Boundary layer formation in the magnetotail: Geotail observations and comparisons with a global MHD simulation

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Abstract. We present Geotail plasma and field observations from the middle magnetotail near X_{GSE} = -46 R_E for the time period 1400 to 1800 UT on December 14, 1994. During that period, the Wind satellite monitored the solar wind plasma and interplanetary magnetic field (IMF) upstream of the bow shock. The IMF was northward and the plasma parameters near average. Geotail observed slow tailward flows and a northward field. The plasma and field parameters indicate that Geotail is either in the plasma sheet or in a boundary layer. We used the Wind solar wind plasma and IMF data as input for a global simulation of that time interval. Comparison of the simulation results with the observational data show very good overall agreement of the magnitudes of the plasma and field parameters. In particular, the simulation reproduces the slow tailward flows and northward field found at Geotail. Small scale temporal variations are less well reproduced. The simulation shows the formation of a broad boundary layer (which we call tail flank boundary layer, TFBL) that consists of closed flux which formed by magnetic reconnection of IMF and lobe field lines. The simulation results indicate that Geotail is located very close to the TFBL and may have entered the TFBL proper. We show that the TFBL plays an important role in energy transport from the solar wind into the magnetosphere during northward IMF conditions.

Introduction

With the successful launch of the Wind mission in late 1994, and the Geotail spacecraft's concurrent survey of the magnetotail, new opportunities have arisen for studying the coupling of the solar wind with the magnetosphere. A long outstanding unknown of magnetospheric physics is the structure of the tail and how it depends on solar wind parameters. In most models of the tail, the lobe field lines are assumed to be open, i.e., connected to one of earth's polar caps on one end and to the IMF through the magnetopause on the other end [*Crooker*, 1977]. It is also generally assumed, that reconnection of lobe field lines occurs at almost any time. During geomagnetically quiet times, reconnection is believed to occur in the distant tail at an X-line that is located around 100 R_E from earth [*Slavin et al.*, 1985], while during geomagnetically active times, one or more X-lines develop closer to earth, leading to the formation of plasmoids or flux ropes that are ejected through the distant tail [*Hones*, 1979]. The models predict that convection associated with the reconnection sites is generally earthward on the earthward side of an X-line and tailward on the tailward side [*Dungey*, 1961; *Cowley*, 1980]. Thus, the cross-tail electric field is predominantly duskward, with the exception when multiple X-lines are present in the tail and in the front part of a departing plasmoid for a single X-line. Statistical surveys of the tail plasma sheet flow and magnetic field by ISEE 3 [*Slavin et al.*, 1985] and Geotail [*Nishida et al.*, 1995] show, however, that northward magnetic fields are most often associated with tailward flows, i.e., the predominant electric field direction is from dusk to dawn. This effect is most pronounced during geomagnetically quiet times, i.e., when the IMF is northward. In the more distant tail, the power to maintain the tailward flows with northward B_z was just thought to come from the momentum of the solar wind and ionospheric outflow ions in the mantle flowing tailward and/or some "quasiviscous" momentum transfer from the solar wind at the flanks of the tail [*Owen and Slavin*, 1992].

Global simulation studies of the magnetosphere under northward IMF conditions have shown that magnetic reconnection occurs between the IMF and the lobe field at high latitudes [*Raeder et al.*, 1995], leading to a reduction [*Raeder*, 1995] or even a total elimination of open tail lobe field [*Fedder and Lyon*, 1995]. New closed flux tubes are created at the high latitude magnetopause and convected into the tail flanks, partly or completely replacing the open lobe field. Thus, these models indeed predict the observed cross-tail electric field that is predominantly from dusk to dawn. However, although these studies show a possible mechanism that leads to the observed electric fields, the results are difficult to compare with the statistical observations that assume solar wind conditions that are rarely observed.

