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Global modelling of geotail and ring current dynamics under disturbed conditions

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The storm-time dynamics of magnetospheric current systems during several magnetic storms of different intensities was investigated in terms of the paraboloid model of the Earth's magnetosphere. The moderate magnetic storm on June 25-26, 1998 and severe magnetic storm on October 21-23, 1999 were studied in details. The relative contributions from the ring, magnetotail and magnetopause currents to the Dst-index were calculated to analyse the storm-time current systems dynamics. The calculations were based on the ”official” methodics of Dst calculations. The quiet time level and quiet time contributions from different current systems were subtracted from the horizontal component of magnetospheric magnetic field calculated for each modeled storm event. Since the currents in the magnetosphere induce currents in the diamagnetic Earth, the contribution of those induced currents to measured perturbation field were also considered. It was obtained that ring current contribution is comparable with tail currents one for moderate storm but it dominates during severe magnetic storm. The ring current/tail current relative contribution to the Dst rises with the growth of the magnetic storm intensity.

1. Introduction

Magnetospheric processes, which take place during magnetic storms, are determined by variations of the magnetospheric current systems. Different sources of the magnetospheric magnetic field change with the different time scales depending on different factors originated from solar wind as well as from magnetosphere and reveai themselves in the complicated dynamics of the measured magnetic field, and, in particular, in the Dst dynamics. Among others, the tail current role in the magnetic storm development is of special interest (Alexeev et al., 1996).

It was accepted during many years, that ring current is the main source of magnetospgeric magnetic field perturbation measured at the Earth's surface during magnetic storm. Nowadays, this point of view is called in question. An analysis carried out on the base of satellite measurements (Greenspan and Hamilton, 2000; Ohtani et al., 2001; Skoug et al., 2003) shows that tail current can be also responsible for a significant part of Dst variation. Unfortunately, the experimental investigations of this problem do not allow to quantitatively estimate the relative contribution of the magnetospheric magnetic field sources to Dst. Several studies estimated the contributions of Dst sources based on model calculations (Maltsev et al., 1996; Alexeev et al., 1996; *Dremuchina et al.*, 1999; Turner et al., 2000; Alexeev et al., 2001; Kalegaev et al., 2001; Ganushkina et al., 2003). Adequately representing the Dst profile, these investigations often give different estimations for contributions of the magnetic field sources to Dst even for the same event. It was shown in Alexeev et al., (2001) that the differences are most likely due to different approaches used in Dst-sources calculations. Up to date, the derivation procedure of the contribution to Dst from the magnetospheric magnetic field sources has not been described in details. Different researchers mean different things by Dst contributions originated from magnetospheric sources. As a result, the authors of different investigations represent physically different quantities by the term ”tail current contribution to Dst”. On the other hand, there is no reason to suggest that we obtain the same maximum tail current / ring current relative contribution for different storms. There exists evidence that tail current role changes depending on the magnetic storm intensity (Turner et al., 2001; Ganushkina et al., 2003; Kalegaev et al., 2005).

In this study, we investigate the magnetospheric current systems dynamics during two storm events, a moderate storm on June 25-26, 1998 when Dst reached -120 nT and an intense storm on October 21-23, 1999 with Dst dropped to -250 nT. On the base of the official method of Dst derivation from measurements, we calculate the tail current/ring current relative contributions to Dst for storms of different intensities by the paraboloid model of the magnetosphere. Based on these calculations, we explain saturation of the magnetic flux through the tail lobes, when the tail current contribution to Dst approaches maximum values for moderately disturbed conditions and does not increase with further disturbance development. During strongly disturbed conditions the ring current becomes the dominant Dst source.

2. Dst derivation from the modeling

One of the key goals of our investigation is to provide a method for correct calculation of the Dst sources using the magnetospheric models, consistent with the official procedure of Dst derivation. In this study we propose that magnetopause currents (CF), ring current (RC), and the tail current (TC) are the main contributors to Dst:

$$Dst = DR + DT + DCF \ , \tag{1}$$

where DR, DT, and DCF are RC, TC, and CF contributions to Dst, respectively.

