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Three-dimensional MHD simulations of the Earth's magnetosphere on Feb 9-10 1995 for northward interplanetary magnetic field and comparison of the lobe field with Geotail observations

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Abstract. Three-dimensional Global magnetohydrodynamic simulations of the quiet-time magnetosphere are compared to data obtained from the Geotail satellite. For the specific event on Feb. 9-10, 1995 when the interplanetary magnetic field was quiet northward and Geotail was in the vicinity of the equatorial plane and around x=-20 R_E, the lobe field was found to be steady for 2.5 hours. During the time interval between UT 00:30, Feb. 10 and UT 3:00, Feb. 10, the lobe field B_x is nearly zero and B_z is around 5 nT which is comparable to the B_z (about 5 nT) of the IMF. This is consistent with predictions from our recent steady-state simulations [*Guzdar et al.*, 2001]. Also performing real event simulations using the global MHD code we find that the time scale for the temporal evolution and magnitude of the the various components of the lobe field agree well with Geotail observations.

1. Introduction

Since the original work by *Dungey* [1961], the steady state magnetosphere with strictly northward IMF has been investigated by numerous authors. With the advent of supercomputers, this problem has been investigated numerically for the last two decades. *Ogino and Walker* [1984], *Wu* [1985] and *Usadi et al.* [1993] showed the reconnection in the cusp region and *Usadi et al.* [1993] showed the closed magnetosphere consistent with Dungey's original view.

In recent work [*Gombosi et al.*, 1998; *Song et al.*, 1999; *Bargatze et al.*, 1999; *Guzdar et al.*, 2001] on global MHD simulations of the steady state magnetosphere for northward interplanetary magnetic field (IMF), it has been shown that for typical solar wind conditions the magnetopshere evolves to a steady state in a few hours. For B_{IMF}=5 nT, the solar wind velocity V_{SW}=400 km/s and plasma density n=5 /cc, the size of the magnetosphere is about 50 R_E. One significant result from the simulation of [*Guzdar et al.*, 2001] is that in steady state of the idealized case the magnitude of the lobe field in the equatorial plane for x<-20 R_E is equal to that of the interplanetary magnetic field. If the magnetosphere relaxes to the steady state from an earlier stressed elongated state, we expect that during the stressed phase the B_x component would be finite in the lobe region and as the tail dipolarizes the lobe field in the vicinity of the equatorial plane would decrease to a very low value. On the other hand the B_z field which in the stressed state would be small, increases during the relaxation phase and attains its steady state value in the equatorial plane equal to that of the interplanetary field strength. The arguments presented to explain the simulation result for the steady state lobe field being equal to the interplanetary field was based on flux conservation (to the lowest order) in the equatorial plane for the nortwhard IMF case as well as force balance in the x direction. This discussion has been elucidated in [*Guzdar et al.*, 2001]. In this letter we report on a specific northward IMF event on the Feb. 9-10, 1995 which has been simulated using the LFM global MHD code [*Fedder et al.*, 1995].

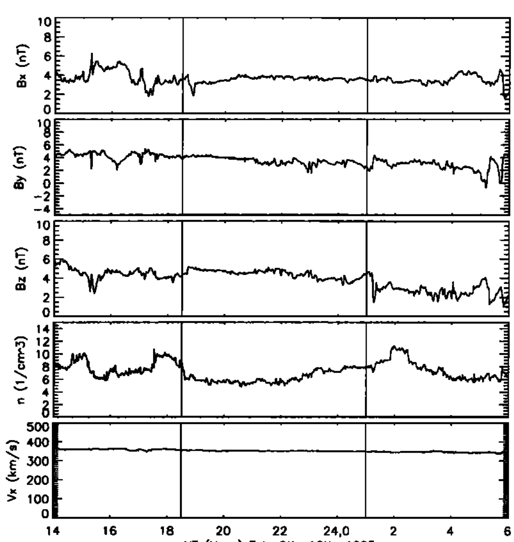

Figure 1. Solar wind condition as observed by the WIND satellite on Feb. 9-10, 1995.

