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Anomalous behavior of cutoff rigidity variation in the region of the Mexico station during a magnetic superstorm on 20 November 2003

V. V. Pchelkin, E. V. Pchelkina, and I. V. Golovchanskaya

Polar Geophysical Institute RAS, Fersman Str. 14, Apatity, Murmansk region, 184200, Russia

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Abstract. The pioneering storm-time model of magnetospheric magnetic field T01S made possible trajectory calculations for the events of giant magnetic storms. We have performed such calculations for a unique magnetic storm on 20 November 2003. In our previous paper, Belov et al. (2005), dedicated to the magnetospheric effects of cosmic rays (CR) during this storm, we revealed an anomalous behavior of a cutoff rigidity variation at the Mexico station. Here, by trajectory calculations, we demonstrate that this peculiarity persists in the latitudinal and longitudinal curves of cutoff rigidity (Rc) for both quiet and storm-time conditions and thus should be considered as physically meaningful.

Keywords. Interplanetary physics (Cosmic rays) – Magnetospheric physics (Current systems; Storms and substorms)

1 Introduction

Extremely high solar and geomagnetic activity persisted in October–November 2003. The event of 20 November 2003, observed in CR, was preceded by a series of solar flares of class M, which occurred on 17–18 November 2003, that initiated the strongest magnetic storm in a series of magnetic storms throughout this period (Belov et al., 2005; Vashenyuk et al., 2005; Dvornikov et al., 2003). After the arrival of a shock wave, the Earth entered an extended magnetic cloud, where the intensity of the interplanetary magnetic field (IMF) was as large as 60 nT, with the B_z IMF being −45 nT. The variations of D_{st}, as well as of the solar wind dynamic pressure and B_z IMF by the ACE satellite observations, are presented in Fig. 1, taken from the paper of Solovyev et al. (2005). In this event, the D_{st} index reached −465 nT at minimum (the K_p index was equal to 9). According to the NOAA classification, this magnetic storm belongs to the class G4–G5 (an extremely strong one), as indicated by the K_p index and to the class r (a giant one), as classified by D_{st}. The auroras were observed in the south of Europe and at mid-latitudes, indicating a strong equatorward shift of the auroral oval (Belov et al., 2005).

Correspondence to: V. V. Pchelkin
(pchelkin@pgi.kolasc.net.ru)

Belov et al. (2005) applied the global survey method to the data of the worldwide neutron monitor network and obtained the latitudinal distributions of changes in magnetic cutoff rigidities at different stages of the storm considered. Hourly data from 39 neutron monitors of the worldwide network have been employed in the detailed analysis. There were 15 high-latitude monitors, 22 middle- and low-latitude ones, and 2 sub-equatorial monitors.

The results enabled one to follow the dynamics of magnetospheric storm-time currents. A remarkable feature of this magnetic storm was that the maximal magnetospheric effect was observed not at mid-latitude stations (the cutoff rigidities of 3–4 GV), as usual, but at low-latitude ones (the cutoff rigidities of 7–8 GV). Another feature of this event was a weak response in monitor count rates during the sudden commence (SC) of the magnetic storm, while the response in CR was significant at the main phase of the storm. The shift of the region of maximal magnetospheric effect in the CR to lower latitudes in the case of a superstorm was related by Belov et al. (2005) to the near approach to the Earth of the magnetospheric ring current and cross-tail current, reaching the geocentric distance of 3 R_E (for the cutoff rigidity of 3–5 GV, this distance is ∼5 R_E). The model of Tsyganenko T01S (2002) was used to calculate the magnetospheric current systems. The applicability of the existing magnetic field models for calculation of magnetospheric currents under different levels of geomagnetic activity has been considered by Tsyganenko (2002), Tsyganenko et al. (2003), Alexeev et al. (2001, 2003), Maltsev and Ostapenko (2001, 2004).

