



This is an electronic reprint of the original article. This reprint may differ from the original in pagination and typographic detail.

Parunakian, David; Dyadechkin, Sergey; Alexeev, Igor; Belenkaya, Elena; Khodachenko, Maxim; Kallio, Esa; Alho, Markku Simulation of Mercury's magnetosheath with a combined hybrid-paraboloid model

Published in: Journal of Geophysical Research: Space Physics

DOI: 10.1002/2017JA024105

Published: 01/08/2017

Document Version Publisher's PDF, also known as Version of record

Published under the following license: CC BY

Please cite the original version:

Parunakian, D., Dyadechkin, S., Alexeev, I., Belenkaya, E., Khodachenko, M., Kallio, E., & Alho, M. (2017). Simulation of Mercury's magnetosheath with a combined hybrid-paraboloid model. *Journal of Geophysical Research: Space Physics*, *122*(8), 8310-8326. https://doi.org/10.1002/2017JA024105

This material is protected by copyright and other intellectual property rights, and duplication or sale of all or part of any of the repository collections is not permitted, except that material may be duplicated by you for your research use or educational purposes in electronic or print form. You must obtain permission for any other use. Electronic or print copies may not be offered, whether for sale or otherwise to anyone who is not an authorised user.

@AGUPUBLICATIONS

Journal of Geophysical Research: Space Physics

RESEARCH ARTICLE

10.1002/2017JA024105

Key Points:

- A new magnetosphere model has been developed which combines hybrid and analytical approaches
 Preliminary tests suggest that this
- approach successfully captures observed magnetospheric features
- The magnetopause is closer to Mercury for southward IMF, while the bow shock position is stable

Correspondence to: D. Parunakian, dp@dp.io

Citation:

Parunakian, D., S. Dyadechkin, I. Alexeev, E. Belenkaya, M. Khodachenko, E. Kallio, and M. Alho (2017), Simulation of Mercury's magnetosheath with a combined hybrid-paraboloid model, *J. Geophys. Res. Space Physics*, *122*, 8310–8326, doi:10.1002/2017JA024105.

Received 1 MAR 2017 Accepted 28 JUN 2017 Accepted article online 15 JUL 2017 Published online 14 AUG 2017

©2017. The Authors.

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

Simulation of Mercury's magnetosheath with a combined hybrid-paraboloid model

JGR

David Parunakian¹, Sergey Dyadechkin^{2,3}, Igor Alexeev¹, Elena Belenkaya¹, Maxim Khodachenko^{1,3}, Esa Kallio², and Markku Alho²

¹ Skobeltsyn Institute of Nuclear Physics, Federal State Budget Educational Institution of Higher Education M.V. Lomonosov Moscow State University, Moscow, Russia, ²Department of Electronics and Nanoengineering, Aalto University School of Electrical Engineering, Espoo, Finland, ³Space Research Institute, Austrian Academy of Sciences, Graz, Austria

Abstract In this paper we introduce a novel approach for modeling planetary magnetospheres that involves a combination of the hybrid model and the paraboloid magnetosphere model (PMM); we further refer to it as the combined hybrid model. While both of these individual models have been successfully applied in the past, their combination enables us both to overcome the traditional difficulties of hybrid models to develop a self-consistent magnetic field and to compensate the lack of plasma simulation in the PMM. We then use this combined model to simulate Mercury's magnetosphere and investigate the geometry and configuration of Mercury's magnetosheath controlled by various conditions in the interplanetary medium. The developed approach provides a unique comprehensive view of Mercury's magnetospheric environment for the first time. Using this setup, we compare the locations of the bow shock and the magnetopause as determined by simulations with the locations predicted by stand-alone PMM runs and also verify the magnetic and dynamic pressure balance at the magnetopause. We also compare the results produced by these simulations with observational data obtained by the magnetometer on board the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft along a dusk-dawn orbit and discuss the signatures of the magnetospheric features that appear in these simulations. Overall, our analysis suggests that combining the semiempirical PMM with a self-consistent global kinetic model creates new modeling possibilities which individual models cannot provide on their own.

