INTERNATIONAL JOURNAL OF GEOMAGNETISM AND AERONOMY
VOL. 3, NO. 1, PAGES 35–44, JANUARY 2002

Substorm study based on the Paraboloid model of the magnetosphere

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Abstract. A substorm is widely accepted to be a global phenomenon in magnetospheric physics. It is a large-scale process consisting of coherent phenomena. It is very interesting to study individual phenomena such as reconnection during the onset of a substorm flows in the tail, ionospheric precipitation, particle injection, etc. However, we would like to emphasize that it is important to investigate the substorm as a unified process depending on the conditions in the solar wind and within the magnetosphere. For this purpose we should use a global magnetospheric model. In this case it is the Paraboloid model. It is important to note that the Paraboloid model comprises all the necessary sources of the magnetic field in the magnetosphere which can be distinguished from each other. This enables calculation of the magnetic field of different sources with different timescales. By using this model, we can also calculate global characteristics of the magnetosphere, such as the magnetic fluxes in the polar cap and in the auroral oval as a function of model parameters depending on time and solar wind conditions. This makes it possible to find the criteria of magnetosphere transformation into the metastable configuration, when development of a substorm becomes inevitable. Using these criteria, constrains were found which should be imposed on the model parameters to determine the substorm onset. The results obtained make it feasible to explain the external substorm triggering by the northward turning of the interplanetary magnetic field in the solar wind. A case study of the 10 January 1997, substorm event confirms our findings.

Introduction

Substorms are currently known as global phenomena consisting of a coherent set of processes within the magnetosphere, ionosphere, and the interplanetary medium. Magnetospheric dynamics during substorms consists of a sequence of energy loading and dissipation events accompanied by well-known observational phenomena such as cross-tail current and polar cap magnetic flux enhancement, field line stretching with subsequent dipolarization, Joule heating in the ionosphere, auroral particle precipitation, ring current enhancement, and plasmoid formation [*Baker et al.*, 1996].

These observations support the idea that a substorm is a global configurational instability of the magnetosphere [*Baker et al.*, 1999; *Sitnov et al.*, 2000]. On the basis of viewpoint, it is important to answer certain questions. Can one apply a global model of the magnetospheric magnetic field to the substorm investigation? If one can, what are the main features of this model?

In our study we used the Paraboloid model of the magnetosphere, and in this paper we try to explain why it can be used for the consideration of substorms triggered by the interplanetary magnetic field (IMF) northward turning.

Substorm triggering by the IMF northward turning is a very interesting and contradictory field of substorm physics. This problem has been studied since 1975. *Caan et al.* [1975] performed a statistical analysis of a large set of substorms and have shown that the onset begins at a time when the IMF B_z changes from a negative value to zero, after a long

Paper number GAI00368.
CCC: 1524–4423/2002/0301–0368$18.00

The online version of this paper was published 24 January 2002.
URL: http://ijga.agu.org/v03/gai00368/gai00368.htm
Print companion issued January 2002.

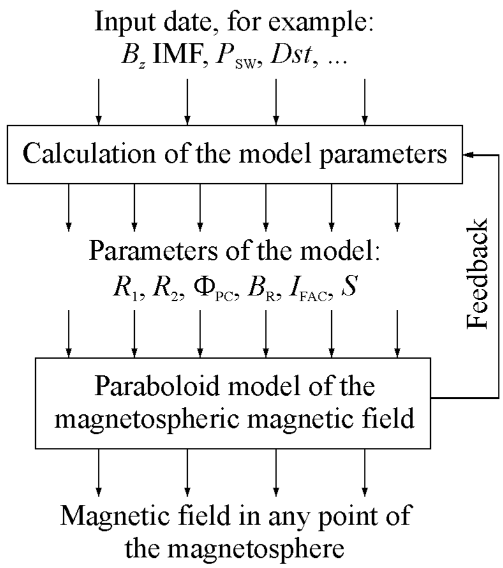

Figure 1. Schematic diagram of the Paraboloid model. R_1 is the distance to the subsolar point, R_2 is the distance to the earthward edge of the tail current sheet, Φ_{PC} is the magnetic flux in the polar cap, B_R is the ring current intensity, I_{FAC} is the intensity of the Region 1 field-aligned currents, S is the flaring of the paraboloid of revolution (magnetopause).

period of being directed southward. *Rostoker et al.* [1982] found a distinct relation between IMF northward turnings and substorm onsets for a number of intense substorms. Later, *Rostoker* [1983] found more evidence for this phenomenon. He showed that B_z remained negative for a period of ~2 hours for the storm on 20 January 1978, and ~1 hour for the storm on August 19, 1978. *Lyons* [1995] noted that sudden changes in the IMF B_y could also control the substorm onset. *Troshichev et al.* [1986] showed that a decrease of $|B_y|$ down to zero can trigger substorm onset. *McPherron et al.* [1986] studied the IMF B_z at the time of onsets and showed that 44% of 126 events were directly related to the IMF northward turning, and 29% of events occurred at a steady negative B_z. Taking into account changes in the IMF B_y investigated by McPherron, *Lyons* [1996] revealed a distinct relation between sudden IMF changes and substorm onsets. *Lyons* [1995] proposed a substorm model that explains the IMF triggering of a substorm expansion by a decrease of the electric field in the near-Earth magnetotail and, as a consequence, development of field-aligned currents. *Nishida* [1997] carried out recently a case study and found no evidence for the Lyons theory. They have found an increase of the electric field just before substorm expansion, a fact contradicting the Lyons theory. Thus there is no commonly accepted theory of the mechanism that connects changes in the IMF to a substorm expansion onset.

