"Physics of Auroral Phenomena", Proc. XXXII Annual Seminar, Apatity, pp. 17 - 20, 2009

Polar Geophysical Institute

MAGNETOTAIL MAGNETIC FLUX CALCULATION USING GLOBAL MHD SIMULATIONS

E. Gordeev, V. Sergeev *(Saint-Petersburg State University, Saint Petersburg, Russia)*

Abstract

We describe the method that allows to determine a shape of the tail magnetopause and calculate the magnetotail magnetic flux in the specified tail cross-section based on results of the global MHD simulations. Several approaches to determine the magnetopause have been tested, including those based on "current density peak", "maximal plasma density gradient" or the "fluopause" based on tracing the solar wind flow streamlines. It was shown that "fluopause method" provides the best determination in the tailward part of magnetopause. After finding the magnetopause the magnetotail magnetic flux was integrated as $F = \sum(B_i \bullet S_i)$, where S_i – cell square of used spatial grid and B_i – magnitude of Bx component of magnetic field in the middle of the cell. This method was employed to test a new empirical method of tail magnetic flux calculation based on simultaneous spacecraft observations in the magnetotail and in the solar wind.

Introduction

Nowadays the time-dependent magnetospheric models play a special and important role in the magnetospheric studies, as they provide the only way of doing experiments under the well-controlled external conditions. Global MHD models is also the only way to simulate the dynamical response of entire complex magnrtosphere, with outputs simultaneously available from its different parts. Such models are based on solutions of magnetohydro dynamic equations in the nodes of adjusted spatial grid under the specified time-dependent solar wind boundary conditions (Raeder, 2003). Global MHD is a powerful tool that satisfactorily describes the large scale phenomena in the magnetosphere.

Three different global MHD models are now publicly available at the Community Coordinated Modeling Center (CCMC), operating at NASA GSFC. They are BATSRUS, Open GGCM and GUMICS. At CCMC webpage one can request the simulation of magnetosphere under specified solar wind conditions. These codes solve the MHD equations in nodes of stretched Cartesian grid within simulation box : $-350<X<24$, $-48<Y,Z<48$ for Open GGCM, $-223<X<33$, $-64<Y,Z<64$ for GUMICS, $-255<X<33$, $-48<Y,Z<48$ for BATSRUS (the distances scaled in Re).

When studying the magnetotail dynamics, the circulation of magnetic flux in the solar wind – magnetosphere system is one of most important physical quantities to control, as it determines the dynamical regime of magnetosphere. Depending on the balance of reconnected flux at the magnetopause and in magnetotail, the magnetosphere can be found at different states (substorm growth or expansion phase, or steady convection) even under the same solar wind conditions. The reasons of this variable behavior of the magnetotail are not finally understood. The values and dynamical behavior of magnetotail magnetic flux is one of few global parameters describing the entire magnetosphere. Monitoring of the magnetic flux is necessary to understand what determines different magnetospheric state, unfortunately this quantity is difficult to determine from observations.

Method description

Since our goal is the tail magnetic flux computation, the most important thing is the accurate magnetopause determination. Three different methods of magnetopause identification have been described in the literature, they are based on finding the maximal plasma density gradient peak or on the current density peak determination (Garcia and Hughes, 2007). In the third (fluopause) method (Palmroth et.al., 2003), the plasma flow streamlines are traced from the solar wind and the surface of innermost solar wind flow lines (called a fluopause) is determined. Each of these methods has their own problems and advantages. According to previous works and our own experience, two first methods appear to work satisfactorily in the polar regions of magnetotail, but had problems in near-equatorial regions (at the flanks), because there are no sharp plasma density and current gradients between magnetosheeth and LLBL plasmas. On the other hand, the fluopause can be reliably determined at all latitudes and agree reasonably well with two other methods in the polar regions where they work well, as will be illustrated below. The principal difficulty is that in the open magnetosphere the solar wind plasma can penetrate into the tail through the magnetopause, so this fluopause surface may indicate rather the low bound for the actual magnetopause location.

