

Numerical modelling of cosmic ray penetration into disturbed magnetosphere of the Earth

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Abstract. In frame of geomagnetic field model, described by the sum of fields of internal (IGRF) and external (Tsyganenko model) sources, the simulation of physical conditions of cosmic ray penetration from the interplanetary space into the magnetosphere of the Earth was carried out. Variations of geomagnetic cutoff rigidity, caused by solar flares, were numerically studied. Analysis of a change of solar particle observation conditions for experiments on the satellites located in the near-Earth orbits was fulfilled for a number of real solar-magnetospheric events. In particular, cutoff rigidity variations along the Mir station orbit during several powerful solar flares in 1991 were calculated. It was shown the sharp (about several times) decreases of cutoff rigidities for the high-litudinal sites of Mir station orbit. Comparison of the results of modelling of cutoff rigidity (energy) variations along the orbit with experimental data on solar proton observation in the near-Earth space, obtained in Mariya-2 experiment on board the Mir station, was carried out. There is a good agreement between modelling and experimental results.

1. Introduction

An effects, connected with penetration of solar cosmic rays deep into the magnetosphere of the Earth under strong geomagnetic disturbance conditions, were observed in a number of high-energy charged particle flux measurements, carried out on board the satellites, situated in the low-altitude orbits (Voronov et al., 1995; Shurshakov et al., 1993; Leske et al., 1997; and references therein).

It was supposed that solar cosmic rays can directly penetrate into the deep layers of the magnetosphere as a result of significant decreasing the cutoff rigidities, and thus particle fluxes in these zones can increase.

Some other mechanisms, in particular, mechanisms, based on the diffusion of solar cosmic rays from interplanetary

space into magnetosphere of the Earth or even on acceleration of the particles in the magnetosphere up to such high energies, were considered also.

However concrete mechanisms, resulting in sharp increasing the fluxes of high-energy charged particles with rigidities less than cutoff rigidities for given regions of the near-Earth space, were insufficiently studied until now.

Analysis of solar proton energy spectra (with energies about 10 - 100 MeV), observed at the same time on the various spacecrafts, was carried out in (Voronov et al., 1995). Spacecrafts GOES-7 and Meteor-3 were located out of range of the magnetosphere and orbital station Mir was situated deep in the magnetosphere (L=4-5) during the observation of solar protons. Conclusion about the possibility of direct penetration of observed particles from the interplanetary space into the deep zone of the magnetosphere in this solar-magnetospheric event was drawn in terms of coincidence of proton energy spectra outside and inside the magnetosphere. That is, significant decrease of cutoff rigidity could be taken place in the disturbed magnetosphere of the Earth. Similar conclusion was also done in a number of other works (e.g., Leske et al., 1997) on the basis of analysis on observation of solar particles with rigidities less than geomagnetic cutoff rigidity during the magnetospheric storms, induced by solar flares.

Of course, for strong evidence of this conclusion it is insufficient to have only experimental facts presented above.

In present work method for quantitative analysis of solar particle observation conditions in the experiments in near-Earth orbits during the solar-magnetospheric events is described. This method is based on the numerical modelling of high-energy charged particle trajectories in the disturbed geomagnetic field.

2. Numerical modelling method

Method, used in this work for modelling of processes of

charged particle penetration from the interplanetary space deep into Earth's magnetosphere, is based on the trajectory particle simulation.

Particle trajectory simulation in the magnetosphere as a software tool is well known and developed for along time. It was widely used for calculations of cutoff rigidities of different ground stations, and global cutoff rigidity distribution maps were plotted (e.g., Dorman, Smirnov & Tyasto, 1971).

The essence of trajectory calculations is the following. Motion equations of charged particle in the geomagnetic field are integrated, and thus, the trajectory of each particle can be calculated in space step by step (Dorman, Smirnov & Tyasto, 1971). Analyzing the behavior of the particle, for example, depending on its rigidity, it is possible to evaluate cutoff rigidity for given region on the ground or in the near-Earth space.

The accuracy of such analysis is defined by the accuracy of the using model of geomagnetic field and by the accuracy of using mathematical algorithms.

In present work numerical modelling of charged particle penetration from the interplanetary space into Earth's magnetosphere and calculation of cutoff rigidity under conditions of magnetosphere disturbed strongly by powerful solar flares were carried out.