1. Introduction

Generally, semiempirical magnetosphere models represent the total magnetospheric field as a sum of current system field contributions. Input parameters for this class of models are usually estimated by executing least squares minimization to fit the model field along a spacecraft trajectory to experimental data. This approach was pioneered by *Mead and Fairfield* [1975], who used over 12,000 vector field averages based on 451 orbits of four IMP satellites. An important feature of many semiempirical models is modularity, i.e., the possibility to fine tune parameters for any chosen current system independently. Some of the early models have had a modular structure from the outset [*Alekseev and Shabansky*, 1972], while others [*Tsyganenko*, 2002] developed this capability as they matured.

Tsyganenko and Usmanov [1982] proposed an analytical model that incorporated a mathematical description of contributions by magnetopause currents, ring current, and magnetotail current sheet. This model required 21 linear coefficients and seven nonlinear parameters for operation. It was later improved by doubling the number of vector averages used for the initial fitting and extending the modeling region far into the magnetotail [*Tsyganenko*, 1987]. The full version of this model required 26 parameters and was valid tailward to distances of $-70 R_E$, while a simplified version only required 20 parameters but was valid to $-30 R_E$. Further enhancements of this model include better description of magnetotail current sheet geometry and thickness [*Tsyganenko*, 1989], fully controlled shielding of magnetospheric current system contributions, an improved shape of the magnetopause [*Tsyganenko*, 1995], heavily revised representations for major field sources [*Tsyganenko*, 2002], and adoption of the approximation of the magnetopause surface introduced in *Shue et al.* [1997].

<mark>_</mark>

The present work is based on the dynamical paraboloid model first introduced in *Alexeev et al.* [1996]. In this case the magnetospheric field is represented as a linear sum of the contributions of distinct magnetic field sources. An improvement to this model introduced by *Alexeev et al.* [1998] describes locations of merging on the magnetopause as a function of interplanetary magnetic field (IMF) orientation. The extended version of the model can be applied to space both inside and outside the magnetopause. The magnetic field in the region between the magnetopause and the bow shock, each approximated by a paraboloid of revolution, is represented as a sum of two components—namely, the uniform field penetrating the magnetopause which is independent of both time and spatial coordinates and the residual field whose normal component is equal to zero at any point of the magnetopause. Although the paraboloid model offers an unrealistic divergent magnetopause shape toward the nightside, it should be noted that in the nightside region magnetopause currents are weak, and the errors introduced are not substantial.

This model is similar to the model introduced by *Kobel and Flückiger* [1994], who also represent the shape of the magnetopause and the bow shock by a rotational paraboloid with a sunward axis. It uses the scalar potential approach to derive an analytical representation of a stationary magnetic field in the magnetosheath that depends on IMF components and the stand-off distances of the magnetopause and the bow shock.

Mercury's magnetopause was first described by the paraboloid model in *Alexeev et al.* [2008]. In this work measurements during two Mariner 10 spacecraft flybys were used to fit the magnetospheric parameters. The magnetic dipole moment was determined to be equal to $B_0 = 192 \text{ nT} \times R_{M'}^3$ and the dipole center was found to be offset by 0.18 R_M along the *Z* axis toward the north pole. These results were slightly revised in *Alexeev et al.* [2010], which used magnetic field measurements taken during two MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) flybys. Various erosion mechanisms partially responsible for reduction of the magnetopause stand-off distance and the changes in the external field were later investigated in more detail by *Heyner et al.* [2016]. In *Johnson et al.* [2012], the paraboloid model was used to fit MESSENGER magnetometer data from March to December 2011 and made it possible to realize an RMS misfit of less than 20 nT. In *Korth et al.* [2015] the modular model of Mercury's magnetopause shape described in *Shue et al.* [1997] for the terrestrial magnetopause.