Fluopause is the surface that separates the magnetospheric cavity from solar wind plasma flow. We define this surface as a set of streamlines that starts in the solar wind and passes most close to X axis. We chose the starting points of streamlines well outside of bow shock in solar wind (2 Re sunward from the most distant bow shock position in the simulation run) and produce there the rectangular grid 20x20 Re in YZ plane with the X-axis in center, and 0.5 Re step size in both Y and Z directions. Beginning from this “start plane” we follow by steps dX and find corresponding dY, dZ from streamline equation dX/Vx=dY/Vy=dZ/Vz from which we have dY=dX*Vy/Vx and dZ=dX*Vz/Vx. The total stepsize dS is controlled to be less than 0.5 Re.

As soon as coordinates of all streamlines are obtained we can determine the contour of fluopause in YZ plane at any specified X position (Fig.1 Left). The example in the Figure 1 have been obtained during a run of Open GGCM model. Dipole tilt for this simulation was -15 deg. Conditions of solar wind appropriate to this moment (80 min from the simulation start) are: IMF Bx=2 nT, By=0 nT, Bz=3 nT, Vx=-600 km/s, Vy=Vz=0, plasma density =5 sm^{-3}, T=$6x10^4$ K. To determine the fluopause the YZ plane is divided in 72 angular sectors, in each 5 degree wide sector we find the coordinates of the streamline which is closest to X axis. A set of so obtained coordinates is grouped in 4 90^o–wide angular sectors $-\pi/4+n*\pi/2 < \alpha < \pi/4+n*\pi/2$ where n =1…4, and are smoothed by using polinomial spline in each sector separately. The so determined fluopause contour is illustrated in Figure 1 (right).

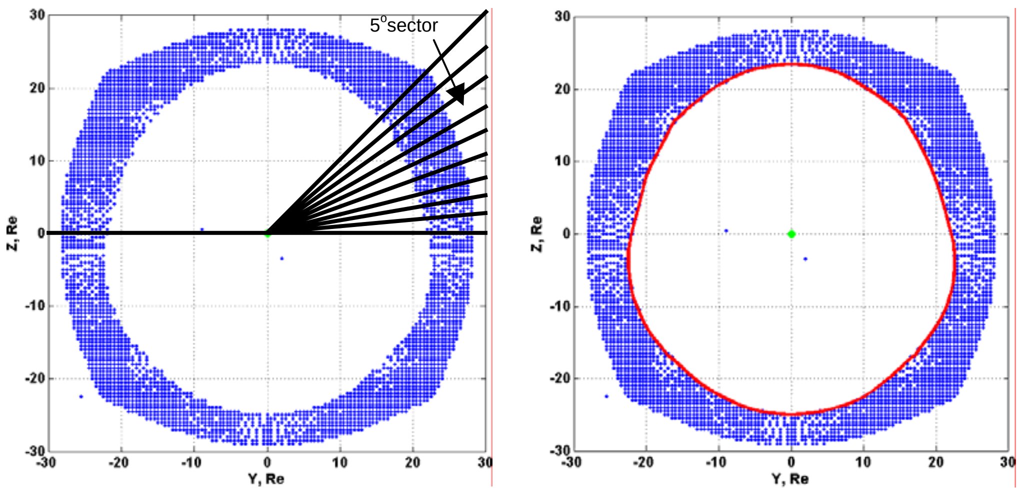


Figure 1 Illustration to the determination of fluopause contour in YZ plane, here at X=-15Re. Left panel: dots – crossing points of solar wind streamlines. Right panel: solid line shows the derived fluopause contour.

