GLOBAL MHD SIMULATIONS FOR SOUTHWARD IMF:
A PAIR OF WINGS IN THE FLANKS

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ABSTRACT

Global magnetohydrodynamic (MHD) simulations have shown that for southward interplanetary magnetic field nightside reconnection takes place only in a limited spatial scale in the cross-tail direction. Between the end of the nightside reconnection line and the flank magnetopause are regions of closed magnetic field lines which move relatively slowly tailward, compared with the magnetosheath flow on the far side and the jet flow produced by nightside reconnection on the side closer to the midnight. The magnetosphere appears to have a pair of extended wings on the nightside. Further refinement of the simulations shows that the wings are not produced by the numerical effects. Similar features have been observed previously and also shown in different simulation models. The existence of the wings in the simulations indicates that the solar wind momentum is transferred to the closed magnetosphere if the simulations are relevant to reality.

INTRODUCTION

Observations from the low-latitude solar wind-magnetospheric boundary provide interesting phenomena associated with the solar wind-magnetosphere coupling. One of the most important phenomena is the so-called low-latitude boundary layer (LLBL) [Eastman and Hones, 1979]. It is a relatively thin region earthward of the magnetopause containing antisunward flow on closed field lines. Unfortunately, the complete phenomenology of the LLBL is not established rigorously. Its topological status and its interplanetary magnetic field (IMF) Bz dependence are among the ambiguities. Nevertheless, models of the formation of the LLBL have been proposed for various IMF orientations [Sonnerup, 1980; Kan and Burke, 1985; Nishida et al., 1992; Song and Russell, 1992; Miura, 1992; Owen and Slavin, 1992; Lotko and Sonnerup, 1995]. The feature to be discussed in this paper may be related to the so-called tailward extension of the LLBL for southward IMF [Slavin et al., 1985].

The topology and structure of the magnetosphere for southward IMF have been studied previously. It is well established that for southward IMF, reconnection at the magnetopause opens magnetospheric field lines and reconnection at the magnetotail current sheet re-closes the open magnetotail field lines [e.g., Dungey, 1961; Fedder and Lyon, 1987; Walker et al., 1993; Raeder et al., 1995; Winglee, 1998; White et al., 1998]. In the paper we present the initial results from our MHD simulations for southward IMF. It shows a new structure that exists between the magnetopause reconnection and magnetotail reconnection regions in the magnetotail. The objective of this paper is to report these simulation results. We show that the existence of this structure is most unlikely due to numerical effects although numerical effects influence quantitatively the structure. The detailed diagnostics and physical understanding of the processes involved in producing this structure will be reported in a later study.

NUMERICAL MODEL AND SIMULATION RESULTS

Description of Model

The code used in this study solves the governing equations of ideal magnetohydrodynamics (MHD) in a computational domain that extends from \( x = 192 \, R_E \) to \( x = -384 \, R_E \) along the Sun-Earth line and from \(-192 \) to \(192 \, R_E \) in the \( y \) and \( z \) directions. The inner boundary of the simulation domain is at \(3 \, R_E \). The inner
boundary conditions are treated in a conventional manner. No mass flux across the inner boundary. The magnetospheric field-aligned currents flow from (into) the magnetospheric inner boundary along a dipole magnetic field into (from) a height-integrated electrostatic ionosphere, where the currents are diverged into (converged from) Pedersen currents. The horizontal electric field generated by the Pedersen currents is mapped along the dipole magnetic field back to the magnetospheric inner boundary. The electric drift velocity caused by the electric field at the magnetospheric inner boundary is then used as the magnetospheric boundary conditions. In the present study, the smallest computational cell is $0.125 \times 0.125 \times 0.125 R_E$ and six levels of refinement are used. The total number of computational cells in our reference run is around 1 million. The height-integrated electrostatic ionosphere is located on a spherical surface with a radius of 1.08 $R_E$. Detailed descriptions of the code can be found in the work of Powell et al., [1999], Groth et al., [1999], and DeZeeuw et al. [2000]. Its applications to the terrestrial magnetosphere have been documented and validated by Gombosi et al. [1998, 2000] and Song et al. [1999, 2000]. All steady state solutions presented here are independent of the initial conditions [Gombosi et al., 2000].

