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A simple model of magnetopause erosion as a consequence of pile-up process and bursty reconnection

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Abstract. A southward turning of the interplanetary magnetic field (IMF) was found to cause an Earthward motion of the magnetopause of 1–2 R_E without a change of dynamic pressure in the solar wind. This effect is known as erosion of the dayside magnetosphere and it has been explained in terms of reconnection of the IMF and the magnetospheric magnetic field. But so far, it is not quite clear how the three most popular models of erosion are connected: The transfer of magnetic flux from the dayside to the nightside magnetosphere, the effect of a Birkeland current loop in the cusp region, and the penetration of magnetic field from the magnetosheath into the magnetosphere. To clarify this question, we investigate erosion as a consequence of local bursty reconnection and pile-up process. It turns out that flux transfer from both sides of the magnetopause, in general, has different rates. This leads to a pressure unbalance for short periods between reconnection pulses, and, hence, to jumps of magnetopause erosion. This model seems to incorporate all three mechanisms of erosion mentioned above, and in particular it emphasizes the importance of the pile-up (magnetic barrier) process in the magnetosheath.

1. Introduction

From the theoretical point of view, the magnetosphere is a direct result of impenetrability or frozen-in magnetic field condition of two highly conducting magnetoplasmas. Hereby, the magnetopause can be interpreted as a tangential discontinuity across which pressure is in balance. Hence, as investigated first by *Mead and Beard* [1964], the standoff distance of the magnetopause can be determined from pressure balance. More specifically, the magnetopause is located at a distance where the planetary magnetic field pressure (the particles make only a negligible contribution) equals the dynamic pressure of the solar wind (neglecting the small contribution of the interplanetary magnetic field (IMF)). It is clear that when parameters defining the pressure balance change, the position of the magnetopause will also vary.

It emerges from the above that the primary source of magnetopause motion is a change in dynamic pressure of the solar wind. However, there is another source that makes the magnetopause move earthward even when the dynamic pressure is constant. This phenomenon is called "erosion" and was identified in the 1970s when magnetopause crossings made by the OGO 5 spacecraft were investigated [*Aubry et al.,* 1970; *Fairfield*, 1971]. Recent observational signatures of erosion in the inner magnetosphere have been reported by *Sibeck* [1994] and *Tsyganenko and Sibeck* [1994].

Quite generally, one can say that erosion happens during intervals when the IMF has a persistent southward component, $B_z < 0$. Furthermore, the amount of erosion depends on the strength of this north-south component and can be of

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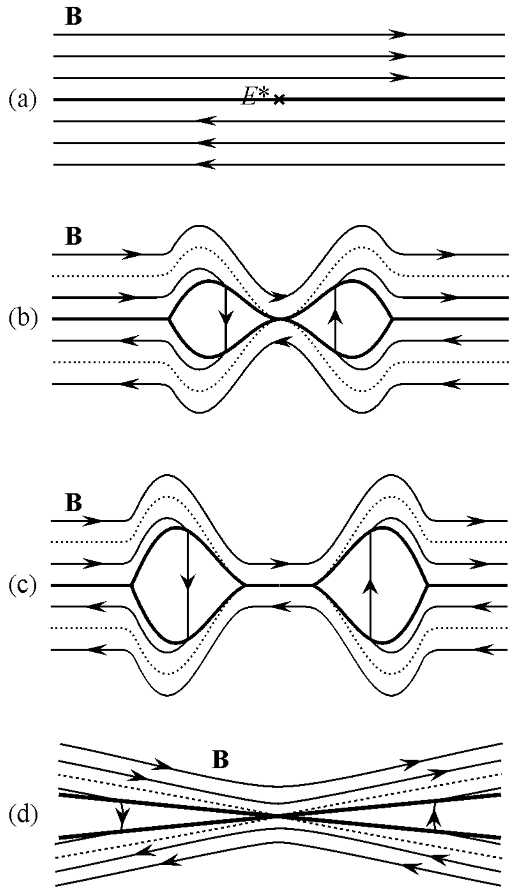

Figure 1. A closer look at the reconnection layer. The plasma approaches from the inflow region (IR), passes the structure of discontinuities, and flows out after transmitting magnetic energy from the field into kinetic energy of the plasma (field reversal (FR) region). (a) Initial current sheet and site of conductivity breakdown. (b) Switch-on phase of reconnection. (c) Switch-off phase of reconnection. (d) Steady-state Petschek reconnection.

the order of 1 R_E for every 5 nT B_z negative [*Kawano and Russell*, 1997]. With this in mind, models of magnetopause shape have been developed that account for both the solar wind dynamic pressure and the IMF B_z component [*Petrinec and Russell*, 1996; *Roelof and Sibeck*, 1993; *Shue et al.,* 1997, 1998]. For fixed dynamic pressure, these empirically based models give the displacement of the magnetopause resulting from the IMF B_z.