The partial ring current (PRC) is an important asymmetrical magnetic field source, which can contribute to Dst. Although the PRC-related magnetic field perturbations in the inner magnetosphere may be significantly large, especially during the magnetic storm's main phase, its contribution to Dst is relatively small (*Tsyganenko et al.*, 2003). Moreover, the PRC location has not been sufficiently studied, and it is difficult to separate the PRC from the other magnetic field sources. In our calculations we propose that PRC contribution to Dst is a part of DR, as was used in (Ganushkina et al., 2003; *Tsyganenko et al.*, 2003).

It was established that magnetospheric magnetic field variations produce terrestrial induced currents, preventing the external magnetic field penetration inside the Earth. We use the value of 30% for the magnetic field increase due to induced currents, which, on average, is in good accordance with the investigations of (*Hakkinen et al.*, 2002). The Earth's currents induced by different magnetospheric magnetic field sources are proposed to be included to the corresponding terms on the right side of (1).

Based on the official procedure of Dst derivation from the measurements (*Sugiura and Kamei*, 1991), we propose a method of Dst calculation in terms of magnetospheric models. It consists of three steps:

1. Calculation of the magnetic field horizontal component variation ($\delta H_i(t)$) (originated from the external (magnetospheric) and corresponding induced currents) at each location reporting to Dst observatories;

2. Calculating of the quiet magnetic field variation during the quietest day of the month ($\delta H_i^q(t)$), and subtracting them from $\delta H_i(t)$ for each observatory;

3. Determination of the Dst, averaging the normalized to the equator differences between storm-time and quiet-time magnetic field variations at the reporting stations for each hour:

$$Dst(t) = \frac{1}{4}\sum_{i=1}^{4}(\delta H_i(t) - \delta H_i^q(t))/cos(\theta_i), \qquad (2)$$

where θ_i are latitudes of observatories.

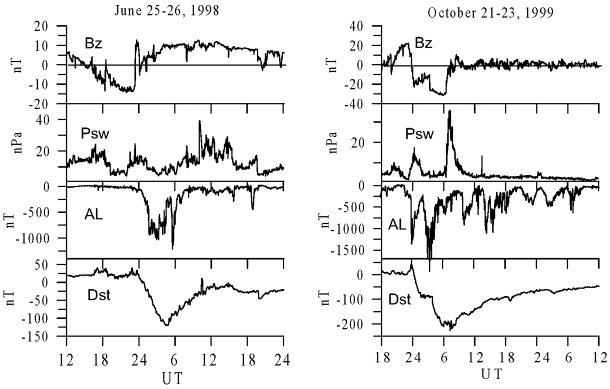
The proposed procedure also may be generalized to unambiguously describe Dst sources when the magnetic field model enables calculation of the magnetic field of different magnetospheric current systems. It allows us to compare the contributions of different sources to Dst obtained in terms of different models.

The Dst index presented by (2) may be rewritten as

$$Dst(t) = \frac{1}{4}\sum_{i=1}^{4}\frac{\delta H_i(t)}{cos(\theta_i)} - \frac{1}{4}\sum_{i=1}^{4}\frac{\delta H_i^q(t)}{cos(\theta_i)} = \delta H(t) - \delta H^q(t), \qquad (3)$$

where the $\delta H(t)$ and $\delta H^q(t)$ are averaged over the equator storm-time and quiet-time variations of the magnetospheric magnetic field. The quiet-time level is a feature of the model, it is about zero for the paraboloid model. That is why the simple magnetic field calculation at the Earth's center used in (Alexeev et al., 1996) gives a good agreement with Dst. However, the magnetic field sources have nonzero quiet day variations.