In the present brief report we have revealed the anomalous behavior of the cutoff rigidity variations in the region of the Mexico station (coordinates of the Mexico station are 19.33

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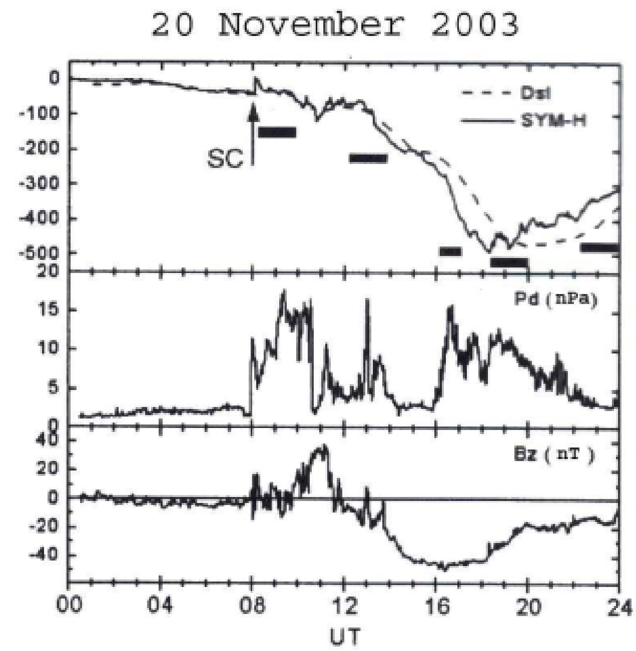

Fig. 1. Variations of the D_{st} and SYM-H indices (in nT), solar wind dynamic pressure Pd (in nPa), and B_z IMF component (in nT) in the course of magnetic storm on 20 November 2003.

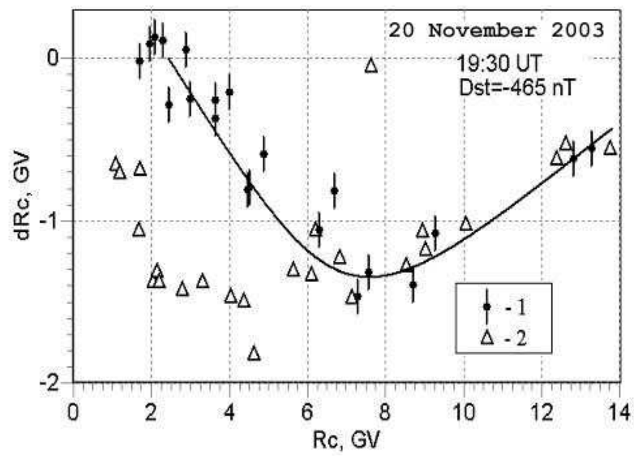

Fig. 2. Cutoff rigidity variation (dRc) vs. the cutoff rigidity (Rc) at the peak of magnetic storm on 20 November 2003. Dots (1) indicate the points with error limits obtained by the global survey method applied to the data of the worldwide neutron monitor network. Triangles (2) mark the results of CR trajectory calculations using the T01S model. Note the deviation of the point for the Mexico station from the smooth variation dRc(Rc).

Lat., −99.18 Long.) during a superstorm on 20 November 2003. The purpose of this paper is to study this anomaly more in detail.

2 Data and modeling technique

The standard technique of cutoff rigidity calculations was described by Smart et al. (1965, 1975). In this work the trajectory calculations were performed with the use of the technique described by Pchelkin and Vashenyuk (2001), which includes the contribution of the penumbra more accurately as compared to the standard technique. In the present study a model of Tsyganenko et al. (2003), which is able to reproduce the magnetospheric magnetic field under the conditions of strong magnetic storms, was used. It should be emphasized that it is the development of this model which made trajectory calculations possible for the superstorm event on 20 November 2003.