In Fig.1 (right panel) one can see two black dots inside the fluopause contour that are the streamlines penetrating deep into magnetosphere. The reason is that for MHD models some streamlines at the subsolar magnetosphere can penetrate through the magnetopause. These two points do not affect the fluopouse position since our algorithm excludes the points inside the circle with radius R=10 Re from fitting, this works well tailwards of the terminator. But if the penetrated streamlines will be closer to magnetopause it can lead to wrong determination of fluopause position. Therefore we place a restriction on start points area, namely, the area of start points with 2 Re radius ($R=(Y^2+Z^2)^{1/2}$) excludes. This procedure have no significant affect to fluopause position but allow us to correctly compute the magnetopause surface routinely.

To trace the solar wind flow lines we used the simulation data interpolated onto equidistant 3d grid. It was found that 0.5 Re grid resolution is acceptable compromise between required precision of magnetopause determination on the one hand, and the available computer resources (common personal computers) on the other hand. This is illustrated by Figure 2. Comparison of fluopause position defined utilizing data with different resolution (from 0.1 Re to 0.5 Re) showed that the maximum difference of magnetopause radius determination between resolutions 0.1 and 0.3 Re is ~0.2 Re, between 0.1 and 0.4 Re resolution it is ~0.4 Re, whereas between 0.1 and 0.5 Re resolution is ~1 Re. Corresponding difference of magnetic flux values are ~0,2 % (0.1 and 0.3 Re res.), ~0.5 % (0.1 and 0.4 Re res.), and ~2 % (0.1 and 0.5 Re res.). There is one more reason to avoid using the data interpolated to a high resolution grid. The spatial grid uses by different global models differ but in average it has a resolution varying from 0.5 to 2.5 Re for the middle tail distances (-15,-30 Re) close to magnetopause. So there is no big reason to interpolate the data to a higher resolution than 0.5 Re.

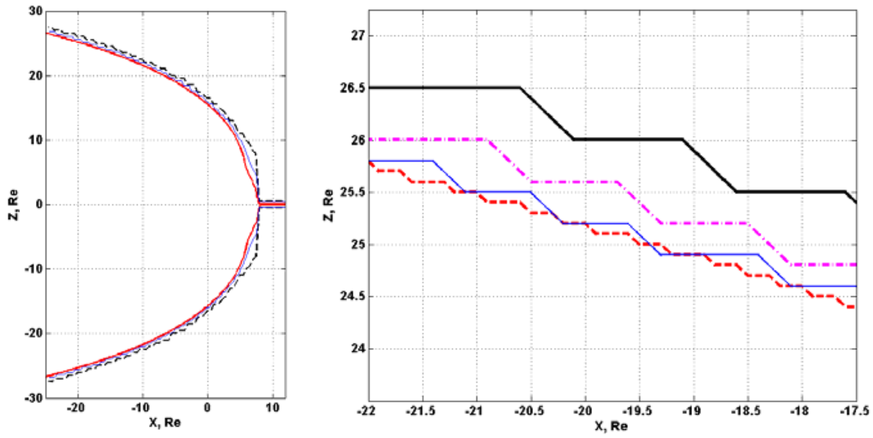


Figure 2 Left panel: comparison of fluopause positions for different grid resolution. Thick solid line – 0.1 Re resolution, thin solid – 0.4 Re, dashed – 0.5 Re. Right panel: zoom of the left figure. Dashed line – 0.1 Re resolution, thin solid – 0.3 Re, dash-doted – 0.4 Re, thick solid – 0.5 Re.

Figure 3 illustrates comparison of different methods of magnetopause determination. For the tailward part magnetopause a good agreement at the near polar regions is clear seen between all three methods, while at the flanks two methods based on current density and plasma density gradients do not work properly and results are not shown in this figure, because in the equatorial parts there is no big contrast and sharp boundary between the magnetosheath plasma and plasma sheet plasma.