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2. Solar Wind Condition on Feb. 9-10, 1995

On Feb. 9-10, 1995, the solar wind conditions observed by the WIND satellite were quiet and northward IMF was maintained for more than 10 hours. Shown in Figure (1) are the solar wind parameters on Feb. 9-10, 1995, observed by the WIND satellite. All the vector components are in the geocentric solar-ecliptic (GSE) coordinates. The solar wind velocity V_x was around 350 km/sec and was quite steady. The other two components of the solar wind velocity (V_y, V_z) were of much smaller magnitude and thus have not been plotted. The time interval of interest for the WIND observations is between UT 18:30 on Feb. 9, 1995 and UT 1:00 on Feb. 10, 1995. The B_z component of the solar wind magnetic field was around 5 nT and quite steady during this time interval. The B_x, B_y components of the magnetic field and the ram pressure of solar wind were also steady. Therefore, the solar wind parameters maintained steady state features for northward IMF for at least 6 hours. The delay for the solar wind propagating from the WIND satellite to the Earth's magnetopause was about 50 minutes.

During this period, Geotail was located on the nightside of the Earth's magnetotail around x=-20R_E and near the equatorial plane. Shown in Figure (2) is the trajectory of Geotail's orbit in X-Y and X-Z plane respectively in geocentric solar magnetospheric(GSM) coordinate. The time interval of interest is from UT 19:00 on Feb. 9, 1995 to UT 3:00 on Feb. 10, 1995. During this period, Geotail was below and close to the equatorial plane. It traveled from (x=-24.55 R_E, y=-2.64 R_E, z=-3.02 R_E) to (x=-17.66 R_E, y=-7.19 R_E, z=-3.92 R_E) during the interval of 8 hours and the trajectory was inside the lobe. The fact that it was inside the lobe can be concluded on the basis of the simulation results where for the parameters of the solar wind cited above, the smallest size of the tail length is about 45 to 50 R_E. Therefore, this is a good case to study the tail lobe field evolution during steady northward IMF.

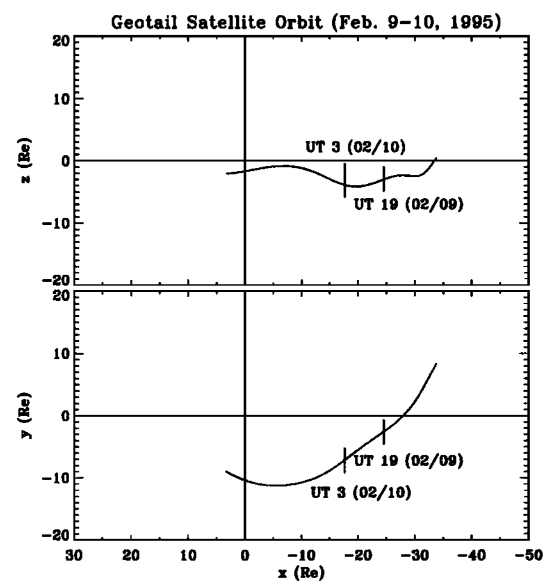
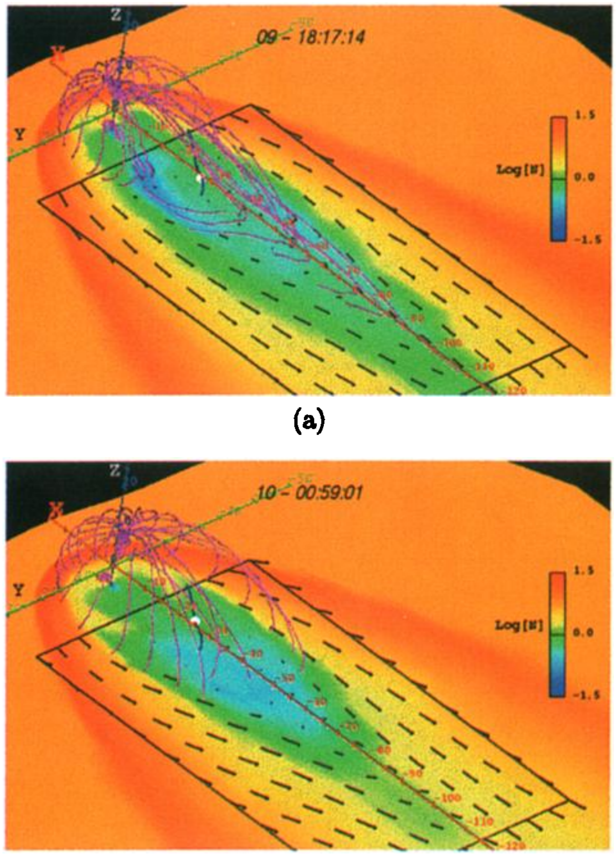