Since a persistent southward orientation of the IMF is a prerequisite for magnetic reconnection, a physical connection between the erosion and reconnection phenomenon was established. The reconnection process "opens" terrestrial field lines; that is, as a result, magnetic field lines exist with one "end" in the ionosphere and another in the flowing magnetosheath plasma, that is ultimately in the solar wind [*Dungey*, 1961]. Indeed, many features of erosion can be modeled in terms of a reconnection model. Nevertheless, one can say in general terms that the physics of dayside magnetosphere erosion is still only partially understood.

So far, the analysis of erosion leads only to the identification of several distinct features, which in turn lead to the development of specific model approaches. These can be summarized as follows:

- Reconnection leads to a transfer of magnetic flux from the dayside to the nightside magnetosphere, where it builds up during the so-called growth phase of a substorm prior to release at substorm onset. On the dayside, magnetic field intensity decreases near the subsolar point, pressure balance is violated, and a motion of the magnetopause toward Earth ensues [*Holzer and Slavin*, 1978]. Possibly when an instability threshold is reached, [*Baker et al.,* 1984, *McPherron et al.,* 1973] reconnection starts in the geomagnetic tail, which returns magnetic flux to the dayside. When the reconnection rates are balanced, the magnetosphere reaches a new equilibrium position and shape, and erosion has stopped.

- *Maltsev and Lyatsky* [1975] and *Sibeck et al.* [1991] proposed a model in which erosion is interpreted as the effect of a Birkeland current loop in the cusp region. When the IMF B_z turns southward, the strength of the region 1 Birkeland currents increases. The fringe fields of these Birkeland currents act to reduce the magnetic field strength within the outer dayside magnetosphere. Thus, when the interplanetary magnetic field turns southward, the dayside magnetopause moves inward to restore pressure balance.

- *Kovner and Feldstein* [1973] attributed erosion to the penetration of the magnetic field from the magnetosheath to the magnetosphere. Their hypothesis was subsequently developed further by *Pudovkin et al.* [1998], who assumed that field penetration is associated with magnetic field reconnection.

Hence, at present, although various aspects of magnetopause erosion have been studied, a global picture of the detailed physics behind this phenomena awaits elaboration.

A goal of this paper is to analyze the above-mentioned approaches and put them into a global perspective. To correctly understand the effects of magnetospheric erosion, it is necessary — in our view — to take into account a variety of interrelated phenomena, including the appearance of the magnetic barrier near the magnetopause, unsteady (bursty) reconnection of the IMF and the magnetospheric magnetic field, and consequences of reconnection such as the penetration of the IMF to the magnetosphere. Only after a careful investigation of all these effects is it possible to analyze pressure balance and investigate erosion phenomenon in detail.

2. Unsteady Reconnection

In the beginning of this paper we do not consider the magnetopause in all its details but instead pay attention to a simple theoretical system consisting of a three-dimensional current sheet separating two uniform and identical plasmas with oppositely directed magnetic fields (Figure 1a).

Due to the frozen-in condition, the plasma and magnetic field from different sources do not intermix and occupy separate regions, magnetosphere and magnetosheath, for example, and in our simple case, half spaces above and below the current sheet. From the physical point of view, it is clear that free energy cannot be accumulated infinitely by adding magnetic flux from outside and storing it at the current sheet. Eventually, the gradients there become so sharp that the plasma loses the frozen-in property, and this is the starting point for reconnection.

Since current sheets such as the magnetopause are highly non-uniform in nature, it seems reasonable to suppose that the breakdown of the frozen-in approximation occurs locally in the current sheet due to some kind of dissipation mechanism rather than instantaneously throughout the whole length. This natural assumption distinguishes Petschek-type reconnection (local dissipation) from magnetic field annihilation theories such as magnetic field diffusion [*Parker*, 1963; *Sweet*, 1958] or the tearing instability [*Galeev et al.,* 1986]. For space and astrophysical applications, pure magnetic field diffusion is too slow to be of interest, but, as was first realized by *Petschek* [1964], those disturbances can be transmitted through the plasma via large-amplitude MHD waves or shocks. These waves rapidly escape from the dissipative region where reconnection is initiated, transfer the reconnection-associated disturbances to other parts of the current sheet, and establish an outflow region for the plasma streaming toward the current sheet (Figure 1b). Plasma entering the outflow region is accelerated and heated at the slow shocks and then collected inside. The outflow region is also referred to as the field-reversal region, since it connects magnetic field lines across the current sheet, thus establishing a topologically new region of reconnected flux. The leading front of the outflow region is propagated along the current sheet with Alfvén velocity, and therefore the size of the outflow region rapidly outgrows that of the diffusion region, so that the former provides the dominant means of converting and transporting energy and momentum during the reconnection process [*Semenov et al.,* 1983].