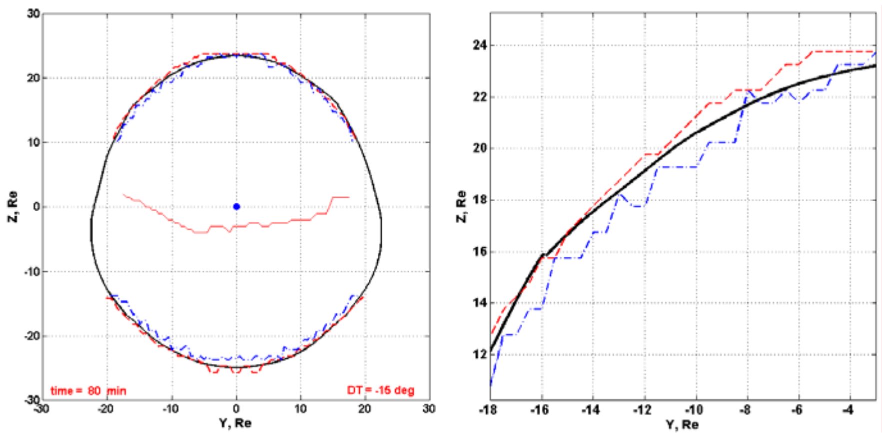
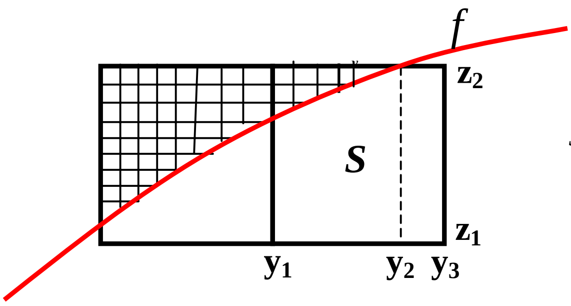


Figure 3: Typical example of magnetopause determination using different methods. Left panel: the cross-tail cut at X=-15 Re. Right panel: zoom of the left figure. Solid line shows the fluopause, dashed lines – results of "current density peak" , dash-dotted lines – "plasma density gradient" method. Thin solid line in the center indicates the neutral sheet.

After finding the magnetopause, the next step is the magnetic flux calculation. Tail magnetic flux is obtained by integration of the magnetic field normal component (Bx) through the elementary cells in the given crosssection as $F = \sum(B_i \bullet S_i)$, where S_i is the square of elementary cell, B_i is magnetic field Bx component value in the middle of cell, defined using linear interpolation.



$$S_i = (y_3 - y_2) \bullet (z_2 - z_1) + \int_{y_1}^{y_2} f \bullet dy$$

Fig.4 Calculation of boundary cells squares for cells crossed by the fluopause. Solid line is the fluopause contour, Si denotes the square of crossed cell.

Squares of cells that are entirely contained in the magnetosphere and don't cross the magnetopause contour is simply equal to dy*dz, where dy and dz is the grid resolution in Y and Z direction respectively ($0.5\times0.5 = 0.25$ Re in our case). Squares of boundary cells are calculated taking into account the magnetopause crossings through it as shown in Figure 4. Direction of magnetic flux (sunward – anti-sunward) cross elementary cell is determined according to the sign of magnetic field Bx – component. Thus the sunward magnetic flux correspond to +Bx, and anti-sunward to –Bx.

The example of computed magnetic flux during the 5h-long simulated event is presented below. In this simulation all parameters of solar wind are stable (IMF Bx=2 nT, By=0 nT, Vx=-600 km/s, Vy=Vz=0, plasma density =5 sm^{-3}, $T=6x10^4$ K), except IMF Bz that shown on the top panel of Figure 5. The magnetic flux is a high dynamical, following after the IMF Bz variations. One can see the substorm onset triggered by northward turn of IMF Bz at t~60min, and the magnetic flux storage in the magnetotail when Bz is southward. The nature of magnetic flux difference in north and south hemisphere is not fully understood, but probably it is the positive IMF Bx component which penetrates into the magnetotail.