Figure 2. Geotail Satellite Orbit on Feb. 9-10, 1995.



(b)

Figure 3. The Earth's magnetosphere from the global MHD simulation of the Feb. 9-10, 1995 event. In both of the panels, the background is the log of density. The black arrows are the velocity vectors in the cut plane. The white ball on the blue curve represents the position of the Geotail Satellite. (a) At UT 18:17 on Feb. 9, 1995; (b) At UT 00:59 on Feb. 10, 1995.

3. Simulation Results and Comparison

We now present results from our simulations using the LFM global MHD code. The WIND satellite observations for the solar wind parameters are used as input at the left boundary of our simulation grid. A time delay of fifty minutes for the the propagation of the solar wind parameters from the location of the WIND satellite to the left boundary is taken into account. The propagation of the WIND solar wind data to the front side of the grid in the LFM model is described in detail in [*Wiltberger et al.*, 2000]. The simulation was performed in the Solar Magnetic (SM) coordinate system allowing for the tilt of the Earth's magnetic dipole relative to the solar wind flow direction to be included. A real ionosphere model described in earlier publications [*Fedder and Lyon,* 1987; *Fedder et al.,* 1995] was used.

Shown in Figure (3) are two panels of the three dimensional configuration of the Earth's magnetosphere from the simulation of the Feb. 9-10, 1995 event. In both of these panels, the background is an equatorial plane at z=-6 R_E perpendicular to the Z axis. The background color map is the log of density with the color legend on the right. The pink lines are the field lines on the last closed field line surface. The blue curve inside the lobe near x=-20 R_E is the trajectory of the Geotail satellite in GSM coordinates. The white ball on the blue curve represents the position of Geotail. During the time period of interest, the Geotail Satellite is below the equatorial plane. The last closed field lines are made sparse on the viewer's side to expose the trajectory of the Geotail satellite clearly. Panel (a) of Figure (3) shows the simulated magnetospheric configuration at UT 18:17 on Feb. 9. The magnetotail has a long tail configuration extending to more than 100 R_E. The low density region (green shaded) in the tail lobe extends further than x=-120 R_E tailward. Panel (b) of Figure (3) shows the simulated magnetosphere configuration at UT 00:59 on Feb. 10. The last closed field line region extends to x$\simeq$-50 R_E and forms a short tail configuration. The cross-tail area at x=-10 R_E in panel (b) is larger than the cross-tail area at x=-10 R_E in panel (a) due to the dipolarization that has occurred with the northward IMF. Before UT 18:30, on Feb. 9, the WIND satellite observations show strongly varying solar wind conditions with high ram pressure and fluctuating solar wind magnetic field. Under these circumstances the tail is highly extended on the night side. With steady northward IMF between UT 18:30, Feb. 9 and UT 1:00, on Feb. 10 as observed by the WIND satellite, the tail lobe relaxes and expands in radius in the plane perpendicular to the equator. When the magnetic field in the cusp region matches the magnitude of the IMF, the field lines reconnect on the night side and peel off thereby establishing a short tail. Finally, the magnetosphere reaches a state of minimum energy. We emphasize that the short tail shown in panel (b) of Figure (3) is in dynamical equilibrium. The reconnection, which occurs in the cusp region, adds flux to the dayside magnetosphere and the solar wind grabs the newly reconnected field line on the night side and transports them downstream. The newly added flux on the dayside is convected along the low-latitude boundary layer (LLBL) to the nightside to supplement the tail lobe flux. Therefore, a steady short tail configuration is maintained.