**Simulation Results**

Figure 1 shows the simulation results in the noon-midnight meridian plane. The parameters used in this run are typical for the solar wind: density 5/cc, velocity 400 km/s, thermal speed 50 km/s, and sonic Mach number 8. The IMF is purely southward with a magnitude of 5 nT. The resulting solar wind Alfvén Mach number is 8.2. The ionospheric Pedersen conductance is uniformly 5 Simens and the Hall conductance is zero. The color coding shows the logarithm of the thermal pressure and the white lines show the magnetic field lines.

Across the bow shock, the plasma is heated while being decelerated. Dayside reconnection occurs at the equator. The solar wind plasma enters the magnetosphere along the field lines heading to the high latitude cusps. The open magnetospheric field lines are re-closed by reconnection in the magnetotail current sheet. Reconnection energizes the particles and traps them on closed field lines. These results are in agreement with conventional magnetosphere models for southward IMF. The nightside reconnection line shown in our simulation is at about $-18R_E$. We comment that the nightside near earth reconnection line is often observed at around -20 to -25 $R_E$ with a variance of a few $R_E$. It has been observed within $-18R_E$ [McPherron and Manka, 1985; Angelopoulos et al., 1994; Nagai et al., 1998].

Red lines in Figure 2 shows the last closed field lines in 3-D. The white lines are disconnected loops which connect with neither the magnetosphere nor the solar wind. The last closed field lines are consistent with conventional models except for the pair of wings extended to the nightside flanks. These two wings consist of highly stretched closed field lines and disconnected loops, and appear to move in the antisunward direction. These loops are topologically similar to plasmoids. However, they are continuing moving features and not impulsively ejecting structures. Questions that need to be answered include whether this feature is purely due to numerical effects or it can possibly be due to some physical processes that have not been recognized. If the feature is not purely due to numerical effects, what generates it. One issue that is particularly interesting is what drives the antisunward flow in the closed field line region adjacent to the magnetopause. The flow is in the solar wind direction with a fraction of the solar wind magnitude. Thus this indicates a significant momentum transfer across the open-closed boundary. The focus of this paper is to report this simulation result and to address partially the first question. Detailed discussion and further simulation evidence regarding other questions will be presented in a separate paper.

Possible mechanisms that have been proposed and discussed extensively in the literature for momentum transfer between the solar wind and magnetosphere are diffusion and viscous interaction. As shown in Figure 2, there exists a clear density gradient across the open-closed boundary. Similar velocity shear also exists, as shown in Figure 3. The velocity decreases inward from the magnetopause. In our simulation model, neither physical viscous force nor diffusion is specifically included. Effects mimicking viscosity, resistivity and diffusion appear in numerical calculations when replacing the differentials with finite differences, associated with the discretization, in the governing equations. Discretization of the ideal MHD equations, whether by finite difference, finite volume or finite element methods, leads to errors proportional to second derivatives of the magnetic field components. These errors, while not directly proportional to physical resistivity, have similar effects. The size of these errors at a particular point in the computational domain depends on: (1)
Fig. 1. Noon-midnight meridian of the simulation results for southward IMF. The upstream conditions are \( n = 5 \text{ cm}^{-3} \), \( u = 400 \text{ km/s} \), acoustic Mach number \( = 8 \), specific heat ratio \( = 5/3 \), and IMF magnitude \( = 5 \text{ nT} \). The white lines with arrowheads are magnetic field lines. The color coding represents the logarithm of the thermal pressure.

Fig. 2. Topological boundary of the magnetosphere for southward IMF. The red lines are last closed field lines. The white lines are disconnected loops. The color coding shows the logarithm of the density in the equatorial plane.

Fig. 3. Zoom-in of predawn sector of the equatorial plane. The color coding shows the magnitude of the velocity and the black arrowheads show the velocity vectors. The purple line is the magnetopause.

The local mesh resolution, (2) the local order of accuracy of the scheme, (3) the particular choice of flux function used in the scheme, and (4) local values of the plasma properties and their derivatives. Because the errors due to these aspects of a model (particularly the second and fourth) are difficult to quantify with any precision, the size of the numerical errors (including artificial resistivity) is best measured by a mesh-refinement study with a given code, which will be discussed further below.