So far, we have described the switch-on phase of reconnection, when a dissipative electric field is generated in the diffusion region. But Petschek's wave mechanism does not operate continuously and at all times. At some stage, reconnection should switch off (Figure 1c), in which case no more reconnected flux is added to the system. The slow shocks and the separatrices, which bound the reconnected flux tubes, detach from the former site of diffusion at the time of switch-off. Since the diffusion region no longer acts as a generator of a dissipative electric field and MHD waves, the outflow region will also detach from the reconnection site, and it propagates like a pair of solitary waves in opposite directions along the current sheet. But the outflow region cannot be considered as a soliton, because the slow shocks previously generated continue to propagate toward the edges of the current sheet and to accelerate and heat plasma so that all plasma inside the reconnected tubes bounded by separatrices will be trapped inside the outflow region. Therefore, the outflow region continues to change shape and increase in size even though no more reconnected flux is added.

During the switch-on phase in the immediate vicinity of the diffusion region, the structure of magnetic field and plasma flow is very similar to the original Petschek model (Figure 1b) and, indeed, it can be shown that the time-dependent reconnection solution tends to Petschek's solution in this limit [*Pudovkin and Semenov*, 1985; *Semenov et al.,* 1983]. So, we can say that our model is an extension of Petschek's wave mechanism for the case of a time-varying reconnection rate. On the other hand, the global structure differs quite a lot from Petschek's picture depicted in Figure 1d, in particular, during the switch-off phase. We believe that a time-dependent reconnection model is more useful for applications than the original Petschek model of steady-state reconnection, since nearly all manifestations of reconnection are strongly time-dependent in nature and even are explosive in character.

We do not know enough about the way in which reconnection is initiated, but we can describe the large-scale consequences of the locally initiated reconnection process by adopting a semi-phenomenological approach. In this approach, we model the initiation introducting a reconnection electric field $E^*(r,t)$ inside the diffusion region rather than by specifying a concrete dissipative process. In addition, we assume, like Petschek, that the diffusion region is very small compared to the size of the system, so that in rough approximation, this region corresponds to the so-called reconnection or X-line. By the way, this is an example of a commonly used technique whereby non-ideal effects are lumped into discontinuities to work in the framework of ideal MHD. So, we are describing the diffusion region and the behavior of the dissipative process inside in terms of an initial-boundary condition to solve ideal MHD equations, and this initial-boundary condition corresponds to the specification of the X-line and the behavior of the reconnection rate $E^*(r,t)$ along it [*Rijnbeek and Semenov*, 1993].

The solution of the reconnection problem in an incompressible plasma in the dimensionless form can be presented as follows [*Biernat et al.,* 1987; *Pudovkin and Semenov*, 1985; *Semenov et al.,* 1983].

$$v_x = 1 \qquad v_z = 0 \tag{1}$$

$$B_x = 0 \qquad B_z = \varepsilon E^*(t-x,y) \tag{2}$$

$$z = \varepsilon x\, E^*(t-x,y) \tag{3}$$

where (1) is the plasma velocity; (2) is the magnetic field inside the field reversal region (FRR); (3) is the shape of Petschek shock for the first quadrant; $E^*(t,y)$ is the electric field along the reconnection line, or so-called reconnection rate. All quantities are normalized to the initial magnetic field B_0, the initial Alfvén velocity $v_A = B_0/(4\pi\rho)^{1/2}$, the length of the reconnection line L, the time L/v_A, the pressure $B_0/4\pi$, and the Alfvén electric field $E_A = B_0 v_A/c$. Here $\varepsilon = E^*/E_A \ll 1$ is a small parameter.