In Figure (4), the solid curve is the tail lobe magnetic field, density and velocity field observed by the Geotail satellite on Feb. 9-10, 1995. The magnetic field and velocity field are both in GSE coordinate. The plasma density and velocity are measured by 2D plasma analyzer and therefore V_z is not present in the observation. Between UT 14:00 and UT 19:00 on Feb. 9, the magnitude of the tail lobe field B_x is around 8 nT and B_z is around 1 nT. Starting from UT 19:00, on Feb. 9, the magnitude of B_x decreased and reached a steady value around 2nT after UT 23:00 on Feb. 9. Also starting from UT 19:00, on Feb. 9, B_z increased and after UT 24:00, on Feb. 9, reached a steady value around 5 nT which is comparable with solar wind magnetic field B_z ($\approx$ 5 nT). Here, we use the term "comparable to", since we do not expect that "equal to" is the case with real event. Both B_x (nearly zero) and B_z (comparable to the magnitude of solar wind B_z) are quite steady in the interval between UT 00:30, Feb. 10 and UT 3:00, Feb. 10. During this whole time period, there is no obvious trend for the change in B_y. The tail lobe density increases to around 1.0 /cc. The tail lobe velocity field is small and during the time interval between UT 00:30, Feb. 10 and UT 3:00, Feb. 10, the velocity field is in the range of -50 km/s< V< 50 km/s.

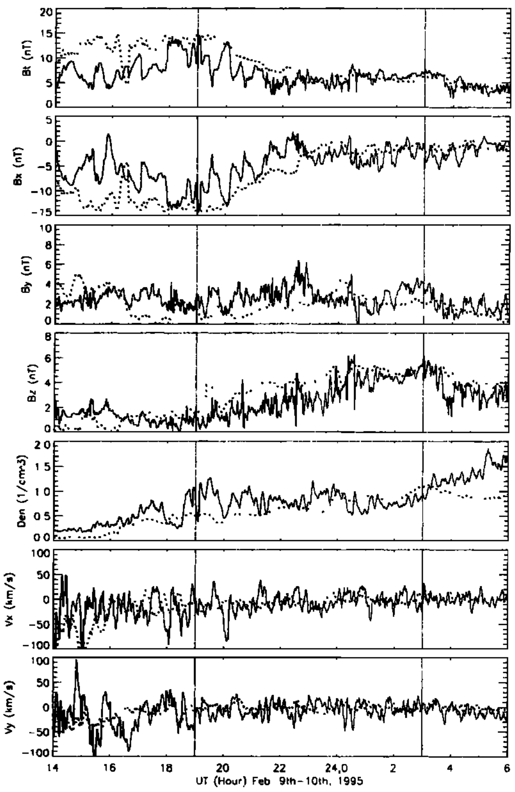


Figure 4. Comparison between Geotail observations (solid curve) and the global MHD simulation results (dotted curve) on Feb. 9-10, 1995. Both the observed and modeled magnetic and velocity field are in GSE coordinate. Bt is the magnitude of the total magnetic field.