Simulation method is based on the particle trajectory calculations.

Quantitative geomagnetic field model – Tsyganenko model (T96) was used. This model describes the typical features of the magnetosphere: magnetopause, geomagnetic tail, polar casps, neutral layer and others. External parameters of Tsyganenko model are the real physical characteristics of the near-Earth space as a medium, in which particles propagate, – speed and density of solar wind (or its dynamical pressure), B_y and B_z components of interplanetary magnetic field, magnetospheric Dst-index.

Charged particles with enough high energy can penetrate from interplanetary space deep into the magnetosphere of the Earth, interacting with geomagnetic field, having such configuration.

Behavior in time of physical factors, affecting on the geomagnetic field, such as solar wind characteristics, interplanetary magnetic field, geomagnetic activity index, result in the change of the configuration of geomagnetic force lines in time. This, in one's turn, result in the variations of cutoff rigidities and changing of conditions for charged particle penetration from interplanetary space into the magnetosphere.

Another circumstance, which also should be taken into account for interpretation of solar particle observation data obtained in the near-Earth orbit satellite experiments, is concerned with movement of themselves spacecrafts. In that case cutoff rigidity, determining the particle observation, can sharply change (in dozens of times) during the several minutes because of movement of spacecraft in space even for stationary (undisturbed) geomagnetic field. This become apparent very strong especially in high latitudinal regions of orbit.

Circumstances mentioned above – variations of physical

factors, disturbing geomagnetic field configuration, and displacement of spacecraft in geomagnetic field have been taken into account under modelling of physical conditions of solar particle observation by satellite experiments in the magnetosphere of the Earth.

Simulation was fulfilled by the following way. Inclination and altitude as spacecraft orbit parameters were given. Spacecraft was located in the given orbit and moved along the orbit step by step. Knowing the spacecraft position coordinates (altitude, longitude and latitude), cutoff rigidity was evaluated with trajectory calculation technique at every step. In these evaluations geomagnetic field configuration was given by values of parameters of solar wind, interplanetary magnetic field and Dst-index taken in current time.

Using this method, modelling of charged particle penetration from interplanetary space into different regions of the Earth's magnetosphere was carried out under different conditions of geomagnetic field disturbances.

3. Results of modelling and comparison with experimental data

To estimate the efficiency of use of the method described above to analysis of real solar-magnetosphere events, the fluxes of solar protons observed in Mariya-2 experiment on board the Mir orbital station on 31 October 1991 were considered.

Powerful solar flare, accompanied generation of protons with energies up to hundreds of MeV, occurred on 30 October 1991. The fluxes of these protons were observed in the vicinity of the Earth by different spacecrafts. As it was pointed out (Voronov et al., 1995), the appearance of solar protons in orbit of Mir station could be connected with significant decreasing of cutoff rigidity in disturbed magnetosphere. In Table 1 data on proton observation in Mariya-2 experiment on 31 October 1991 is presented (Voronov et al., 1995).

Table 1. Conditions of proton flux observation in Mariya-2 experiment on board Mir station on 31 October 1991.

	1-t zone	2-d zone	3-d zone
Time (Moscow), h., m.	4.27-4.37	5.13-5.23	11.28-11.38
Longitude, deg.	155	320	270
Latitude, deg.	-51	51	51
L	4.4	3.4	4.6
B, gauss	0.53	0.43	0.49
Side of orbit	day	night	night
Intensity, (cm ² s sr) ⁻¹	0.03±0.02	0.05±0.03	1.22±0.02
Intensity under quiet geomagnetic conditions: 0.035±0.005 (cm ² s sr) ⁻¹			

One can see from this table, measurements were carried out in three high-latitudinal zones in different times on this day. Significantly increased proton fluxes were observed only in third zone and unobserved in first and second zones, although the L-shells and correspondingly cutoff rigidities

under quiet geomagnetic conditions have been practically the same for all three zones.

In Figure 1 sites of Mir station orbit, in which measurements with Mariya-2 experiment were carried out, were presented. For these sites calculations of cutoff rigidity variations along the orbit were fulfilled by the method described above.