In this paper we would like to answer two questions: (1) Can we use the global magnetospheric model to study substorms, and how can this be done? (2) What is a possible mechanism of substorm triggering by the IMF northward turning? As a case study, we will focus on the substorm of 10 January 1997.

The Model

Let us define the features of the model of the magnetospheric magnetic field used to study the substorm. First, we should consider the time constraints. The characteristic times of different current systems in the magnetosphere are in the range from minutes (as Region 1 field-aligned currents) to tens of minutes (tail current system) and to hours (ring currents). Thus the first feature of the model should be its ability to operate with a time scale of a few minutes. We cannot use a timescale with steps less than a few minutes because the model of the magnetospheric magnetic field does not take into account wave processes.

A level of disturbances in the magnetosphere, which can be estimated by the Dst or Kp indices, can change rather strongly. Fluctuations in the magnetic field have to be either of the same order or exceed the mean value. Thus the second feature of the model should be its ability to provide reasonable calculation results at any level of a disturbance. This means that the calculated magnetic field in each region of the magnetosphere should not contradict observations and physical sense. On the other hand, the appearance of such contradictions should correspond to some active magnetospheric phenomena (as substorm onset) and be accepted as a limit of the model application. This feature should be accompanied by the following: a continuous dependence on the input data. In other words, small differences in the input data (measurements, indices, etc.) should lead to relatively small differences in the calculated magnetic field at the point of interest. This is an important feature that can only be satisfied when the parameters of the model have continuous functional dependencies on the input data and time.

The time-dependent calculation demands that the model parameters follow a time-dependent behavior of different current systems. Thus the next feature is a reasonable set of model parameters. It is also important for the model to make possible using different calculation schemes to obtain the best results for the case study. Different calculation schemes can be used for different sets of input data. Thus the model of the magnetic field should not depend directly on the input data (measurements).

The model that satisfies all these requirements is the Paraboloid model of the magnetosphere which has been developed by I. I. Alexeev and is maintained by a group of researchers from the Skobeltsyn Institute of Nuclear Physics of the Moscow State University [*Alexeev*, 1987; *Alexeev and Bobrovnikov*, 1997, 1999].

The magnetic field calculation using the Paraboloid model is presented in Figure 1. It is important to note that this is a two-step scheme. The first one is the calculation of the model parameters. At this step, some empirical ideas or models ("submodels") can be used to find the parameters. However, the Paraboloid model can be used at this step for the iteration process ("Feedback" arrow in Figure 1) to ob-

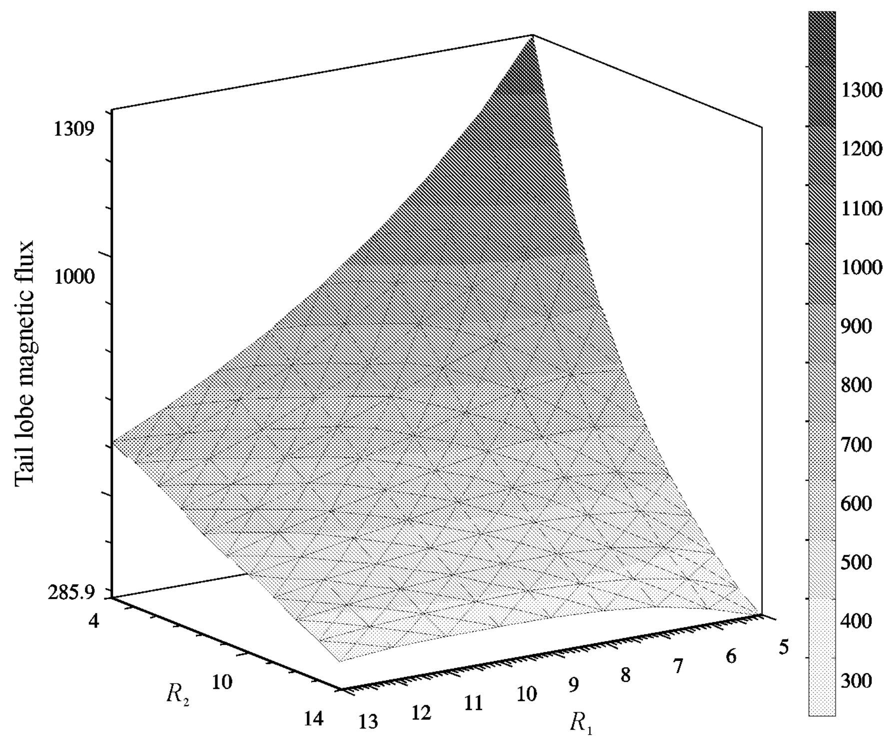

Figure 2. Critical values of the magnetic flux in the tail lobe (polar cap).

tain the best results. It is one of the most important parts of any calculation scheme. It allows us to satisfy the important conditions that cannot be obtained with an appropriate accuracy from empirical "submodels." The second step is a calculation of the magnetic field anywhere in the magnetosphere. An example of the calculation using this scheme is presented below.