In Figure (4), the dotted curve is the modeled magnetic field, density and velocity field from our simulation. The simulated magnetic field and velocity field are also in GSE coordinate. The modeled magnetic field is taken from the simulation through interpolation along the trajectory of the Geotail satellite. For B_x and B_z, the agreement between simulation and observation is good. The simulation reproduces the transition of B_x from B_x $\simeq$-10 nT to B_x $\simeq$0 nT and the transition of B_z from $B_z \simeq 0$ nT to $B_z \simeq 5$ nT. Both the transition slope and the average magnitude of the magnetic field before and after the transition agree well with the observations. Especially for the steady stage between UT 00:30 and UT 03:00, Feb. 10, the agreement is quite good. The evolution of the density in the simulation also agrees with the observation. The increase of the lobe density is due to the relaxation and shrinkage of the tail lobe during the steady state. Since the satellite is inside the tail lobe, the simulated tail lobe velocity is small (in the range of -50 km/s< V< 50 km/s) during the time interval between UT 19:00, Feb. 9, and UT 3:00, Feb. 10. This is consistent with the observations.

The observation shows small oscillations on the time scale of several minutes. The simulation however shows a smoothed average trend in the evolution of the magnetic field. We don't expect the MHD model to reproduce the features of minutes-scale oscillations, since the spatial resolution in our numerical grid is 1 R_E in the region of interest. There are some mismatches in the magnitude of B_x between the simulation and the observation before UT 18:00, Feb 9. The simulation shows a larger magnitude than the observations. We speculate that this is due to mismatches in current sheet thickness between the global MHD model and real situation. Also, the agreement of B_y between the simulation and the observation is not as good as B_x and B_z. Since we are interested in the transition process from a long stretched tail to a short-closed tail during steady northward IMF, these mismatches don't affect our conclusions on the final steady state as well as on the timescale of evolution.

The evolution of the lobe magnetic field B_x from around 8 nT to 2 nT and B_z from nearly 0 nT to 5nT corresponds to the dipolarization of the magnetotail. This is the results of the transition from a long stretched tail configuration to a short tail configuration. During this process of relaxation, our earlier simulations [*Guzdar et al.*, 2001] showed the tail lobe flux can be assumed to be almost conserved. Therefore, the increase in the lobe field B_z implies a decrease in the tail lobe cross-equatorial-area which in turn means a shortening of the magnetotail. As we have shown, the solar wind condition is steadily northward IMF with $B_z = 5$ nT for the time interval between UT 18:30 on Feb. 9 and UT 1:00 on Feb. 10. The dipolarization of the magnetotail or the evolution of the magnetosphere from a long tail to a short tail takes more about 4 hours. This time scale is of the order of the Alfven time for the long stretched configuration. The system can relax to a steady state since the solar wind was in a nearly steady state condition for about 6 to 7 hours, which is longer than the relaxation time of four hours.

With only one satellite in the magnetotail lobe, it is difficult to determine the tail length of the closed magnetotail. But we emphasize that during the steady state the magnetotail lobe field B_z (around 5nT) observed by the Geotail satellite is comparable with solar wind magnetic field B_z ($\approx$ 5nT) and lobe field B_x is nearly 0. This is what our simulations of the steady state magnetosphere with northward IMF [*Guzdar et al.*, 2001]had predicted and the explanation was based on the fact that the continuity of magnetic pressure requires that the steady tail lobe magnetic field be equal to solar wind magnetic field B_z across the open-closed field-line boundary in the equatorial plane. Thus the global MHD code provides a very reliable comparison of the northward IMF steady state since the final dynamic equilibrium state depends on general global force balance and not on details of non-MHD physics.

4. Conclusion

The good agreement between our global MHD simulations and the Geotail satellite observations leads us to conclude that the earth's magnetosphere during the time interval between UT 00:30, Feb. 10 and UT: 3:00, Feb. 10, is in steady state with a short tail of 50 R_E long. During steady stage, the lobe magnetic field B_x is nearly zero in the region x<-20 R_E and near the equatorial plane and B_z (around 5 nT) in the same region is comparable to the solar wind magnetic field B_z ($\approx$ 5nT). Although a single satellite observation cannot establish the tail size, the good agreement of the simulation results with Geotail's magnetic field data suggests that the short tail steady-state magnetosphere for long northward turnings (in excess of four hours) observed in the simulations is a possible realistic size.

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