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ASTRONOMY, ASTROPHYSICS, AND COSMOLOGY

Magnetospheric Dynamics during the Storm of February 14, 2009

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Abstract—The structure of the magnetic field in the magnetospheric during the storm of February 14, 2009 is studied. The model parameters that characterize the magnetospheric magnetic field are calculated every hour on the basis of solar wind data and the evolution of the magnetic field during the storm is reproduced using the A2000 model of the Earth's magnetosphere. It is shown that extremely quiet geomagnetic conditions in 2009 promoted the expansion of the magnetosphere and were favorable for the formation of magnetic-island-like structures (plasmoids) in the geomagnetic tail. It is ascertained that negative variations in the B_z component could occur in the nightside magnetosphere in situations where the magnetic flux through the tail lobes exceeded certain thresholds, which depend on the parameters of the magnetospheric current systems. It is shown that the formation of magnetic islands decreases the magnetic flux through the tail lobes and prevents excessively strong development of the magnetic field in the tail.

Keywords: Earth's magnetosphere, magnetic islands, plasmoid, magnetic storm.

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INTRODUCTION

The Earth's magnetosphere is produced by the interaction of the solar wind with the Earth's magnetic field. The nightside magnetosphere is characterized by a specific structure of the magnetic field, viz., oppositely directed magnetic fields in the northern and southern parts form the magnetotail, which is a structure that is supported by electric currents across the tail that closes through the magnetopause [1]. The intensity and spatial localization of the currents in the magnetotail depend on external conditions, viz., the solar wind parameters and the interplanetary magnetic field (IMF) vector [2–5].

The magnetotail currents, along with other magnetospheric current systems (the ring current, magnetopause currents, longitudinal currents, and Chapman–Ferraro currents), depend on the solar-wind activity and are responsible for the development of magnetic disturbances, such as magnetic storms and substorms [6–8]. The mutual dynamics of the internal magnetic field and the fields produced by external sources (especially the magnetotail field) determines the magnetic field structure in the magnetotail. On the other hand, the tail and ring currents determine variations in the magnetic field inside the magnetosphere and are responsible for the magnetic depression observed on the Earth's surface during geomagnetic disturbances.

The Dst index is an indicator of magnetospheric disturbance. It characterizes the magnetic-field depression that is connected with the development of storm current systems in the magnetosphere. The analysis of variations in the Dst index during magnetic storms of different intensities shows that the variation in the ratio of the contributions of different current systems to the magnetic field during a storm depends on the intensity of a storm. During storms with the maximum Dst (>150 nT), the saturation of the magnetic flux of the magnetotail currents occurs [9] and the contribution of the magnetotail currents to the Dst index is limited to values from –150 to –200 nT. This effect is determined by the saturation of the magnetic flux through the magnetotail lobes, which is related to a global reconstruction of the magnetic field as the magnetotail currents increase above the threshold values.

Development of large-scale magnetospheric current systems during a geomagnetic storm can promote the formation of specific systems in the magnetic field, which are absent in the quiet magnetosphere. Their temporal and spatial parameters are manifestations of the dynamics of different current systems. Formation of the dipolization front and of closed magnetic structures (plasmoids) is one of the characteristic phenomena that occur in the tail of the disturbed magnetosphere. In this work, we study the magnetic-field dynamics during the geomagnetic