Careful examination of the flow field shown in Figure 3 indicates that the flow on the magnetospheric side has a small but non-zero velocity toward the magnetopause; indicating that the plasma is flowing out of, instead of flowing into, the magnetosphere. This is contrary to the expectation for diffusive transport. In fact the flow is diverted from the equatorial plane at the magnetopause into north-south directions. Nevertheless, numerical viscosity and diffusion are among the top suspects in causing the wings.

The numerical viscosity and diffusion coefficient are proportional to the scales of the grid. They decrease when the spatial resolution of the simulations increases. When the resolution is higher than a certain level, the numerical viscosity and diffusion become negligibly small compared with physical terms. Therefore, the effects of the numerical viscosity and diffusion can be investigated by varying the resolution of simulations,
which we refer to as mesh-refinement studies. For semidiscrete methods (such as the one employed by the Michigan group) the steady state solution is independent of the time step, and therefore numerical errors depend only on the spatial resolution (we note that the constrained transport method employed by several other MHD groups does not fall into this category). In a mesh-refinement study the same case is run on a series of sequentially finer meshes.

Application of the mesh-refinement method to investigate the effects of the numerical diffusion and viscosity has been tested and validated for our model for northward IMF [Song et al., 1999]. This validation took two steps. First, Song et al. showed that with very low resolutions (and hence very large numerical viscosity) the magnetotail is longer for northward IMF, as expected by viscously driven mechanisms. As the resolution increases, the tail length decreases. After the resolution reaches a certain level, the length of the tail remains unchanged even if further increasing the resolution. Therefore, the numerical viscosity becomes negligibly small at higher resolutions. The tail in these situations must be driven by mechanisms other than viscosity. For the northward IMF case, the numerical viscosity can be neglected when the simulation contains more than half million cells. Second, in the absence of the numerical artifacts the simulation results have to be understandable in terms of other mechanisms. Song et al. [1999] showed that according to reconnection models, the tail length is proportional to the plasma beta at the subsolar region. This proportionality is confirmed by the simulation runs with different solar wind conditions. To conclude, the mesh-refinement method is widely accepted technique to test the numerical artifacts and has been tested with our code.

Figure 4 shows the results from our refinement study for southward IMF. It shows the sign of $B_z$ in the equatorial plane for several simulation runs with the same solar wind conditions but different spatial resolutions. The spatial resolution is proportional to the number of grid points as indicated at the upper-left corner of each panel. The color coding shows the polarity of the $B_z$. The southward (northward) field is shown in blue (red). The line separating the two colors may be considered as a topological boundary in regions other than the inner side of the two wings. The topological status of the field lines in the wings will be discussed in section 4. As we discussed above, if the wings are generated by numerical viscosity or diffusion, they are expected to be longer when the spatial resolution is lower. It is obvious from Figure 4 that the length of the wings is proportional to the spatial resolution, opposite to the expectation of the wings being driven by the numerical viscosity. If the criterion, that the numerical viscosity can be neglected when the number of cells is greater than half million, obtained from northward IMF runs is applicable in this case, our last run in Figure 4 is qualified for minimum numerical viscosity. Here we take a note on the change in the grid size at $y = -8R_E$ and $y = 8R_E$ near the nightside reconnection line. This change does not control the length of the reconnection line because in the low resolution run, the reconnection line extends beyond the region of denser grids. Therefore we conclude that the wings and the antisunward flow within them are most likely driven by mechanisms other than viscous interaction and diffusion although a finite diffusion is critical to reconnection processes. In fact, careful examination of the density distribution, streamlines and velocity vectors shows that the density gradient is most significant on the magnetosheath side. There is no evidence for inward flow from the magnetopause boundary to the magnetosphere.

From a different point of view, the results shown in Figure 4 are not surprising. For a smaller viscosity and diffusion coefficient, the velocity shear and density gradient are larger for a given difference between the solar wind and magnetosphere plasmas. One should expect a sharper transition at the boundary. The shorter wings for higher viscosity and diffusion result from the smearing of the transition. When the resolution is higher, more fine structures can be resolved. However, the width of the wings is greater than one grid in all runs in Figure 3; indicating that the existence of the wings does not depend on resolution. Furthermore, a denser mesh leads to a smaller resistivity and hence a lower reconnection rate. To Reconnect the same amount of fluxes, a longer reconnection line is required. This may correspond to the higher resolution case.