Substorm Onset in the Model

Substorm onset is the most important feature of substorms. Thus the model we are going to use should represent the substorm onset in terms of its parameters. Let us consider three principal parameters of the Paraboloid model: the distance to the subsolar point R_1, the distance to the earthward edge of the tail current sheet R_2, and the magnetic flux in the polar cap Φ_{PC}. There are also three sources of the magnetospheric magnetic field: the dipole, the magnetopause currents screening the dipole, and the tail current system consisting of the cross-tail current and magnetopause screening (and closure) currents. Playing with these parameters of the magnetic field, we found that at appropriate values of these parameters a point with $B_z = 0$ appears at the inner edge of the tail current sheet. This can be associated with neutral line formation in the plasma sheet at the onset time. However, the question that remains to be answered is: Does it really have physical meaning?

The neutral point appears at relatively high values of the magnetic flux in the polar cap (in the tail lobe). This high value of Φ_{PC} corresponds to the enhanced cross-tail current observed during substorms. Thus the neutral point in the Paraboloid model is formed when the cross-tail current is highly enhanced, the situation being very similar to the substorm onset conditions.

The Paraboloid model enables calculation of all possible values of the model parameters corresponding to the neutral point formation. The results obtained are presented in Figure 2. It can be seen that the critical value of Φ_{PC} increases strongly when the distances to the subsolar point and to the inner edge of the tail current sheet decrease and vice versa. It is important to note that taking into account the ring current and Region 1 field-aligned current slightly changes the results of the calculations.

On the basis of Figure 3, which shows the field lines in the Paraboloid model at the noon-midnight meridian, we define three magnetospheric domains and their magnetic fluxes.

1. Φ_{head} is the magnetic flux in the inner magnetosphere.
2. Φ_{lobe} is the magnetic flux in the tail lobe (at the infinity) equal to the polar cap magnetic flux (Φ_{PC}).
3. Φ_{PS} is the magnetic flux through the plasma sheet (from the inner edge of the current sheet up to infinity), forming the auroral oval.

Therefore the main condition for the stability of the magnetosphere is

$$\Phi_{\mathrm{dipole}} = \Phi_{\mathrm{head}} + \Phi_{\mathrm{lobe}} + \Phi_{\mathrm{PS}} \tag{1}$$

Φ_{dipole} is the total magnetospheric magnetic flux which is equal to the magnetic flux of the Earth's dipole. Formation of the neutral point violates this equation. At this time,