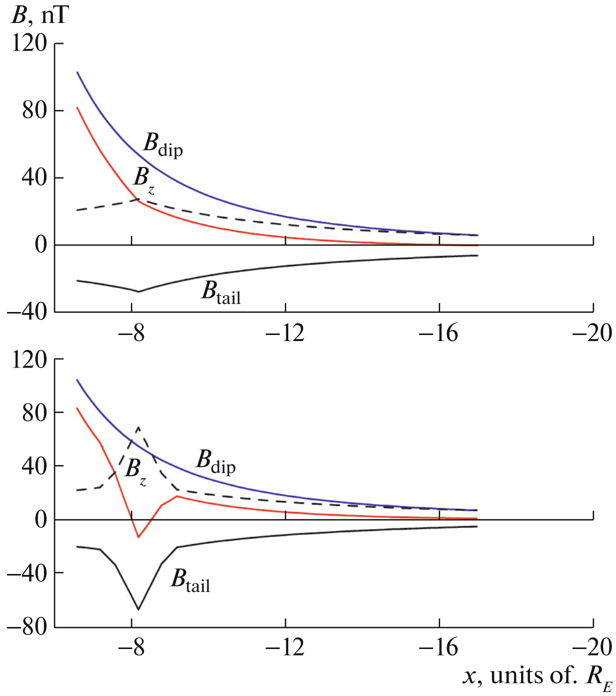

Fig. 1. (bottom) The structure of the magnetic field (black curve) produced by superposition of the Earth's magnetic field (blue curves) and tail currents (red curve); the reverse tail field (dashed curve) is shown for comparison with the Earth's field. The tail-current field was enhanced, which led to a negative resultant field. (top) The typical situation with the weak tail-current field.

storm of February 14, 2009. THEMIS satellite measurements during that event showed the presence of structures with a negative B_z component of the magnetic field in the magnetotail. Such magnetic configurations indicate the formation of a plasmoid connected with an excessive gain in the magnetic flux though the magnetotail lobes.

1. THE FORMATION OF MAGNETIC ISLANDS IN THE MAGNETOTAIL

The magnetic field inside the magnetosphere is induced by two sources of different natures: currents inside the Earth's liquid outer core (terrestrial field, B_{in}) and large-scale currents in the magnetosphere. The main sources of the magnetospheric field are Chapman–Ferraro currents (B_{CF}), ring current (B_R), the magnetotail current (B_T), and field-aligned currents (B_{fac}):

$$B = B_{in} + B_{CF} + B_R + B_T + B_{fac} + B_{trans}.$$

Terrestrial currents experience slowly secular variations, which are significant on time scales of approximately 1 year, while magnetospheric sources are subject to much more rapid variations, within days and even hours, during geomagnetic disturbances, such as magnetic storms and substorms. These variations are caused by changes in the conditions in interplanetary space, which result in variations in the magnetospheric parameters and asynchronous variations in magnetospheric currents, which determine the magnetospheric field dynamics.

Significant changes can occur in the global structure of the magnetic field in the magnetosphere during a storm; for example, under strong amplification of currents in the magnetotail, a magnetic island, a plasmoid, can be formed there due to summation of the terrestrial field (with the positive B_z component) with amplified magnetotail currents (with $B_z < 0$). Figure 1 qualitatively shows the pattern of plasmoid formation. The profile of the B_z component of the magnetic field is shown; to the first approximation, it is the sum of the contributions of the dipole and magnetotail currents (B_{dip} and B_{tail}, respectively; B_{dip} is positive and B_{tail} is negative). The dipole magnetic field is usually stronger than the field of the magnetotail currents; hence, the total B_z is positive, as in the top figure. Here, the dashed curve shows the field B_{tail} that is opposite in sign for the visual comparison between $|B_{tail}|$ and B_{dip}. When the tail currents are strongly amplified and $|B_{tail}|$ exceeds B_{dip}, then a region with a negative B_z component of the magnetic field originates near the inner edge of the magnetotail-current sheet (bottom figure). This is the so-called plasmoid, viz., the region of the local minimum of the magnetic field near the inner edge of the magnetotail current system. An X-point originates in a magnetic field of this structure at the plasmoid–magnetospheric internal field interface. The effects of other sources of a magnetic field (mainly, magnetopause currents) are ignored in Fig. 1. These could positively contribute approximately tens of nT to the total B_z field component, but this does not qualitatively change the pattern.