It has also been argued [*Song and Russell*, 1992] that lobe reconnection is responsible for the formation of the low latitude boundary layer (LLBL) [*Eastman and Hones*, 1979] during northward IMF conditions. However, little is known about how far the LLBL extends into the middle and distant tail beyond about X = -20 R_E [*Eastman et al.*, 1985] and its relation with the plasma sheet in that region. Beyond X = -20 R_E the only work on the LLBL has been the magnetic field studies by Fairfield [1979] and Slavin et al. [1985] show-

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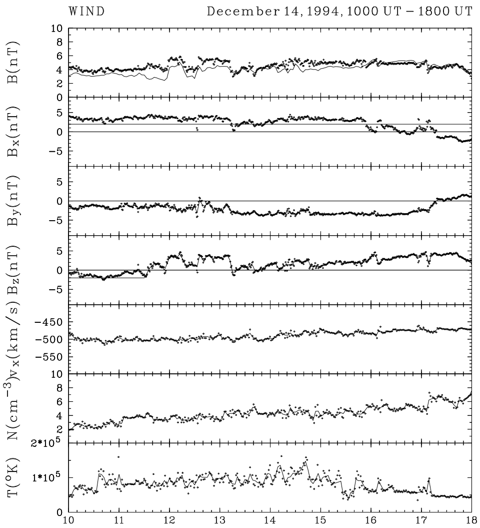

Figure 1. Solar wind and IMF data (dots) and input data stream for the simulation (solid lines) for December 14, 1994. The panels show, from top to bottom: the total field, B_x, B_y, B_z, v_x, the number density, and the proton temperature.

ing continuous, strong northward B_z at the flanks of the plasma sheet. Both of these studies suggested that these flank regions of strong northward B_z in the plasma sheet represented the tailward extension of the LLBL.

In this study we examine a time period of rather typical northward IMF conditions. Using solar wind data from the Wind spacecraft as input to our three-dimensional magnetosphere-ionosphere simulation, we model the structure and dynamics of the magnetosphere and the tail for that period and compare the simulation results with Geotail observations from the middle magnetotail.

Wind Observations

On December 14, 1994, the Wind spacecraft was located in the solar wind, upstream of the bow shock, near (24,-38,0) R_E in GSE coordinates. The Goddard Space Flight Center (GSFC) plasma instrument (SWE) [*Ogilvie et al.*, 1995] and the GSFC magnetometer [*Lepping et al.*, 1995] on board the Wind spacecraft provided the interplanetary parameters.

Figure 1 shows the solar wind plasma and IMF parameters between 1000 UT and 1800 UT on that day (dots). The time resolution of the data is 46 seconds for the magnetic field data and 80 seconds for the plasma data. We have also overlayed the actual time series that were used as input to the simulation model (solid lines). These differ from the solar wind data only in that they are 3 minute averages, that the IMF B_x was held constant at its average value of 2 nT between 1400 UT and 1800 UT, and that the B_z component was set to -2 nT for the first 90 minutes for the start-up of the simulation.

The solar wind parameters during this period are rather typical, with a solar wind density of 4 - 6 cm^{-3}, a velocity of 450 - 500 km s^{-1}, and a temperature of 5 - 10 $\times$ 10^4 K. The IMF was predominantly northward at around 4 nT, with B_y of comparable magnitude, and B_x around 2 nT. For such conditions one would expect a quiet magnetosphere; indeed, the Kp index for this period was between 1 and 2.

The Model

For this study we use our global MHD magnetosphere - ionosphere simulation model that has been used extensively for other studies of the solar wind - magnetosphere - ionosphere interactions in the past. Detailed descriptions of the model can be found in [*Raeder et al.*, 1996]. Thus we give only a brief description of the model parameters pertaining to this study. The resistive MHD equations are solved on a nonuniform rectangular grid extending from X_{GSE} = -300 to $X_{GSE} = 22$ R_E, and from -40 R_E to 40 R_E in the transverse directions, thus placing all outer boundaries into supermagnetosonic flows. The grid resolution is about 0.35 R_E near the earth and increases towards the boundaries of the simulation box. Magnetospheric Birkeland currents are closed by using an ionosphere model that computes the ionospheric potential and uses magnetospheric parameters to model self-consistently electron precipitation and ionospheric Hall and Pedersen conductances. For this simulation, the dipole tilt was set to earth's dipole orientation for Dec 14, 1994 at 1600 UT and held constant through the run. The simulation run starts at 1000 UT with the data input that is displayed in Figure 1.