Plasma and magnetic field in Mercury's magnetosphere have been investigated by several different numerical simulation methods. Test particle simulations have provided insight into the acceleration of charged particles in given electric and magnetic fields [e.g., *lp*, 1987; *Delcourt et al.*, 2002]. Magnetohydrodynamic (MHD) models treat plasma as a charged fluid and have enabled studying the self-consistent properties of plasma and fields [e.g., *Kabin et al.*, 2000; *Jia et al.*, 2015]. Hybrid models treat ions as particles and electrons as a massless neutralizing fluid and provide a self-consistent approach which includes ion kinetic effects. Such models can have a non-Maxwellian velocity distribution function [e.g., *Kallio and Janhunen*, 2003a, 2003b; *Trávníček et al.*, 2007; *Müller et al.*, 2012]. Full kinetic particle-in-cell (PIC) models contain electron kinetics and charge separation effects [e.g., *Nakamura et al.*, 2010].

All of these numerical simulation approaches have their advantages and weaknesses. The change of the model approach from test particle simulations to MHD, to a hybrid, and to a PIC model increases the self-consistency of the approach and reduces the number of necessary assumptions at the expense of performance. Computational costs must then be compensated, for example, by making a local simulation, using a coarse spatial resolution, or by using different modeling approaches in different space regions, such as using a local PIC simulation within a global MHD simulation [e.g., *Töth et al.*, 2016]. Therefore, the choice of the most useful modeling approaches depends on the purpose of the simulation run and the specific application.

The goal of this paper is to combine a numerical model and a semiempirical model in order (1) to decrease computational costs of numerical kinetic simulations for a relatively large grid size and (2) to introduce the bow shock the and magnetopause current sheets into the initial magnetic field condition; improving the accuracy of determining positions of the bow shock and the magnetopause (which are by definition magnetosheath boundaries) allows us to better understand the dependence of magnetosheath geometry on external parameters. This methodology enables us to determine the region in the magnetosheath where non-linear IMF effects are realized and to study the magnetosheath velocity and density distributions as well as the effects of the magnetic field draping and of IMF and planetary magnetic field reconnection. Also, this combination results in a model which includes both kinetic effects and an empirical high-resolution magnetosheric

magnetic field. Moreover, in the model the electric field is connected self-consistently to the properties of plasma and the magnetic field. This results in a new 3-D modeling approach which provides new possibilities to study not only Mercury's magnetosphere but also other planetary and exoplanetary magnetospheres.

In section 2, we describe the mathematical foundations of both the semiempirical model and the hybrid model applied in this work and define used parameters and grid structure. We describe the results produced by the modeling efforts in section 3 and discuss them in detail in section 4.

2. Model Information

2.1. Overview

Traditionally, a planetary dipole field is used as the initial magnetic field condition for hybrid simulations. While this approach has proved fruitful, evidently, it leaves much room for improvement [see, e.g., *Kallio and Janhunen*, 2003a]. By adding all the paraboloid magnetosphere model (PMM) current systems to the initial conditions we start the model from a state closer to the final solution. The magnetopause currents and magnetotail current system are most certainly present in a stationary solution despite being generated by the plasma flow. Additionally, there is a permanent influence exerted by a portion of the interplanetary magnetic field penetrating the magnetosphere.

We first note that since $-\nabla \times \mathbf{E}(\mathbf{r}, t) = \frac{\delta \mathbf{B}(\mathbf{r}, t)}{\delta t}$, we can safely add to the PMM an arbitrary constant uniform externally induced magnetic field while maintaining the integrity of the MHD solution. We can take advantage of this by utilizing the property of the paraboloid magnetosphere model [Alexeev, 1986] that the magnetic field terms are linearly independent in parabolic coordinates. We also note that modeling a very thin current sheet would require a higher grid resolution; this can make the simulation computationally expensive and may cause numerical instabilities that can destroy the solution. On the other hand, inclusion of numerical diffusion for stability reasons would smooth out sharp electric current sheets.

2.2. Hybrid Model

While the hybrid simulation [*Kallio and Janhunen*, 2003a] used enables modeling of multiple ion species, in this work we have limited its scope to only include solar wind protons; studying the influence of addition of planetary ions such as Na⁺ and K⁺ ions on the combined model is one of the planned future studies.