It is seen that this untypical magnetic field structure with a negative B_z component occurs due to both amplification of the magnetotail currents above the threshold and a shift of its inner edge toward the nightside. It is important that moderate currents are required for plasmoid formation while the magnetotail currents are moving away. If the inner edge of the tail currents is located at a distance of ~7R_E, then the magnetotail field should attain –100 nT to exceed the field induced by the terrestrial currents. Abnormally quiet geomagnetic conditions in 2009 resulted in enlargement of the magnetosphere and individual current systems, which promoted the occurrence of favorable conditions for the formation of magnetic-field structures in the geomagnetic tail with the negative B_z component. We use THEMIS measurements for derivation of magnetotail parameters during different stages

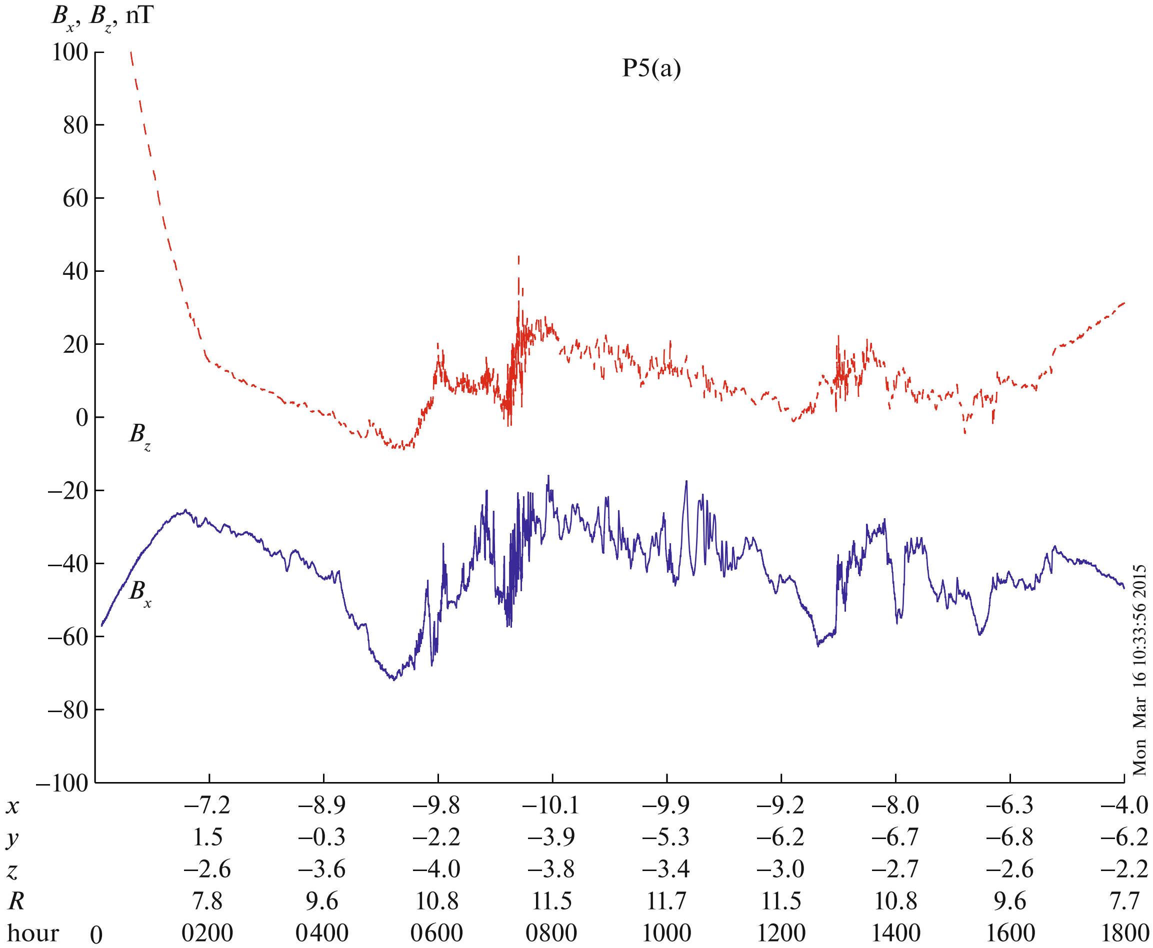

Fig. 2. Magnetic-field components B_x (blue solid curve) and B_z (red dashed curve) along the THEMIS P5 orbit on February 14, 2009. The B_z component is omitted.

of the magnetic storm and search for the magnetic-field structure characteristic of the plasmoid formation.