Geotail Observations and Comparison With the Model

The Geotail observations were obtained with the CPI plasma instrument [*Frank et al.*, 1994] and the MGF magnetometer [*Kokubun et al.*, 1994]. During the period of interest from 1400 UT to 1800 UT Geotail was located around (-45.9,-11.5,-6.5) R_E in GSE coordinates.

Figure 2 shows the field and plasma parameters observed by Geotail (solid line) and predicted by the simulation at the location of Geotail (dots); the top 4 panels show the magnetic field components and the total field. The magnetic field shows fairly little structure during the four hour interval. B_x is negative, indicating the spacecraft is south of the neutral sheet. B_y is almost constant around -3 nT, which indicates a much stronger IMF B_y penetration than is usually observed [*Fairfield*, 1979; *Tsurutani et al.*, 1986]. The B_z component is positive around 2 nT. Most of the time the total field is near 10 nT. The MHD simulation results match the observed field very well, except for the first and last 30 minutes of the interval and for small scale time variations. The differences at the beginning of the time interval may well be due to residual distortions of the simulation startup, while the differences at the end of the interval could be attributed to a rotation of the IMF B_x that was not included in the input data stream.

The plasma bulk flow is tailward directed. The v_y and v_z components are virtually zero with small fluctuations of about ± 20 km s^{-1}. The v_x component fluctuates around -50 km s^{-1} with an amplitude of about ± 50 km s^{-1}. The simulation results show fewer fluctuations, but values that lie very close to the observed values. In particular, the flow is tailward directed as observed by Geotail.

The plasma density fluctuates around 0.2 cm^{-3}, and the plasma pressure lies between 10 and 50 pPa. The plasma density obtained from the global simulation is consistently higher than the observed density, which can be explained by the fact that it probably takes considerably longer than a few hours to establish the tail plasma populations. Kinetic effects due to gradient and curvature drift motions that are not included in the MHD equations may also play a role by causing a dawn - dusk asymmetry. On the other hand, the plasma pressure and the total pressure (plasma plus magnetic field pressure) are much closer to the observed values.

The bottom panel shows the plasma ion β. The plasma β falls never below 0.1, stays around 0.5 most of the time, and reaches values that are well above one around 1430 UT and 1700 UT. If Geotail were in the lobe, one would expect plasma ion β values of 0.1 or below, because the observed electron β lies in the range from 0.002 to 0.05 [*Slavin et al.*, 1985]. Although the magnetic field often looks lobe-like, the high plasma β and the fact that the field shows considerable fluctuations indicate the Geotail is not located in the lobe, but either in the plasma sheet or in a boundary layer.