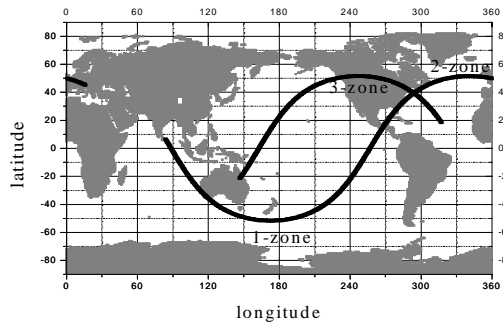


Fig.1. Sites of Mir station orbit in which experiment Mariya-2 was carried out on 31 October 1991.

For evaluation of geomagnetic field configuration it was used experimental information about speed and density of solar wind plasma, B_y and B_z components of interplanetary magnetic field, Dst-index. This information was obtained on the basis of various satellite measurements and is presented by National Space Science Data Center of NASA (<http://nssdc.gsfc.nasa.gov/omniweb/form/dx1.html>). We chose the data corresponded to time of measurements with Mariya-2 instrument on Mir station.

In Figure 2 calculated variation of geomagnetic cutoff energy (for the convenience of comparison with experimental data we used here energy instead of rigidity) along the Mir station orbit for 3-d zone is shown.

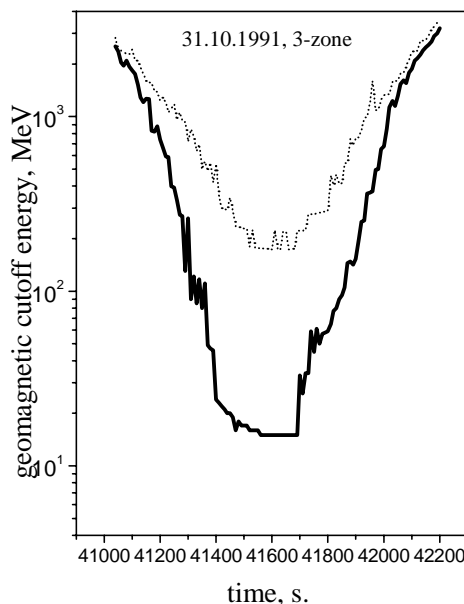


Fig.2. Geomagnetic cutoff energy along the Mir station orbit for 3-d zone (solid line under real conditions, dashed line under quiet conditions).

As it was pointed out, solar protons were observed in this zone. Also geomagnetic cutoff energy for quiet conditions was presented in this figure. Proton energy range for Mariya-2 instrument is 35-110 MeV (Voronov et al., 1991). These energies are much less than geomagnetic cutoff value. That is, protons with such energies can not penetrate from interplanetary space into this region of the near-Earth space in quiet magnetosphere.

Situation considerably changed on 31 October 1991. One can see from Figure 2, that cutoff energy decreased in several times in this region and reach the value about 20 MeV in minimum of 3-d zone. It means that this region of the near-Earth space become opened for penetration of protons with energies more than 20 MeV from interplanetary space under conditions of strong disturbance. It should be noted that minor and fast jitter of lines in this figure reflects the influence of penumbra effect.

In Figure 3 counting rate of protons (35-110 MeV) observed by Mariya-2 instrument on 31 October 1991 along the orbit in the vicinity of third zone is presented. Sharp increase of proton flux in time interval 11h.26m.–11h.31m. is evident from this figure.

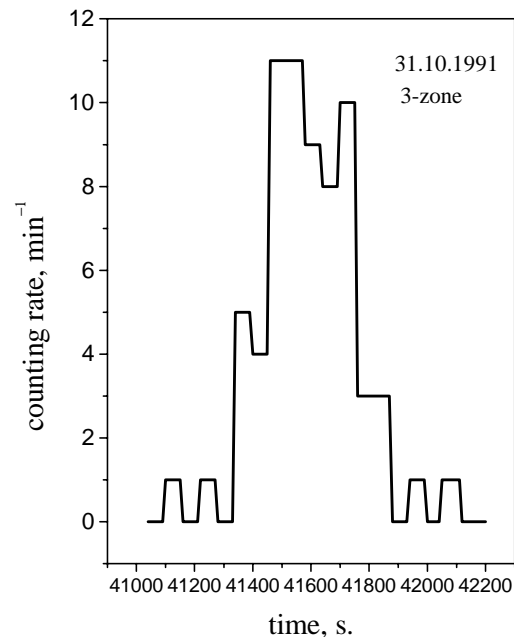


Fig.3. Counting rate of protons (35-110 MeV) observed by Mariya-2 instrument on 31 October 1991 along the Mir station orbit for 3-d zone.