THEMIS satellites were located near the apogee along the geomagnetic tail every 4 days during the winter of 2009. We can retrieve the tail-current system parameters (inner-edge position, maximum intensity, radial distribution, and dynamics) at certain time points from the satellite measurements. Figure 2 shows a typical magnetic field measured along the THEMIS P5 trajectory. The B_x and B_z components of the magnetic field are shown in the GSM coordinates. The magnetic field equals several thousands of nT in the magnetic field perigee; however, the magnetospheric dynamics are already seen at distances longer than two Earth radii: the contribution of tail currents is shown in strong variations in the magnetic field components at 10:00 UT and later. The ring and magnetopause currents also contribute to the satellite-measured magnetic field.

2. MAGNETOSPHERIC CONDITIONS ON FEBRUARY 14, 2009

Let us analyze the event of February 14, 2009 with the goal of studying the magnetospheric field dynamics under the action of the solar wind. February of 2009 was characterized by very quiet external conditions. Weak variations in IMF, plasma density and speed, and solar wind dynamic pressure were fixed on February 13, before the day that is under study here. The external conditions induced the enlargement of the magnetosphere, i.e., an increase in the distance to the subsolar point to 12–13R_E (as calculated with model [10]) and a shift of the inner edge of the current sheet toward the nightside up to distances of 10–12R_E. The Dst index did not show any significant variations that are typical for magnetospheric activity.

An accelerated flux of dense solar-wind plasma reached the Earth's magnetosphere on February 14, 2009. Figure 3 shows the B_z component of IMF, the solar wind density, speed, and pressure, and Dst and AE indices downward. The proton density started to