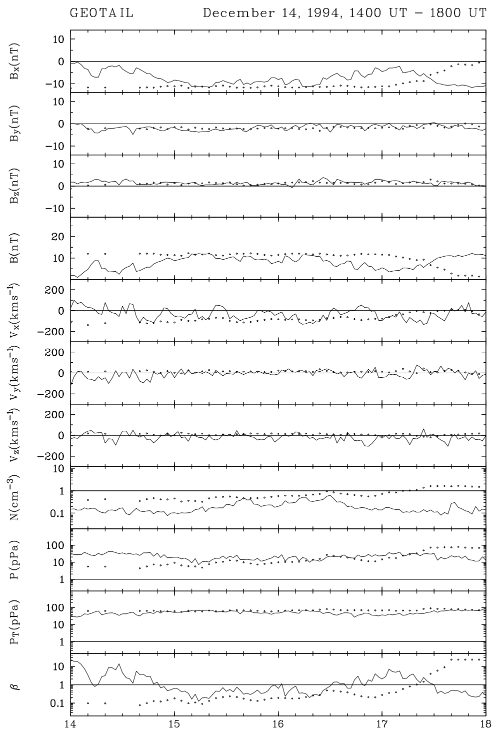

Figure 2. Plasma and field parameters from Geotail (solid lines) and from the global simulation (dots) for December 14, 1994. The panels show, from top to bottom: The field B_x, B_y, B_z components, the total field, the v_x, v_y, and v_z flow components, the number density, the plasma pressure, the total pressure (sum of plasma and magnetic field pressure), and the ion plasma β.

Tail Structure

Figure 3 shows a three-dimensional rendering of the magnetospheric configuration at 1700 UT, as viewed from a dawnward-sunward-northward angle. The blue sphere at the center is the inner boundary of the MHD simulation at 3.7 R_E. The meridional plane (Y=0) shows the color coded logarithm of the plasma pressure. The highest pressure (yellow) can be seen in the magnetosheath and the lowest pressure (pink) in the lobes. Black arrows (scaled to the square root of the velocity) indicate the speed and direction of the bulk flow. The Z = -8 R_E plane shows color coded values of $|v_x|$. The plasma flows in the tail are mostly tailward and of small velocity. Earthward and accelerated tailward flows emanate from an X-line at about X = -30 R_E near the tail axis. However, this region is of very limited extent in the Y direction and Geotail is not in a position to observe these flows.

The plane at X = -46 R_E shows the color coded magnetic topology. Orange areas are threaded by solar wind (unconnected) field lines, blue areas by open lobe field lines (one foot on earth), and magenta areas are threaded by closed field lines. The set of thin blue field lines is anchored at 70 degrees magnetic latitude and every 15 degrees in longitude in the northern hemisphere.

The position of Geotail is marked by the grey sphere at the intersection of the Z = -8 R_E plane and the X = -46 R_E plane. The gray field line passes through the Geotail position. Geotail is located on a lobe field line, but very close to a broad boundary layer of closed flux. A similar type of boundary layer was found previously in global simulations for due northward IMF [*Raeder*, 1995] and was named the tail flank boundary layer (TFBL).

The formation of the TFBL can be explained by the magnetic field reconnection that occurs at high latitudes between IMF and lobe field lines. The northern hemisphere reconnection site lies near (-7,-10,17) R_E. Four field lines in the vicinity of the reconnection site are displayed in Figure 3.