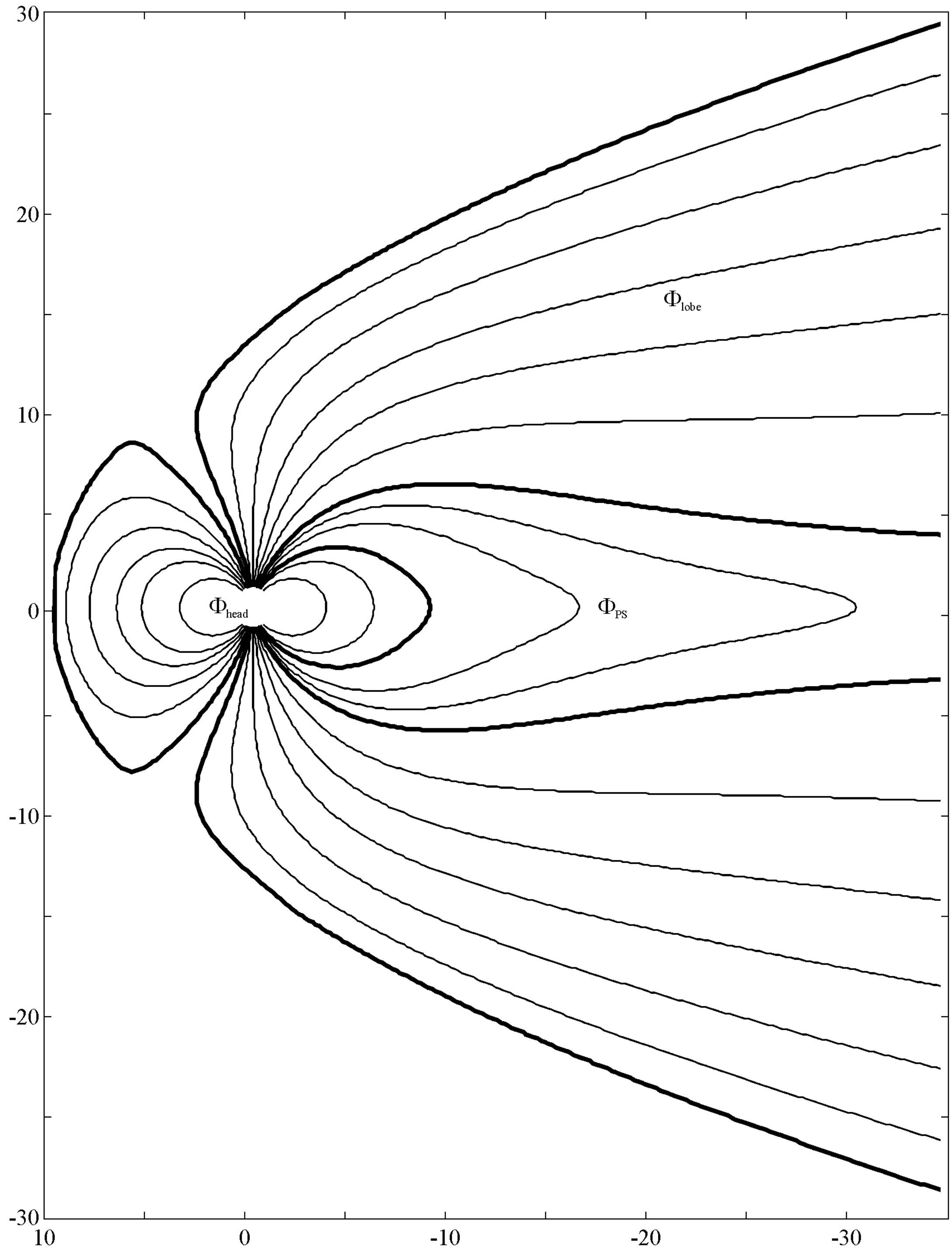

Figure 3. Magnetic field lines in the Paraboloid model (noon-midnight cross section) and division in three major magnetospheric domains.

Φ_{PS} becomes different from the auroral oval magnetic flux, and Φ_{lobe} becomes different from the polar cap magnetic flux. The polar cap and auroral oval magnetic fluxes decrease abruptly and the magnetic flux in the inner magnetosphere increases (dipolarization). This is the process that goes on after the expansion of a substorm. We believe that we defined the substorm onset conditions in terms of the model parameters.

The location of the neutral point remains to be mentioned. In our model the neutral point appears at the inner edge of the tail current sheet close to the magnetopause, and one can say that it is not a proper place for a substorm onset initiation. As mentioned above, "contradictions to the observations should correspond to some of the active magnetospheric phenomena and should be considered as a limit for the model application"; that is, formation of the neutral point corresponds to the limit of the model applicability. The results of the calculations performed after this limit time cannot be treated as reliable.

Indeed, for our study it is most important that the B_z component of the magnetic field becomes zero somewhere in the magnetosphere as the cross-tail current increases. It corresponds to the conditions when an additional magnetic flux is needed to transform the magnetospheric configuration. This is what we call global instability of the magnetosphere. The neutral point formation is considered as an incapability of the magnetosphere to redistribute the magnetic flux according to new external or internal conditions.

Equation (1) yields that an increase of the magnetic flux in one of the defined domains leads to a decrease of the fluxes in the other domains. After the IMF turns northward, the inner magnetospheric domain grows, and Φ_{head} increases. At the same time, the tail lobe magnetic flux Φ_{lobe} does not change. In fact, this process must be accompanied by a decrease of the magnetic flux in the plasma sheet. If this decrease is larger than the initial Φ_{PS}, the neutral line should appear.

Thus the final statement of this section is that the above considerations are model independent: only real values of the magnetic fluxes depend on particular model.

Scenario of a Substorm

Now we would like to propose a possible scenario for substorms triggered by the IMF northward turning. This kind of substorm is chosen it has the most obvious influence on the model parameters.

Again, let us consider three parameters of the model: R_1, R_2, and Φ_{lobe}. During the growth phase of the substorm the standoff distance decreases, the magnetopause shifting earthward. The subsolar distance and the magnetopause form were found as functions of solar wind parameters by *Shue et al.* [1997]. It has been noted that this distance depended on the IMF B_z component, decreasing when the IMF B_z becomes negative. We think this phenomenon may have two explanations. The first cause: when the IMF turns southward the intensity of the field-aligned currents increases significantly. They give a negative contribution of about 10 nT to the magnetic field in the dayside magnetosphere [*Alexeev et al.*, 1997; *Tsyganenko and Sibeck*, 1994]. The other cause is an increase of the cross-tail current. Its contribution to the dayside magnetosphere is of the same order as that of the field-aligned currents [*Alexeev and Bobrovnikov*, 1997; *Alexeev et al.*, 1997]. The magnetic pressure at the subsolar point decreases with the enhancement of the field-aligned or tail currents. This is followed by a decrease of the standoff distance.

Other parameters changing during substorms are the distance to the inner edge of the tail current sheet and the magnetic flux in the tail lobe. It is also well known that during the substorm growth phase the magnetic flux increases and the tail current sheet moves earthward. An increase of the magnetic flux corresponds to a high level of energy transport from the solar wind to the magnetosphere, the cross-tail current enhancing simultaneously.

We assume that the magnetosphere tends to develop in such a way that the energy of the solar-wind–magnetosphere interaction remains minimal. An increase of the tail lobe magnetic flux increases the flaring angle of the magnetosphere, leading to an enhancement of the magnetosphere cross section as viewed from the Sun. If one considers the dependence of the magnetic flux on the distance to the inner edge of the tail current sheet with other fixed parameters (the subsolar distances and current at the inner edge of the current sheet), one finds that the magnetic flux decreases as the cross-tail current moves earthward. Taking into account this feature, we can present the growth phase as a sequence of two-step processes: (1) the enhancement of the cross-tail current and magnetic flux in tail lobe and (2) the earthward displacement of the current sheet.