In this model, batches of protons are represented as cubic clouds of uniform charge density and of the same dimensions as MHD grid cells. Such clouds are referred to as macroparticles. A macroparticle contributes to all grid cells it overlaps with, weighted proportionally to the volume overlapping with each cell:

$$dw_j(\mathbf{r}_k) = w(dV_j(\mathbf{r}_k)/dV)$$

Here dV is the volume of grid cells where the center of macroparticle is, $dV_j(\mathbf{r}_k)$ is the volume of the intersection of a given macroparticle *j* with the grid cell at \mathbf{r}_k , w_j is the resulting weighting parameter determining the contribution of the macroparticle *j* to the grid cell, and *w* is the total number of real particles in a macroparticle. Multiple macroparticles can overlap with any one cell; the resulting particle density *n* and the proton bulk velocity *U* are therefore calculated as

$$n(\mathbf{r}_k) = \frac{\sum_j w_j(\mathbf{r}_k)}{V}$$
$$\boldsymbol{U}(\mathbf{r}_k) = \frac{\sum_j w_j(\mathbf{r}_k) \mathbf{v}_j}{\sum_i w_j(\mathbf{r}_k)}$$

where \mathbf{v}_i is the velocity of macroparticle *j*.

2.3. Paraboloid Magnetosphere Model

As follows from its name, the key concept of the PMM is the assumption that the magnetopause can be represented by a paraboloid of revolution around the sunward axis in the solar-magnetospheric coordinate system centered on the planetary dipole position. The PMM represents the total magnetospheric field as a linear superposition of magnetic fields from various sources, including fields created by magnetopause currents and the tail current system. We propose to represent the total IMF vector as a sum of two magnetic field components, based on the assumptions made in *Alexeev and Kalegaev* [1995]:

$$\boldsymbol{B}_{\mathsf{IMF}} = \boldsymbol{B}_{\mathsf{IMF1}} + \boldsymbol{b}_0 \tag{1}$$



Figure 1. Comparison of MESSENGER data (black line) and paraboloid model forecast (red line) (Orbit 418). (top left) |B| and (top right) B_X . (bottom left) B_Y and (bottom right) B_Z field components. PMM parameters used: $B_D = -196$ nT, $B_T = 61$ nT, $R_1 = 1.45 R_M$, $R_2 = 1.70 R_M$, and $B_{IMF} = [4.0, -10.0, 10.0]$ nT.

Here $B_{\rm IMF1}$ is the IMF component fully shielded by the magnetopause currents. This magnetic field is mostly undisturbed upstream of the bow shock aside from the contribution of reflected ions. The influence of $B_{\rm IMF1}$ deforms the draping around the magnetopause and creates a magnetic barrier. The $B_{\rm IMF1}$ component is strongly controlled by plasma currents in the simulation box [*Heyner et al.*, 2016]. The b_0 component is the residual uniform field penetrating the magnetosphere; it is determined by the reconnection efficiency. If the reconnection efficiency grows to 1, b_0 grows to the total IMF value (20 nT in our case); if the reconnection efficiency falls to 0, b_0 also falls to 0. The uniformity of b_0 is a consequence of the fact that both the magnetic diffusion velocity and the radius of the paraboloid are proportional to \sqrt{X} [*Alexeev*, 1986] in the Mercury Solar Orbital (MSO) coordinate system; in this system, the X axis points from Mercury's center toward the Sun, Z points northward normally to the orbit plane, and Y completes the right-hand system nominally directed opposite Mercury's orbital velocity around the Sun. Thus, we observe the same penetrating field independent of the tailward distance X. The uniform field \mathbf{b}_0 cannot be created by currents inside the simulation box; rather, it is generated by currents or constant magnets located at infinite Z outside the simulation box. Thus, this field must be defined as some \mathbf{b}_0 , which is not included in the induction equation, while \mathbf{B}_{IMF1} determines boundary conditions on the left side of the box and induction equations.

The general solution for the IMF-induced perturbation field \mathbf{b}_0 is a uniform field collinear to the undisturbed IMF field, $\mathbf{b}_0 = \kappa \mathbf{B}_{\text{IMF}}$, where κ denotes the factor of reconnection efficiency. For instance, a value of magnetic Reynolds number $R_m = 10^4$ [Alexeev, 1986] corresponds to $\kappa = 0.07$. Generally, we can verify this value by running the simulated flow past some nonconductive paraboloid-shaped body while maintaining the condition of $V_n = 0$ at the paraboloid surface (the magnetopause). We can then use the strength of the magnetic field inside the paraboloid to compute the reconnection efficiency. An independent way to estimate the reconnection efficiency (which is used in this work) would rely on using the Mach number $\kappa = M_A^{-1} = \frac{V_A}{V_{sw}}$ [Heyner et al., 2016]; e.g., in case of $V_A = 40$ km/s and $V_{sw} = 400$ km/s, only $\kappa = 0.1$ of the total *B* penetrates into magnetosphere.