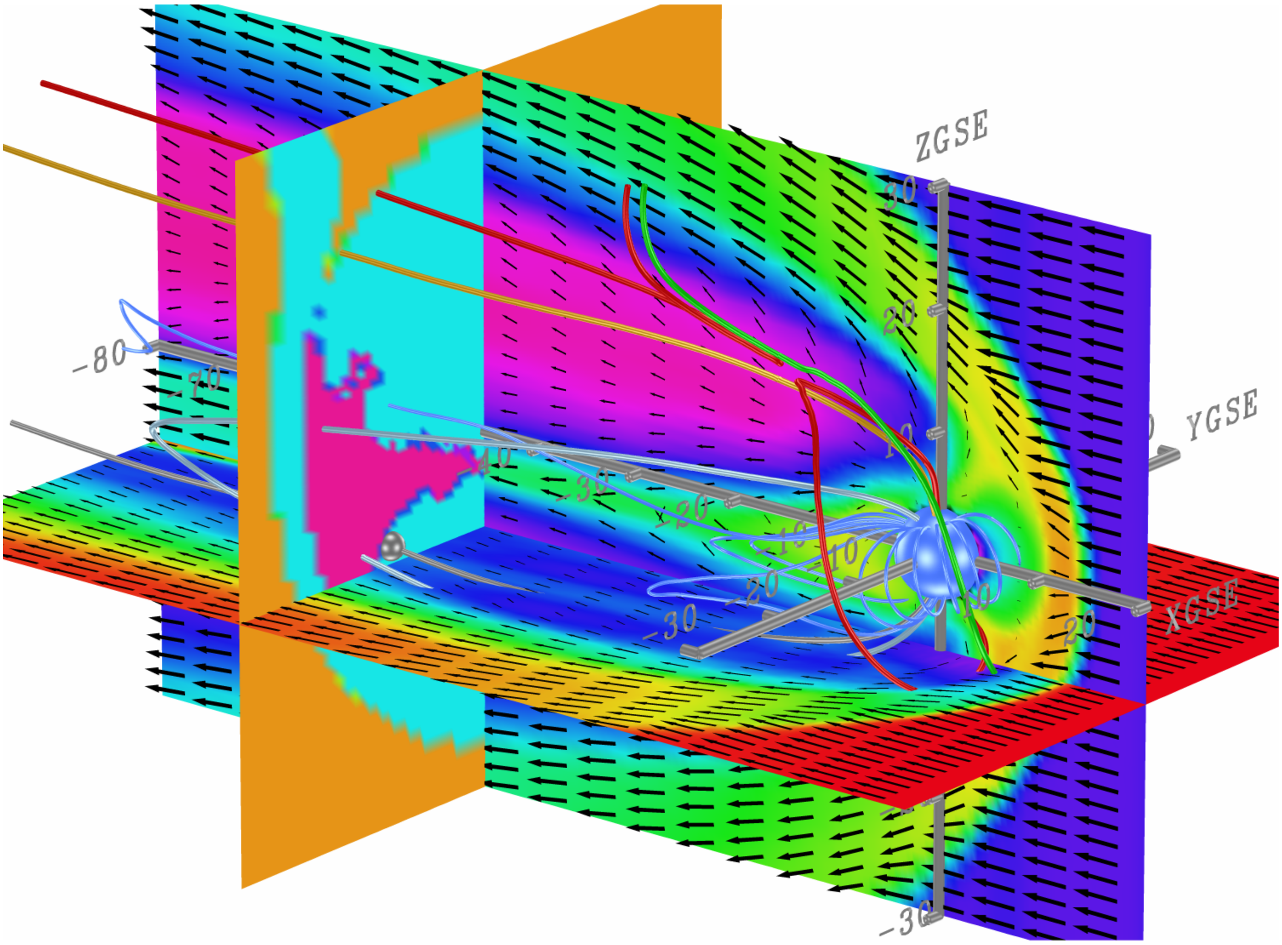

Figure 3. Three-dimensional rendering of the magnetospheric configuration at 1700 UT on December 14, 1994. See text for details.

The green line is an IMF field line that passes just north of the reconnection site and is draped around the magnetosphere; the yellow line lies just south of the reconnection site and represents a lobe field line that is just about to reconnect; the two red field lines that pass between the yellow and the green field line have just reconnected. The red field line on the tailward side has become unconnected and is being stripped off from the lobe while the red field line on the earthward side is closed. Presumably the latter field line is an IMF field line that has previously reconnected at the southern lobe, because there the field line emanates from the southern polar cap and drapes over the dayside magnetosphere.

Of the newly created closed field lines the part that comes from the IMF is embedded in magnetosheath flow and drifts tailward around the magnetosphere, forming the TFBL. As these field lines drift tailward, they slow the plasma flow because the curvature of these field lines causes a sunward $\mathbf{j}\times\mathbf{B}$ force. However, the momentum flux of the magnetosheath flow is too large to stop the field lines. In addition, there may also be numerical viscous drag present that pulls these field lines tailward. Because $\mathbf{v}$ and $\mathbf{j}\times\mathbf{B}$ are of opposite signs, this process acts as an MHD generator, i.e., the energy conversion term $\mathbf{E}\cdot\mathbf{j} = \mathbf{v}\cdot\mathbf{j}\times\mathbf{B}$ is negative. The electromagnetic energy is stored in the stretched field lines, and part of it is transferred into the ionosphere by field aligned currents that are a consequence of field line twisting at lower altitudes.