The first order corrections to the x component of the magnetic field and to the total (gas + magnetic) pressure in the

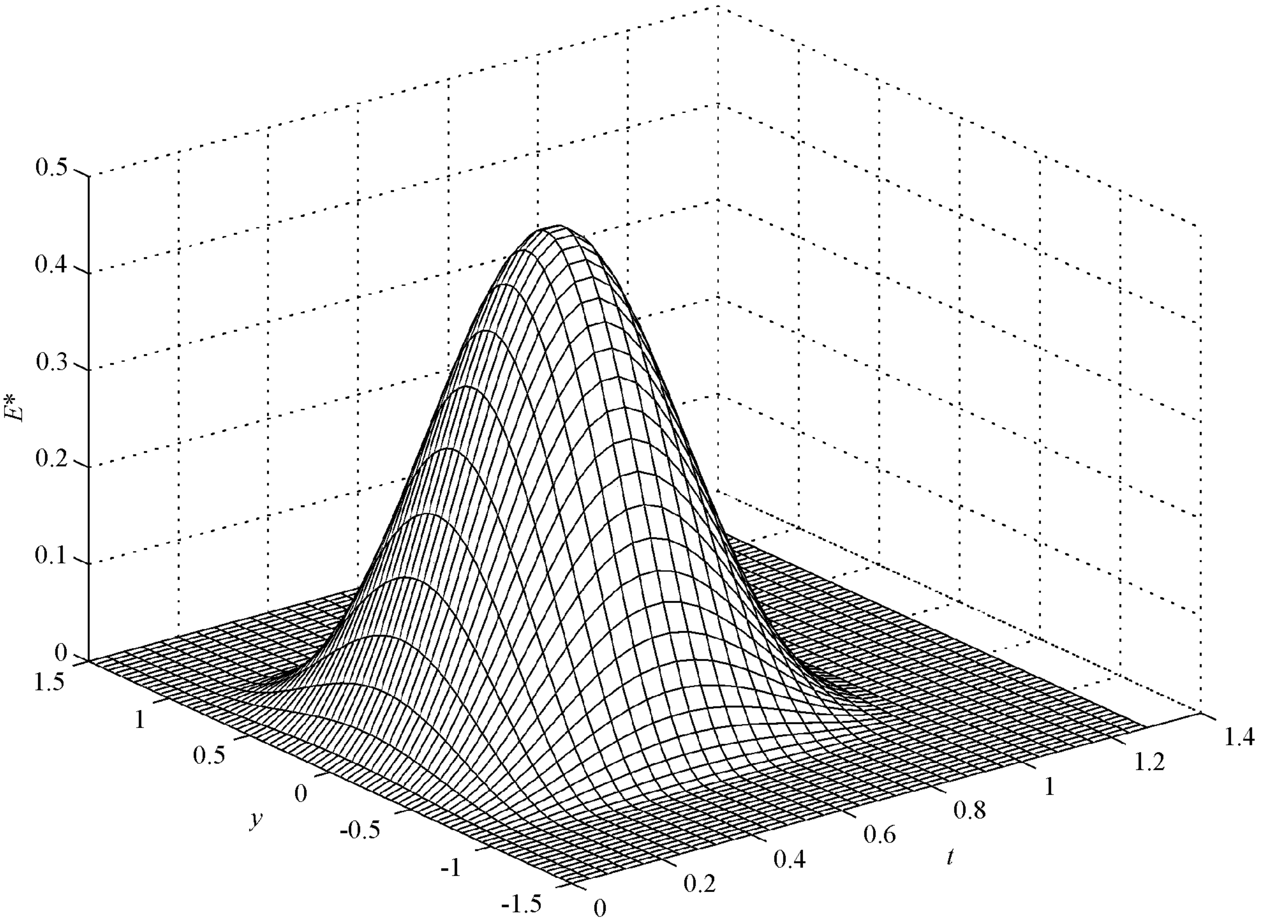

Figure 2. Behavior of the reconnection electric field as a function of time t and position along the reconnection line y.

inflow region (IR) can be obtained from the Poisson integrals

$$(B_x^{(1)},\, P^{(1)}) = \frac{\varepsilon}{2\pi}\int_{-t}^{+t} d\tilde{x} \int_{-1}^{+1} d\tilde{y}$$

$$\times \frac{(x-\tilde{x})\,(h_B, h_P)\,(\tilde{x},\tilde{y},t)}{((x-\tilde{x})^2+(y-\tilde{y})^2+z^2)^{3/2}} \qquad (4)$$

where

$$h_B(x,y,t) = 2E^*(t-x,y) - x\frac{d}{dt}E^*(t-x,y) \qquad (5)$$

$$h_P(x,y,t) = 2E^*(t-x,y) \qquad (6)$$

The whole solution (1)–(6) is defined by the reconnection rate $E^*(t,y)$. To model bursty reconnection, we can use series of pulses; one is shown in Figure 2.