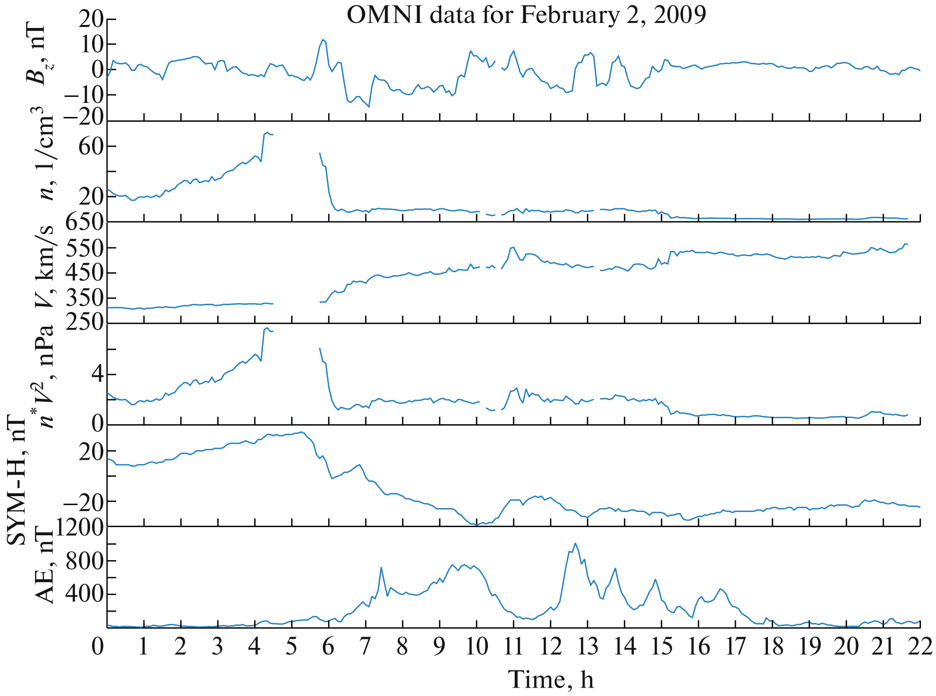

Fig. 3. Solar wind parameters (IMF B_z, nT), proton density (ptc/m^3), speed (km/s), and pressure (nPa), and Dst (nT) and AE (nT) indices on February 14, 2009.

increase at 22:00 UT on February 13 and attained 70 ptc/cm^3 at 04:30 UT on February 14, when the speed was approximately 300 m/s. After attaining the maximum, the density dropped sharply, but the speed started to increase and reached 400 km/s (in an hour) and then 500 km/s. The initial phase of the magnetic storm started at 02:00 UT during compression of the magnetosphere by the solar wind. Amplification of the Chapman–Ferraro currents was recorded, which reached a maximum at approximately 05:35 UT according to Dst data. The B_z component of IMF changed the direction to the southward at 06:00 UT and provoked the onset of the main phase, during which the Dst minimum of approximately 40 nT was fixed at approximately 10:00 UT, while the recovery phase started at approximately 16:00 UT.

Variations in the Dst index during February 14, 2009 are characteristic of a typical although small-scale storm, viz., an increase in Dst during the solar-wind pressure pulse and then the development of a small negative disturbance of the geomagnetic field.

3. THE MAGNETOSPHERIC MAGNETIC FIELD STRUCTURE DURING THE STORM OF FEBRUARY 14, 2009

Models of the magnetosphere [8, 11, 12] can be used for quantitative estimates of the magnetic field. The paraboloid model of the Earth's magnetosphere A2000 [8, 13] defines the magnetospheric magnetic field of each large-scale current system as an analytical solution to a Laplace equation at a fixed shape of the magnetopause (a paraboloid of revolution). The magnetic-field components normal to the magnetopause are considered zero. The model represents the magnetic field in the magnetosphere as a superposition of the magnetic fields of the ring current (B_R), tail currents (B_T), the field-aligned currents of region 1 (B_{fac}), magnetopause currents that screen the dipole field (D_{sd}), and the magnetopause currents that screen the ring field (B_{sr}):

$$B_m = B_{\text{sd}}(\psi, R_1) + B_T(\psi, R_1, R_2, \Phi_\infty) + B_R(\psi, b_r) + B_{\text{sr}}(\psi, R_1, b_r) + B_{\text{fac}}(I_\parallel).$$

The A2000 model is independent of a specific database of measurements, which could impose some limitations on the applicability of the model. Thus, the model describes the magnetic field well for both quiet and disturbed and extremely disturbed geomagnetic conditions, where experimental data are restricted and the use of empirical models is limited. The magnetospheric dynamics during a storm is represented by temporal variations in the large-scale current systems.

The model input consists of the key parameters of the magnetospheric current systems, which represent their location and intensity:

• the geomagnetic dipole tilt angle ψ,

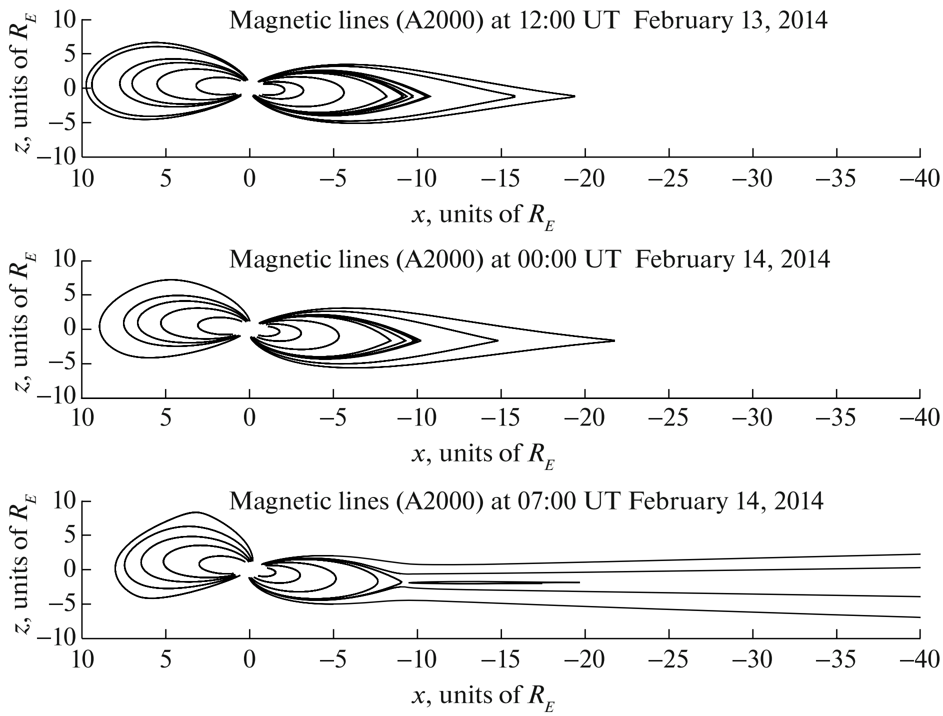

Fig. 4. The distribution of the B_z component of the magnetic filed along the x_{GSM} axis and the magnetic field structure at (top) 12:00 UT on February 13, (center) 00:00 UT on February 14, and (bottom) 07:00 UT on February 14, 2009, calculated with the A2000 model.

• the distance to the subsolar point 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,

• the field-aligned current intensity maximum $I_\|$.

Model parameters are calculated on the basis of empirical data, viz., the solar wind and IMF parameters and geomagnetic Dst and Al indices [13, 14].

The radial profiles of the magnetic field of magnetotail currents were retrieved in [15] from THEMIS measurement data using the A2000 and IGRF models, which allowed calculation of the model parameters during the magnetic storm and contribution of current systems other than the tail-current sheet to the satellite measurements. Figure 4 shows the distribution of the magnetic field along the magnetotail and magnetic lines calculated for 12:00 UT on February 13, 00:00 UT and 07:00 UT on February 14 with the A2000 model from magnetosphere parameters calculated in [15]. It is evident that the magnetosphere was compressed while the storm was developing. The tail currents became amplified at 00:00 UT on February 14, which resulted in a flux gain and the cessation of compression during the main phase of the storm. Finally, at the storm's onset at 07:00 UT on February 14, one can see formation of the dipolization front. It is characterized by a change in sign of B_z (as seen in Fig. 2) with the X-type neutral point. The magnetic field becomes a dipole to the left of the X-point, and a plasmoid, or magnetic island, is formed to the right. Formation of these magnetic structures (magnetic islands or plasmoids) is the natural result of the global magnetospheric dynamics under conditions of a sharp gain in the magnetic flux in the magnetotail. In this case, it occurred due to increased sizes (as compared to the usual case) of the magnetosphere, in particular, a long distance to the inner edge of the tail-current sheet. Similar structures could originate due to high substorm activity, where the local magnetic field exceeds the positive geomagnetic dipole field even at shorter distances to the Earth, as compared to that considered above. THEMIS measurements showed formation of regions with a decreased magnetic field during several substorms on February 14, 2009, which were probably accompanied by the formation of dipolization fronts near 12:00 and 16:00 UT.