Representing storm-time and quiet-time variations as a sum of the contributions produced by all the magnetospheric current systems, one can obtain



(a) (b)

Fig. 1. The IMF B_z, solar wind dynamical pressure, AL and Dst indices during June 25-26, 1998 moderate (a) and October 21-23, 1999 intense (b) storm events.

$$Dst = \delta H_R - \delta H_R^q + \delta H_T - \delta H_T^q + \delta H_{CF} - \delta H_{CF}^q. \qquad (4)$$

Using (1) one can suggest that $DT = \delta H_T - \delta H_T^q$. We will determine the other Dst sources (DR and DCF) as result of subtraction of the corresponding quiet-time variation from storm-time one.

3. June 25-26, 1998 and October 21-23, 1999 storm events

Figure 1 shows the solar wind conditions and interplanetary magnetic field (IMF), as well as the geomagnetic indices during magnetic storms on June 25-26, 1998 and on October 21-23, 1999.

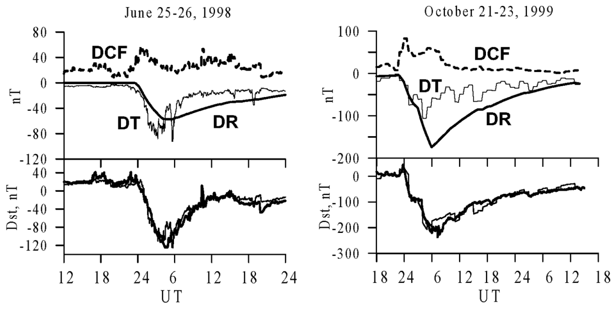
On June 25, 1998 the IMF B_z shows a sudden jump to more than +15 nT from the level of -13 nT at 2300 UT (Figure 1a). The solar wind dynamic pressure had several peaks around 8-10 nPa. The AL index reached a peak value of -1000 nT around 0255 UT on June 26. The Dst index started to decrease at the beginning of June 26 and reached -120 nT around 0500 UT.

During the intense storm on October 21-23, 1999 IMF B_z turned from +20 nT to -20 nT at about 2350 UT on October 21 and dropped down to -30 nT around 0600 UT on October 22 (Figure 1b). Solar wind dynamic pressure showed two main peaks, a 15 nPa peak around 2400 UT on October 21 and a 35 nPa peak around 0700 UT on October 22. There were several peaks in the AL index reaching -1000 nT - -1500 nT. The Dst index dropped to -230 nT at 0600-0700 UT on October 22.

4. Storm-time magnetospheric model and Dst calculation

We can not explicitly distinguish the contributions from different magnetospheric current systems, which are contained in the observed magnetic field. However, we can estimate them using the modern magnetospheric models, which can provide a separate calculation of the magnetospheric magnetic field sources.

In this study we use the paraboloid magnetospheric model A2000, which allows to investigate the storm-time dynam-



(a) (b)

Fig. 2. Dst sources (top panel), together with the observed Dst (thick line) and the modelled Dst (thin line) (bottom panel) for June 25-26, 1998 (a) and October 21-23, 1999 (b) magnetic storms calculated by A2000 model.

ics of different current systems, as well as of their parameters. The paraboloid model of the Earth's magnetosphere (Alexeev et al., 1996; Alexeev et al., 2001) is based on an analytical solution of the Laplace equations for each large-scale current system in the magnetosphere with a fixed shape (paraboloid of revolution). The magnetic field in the paraboloid model B_m can be calculated in the form:

$$B_m = B_d(\psi) + B_{cf}(\psi, R_1) + B_t(\psi, R_1, R_2, \Phi_\infty) + B_r(\psi, b_r)$$

where B_d, B_{cf}, B_t, and B_r are the magnetic fields of geomagnetic dipole, of currents on the magnetopause, of tail current and ring current respectively. The different magnetic fields depend on parameters of magnetospheric current systems (intensities and locations) as input. There are: the geomagnetic dipole tilt angle ψ, the magnetopause stand-off distance R_1, the distance to the inner edge of the tail current sheet R_2, the magnetic flux through the tail lobes Φ_∞, the ring current magnetic field at the Earth's center b_r, and the maximum intensity of the field-aligned current $I_\parallel$. These input parameters depend on the solar wind, IMF, and geomagnetic indices and can be determined from empirical data using submodels.