3. Current Sheet Motion

Reconnection leads to transfer of magnetic flux from the reconnection site along the current sheet (see Figure 1). As a consequence, magnetic field intensity weakens near the diffusion region, and hence the total pressure decreases also. The behavior of disturbances $B_x^{(1)}(t)$ and $P^{(1)}(t)$ near the diffusion region (at $x = y = 0,\ z = 0.3$) is shown in Figure 3. It can be seen that the reconnection event also produces the negative pressure pulse in the vicinity of the reconnection site. The electric field in the diffusion region is first switched on, reaches its maximum value, and then decreases (Figure 2). Similarly, total pressure begins from the background value, reaches its minimum value, and increases when the FRRs run away during the switch-off phase (Figure 3). Asymptotically, the behavior of the total pressure disturbance during this last stage is as follows

$$P^{(1)} \sim -\frac{F_0}{\pi t^2}$$

where F_0 is the reconnected magnetic flux.

Such pressure variations happen from both the magnetosheath (sh) and the magnetosphere (mg) sides of the current sheet for the symmetric model used so far

$$P_{\rm sh} = P_{\rm sh}^{(0)} + P_{\rm sh}^{(1)} = P_{\rm mg} = P_{\rm mg}^{(0)} + P_{\rm mg}^{(1)} \qquad (7)$$

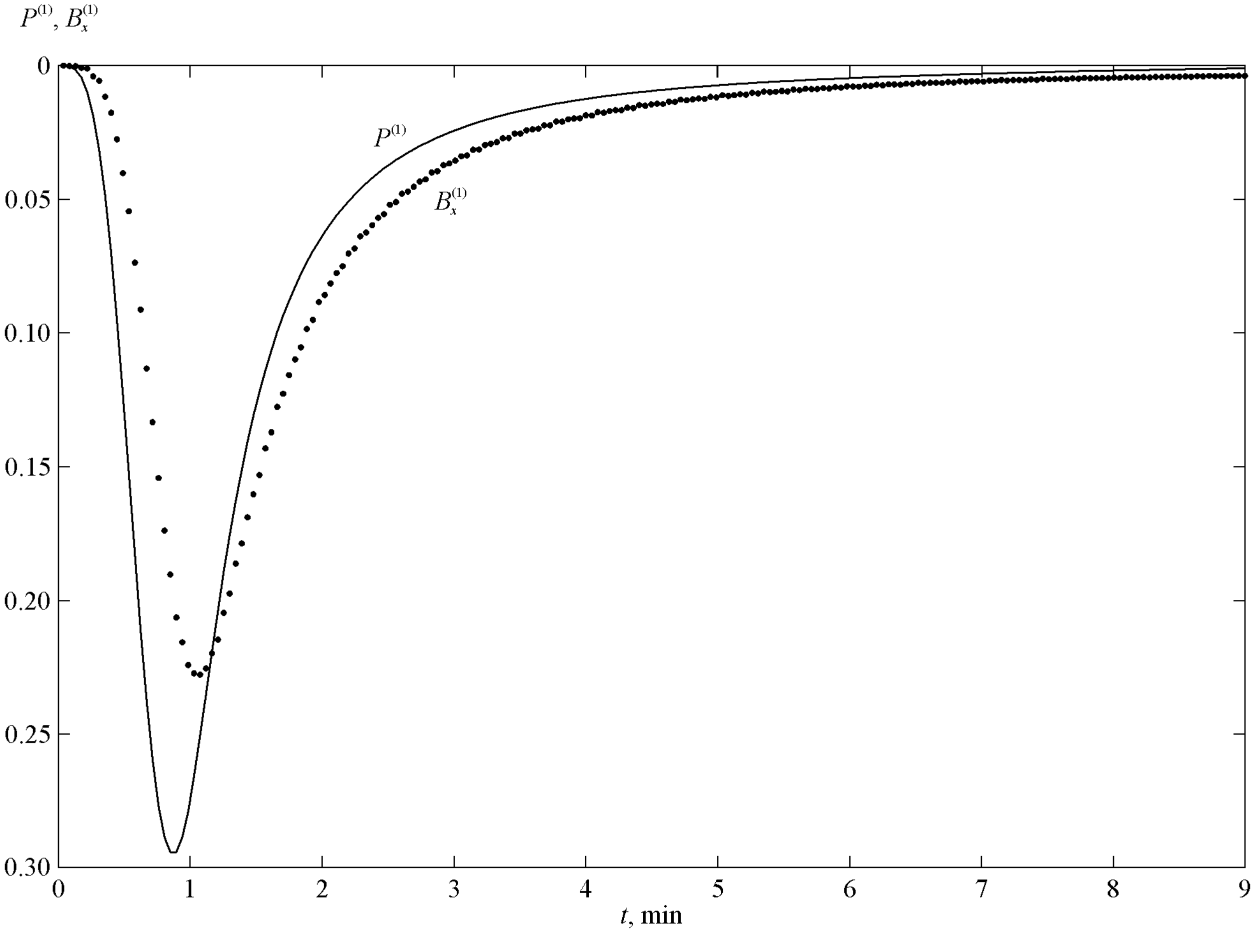

Figure 3. Behavior of disturbances tangential to the current sheet component of magnetic field $B_x^{(1)}$ (dotted curve) and total pressure $P^{(1)}$ (solid curve) near the diffusion region as a function of time.