The last step partially compensates the increase of the magnetic flux and is limited by magnetohydrodynamic (MHD) equilibrium conditions in the tail. Thus the earthward displacement of the current sheet reduces the energy of the solar-wind–magnetosphere interaction. It can also be noted that the R_1 and R_2 values cannot decrease without limit. The displacement is limited by the pressure balance on the magnetopause and MHD equilibrium in the tail.

Now the scenario of substorm growth and expansion can be described as follows: When the IMF turns southward and energy transfer into the magnetosphere increases, both of the above mentioned distances (R_1 and R_2) decrease and an increase of the tail flux (Φ_{lobe}) begins. This process has a low probability to reach the critical values and thus low probability of substorm onset. The tail lobe magnetic flux comes very close to the "critical" value, but the behavior of the model parameters (R_1 and R_2) does not allow Φ_{lobe} to exceed it. When the IMF turns northward, the negative contribution of the Region 1 field-aligned currents to the magnetic field in the dayside magnetosphere disappears, the magnetic field pressure in the dayside magnetosphere increasing and the magnetopause moving away from the Earth. Moreover, the positive contribution of the field-aligned currents to the magnetic field in the nightside magnetosphere also disappears, the Ampere force decreasing and the tail current sheet moving tailward. It is important to note that changes in the IMF, which first appear at the subsolar point, can change the current in the plasma sheet with some delay. This delay can be estimated as 5–15 min. During this period the following process will take place.

When IMF turns northward, the Region 1 field-aligned currents disappear, the magnetic pressure at the dayside magnetosphere (near the subsolar point) increasing. The magnetopause moves away from the Earth (R_1 increases). The same process begins in the tail: the current sheet moves tail-ward (R_2 increases). During this period of time the tail lobe magnetic flux Φ_{lobe} does not decrease, but the critical value does. If, during the substorm growth phase, a sufficient amount of energy has been stored in the magnetospheric tail