The refinement of the standard technique performed by Pchelkin and Vashenyuk (2001) included two points: (i) clarification of the criterion which determines whether a calculated trajectory is trapped. In the standard approach, those particles which stay near the Earth "too long" are considered to be "trapped" and their trajectories are assumed to be forbidden. At the same time, more accurate trajectory calculations indicate that some of these trajectories are allowed. The criterion "too long" appears to be rather qualitative than quantitative, which leads to uncertainty in the accuracy of the calculated cutoff rigidity. Pchelkin and Vashenyuk (2001) by more accurate integration of trajectories in the penumbra range of rigidities examined the above problem quantitatively. They obtained the curves showing how calculated cutoff rigidities are tending to asymptotic values by increasing the time during which a particle trajectory is followed. In the study of Pchelkin and Vashenyuk (2001), recommendations were given as to how long one should follow the trajectory of a quasi-trapped particle at different latitudes; (ii) in most of the previous treatments the step in calculating the cutoff rigidities was ∼0.01 GV, while in the present study this step is taken as 0.002 GV.

To calculate the input parameters for the T01S model (Tsyganenko et al., 2003), we have used the Wind observations of the B_y IMF, B_z IMF, solar wind velocity, proton number density and solar wind dynamic pressure.

3 Results

We have performed extended trajectory calculations for different phases of a magnetic superstorm on 20 November 2003.

In Fig. 2 the dots (1) with error limits (some points that were obtained by the global survey method) indicate the changes in the cutoff rigidities vs. Rc, as derived from the data of the worldwide neutron monitor network. The curve refers to the peak of the magnetic storm (UT=19:30). The approximation curve (solid line in Fig. 2) is a 3rd order polinomial fit, whose coefficients were calculated by a least-squares technique. This curve only has a visualization purpose. The

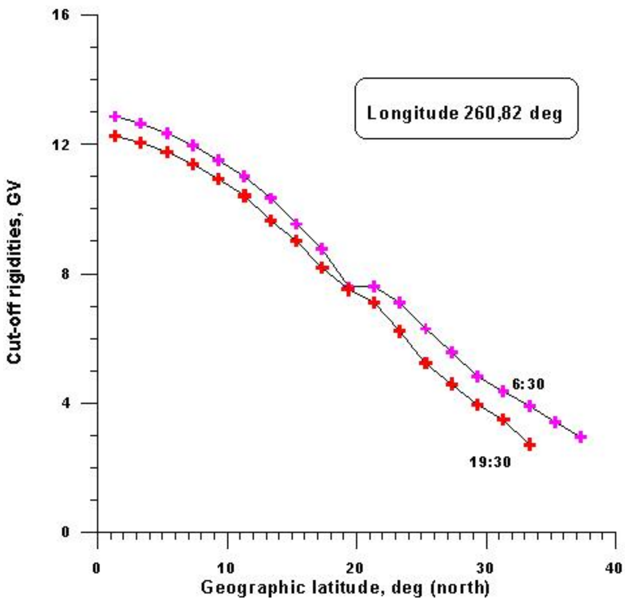

Fig. 3. Variations of the cutff rigidity along the geographic meridian of the Mexico station for the quiet conditions (pink) and at the peak of the magnetic storm on 20 November 2003 (red).

