sphere of directions of the arrival consists in a general expansion of the areas occupied by CR reflected from the shock front and coming from the region behind a front. CR whose arrival directions belong to the empty region and the region marked by dark blue points are not connected with a disturbance. CR whose arrival directions belong to the region marked by red crosses provide the CR pre–increase because protons increase their energy and correspondently increase their amplitude of the intensity when ones are reflected from the shock front moved in the opposite direction. CR whose arrival directions belong to the region marked by black triangles provide the CR pre–decrease because their trajectories are connected with the region of decreased intensity of CR — the Forbush–decrease region. One should note that as is seen from Figure 1a,b,c the CR pre–decrease and CR pre–increase firstly are formed on the arrival directions of CR having small pitch angles ($\alpha = \pi/4, \beta = \pi$), then this phenomenon is extended to CR with large pitch angles as it is usually observed (see, for example, [4]). Nagashima et al. [5] explain the observing collimation of CR flux responsible for the CR pre–decrease with a large difference between strengths of magnetic fields in the regions inside and outside of the disturbance only. According to the model, additional collimation of CR flux takes place as the flux propagates in the inhomogeneous IMF from the disturbance up to the Earth's orbit. Besides that, according to measurements, the area occupied by CR pre–increase before the disturbance arrival has large angular sizes that is well corresponded to the model.

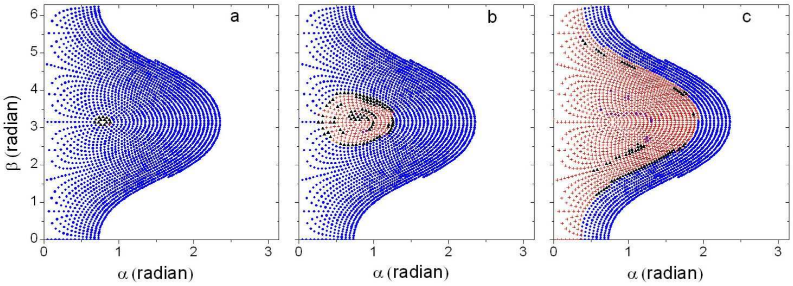

Figure 3. Directions of arrival CR to the Earth's magnetosphere for 3 positions of the central disturbance : Fig. 3a corresponds to $R_S = 0.1$ AU; a Fig. 3b – $R_S = 0.5$ AU; a Fig. 3c – $R_S = 0.9$ AU.

4. Conclusions

The validity of CR trajectory model for the description of CR intensity anisotropy dynamics in the presence of large–scale solar wind disturbance can be caused by the fact that the distance between the disturbance — the source of formation of anisotropy — and the Earth's orbit — the place of its registration— less than free path length of relativistic protons before scattering. We have determined the form of volume occupied by CR arriving to the Earth's magnetosphere from different directions, for different positions of the Earth and for different magnetic cycles of the Sun. The CR trajectories are subdivided into three types on the sphere of directions of their arrival to the Earth's magnetosphere in the presence of solar wind disturbance: 1) CR trajectories going to the Sun from external region with respect to the Earth's orbit and going from the Sun after their reflection from a magnetic plug; 2) CR trajectories going from the Sun after their reflection from moving shock front of disturbance; 3) CR trajectories going from the Sun after their going out of internal region of the disturbance and crossing of shock front. The CR trajectories of 1-st type are not connected with the disturbance; the trajectories of 2-nd type provide the CR pre–increase and the trajectories of 3-rd type provide the CR pre–decrease. The dynamics of CR intensity of anisotropy caused by the movement of disturbance consists in the change of configuration of areas on the sphere of directions of arrival to the Earth's magnetosphere. Pitch angles of CR whose trajectories relating to the 2-nd and 3-rd types grow in the process of movement of the disturbance that is explained by the fulfillment of the 1-st adiabatic invariant.

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