The precise value of magnetic field to be added can be determined by fitting the PMM magnetic field along the MESSENGER orbit to magnetometer data by running the Levenberg-Marquardt algorithm [*Marquardt*, 1963] to solve the least squares curve fitting problem of optimizing the PMM parameters to match magnetic field measurements along individual MESSENGER orbits for follow-up research.

We find that the paraboloid magnetosphere model is in good agreement with Mercury's magnetospheric field per MESSENGER magnetometer observations, with a global RMS misfit of less than 20 nT [*Alexeev et al.*, 2010] (Figure 1). The PMM has also been validated by examining the accuracy of its description of individual contributions of the magnetopause, magnetotail, and internal magnetic fields [*Johnson et al.*, 2012].

We then proceed to calculate the magnetic field produced by the PMM seeded with parameter values found during the fitting process for an individual orbit in the nodes of a parallelepipedal grid and assimilate these values into the hybrid model.

2.4. Combined Hybrid Model

2.4.1. Magnetic and Electric Fields

The magnetic field in the new combined hybrid model (CHM), B(r, t), is a combination of three magnetic field terms:

$$\boldsymbol{B}(\boldsymbol{r},t) = \boldsymbol{B}_{HM}(\boldsymbol{r},t) + \boldsymbol{b}_0 + \boldsymbol{B}_{PMM}(\boldsymbol{r})$$
(2)

The terms in this equation are the following:

1. **b**₀ is constant penetrating interplanetary magnetic field (IMF).

2. $\boldsymbol{B}_{PMM}(\boldsymbol{r}) = \boldsymbol{B}_{PMM}(\boldsymbol{r}) |_{r < r_{MP}}, \boldsymbol{B}_{PMM}(\boldsymbol{r}) = 0|_{r > r_{MP}}$ is a time-independent paraboloid magnetospheric model (PMM) magnetic field.

3. $B_{HM}(r, t)$ is hybrid model (HM) magnetic field associated with the electric current of ions and electrons.

The PMM magnetic field $B_{PMM}(r)$ is zero outside the magnetopause (MP), i.e., at $r > r_{MP}$. It can be defined inside the simulation box as a sum of three terms:

$$\boldsymbol{B}_{\mathsf{PMM}}(\boldsymbol{r}) = \boldsymbol{B}_{\mathsf{DIP}}(\boldsymbol{r}) + \boldsymbol{B}_{\mathsf{CF}}(\boldsymbol{r}) + \boldsymbol{B}_{\mathsf{TC}}(\boldsymbol{r}), \tag{3}$$

where $B_{DIP}(r)$ is the field of the planetary dipole, $B_{TC}(r)$ is the field of the tail current, and $B_{CF}(r)$ is the Chapman-Ferraro current magnetic field, which confines the dipole field inside the magnetopause. Therefore, the magnetopause divides the magnetic field into two regions (Figure 2):

$$\boldsymbol{B}(\boldsymbol{r},t) = \boldsymbol{B}_{HM}(\boldsymbol{r},t) + \boldsymbol{b}_0 |_{\boldsymbol{r} > r_{MP}}$$
(4a)

$$\boldsymbol{B}(\boldsymbol{r},t) = \boldsymbol{B}_{\mathsf{PMM}}(\boldsymbol{r}) + \boldsymbol{b}_0 \mid_{\boldsymbol{r} < \boldsymbol{r}_{\mathsf{MP}}}$$
(4b)

At the beginning of simulation at t = 0 s the magnetic field within the whole simulation box is initialized with a constant IMF field and the PMM magnetic field:

$$\boldsymbol{B}(\boldsymbol{r},0) = \boldsymbol{B}_{\mathsf{PMM}}(\boldsymbol{r}) + \boldsymbol{b}_0 \tag{5}$$



Figure 2. Magnetic field regions in the combined hybrid model (CHM). Cells marked by blue color form a region above the magnetopause of the PMM where the time-dependent magnetic field is a superposition of the magnetic field of the hybrid model (B_{HM}) and a constant IMF (b_0). Cells marked by red color form a time-independent magnetic field region where the magnetic field is a combination of the PMM magnetic field of (B_{PMM}) and a constant IMF. Cell size is 0.33 R_M (805 km), and the sphere shows the size of Mercury.