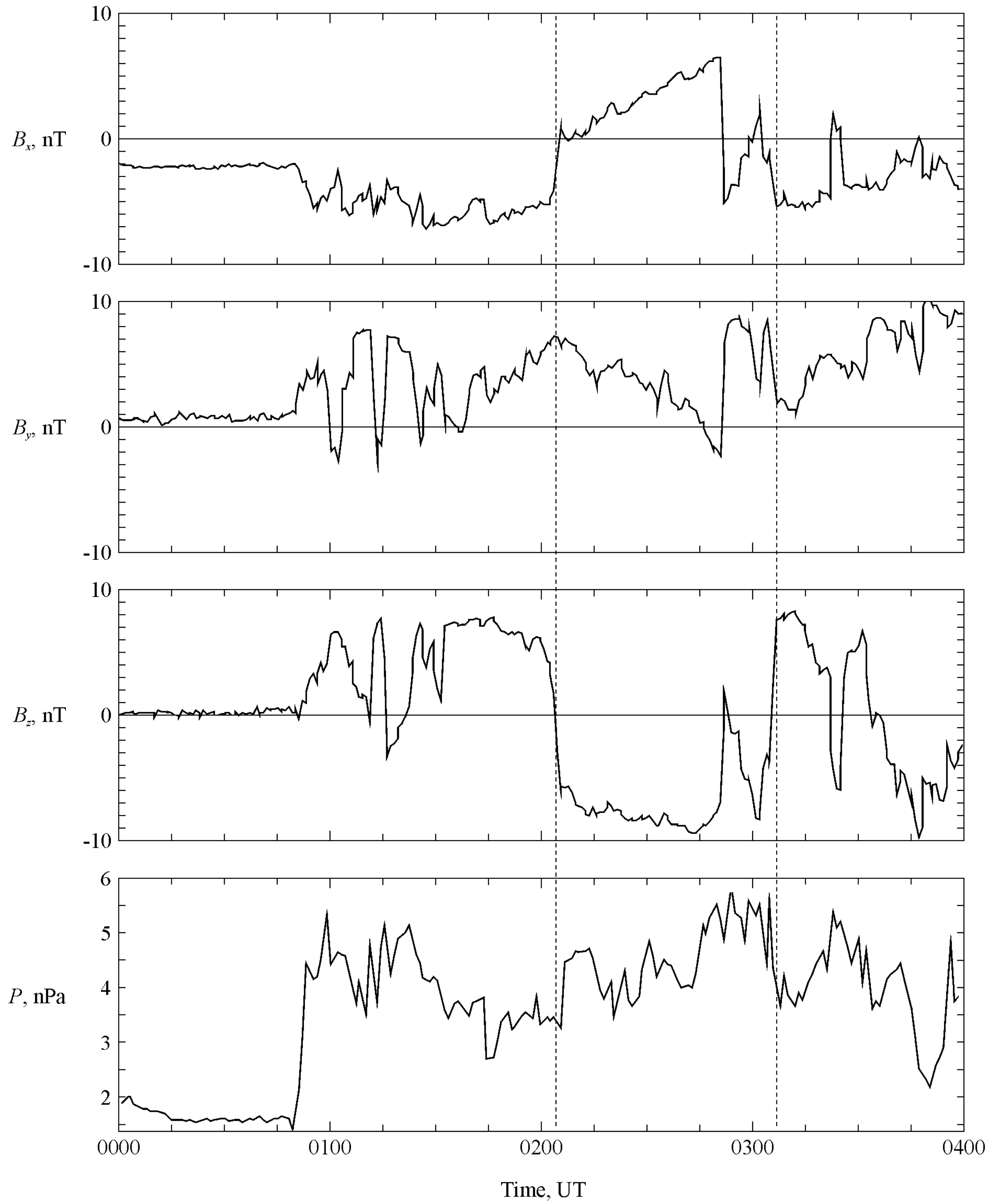

Figure 4. Wind spacecraft data during a substorm, 10 January 1997.

or tail lobe, the magnetic flux comes very close to the "critical" value (metastable state), and it is quite possible for the $\Phi_{\rm lobe}$ magnetic flux to reach and exceed the critical value.

It is important to note, again, that the tail will react to the changes in the IMF with some delay, but the Region 1 field-aligned currents will react to these changes almost simultaneously. This is the core of the substorm triggering by the IMF northward turning [*Alexeev and Bobrovnikov*, 1999].

Substorm Event of 10 January 1997

Although the scenario described in the previous section looks rather promising, it is very important to test it with a real event, using the above described calculation scheme. There is an interesting approach to the study of magnetospheric substorms by using nonlinear filters [e.g., *Sitnov et al.*, 2000; *Vassiliadis et al.*, 1995]. The basic idea of these filters is to reproduce the output time series of the substorm activity, mainly the AL index, based on the input time series, which are mainly the solar wind parameters and the interplanetary magnetic field. This technique can also be called a forecasting of the AL index. In such methods, filters represent the magnetospheric dynamics, no real magnetospheric processes being involved in the scheme. In this case, the magnetosphere acts as a "black box" with an input gate for the solar wind data and an output gate for the magnetospheric indices.

Another widely used approach is a detailed investigation of the plasma processes in various domains of the magnetosphere and ionosphere. The essence of such type of research is to study a sequence of local processes in the magnetosphere by applying the sophisticated physical models of plasma processes based on local MHD, particle, or wave simulation. When this approach is used, a substorm as a global phenomenon becomes hidden.

As it was mentioned earlier, current studies support the idea that a substorm is a global instability of the magnetosphere. From this viewpoint the former approach seems more adequate but veiling the magnetosphere as a system of the magnetic field and plasma processes. In this paper we would like to present the calculation scheme, which resembles the filtering approach but uses the real magnetospheric model in the core of the filter.

Let us now explain our choice of the substorm event. First of all, it is a typical and clear case of the substorm triggering by the IMF northward turning, and it can thus support (or reject) our scenario of such events. The other reason is that it presents a well-investigated substorm, and most of the investigations support our ideas, especially those concerning time delay between the changes in the IMF and substorm expansion onset. *Tsurutani et al.* [1998] estimated it to be about 8–12 min, and this value is also supported by the Lyons study [*Lyons et al.*, 1998]. In the latter paper the degradation of the ionospheric convection related to the Region 1 field-aligned currents was observed immediately after the IMF turned northward. It presents the evidence that we are right in assuming that the Region 1 field-aligned currents play a key role in substorm triggering by IMF northward turning.

Now we present the calculation scheme taking into account the solar wind dynamic pressure, IMF B_z component, and time delay (6–8 min) between the changes in the IMF and the tail reaction to them.

Using the input data presented in Figure 4, let us try to satisfy the pressure balance at the subsolar point. Then the calculation scheme can be described as follows:

1. Take a reasonable value of R_1 (the magnetopause subsolar distance) based on, for example, *Shue et al.* [1997].
2. Calculate R_2 (the distance to the earthward edge of the tail current sheet) with the simple formula $R_2(t) = K(B_z(t-\Delta t)) \times R_1(t-\Delta t)$ (taking into account the time delay).
3. Take the value of the magnetic flux $\Phi_{\rm lobe} = 380$ MWb as the initial value for iterations.
4. Trace the inner edge of the current sheet (R_2) along a magnetic field line to the ionosphere, which can be done in the Paraboloid model very simply.
5. Calculate the new flux $\Phi_{\rm lobe}$ through the polar cap. At this point we use the empirical relation between the auroral oval magnetic flux, which can be calculated directly, and the polar cap magnetic flux. This relation depends on the IMF B_z with the same delay.
6. Compare the new value of the magnetic flux with the old one and repeat steps 4 and 5 to attain appropriate precision by changing R_2.
7. If the pressure balance is not attained, change R_1 with the appropriate step and repeat the scheme from step 2 except for the initial magnetic flux, which should now have the last calculated value.

The results of the calculations are presented in Figure 5. At the time, marked by the second vertical dashed line, the magnetic flux in the tail lobe exceeds its critical value. This time corresponds well to the auroral intensifications observed onboard the polar spacecraft and by the ground-based magnetometers.