and therefore, they can not lead to motion of the magnetopause. For motion to start, evidently some kind of asymmetry has to appear, and, indeed, physical conditions in the magnetosheath and in the magnetosphere are highly different. First of all, in the magnetosheath there is powerful solar wind flow. Second, there is bow shock at which dynamic pressure remains unchanged at $P_{\rm sh}^{(0)} = {\rm const}$ for the erosion events under consideration. Therefore, disturbances produced by reconnection at the magnetopause have to propagate against solar wind flow and then reflect from the bow shock. In the magnetosphere, there is neither bow shock nor strong plasma flow; hence, evolution of pressure disturbances produced by reconnection must be different in the magnetosheath and inside the magnetosphere.

Bearing these circumstances in mind, we can believe that total pressure from the magnetosheath side of the diffusion region has to tend to asymptotic value $P_{\rm sh}^{(0)} = {\rm const}$ more quickly than from the magnetosphere side.

Theoretically, it is rather difficult to determine exactly how fast $P_{\rm sh} \to P_{\rm sh}^{(0)}$, but we can make a simple estimation for the first consideration. We suppose that $P_{\rm sh} \to P_{\rm sh}^{(0)}$ with some characteristic time $t_{\rm sh}$, so that pressure balance at the magnetopause takes the form

$$P_{\rm sh} = P_{\rm sh}^{(0)} + P_{\rm sh}^{(1)} e^{-t/t_{\rm sh}} = P_{\rm mg} = P_{\rm mg}^{(0)} + P_{\rm mg}^{(1)} \qquad (7a)$$

A pressure pulse decays mostly due to the fast mode wave; therefore, t_{sh} can be estimated approximately as time propagation of the fast wave v_s from subsolar point to the bow shock $t_{\rm sh} = L_{\rm sh}/v_s$, where $L_{\rm sh} \sim 3R_E$ is the width of the magnetosheath. The relaxation time $t_{\rm sh}$ also can be estimated from the exact solution of unsteady annihilation [*Heyn and Pudovkin*, 1993] or from numerical simulation [*Pudovkin and Samsonov*, 1994].

The main idea of our model is that the breach in total pressure made by reconnection is closed faster from the magnetosheath side due to the powerful flow of the solar wind than from the magnetosphere side. This leads to an asymmetry in pressure balance and earthward motion of the magnetopause after each pulse of reconnection. The position of