Technically, the IMF and the PMM magnetic fields are included in the simulation by deriving their values in the centers of simulation cells. In the hybrid model the magnetic field is propagated by Faraday's law from the electric field *E* [Kallio and Janhunen, 2003a]:

$$\frac{\delta \boldsymbol{B}(\boldsymbol{r},t)}{\delta t} = -\nabla \times \boldsymbol{E}(\boldsymbol{r},t) \tag{6}$$

The electric field is derived from the electron momentum equation from proton bulk velocity U_{H^+} , density n, and the associated magnetic field [Kallio and Janhunen, 2003a]:

$$\boldsymbol{E} = -\boldsymbol{U}_{H^+} \times \boldsymbol{B} + \frac{\boldsymbol{j} \times \boldsymbol{B}}{en} = -\boldsymbol{U}_{H^+} \times \boldsymbol{B} + \frac{(\nabla \times \boldsymbol{B}) \times \boldsymbol{B}}{en\mu_0}$$
(7)

where e is the positive unit charge and μ_0 is the vacuum magnetic permeability.

Here we assume that plasma is quasi-neutral, i.e., that the density of protons is equal to the density of electrons. The magnetic field is therefore propagated as

$$\frac{\delta \boldsymbol{B}(\boldsymbol{r},t)}{\delta t} = -\nabla \times \left(\boldsymbol{U}_{H^+} \times \boldsymbol{B} - \frac{(\nabla \times \boldsymbol{B}) \times \boldsymbol{B}}{e n \mu_0} \right)$$
(8)

It is informative to observe how this equation looks outside and inside of the magnetopause, i.e., at $r > r_{MP}$ and $r < r_{MP}$, respectively:

$$\frac{\delta \boldsymbol{B}(\boldsymbol{r},t)}{\delta t} = \nabla \times \left[\left(-\boldsymbol{U}_{H^+} + \frac{\nabla \times \boldsymbol{B}_{HM}}{en\mu_0} \right) \times \left[\boldsymbol{B}_{HM} + \boldsymbol{b}_0 \right] \right] \mid \boldsymbol{r} > r_{MP}$$
(9a)

$$\frac{\delta \boldsymbol{B}(\boldsymbol{r},t)}{\delta t} = 0 \qquad |\boldsymbol{r} < \boldsymbol{r}_{\mathsf{MP}} \tag{9b}$$

Equation (9a) implies that outside of the PMM magnetopause the magnetic field is propagated as typically done in the hybrid model and that the resulting magnetic field is propagated in time self-consistently by using plasma properties. Equation (9b) shows that the magnetic field is assumed to be unchanged within the magnetosphere. Our approach is valid as long as the IMF in Mercury's environment does not change during the orbit duration. Conditions such that the IMF vector is the same during the inbound and outbound sections of a MESSENGER orbit are actually a common occurrence. It would be also natural to constrain the selection of orbits to those that display identical solar wind plasma parameters; however, since the MESSENGER mission lacked a suitable instrument for low-energy plasma measurements, creating such a filter appears to be infeasible at this time.

2.4.2. Particles

The two macroscopic plasma parameters needed in the magnetic field propagation, n and U_{H^+} , are derived by accumulating the mass and momentum of protons within cells (see *Kallio and Janhunen* [2003b] for details of the used particle accumulation schema). Protons are accelerated by the Lorentz force

$$m\frac{\delta \mathbf{v}}{\delta t} = e(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \tag{10}$$

where v and m are the velocity and the mass of a proton, respectively. The magnetic and electric fields in equation (10) are given by equations (2) and (7), respectively.