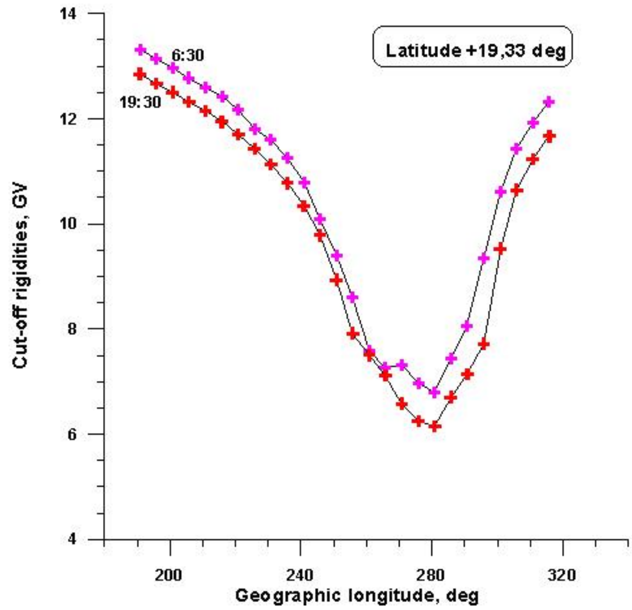

Fig. 4. Variations of the cutff rigidity along the geographic parallel of the Mexico station for the quiet conditions (pink) and at the peak of magnetic storm on 20 November 2003 (red).

triangles (2) in Fig. 2 plot the results of trajectory calculations. When Belov et al. (2005) performed their study, the data of several very important neutron monitors, including the monitor of the Mexico station, were absent. Still, for some of these stations, the trajectory calculations were performed by Belov et al. (2005). This is why the lists of the stations included in the experimental and theoretical research are only partly coincident.

A detailed analysis of dRc vs. Rc curves for other times of the event was performed by Belov et al. (2005). Here we focus on the deviation of calculated points for the Mexico station from the approximated curves. To verify this feature we have modeled by trajectory calculations the cutoff rigidities along the geographic meridian (Fig. 3) and geographic parallel (Fig. 4) running through the Mexico station. The results show the anomalous behavior of both latitudinal and longitudinal curves in the region of ∼5°–7° wide around this station in the quiet period (UT=06:30). During the storm (UT=19:30), the curves change in such a way that there is practically no variation in Rc at this station.

The calculations have also been performed for the Chacaltaya (Figs. 5, 6) station, where we expected the same effect. However, the curve obtained for the Chacaltaya station is rather smooth and does not show an anomaly that would be analogous to the Mexico anomaly.

4 Discussion

As seen from Fig. 2, the latitudinal curve, obtained by trajectory calculations agrees well with the results derived from the analysis of ground-based observations for cutoff rigidities greater than 6 GV, indicates the same maximal changes of Rc in the course of the storm (∼1.5 GV) but yields a different position of the minimum.

The observational and calculation results (Fig. 2) have revealed an anomalous behavior of storm-time cutoff rigidity variation in the region of Mexico station. This feature is also indicated in the calculated variations of Rc along the geographic meridian (Fig. 3) and parallel (Fig. 4) of the Mexico station. Under quiet conditions, the presence of the revealed anomaly is presumably related to the local irregularities of the geomagnetic field in this region, caused by the Brazil magnetic anomaly. As for the storm period, the recent studies of the magnetospheric current systems (Greenspan and Hamilton, 2000; Maltsev, 2004; Maltsev and Ostapenko, 2004) evidence that the currents responsible for the storm-time magnetic field depression have a strong longitudinal asymmetry. They produce an axially asymmetric disturbance in the magnetospheric magnetic field, which can affect the global distribution of cutoff rigidities in a complicated way. As a consequence, in the regions of strong gradients and anomalies it is quite possible that the cutoff rigidity in some geographic points will not change in the transition to the storm conditions or even exhibit an increase.

Unfortunately, at present, we are not able to compare such an interesting dynamical behavior of geomagnetic cutoff rigidity near the Mexico station with the data obtained by the global survey method. Hopefully, this comparison will be undertaken in the future.