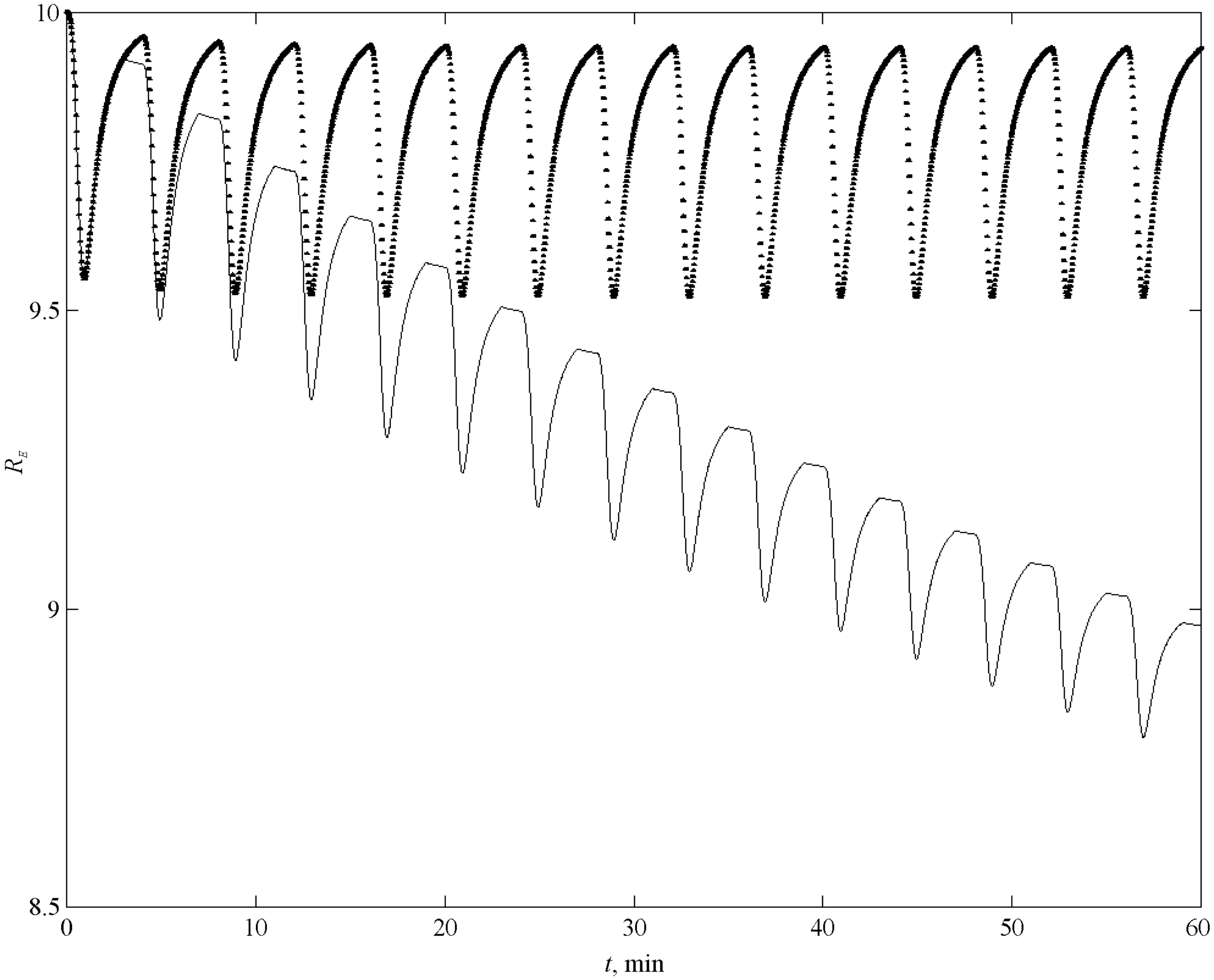

Figure 4. Inward motion of the magnetopause with (solid curve) and without (dotted curve) effect of field-aligned currents.

the magnetopause can be easily found from (7a)

$$r = 10\left(1 + P^{(1)}(t)(e^{-t/t_{sh}} - 1)\right)^{1/6} \tag{8}$$

where the variation of total pressure has to be taken from the equation (4), and initial position is supposed to be $r = 10\,R_E$. We can include N pulses of reconnection with time repetition t_r

$$r = 10\left(1 + \sum_{k=1}^{N} P^{(1)}(t - kt_r)(e^{-(t-kt_r)/t_{\mathrm{sh}}} - 1)\right)^{1/6} \tag{9}$$

We take the following initial parameters for the numerical calculation: The half-length of the reconnection line is $L = 3\,R_E$, the Alfvén velocity is $v_A = 300$ km s^{-1} as average of Alfvén velocity in the magnetosphere and in the magnetosheath, the reconnection rate is $\varepsilon = 0.3$, the pressure relaxation time is $t_{\mathrm{sh}} = 3$ min, the repetition time of reconnection pulses is $t_r = 5$ min.

The resulting stand-off distance of the magnetopause as a function of time is shown in Figure 4 (upper dotted line). It can be seen that each reconnection event leads to a jump-like motion to the Earth with a more smooth return nearly to the same level afterwards. It turns out that on average, the magnetopause shifts less than 1/4 R_E per hour. The contribution of all reconnection pulses is not enough for the observed 1 R_E erosion of the magnetopause, because each pressure pulse decreases rather fast $\sim 1/t^2$ (see (7)).

We still did not take into account the appearance of region 1 field-aligned currents. It is well known that a reconnection event generates field aligned currents [*Pudovkin and Semenov*, 1985]. As far as an FR-region moves along the current sheet (the magnetopause in our case), the contribution of this current system is included automatically in the pressure behavior near the diffusion region, but when reconnection-associated disturbances turn off from the current sheet (turn off from the magnetopause to the ionosphere in the cusp region), we have to take into account the contribution of the field-aligned current system separately.

Generally speaking, this problem is rather difficult, because we have to find a field-aligned current from each reconnection pulse, propagation of the field-aligned current in the form of an Alfvén wave from the cusp to the ionosphere, and then determine the contribution of this current system to pressure balance near the subsolar point. For the simple model under consideration, we will not attempt to solve this difficult problem but instead try to estimate the contribution of the region 1 field-aligned current system.