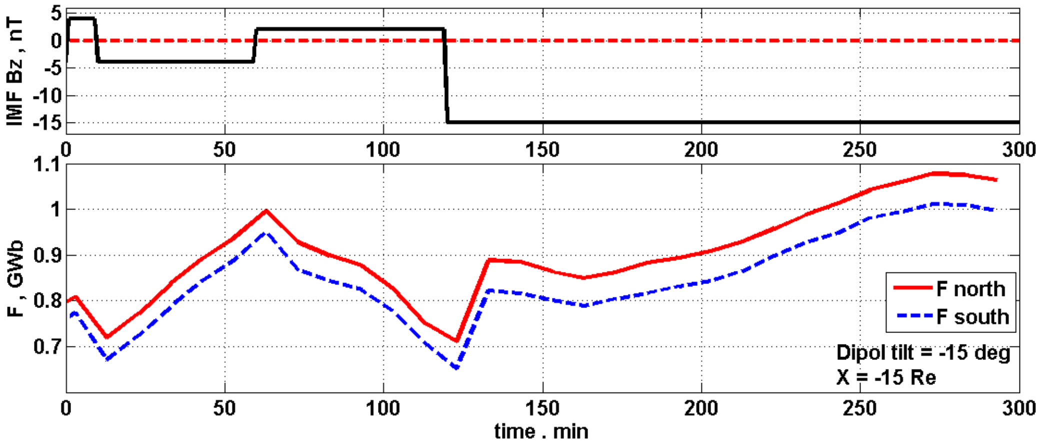


Figure 5. Results of global MHD simulation run 'Evgeniy_Gordeev_070209_1' at CCMC using Open GGCM model.. Top panel: solid line shows the IMF Bz (input). Bottom panel: solid line shows calculated magnetic flux in the northern hemisphere, dashed line similar magnetic flux calculated in the southern hemisphere.

Conclusions

The method of the tail magnetic flux calculation utilizing global MHD models was developed. This method was successfully used to test the algorithm which allow the computation of time-varying magnetotail magnetic flux based on simultaneous spacecraft measurements in the magnetotail and near-Earth solar wind (Shukhtina et.al., 2009). Also it can be used for comparison of different global MHD models between themselves and with existing empirical models (magnetopause location, magnetic field in lobes), as well as to be used in understanding different dynamical regimes of the magnetotail in strong driving conditions (SMC or substorms?).

References

Garcia, K.S. and Hughes, W.J.: Finding the Lyon-Fedder-Mobarry magnetopause: A statistical perspective, *J. Geophys Res*., 112, A06229, doi: 10.1029/2006JA012039, 2007

Palmroth, M., Pulkkinen, T.I., Janhunen, P.,Wu, C.-C.: Stormtime energy transfer in global MHD simulation, *J. Geophys. Res*., 108(A1), 1048, doi:10.1029/2002JA009446, 2003.

Shukhtina, M.A., E.I. Gordeev, V.A. Sergeev: Time-varying magnetotail magnetic flux calculation: a test of the method, *Ann. Geophys*., 27, 1583-1591, 2009.

Petrinec, S.M. and Russel, C.T.: Near-Earth magnetotail shape and size as determined from magnetopause flaring angle, *J. Geophys. Res*., 101, 137-152, 1996.

Sotirelis, T., and C.-I. Meng, Magnetopause from pressure balance, *J. Geophys. Res*., 104(A4), 6889-6898, 1999.

Shue, J.-H., et al., Magnetopause location under extreme solar wind conditions, *J. Geophys. Res.*, 103(A8), 17691–17700, 1998.

Fairfield, D. H., and J. Jones, Variability of the tail lobe field strength, *J. Geophys. Res.*, 101(A4), 7785–7791, 1996.

J. Raeder, Global magnetohydrodynamics – a tutorial, *Space Plasma Simulation*, 2003.