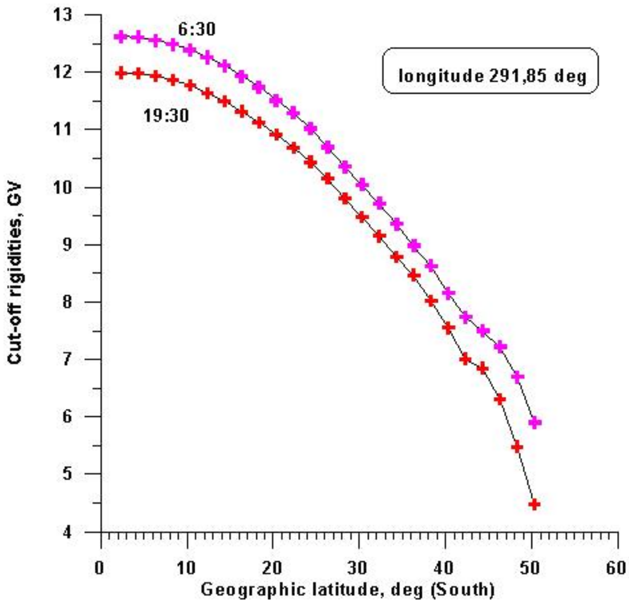

Fig. 5. The same as in Fig. 3 but for the Chacaltaya station.

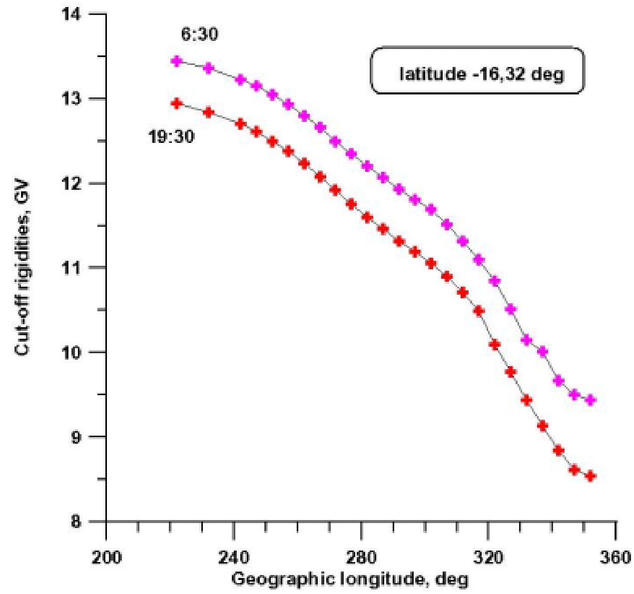

Fig. 6. The same as in Fig. 4 but for the Chacaltaya station.

5 Summary

On the basis of the above consideration we can make the following conclusions.

1. During a giant magnetic storm of 20 November 2003, cutoff rigidities exhibited an extraordinary large variation up to 1.5 GV, which is confirmed by both the trajectory calculations and the results of analysis of neutron monitor data.

2. Unlike the dipole field, which is axially symmetric, the real magnetic field is distorted by the presence of the local magnetic anomalies and external sources. This, in turn, violates the smooth character of latitudinal and longitudinal variations in the cutoff rigidities. The region of the Mexico station is one of the examples of local irregularities in the worldwide distribution of the cutoff rigidities, which can be caused by the closeness of this station to the Brazil magnetic anomaly.

3. According to the present views, the principal contribution to the storm-time geomagnetic depression is due to the magnetospheric partial ring current, which is closed to the Region 2 field-aligned currents, and the cross-tail current, which is closed to the lobe magnetopause currents. Both current systems are highly asymmetric in the magnetic local time (MLT) and lead to a complicated redistribution of cutoff rigidity isocontours on a geographical map in the transition to the storm conditions. This may have a kind of "counter-effect" in the storm-time variation of cutoff rigidities in the regions of strong gradients and anomalies (e.g. around the Mexico station), resulting in the unchanged or even increased values of Rc during a magnetic storm. To verify this suggestion, a global modeling of cutoff rigidity distributions under quiet and storm-time conditions should be carried out, which cannot be done at the present stage because of limited computational abilities.

4. The use of the pioneering "storm-oriented" magnetospheric model of Tsyganenko (2003) in trajectory calculations under the conditions of a superstorm yields the values of cutoff rigidities, which are consistent with those obtained by the global survey method. The model reasonably reproduces not only the overall distribution of Rc but even some fine details in this distribution, whose verification by other means presents an excellent possibility to test the T01S model.

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