We detected the plasmoid formation by a change in the sign of the B_z component of the magnetospheric field. In fact, only the magnetic field though the tail lobes is a key parameter, which characterizes the tail-current system intensity and indicates the formation of plasmoid-like magnetic structures. Variations in the magnetic flux in the tail lobes due to both a shift of the

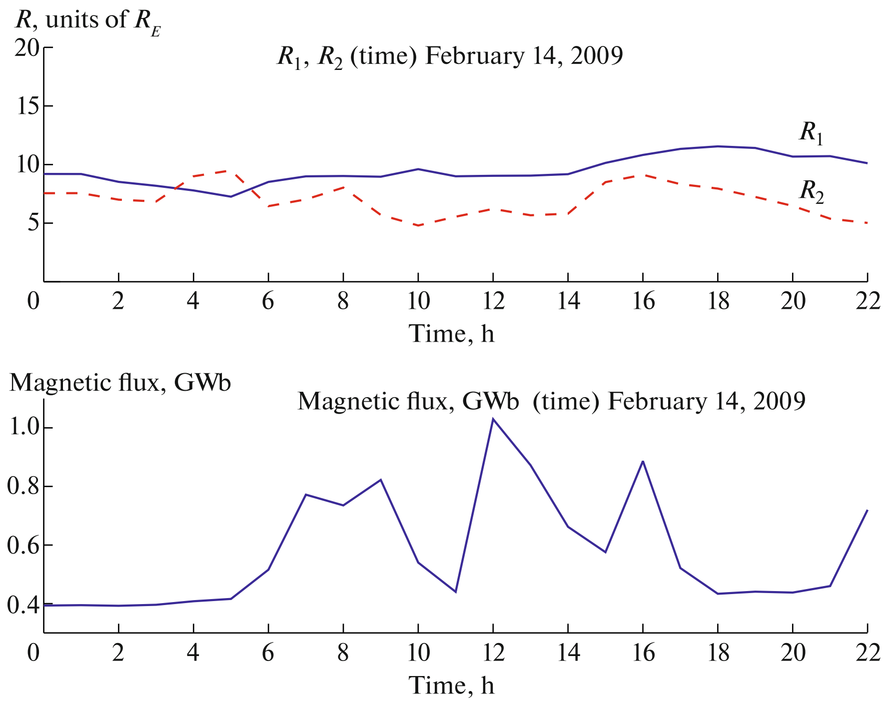

Fig. 5. (top) The instantaneous values of R_1 (blue solid curve) and R_2 (red dashed curve) for every hour. (bottom) The model magnetic flux through the tail lobes during the magnetic storm from 00:00 to 22:00 UT on February 14, 2009.

current sheet and amplification of the current across the tail are responsible for the formation of plasmoids in the nightside magnetosphere.

Let us consider the dynamics of the magnetospheric parameters during the storm of February 14, 2009. The model parameters were calculated from data on the solar wind and geomagnetic indices using submodels, or direct measurements of the parameters were used if was possible. The R_2 values were calculated by projecting the subequatorial boundary of the auroral zone at midnight onto the tail-current sheet in a real magnetic field calculated by the A2000 model. Figure 5 shows the profiles of the magnetospheric parameters R_1 (distance to the subsolar point), R_2 (the distance to the inner edge of the tail-current sheet), and Φ (magnetic flux). It is seen that the plasmoid was formed under conditions of a sharp gain in the magnetic flux in the magnetotail with recovery of the size of the magnetosphere.

CONCLUSIONS

The structure and dynamics of the magnetic field in the magnetosphere during the magnetic storm of February 14, 2009 were studied on the basis of THEMIS data and magnetospheric modeling, as well as the structure of the B_z component of the magnetic field on the basis of THEMIS measurements during the SSC storm on that day. It is shown that geomagnetic conditions in 2009 promoted the enlargement of the magnetosphere and were favorable for the formation of magnetic-field structures with negative B_z in the geomagnetic tail. Magnetic islands were formed when the magnetic flux through the tail lobes exceeded a certain threshold, which transformed the magnetic flux through the tail lobes into closed magnetic structures (magnetic islands) and prevented excessively strong development of the magnetic field in the tail.

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