To calculate Dst based on official procedure of Dst derivation we must determine the quietest days of the month. The quietest days for the June 25-26, 1998 and October 21-23, 1999 storm events were June 17, 1998 and October 20, 1999. The average quiet time Dst were -0.58 nT and 2.74 nT, respectively.

Figure 2 shows the model contributions and total Dst during June 25-26, 1998 and October 21-23, 1999 storm events calculated by parabolid model. We can see the contributions from the magnetopause current (dashed line, marked by ”DSF”), ring current (thick line, marked by ”DR”) and tail current (thin line, marked by ”DT”) (top panel) together with the observed Dst (thick line) and the modelled Dst (thin line) (bottom panel) for June 17, 1998 (a) and October 20, 1999 (b). The ground induced currents effect (30% of the variation) was taken into account in the calculations. The quiet-time contributions from the different current systems are calculated for quietest days of June 1998 and October 1999 and subtracted from the modeled magnetic field variations.

During the moderate storm on June 25-26, 1998, tail current begins to develop before the ring current. Its contribution to the Dst index almost follows the drop of the total Dst. During the storm main phase, the tail current gives a slightly larger contribution to Dst than the ring current. During the recovery phase, the ring current remains more enhanced than the tail current.

The situation is quite different for the intense storm on October 21-23, 1999. The tail current develops first, when Dst begins to decrease in a manner similar to the tail current behavior during the moderate storm. During the storm maximum, the ring current becomes the dominant contributor to the Dst index.

5. Discussion and conclusions

We can see that the tail current plays a significant role in the magnetic storm development. Computations of the tail current's contribution to Dst using the A2000 and G2003 models, show that during a storm, maximum DT can approach values comparable with the ring current contribution to Dst. Detailed investigation of tail and ring current dynamics shows that the tail current's (as well as other magnetospheric currents') contribution to Dst varies during a magnetic storm: the tail current begins to develop earlier than the ring current and starts to decay while the ring current continues to develop. The magnetotail global changes during the magnetic storm are controlled mostly by the solar wind and the IMF, but are accompanied by sharp variations associated with substorm-related processes. Clear correlation of the tail current contribution to Dst with the substorm activity is apparent in the results obtained from the model. The tail current development in that model is controlled by the magnetic flux through the tail lobes (which is the same as polar cap magnetic flux):

$$\Phi_\infty = \Phi_0 - \frac{AL}{7}\frac{\pi R_1^2}{2}\sqrt{\frac{2R_2}{R_1}+1}. \qquad (5)$$

The geocentric distance R_1 to the subsolar point is a function of the solar wind dynamic pressure and IMF B_z component (Shue et al., 1998). The distance to the inner edge of the tail current sheet R_2 is obtained by mapping the equatorward boundary of the auroral oval at midnight to the equatorial plane. $\Phi_0 = 400MWb$ is the magnetic flux through the tail lobes during quiet conditions. The A2000 model parameterization is described in details by Alexeev et al. (2001).