Comparison of Figure 2 and 3 shows that protons were observed in that site of Mir station orbit, for which modelling cutoff energy less than 100 MeV. This result unambiguously gives the evidence of direct penetration of such protons from the interplanetary space into the Earth's magnetosphere owing to sharp decrease of cutoff rigidity in

strongly disturbed magnetosphere.

In Figure 4 cutoff energy along the Mir station orbit is presented for 1-st zone. Symbols in this figure are the same as for Figure 2.

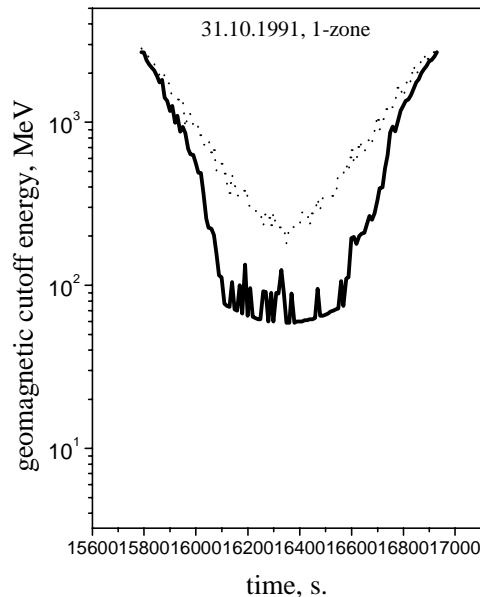


Fig.4. Geomagnetic Cutoff energy along the Mir station orbit for 1-d zone (solid line under real conditions, dashed line under quiet conditions).

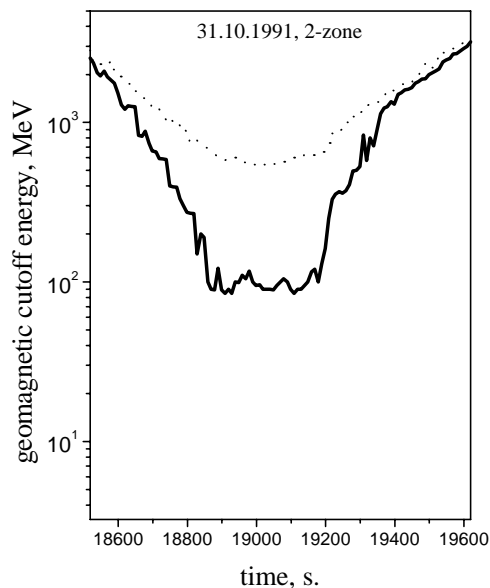


Fig.5. Geomagnetic cutoff energy along the Mir station orbit for 2-d zone (solid line under real conditions, dashed line under quiet conditions).

Also one can see the significant decrease of cutoff energy on 31 October 1991 in comparison with quiet geomagnetic conditions. However, cutoff energy decreased only to the

value of about 70-80 MeV in this zone. And so, the 1-st zone has been opened only for protons with energies more than about 70-80 MeV. If to take into account steep energy spectrum of observed solar protons in this event (power law index is about $-3,7$) (Voronov et al., 1995), then expected flux of solar protons with energies more than 70-80 MeV will be about $0.02 \text{ (cm}^2 \text{ s sr)}^{-1}$. This flux is less than the background (albedo) proton flux, observed under quiet geomagnetic conditions.

In Figure 5 cutoff energy along the orbit is presented for 2-d zone, for which solar protons were also lacking. As one can see from this figure the conditions of particle observation for second and for first zones was practically the same.

4. Conclusion

Results, presented in this work, show the efficiency of considered modelling method, based on the trajectory calculations in disturbed magnetosphere, for interpretation of experimental data on observation of solar-magnetosphere events on board the satellites.

Quantitative analysis, carried out in this work, demonstrated that significant decrease of geomagnetic cutoff rigidity takes place in disturbed magnetosphere. This can explain results of satellite experiments on observation of solar cosmic rays in the magnetosphere.

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