**DISCUSSION**

**Topology and Formation of the Wings**

To investigate the formation of the wings and hence to understand the transition between magnetopause reconnection and magnetotail reconnection, we examine the topology of the field lines in the wings. In Figure 2 red lines indicate last closed field lines connected to the earth and white lines indicate the field lines disconnected from the magnetospheric field. Many of the field lines in the wings appear to be loops
disconnected from the magnetosphere. Note that for these loops, i.e. topologically O-lines, the polarity of the magnetic field $B_z$ changes at the center of the O-lines. Therefore, only the portion of the wings with positive $B_z$ appear in Figure 4. The wings actually extend further towards the sun-earth line.

Figure 5 shows a series of meridian cuts with decreasing local time in the predawn sector as indicated by the white lines in the bottom panel. The black (red) lines indicate magnetosheath (closed magnetospheric) field lines, and the green lines are disconnected loops. Figure 6 shows a cartoon version of the field topology involved. On the right-hand side of the left vertical dashed line, the sequence from panels (b) to (e) can be envisioned as the antisunward convection of the magnetospheric flux tubes in the predawn sector. The magnetopause is indicated by a vertical dashed-line on the right. In fact the magnetopause distance increases rapidly as the local time decreases, but for illustration we have drawn it disproportionally. The magnetospheric field lines are opened by magnetopause reconnection as indicated in panel (a) by the blue
Magnetic fieldlines for four "cuts" are shown from the simulation.

Fig. 5. Topology of the wing. The top four panels show a series of meridian cuts, the location of which are shown in the bottom panel. The black (red) lines indicate magnetosheath (closed magnetospheric) field lines, and the green lines are disconnected loops.

Fig. 6. Illustration of the topology of the wing shown in Figure 2. The left (right) vertical dashed line corresponds to the tail (magnetopause) reconnection line. The middle tilted dashed-line corresponds to the center of the O-line. The spatial scale has not been drawn proportionally. Panels a, b, d, and e correspond to cuts 1 to 4 in Figure 1, respectively.

The remaining closed field, namely the red line and green line, continues to convect antisunward with a decreasing local time, e.g., panel (b). As the flux tubes convect to a certain local time, the meridian cut meets the nightside reconnection line as indicated by the vertical dashed line on the left. Tail reconnection at the region of a large $y$ value disconnects closed field lines which are surrounded by closed field lines, e.g., green line in panel (b). This in turn forms closed loops. Continuously convecting tailward, out of the page and to the right, these loops are opened up by reconnection at the magnetopause and are connected to the magnetosheath field, e.g., red line in panel (c) and green line in panel (d). At the tip of the wing, panel (e), all loops are open and connected with the magnetosheath. Notice that there is a field reversal at the center of the loops (O-lines). The tilted dashed-line in the middle indicates the location of the field reversal. The polarity of the $z$ component of the field is indicated by a horizontal bar between panel 2 and panel 3 and its color coding is the same as Figure 4. Earthward of the tail reconnection line, the flow moves earthward (to the left) and into the page in Figure 2.

It is interesting to note that the loops slant. In comparison, the loops in a plasmoid are oriented in the x-z plane. There are two reasons for the loops to slant. First, the field before reconnection is highly stretched tail field. It is slanted from the earth. Second, the flow is sheared. It convects faster near the magnetopause. It is also noted that reconnection at the magnetopause extends far downstream while the near earth tail reconnection line is rather short. Reconnection at the magnetopause and that at the tail are in principle
independent. In steady state, it is required that the total magnetic fluxes reconnected at the two regions are the same. This is that the normal velocity times field strength integrated over length in the two regions is same. Tail reconnection has a more favorite condition and hence can reconnect at a similar speed across the tail. The reconnection rate at the magnetopause decreases from the subsolar region to the flanks. Therefore it takes a longer distance to reconnect the same amount of fluxes at the magnetopause as tail reconnection does in a short distance.