Now it is time to answer the question: What can we obtain from this scheme? The answer is simple. As our scheme resembles the use of filters on the solar wind data, it enables prediction of some features of a substorm. First of all, the time of the substorm expansion onset is predicted. It can be seen from Figure 4 that there are two IMF northward turnings during the period of substorm development. However, only the latter one produces the substorm onset in reality and in our calculations.

The major advantage of our method is that we have a set of model parameters continuous in time. It enables various calculations based on the Paraboloid model. They may be a calculation of Dst index, a calculation of the magnetic field at geostationary orbits during substorm, a field-line tracing that reveals the dynamics of the magnetic field line during the substorm growth phase, and calculation of the auroral oval and polar cap boundaries, which enables estimation of the substorm energetics. An example of the results of such calculations is shown in Figure 6. This figure shows the auroral oval and polar cap boundaries for the quiet magnetosphere (left) and for the late substorm growth phase. A significant increase of the polar cap and auroral oval due to the substorm development can be seen. The equatorward edge of the auroral oval approaches 60° of latitude and this is in a good agreement whith the ultraviolet images (UVI) images from the polar spacecraft. Our calculations of the polar cap behavior are also in a good agreement (minimum at 0240 UT and maximum at 0337 UT) with the results obtained by *Brittnacher et al.* [1999].

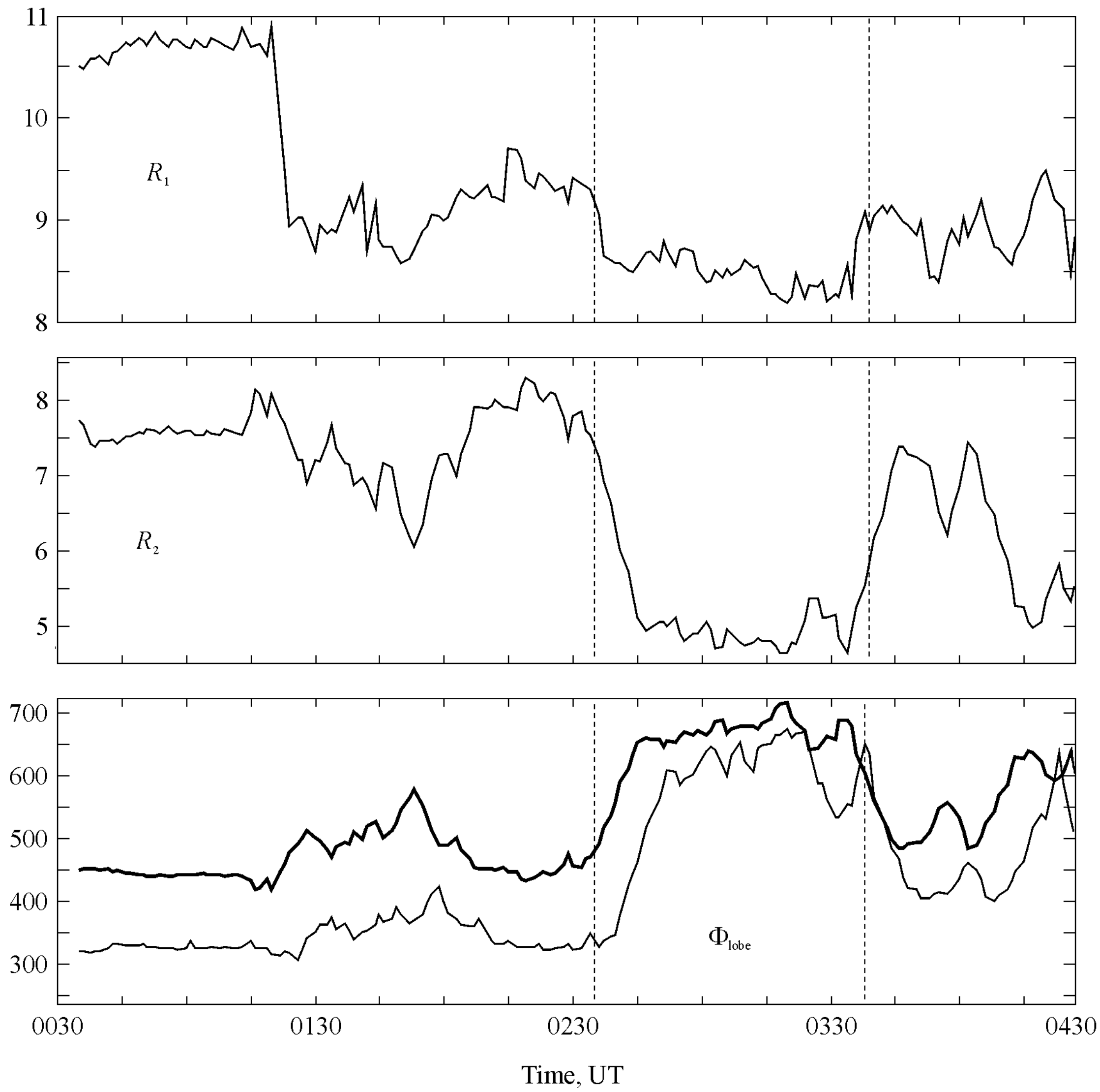

Figure 5. Dynamics of the model parameters during the 10 January 1997, substorm.