In our model, the FR-region propagates toward the cusp region and then turns off to the ionosphere along a magnetic field line. The pressure variation $P^{(1)}_{\rm mg}(t)$ can be calculated from equation (4) until the FR-region reaches the cusp. Our suggestion is that the contribution of the field-aligned current to the pressure balance at the subsolar point is constantly of the order of $P^{(1)}_{\rm mg}(t_{\rm cusp})$, where $t_{\rm cusp}$ is the time propagation of the FR-region from the diffusion region to the cusp. This implies that we suppose that for each reconnection event for $t < t_{\rm cusp}$ the pressure disturbance is determined by (4) and then keeps const $= P^{(1)}_{\rm mg}(t_{\rm cusp})$ for $t > t_{\rm cusp}$.

The result of magnetopause erosion based on this assumption is shown in Figure 4 (solid line). The jump-like behavior of the magnetopause motion is the same as previously, but the average shift is much bigger, $\sim 1\ R_E$. Therefore, the details (jumps) of magnetopause motion are determined by bursty reconnection, but erosion itself mostly depends on the strength of the region 1 field-aligned current system.

4. Discussion

The model described above naturally incorporates all three approaches to magnetopause erosion.

(1) Flux transfer [*Holzer and Slavin*, 1978]. Our model is based on the solution of the impulsive reconnection problem, which is determined by the reconnection electric field $E^*(t, y)$ (see (1)–(6)). The main physical reasons for the pressure pulse and the region 1 field-aligned current system are reconnection events and the transfer of reconnected flux from the dayside to the nightside of the magnetosphere.

(2) Penetration of the magnetic field from the magnetosheath to the magnetosphere [*Kovner and Feldstein*, 1973; *Pudovkin et al.*, 1998]. Let us rewrite pressure balance in terms of magnetic fields. For our simple model with a symmetric current sheet, we can suppose that the gas pressure in the magnetosheath and in the magnetosphere is the same; hence, the pressure balance is the following:

$$(B^{(0)}_{\rm sh})^2 + 2B^{(0)}_{\rm sh}B^{(1)}_{\rm sh}e^{-t/t_{\rm sh}} = (B^{(0)}_{\rm mg})^2 + 2B^{(0)}_{\rm mg}B^{(1)}_{\rm mg} \qquad (10)$$

After each reconnection event, the second term on the right-hand side of equation (10) is small for $t > t_{\rm sh}$. This implies that magnetosheath magnetic field effectively penetrates the magnetosphere at a relaxation time scale $t > t_{\rm sh}$ but magnetospheric field does not penetrate into the magnetosheath. It cannot be emphasized enough that no magnetic charges appear, and the same reconnected flux is subtracted from the magnetosphere and the magnetosheath initial flux. Penetration of magnetic field from the magnetosheath to the magnetosphere needs to be understood effectively as a consequence of different pressure pulse evolution in the magnetosheath and magnetosphere as it was described above. The bow shock and pile-up process (magnetic barrier) make an asymmetry in pressure pulse propagation, which leads to a jump-like motion of the magnetopause. Therefore, this effect is the essential component of the magnetopause erosion theory.

(3) Field-aligned currents [*Maltsev and Lyatsky*, 1975; *Sibeck et al.*, 1991]. Erosion is most often interpreted as an effect of the region 1 Birkeland current system. It turns out that the fringe fields of these Birkeland currents reduce magnetic field strength near the subsolar point, and as a consequence, the dayside magnetopause moves inward to rebuild pressure balance.

Compared with the pressure pulse effect (or the effect of penetration of the magnetic field from the magnetosheath to the magnetosphere), the contribution of field-aligned currents from a reconnection event is rather small. But it is important to note that the effects of field-aligned currents from several reconnection pulses are accumulated. Therefore, after each reconnection event the magnetopause first quickly moves inward and then reverts to a position slightly shifted to the Earth (see Figure 4). The difference between forward and backward motion of the magnetopause is the effect of the region 1 Birkeland current system. Hence, time averaged erosion mostly depends on field-aligned currents.

5. Conclusions

1. A simple model of magnetopause erosion based on analytical impulsive reconnection theory is presented.
2. It is shown that bursty reconnection leads to an inward jump-like motion of the magnetopause.
3. The model incorporates all three most popular approaches: Flux transfer, penetration of the magnetic field from magnetosheath to magnetosphere, and the effect of a region 1 Birkeland current system. The first two effects are responsible for the jump-like motion of the magnetopause, and the last one is responsible for the shift of the magnetopause to Earth.

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