The driving mechanism is a more complicated problem. It deserves more extensive discussion and requires more simulations and detailed analysis in order to substantiate any proposal. In this preliminary report, we briefly describe our proposal that is based on a set of simulations and diagnostic analysis, as well as MHD theory. Reconnection at the magnetopause in the flanks takes place in regions with strong velocity shears. When the magnetospheric field and the sheath field reconnect, the electric field associated with reconnection causes the newly open magnetospheric field to move in the antisunward direction. This process transfers the solar wind momentum to the open magnetospheric field. The electric currents generated by the topological change of the magnetospheric field exert a force on the closed magnetospheric field, and hence transfer the momentum into the closed field region. These two processes can be formally represented in an analysis of the magnetic tensor in this geometry. However, we will defer the detailed discussion in a separate paper when more runs are made to isolate different effects.

**Observations**

The relevance of a simulation result must be justified by comparison with observations. In magnetotail observations, evidence for tail reconnection and tailward fast flow is well-established. Slavin et al. [1985] first reported an interesting phenomenon, which was referred to as the tailward extension of the LLBL, on a statistical basis. During disturbed days in the distant tail, while the Bz is negative near local midnight, it becomes positive when away from midnight. Meanwhile, the antisunward flow is fastest at midnight, but reduces by half at the flanks. These observations indicate that near the flanks the field and flow are quite different from what is expected for a simple cross-tail reconnection picture. Richardson et al. [1989] further investigated a few cases and confirmed this phenomenon. In both studies, a magnetotail with two wings was drawn based on the observations. The wings have been shown to contain magnetospheric particles moving slowly antisunward and have also been termed "slow plasma sheet". As one can easily see from our discussion, these characteristics are consistent with that of the wings shown in our simulations under similar conditions. However, the antisunward extent of the wings differs. Observations of the wings occurred further downtail than indicated in the simulation, although similar interesting features may have also been reported closer to the earth [Fujimoto et al., 1998; Fuselier et al., 1999] and in some MHD simulations [Birn, 1984; Raeder et al., 1997]. The causes for this difference are not clear at this moment and need to be further investigated.

**CONCLUSIONS**

We have shown in MHD global simulations the existence of a pair of extended wings in the nightside magnetosphere for southward IMF, see Figure 2. Mesh-refinement studies, see Figure 3, have shown that the wings are unlikely to be caused by numerical diffusion and viscosity. Similar features have also been reported in observations [Slavin et al., 1985; Richardson et al., 1989]. The physical reason for its existence may be the difference between the magnetopause and magnetotail reconnection rates. The magnetopause reconnection rate may decrease rapidly from the dayside to the flank magnetopause, while the magnetotail reconnection rate may remain similar in the cross-tail direction. To reconnect the same amount of fluxes, the magnetotail reconnection line is much shorter than that of the magnetopause. The magnetotail reconnection line does not extend to the flank magnetopause. The gap between the two reconnection lines provides the room for the formation of the wings. The detailed topology of the formation of the wings involves three-dimensional geometry of the two reconnection processes. Following a meridian plane of magnetospheric field lines convecting from the terminator tailward, see Figures 1 and 2, magnetopause reconnection opens up the field lines at higher latitudes first. Magnetotail reconnection disconnects some closed field lines and forms detached loops and low latitude closed field lines. After magnetopause reconnection eventually opens all closed field available, it starts opening the loops. The wings end when all loops are opened. The momentum in the magnetosheath is transferred to the magnetosphere to drive the antisunward convection of the wings.
The momentum transfer is caused by the electromagnetic force associated with the reconnection processes in the presence of a velocity shear across the reconnection layer.

ACKNOWLEDGMENTS

We are indebted to H. Petschek for his valuable comments and discussions. We thank B. U. O. Sonnerup and V. Vasyliunas for helpful comments. This work was supported by NSF/ONR under Award NSF-ATM9713492, by NSF under Awards NSF-ATM-9729775 and NSF-ATM-0077655, by the NSF-NASA-AFOSR interagency grant NSF ATM-9318181, and by NASA HPCC Grand Challenge Cooperative Agreement NCCS5-146.

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