The proximity of Geotail to the TFBL (see Figure 3) explains why the field is northward in the predicted time series at Geotail (Figure 2). Because the field orientation cannot change very much in the short distance to the TFBL without creating a discontinuity, the lobe field orientation of that area must be similar to that of the TFBL.

Of course, the accuracy of the simulation is limited and we do not expect that the model predicts the plasma and field boundaries so precisely that we could say with certainty that Geotail lies on a lobe field line. However, if Geotail is not in the lobe, the model indicates that it is most likely in the TFBL. The evidence from the Geotail observation and from the simulation, taken together, therefore suggests that Geotail enters the TFBL proper, at least at times.

Summary and Discussion

We have presented Geotail observations and global MHD model results for a time period of fairly typical solar wind plasma and northward IMF parameters. The Geotail observations confirm earlier statistical findings [*Slavin et al.*, 1985; *Nishida et al.*, 1995] that under typical conditions, flows in the tail, excluding the lobes, are predominantly tailward while the field is northward. The simulation results provide insight into the physical processes that lead to these phenomena. Magnetic reconnection at the lobes leads to the creation of new closed flux tubes at the dayside magnetopause. This process was proposed by *Song and Russell* [1992] as being responsible for the formation of the dayside LLBL. As the simulation results show, this process also holds when there is a substantial IMF B_y component present. Furthermore, the boundary layer extends well into the flanks of the middle and distant tail, where we call it the tail flank boundary layer. Flux tubes in the TFBL portion of the LLBL are carried by the momentum flux of the magnetosheath plasma in which they were created. Some of that momentum flux is converted into electromagnetic energy by stretching and twisting the TFBL flux tubes. The twisting of the flux tubes at lower altitudes generates field aligned currents that flow into the ionosphere and are dissipated there. The energy that goes into the flux tube stretching is eventually released when the IMF conditions change to southward B_z, and when the formation of near-earth X-lines pinches off the TFBL flux tubes.

The stretching of the TFBL flux tubes should also have a profound effect on the plasma carried by them. In the early stage of the creation of new closed flux tubes the plasma becomes compressed (see discussion by *Song and Russell* [1992]). However, when the flux tubes are convected and stretched along the tail flank, their volume increases. Assuming that there is no exchange of plasma with neighboring flux tubes, the plasma expands adiabatically. Thus, the plasma of the TSBL is expected to be cooler and less dense than the magnetosheath-like plasma that occupies them directly after their creation. Because part of the flux tubes is of magnetospheric origin, there should also be a population of hot magnetospheric particles present. Such a mixture of hot magnetospheric and cold magnetosheath plasma has indeed been observed in the near earth tail boundary layer [*Eastman et al.*, 1985]. However, in these studies the boundary layer observations have not been correlated with IMF data, and these studies did not address the boundary layer of the middle and distant tail.

Eventually, when the flux tubes become very long (at several hundred R_E), their magnetic and plasma properties become nearly indistinguishable from open lobe flux tubes. However, unlike the situation for southward IMF conditions, there is no net change of the total lobe flux, because for every flux unit added to the TFBL, one flux unit is stripped away from the lobes by the high latitude reconnection.

In summary, we have compared 4 hours of Geotail observations in the middle tail during northward IMF with global modeling results. The simulation predicts, in good agreement with the Geotail observations, slow tailward flow and a northward field. Geotail is shown to be located in the vicinity of, or in the proper of a broad boundary layer that forms on the dayside and high latitude nightside by reconnection of lobe and IMF field lines and is convected into the flanks of the tail. This boundary layer converts solar wind flow energy into electromagnetic energy and allows for plasma entry into the tail.

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