The calculations show that the relationship between tail and ring currents depends on the magnetic storm intensity. Calculations give tail current contribution to Dst comparable with the ring current contribution during a moderate storm, but ring current becomes the dominant contributor to Dst during an intense storm (see also (Ganushkina et al., 2003)). Apparently, the magnetic flux through the tail lobes ”saturates” during extremely disturbed conditions, while the ring current continues to develop. In particular, we can see that AL / AE index approaches similar values during both the moderate and the intense storms under consideration (see Fig. 1). The polar cap area also does not demonstrate a significant growth during intense storms, compared to moderate

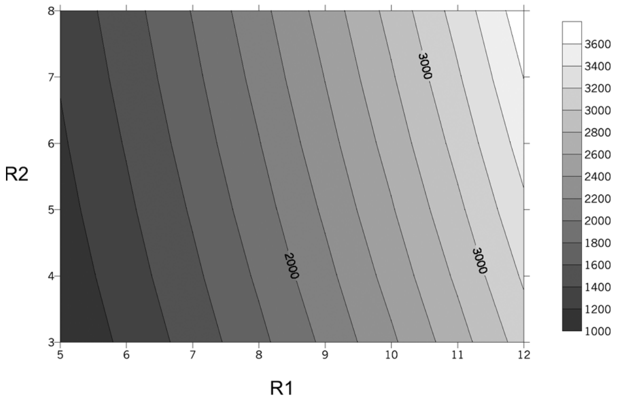


Fig. 3. The magnetic flux through the tail lobes distribution calculated by paraboloid model for AL=-2000nT depending on R_1 (distance to the subsolar point), and R_2 (distance to the inner edge of the tail current sheet).

ones. That is why we obtained the approximately equal maximum DT values during the different storms.

One can suggests, that saturation effect is the result of global magnetospheric morphology. The polar cap size is (theoretically) limited by the Earth's hemisphere area. The magnetic flux through the polar cap / tail lobes

$$\Phi_\infty = 2B_0\pi R_E^2 \sin^2\theta_{pc}$$

approaches the maximum value of about 3000 MWb for the polar cap radius $\theta_{pc} = 40^o$, evidently an overestimated value (here B_0 is the dipole magnetic field at the equator, R_E is the Earth's radius).

Figure 3 shows the magnetic flux through the tail lobes calculated by (5) for AL=-2000nT depending on parameters R_1 and R_2. Actually, for the reasonable values of R_1 and R_2, Φ_∞ can not exceed the upper value of 2500 MWb. In terms of the paraboloid model, it corresponds to the magnetic variation at the Earth's surface, about of 200 nT. Apparently, this is the maximum possible contribution of TC to Dst (see also (Kalegaev et al., 2005).

Turner et al. (2001) studied the energy content in the storm time ring current. They found that the ratio of the total plasma energy content in the dayside to Dst^*, the solar wind dynamic pressure corrected Dst, falls twice when Dst^* changes from 0 to -100 nT. It means that for moderate storms, DR and DT are about of the same order, which is in agreement with results obtained by (Alexeev et al., 1996, Ganushkina et al., 2003).

Figure 4 represents the ratio DR/Dst^* (triangles) depending the Dst^* taken at maximum of storms together with the same figure, which represents the results obtained by Turner et al. (2001). We used DR and Dst^* at the maximum of the storms under consideration as well as during two additional storms 6-8 April, 2000 and 9-12 January 1997.

One can postulate that the tail current gives a negligible contribution to quiet-time Dst, but during moderate storms, TC produces a contribution to on-ground magnetic field comparable with that of the ring current. Under moderately disturbed conditions, TC saturates, approaching the maximum possible values, while the ring current still remains undeveloped. During severe storms, ring current continues to develop and becomes the major contributor to Dst, while tail current has already reached the maximum value.

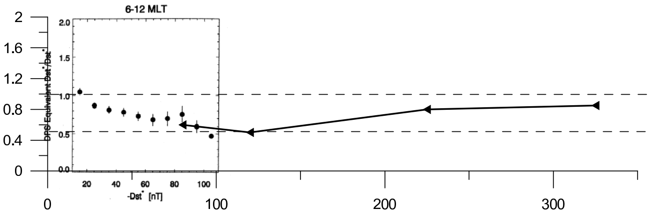


Fig. 4. The ring current relative contribution to Dst^*, depending on storm intensity.

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