Discussion and Conclusions

In conclusion, we would like to point out the advantages and disadvantages of our study. First of all, it concerns the Paraboloid model of the magnetospheric magnetic field and the appearance of the neutral point. The neutral point appears at the inner edge of the tail current sheet close to the magnetopause, but measurements show that this should happen close to the Earth–Sun line at ~10–20 R_E. This discrepancy can be explained by a relatively simple model of the tail current system magnetic field. For example, this model has insufficient warp of the inner edge around the Earth, so the magnetic field produced by the tail current system in the near magnetopause region at the earthward edge becomes overestimated. However, the displacement of this point would not influence the essence of our approach. Assuming the substorm to be a global instability of the magnetosphere, we would like to answer the following question: Why can the IMF northward turning trigger the substorm, and we would not like to answer the question where the onset starts.

The presented scenario of the external triggering is based on well-examined facts. It is well known that the magnetopause moves earthward during the substorm growth phase and there exists a number of models of the standoff distance [e.g., *Shue et al.*, 1997]. The enhancement of the lobe magnetic flux is also well known due to measurements of the lobe magnetic field and polar cap boundaries. The earthward displacement of the tail current sheet is also confirmed by an increase of the auroral oval size. We tried to clarify the causes of such magnetospheric dynamics and to create the simplest scenario of the substorm growth phase.

We have a simple scenario, and we have a simple calcu-

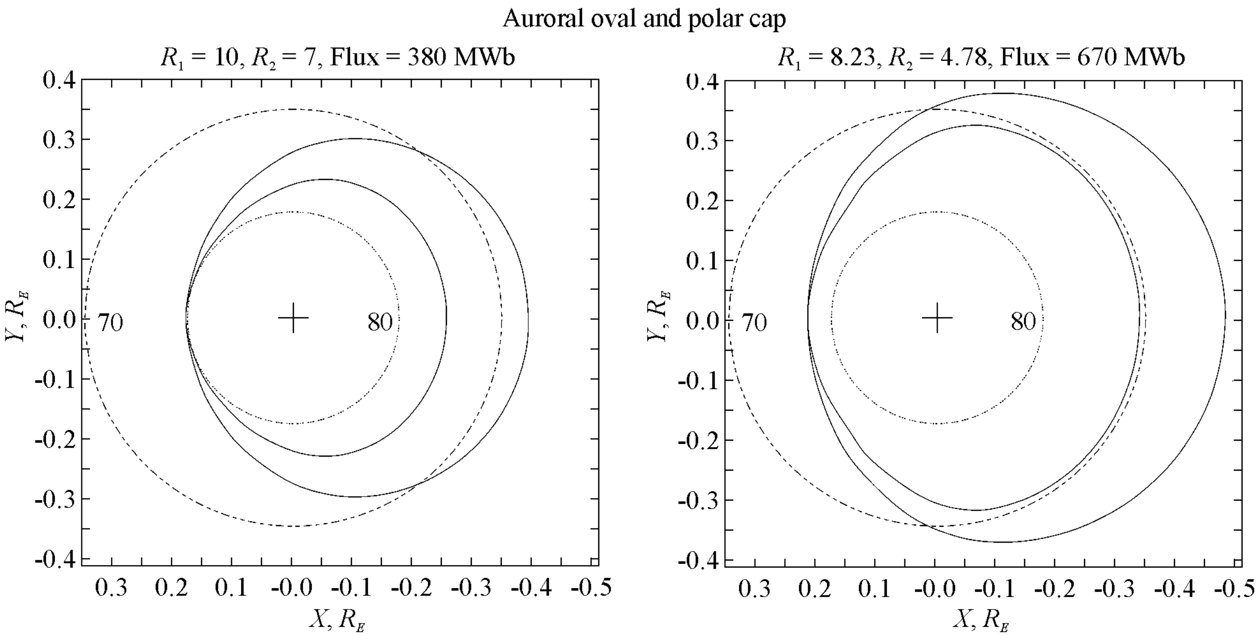

Figure 6. Polar cap and auroral oval for the quiet/average magnetosphere (left) and during the late substorm growth phase (right).

lation scheme based on simple assumptions on the model parameter dependencies upon the solar wind and interplanetary magnetic field data. In the future we plan to develop a better scenario of substorms, taking into account a greater number of the input data and the model parameters.

Now, what can be inferred from our study? First, we would like to support the idea that a substorm is a global magnetospheric phenomenon which comprises many different processes with different spatial timescales and intensity. To answer the questions when and where the onset will start and what will be the intensity of the expansion phase, we need to know simultaneously the conditions in many regions of the magnetosphere, in the ionosphere, and in the solar wind. We would also like to point out that it is possible to determine the onset time and intensity of the substorm expansion phase using the global model, which yields the information about the magnetic field in every magnetospheric region, and knowing the conditions in the solar wind. Finally, the presented scenario of substorms triggered by the IMF northward turning and the calculation scheme can be described as a good approximation of real events. However, it is important to improve the scenario to be able to investigate a wider range of substorms.

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(Received 14 August 2001; accepted 16 October 2001)