2.4.3. Simulation

The coordinate system we use is as follows. The X axis points from the origin (dipole position) toward the Sun. The dipole magnetic moment is oriented along the Z axis, which is perpendicular to the X axis, and the Y axis completes the right-hand coordinate system. Mercury is represented as a sphere of an $R_M = 2440$ km radius. The planet's center is shifted southward by $0.2 R_M$ along the Z axis. The dimensions of the simulation box span $[-4 R_M, 4 R_M]$ along the X axis and $[-5 R_M, 5 R_M]$ in all other directions, cell size is $dx = dy = dz = 0.33 R_M =$ 488 km, the average number of macroparticles per cell is 30, and the simulation time step is dt = 0.00125 s. Bulk velocity U_{sw} , particle density n_{sw} , and temperature T_{sw} of the solar wind protons are 430 km/s, 76 cm⁻³, and 2.24×10^5 K, respectively. The IMF X and Y components are equal to 0, but the value of the Z component varies in order to study how the solution differs in the "closed" and "open" magnetosphere cases, i.e., when the IMF Z component is positive and negative, respectively.

2.5. Model Restrictions and Simplifications

To improve the accuracy of the seed field, we need to take into account the aberration of magnetosphere by Mercury's relative motion. Since the orbit of the planet is highly eccentric ($\epsilon \sim 0.66$), Mercury's orbital velocity varies from 40 km/s to 50 km/s. As this value is in the range of 5% to 10% of solar wind flow velocity, it is to be expected that Mercury's magnetosphere will not be exactly sunward oriented but will rather experience aberration reflecting the actual direction of solar wind arrival. While we have successfully applied this correction in other work [*Parunakian et al.*, 2016], we are yet to introduce it to our combined hybrid modeling efforts.

We also assume that the magnetic dipole axis and the planet's rotation axis coincide and are aligned normally to the orbital plane. This is not strictly true but is acceptable as a first approximation.

3. Results

3.1. Model Run Parameters and Variables

For the purpose of sanity check the model was initially run in a synthetic environment. We used the following parameter values to compute the PMM seed field: (1) Mercury radius $R_M = 2440$ km; (2) magnetic dipole field at the magnetic equator on Mercury's surface $B_D = -196$ nT and the magnetic field at the inner edge of the tail current $B_t = 131$ nT (which corresponds to open field line magnetic flux of $\Phi = 4$ *MWb*) as found by fitting the PMM to MESSENGER flyby data [*Alexeev et al.*, 2010]; the dipole is assumed to be oriented along the *Z* axis; (3) subsolar distance to the magnetopause $R_1 = 1.4 R_M$; (4) distance to the inner edge of the tail current system $R_2 = 1.25 R_M$; and (5) northward dipole displacement in the MSO coordinate system $dz = 0.2 R_M$.

In the Mercury Solar Orbital coordinates the X axis is directed from Mercury center to the Sun, the Y axis is directed parallel to Mercury's orbital velocity and is located in Mercury's orbital plane, and the Z axis is perpendicular to the XY plane and parallel to Mercury's axis. Since the MESSENGER mission was not equipped

to measure solar wind parameters, they must be determined based on our knowledge of the magnetopause location, as it is determined by the balance of magnetospheric magnetic pressure and solar wind pressure:

$$P_{\rm sw} = k \rho_{\rm sw} V_{\rm sw}^2 = k m_p n_{\rm sw} V_{\rm sw}^2 = \frac{B_{\rm ss}^2}{2\mu_0}$$
(11)

Here $m_p = 1.6726219 \times 10^{-27}$ kg is the mass of the proton, $\mu_0 = 4\pi 10^{-7} T \cdot m/A$ is the vacuum permeability constant, $k \approx 0.88$ is a constant for the high Mach number flow of monatomic gas, and B_{ss} is the magnetospheric magnetic field in the subsolar point at the surface of magnetopause.

For instance, if we assume mean solar wind dynamic pressure at 1 AU to be equal to $P_{1Au} = 2.15$ nPa [*Vulpetti*, 2012], and $V_{sw} = 390$ km/s [*King and Papitashvili*, 2005], then $P_M = 10.62$ nPa and $n_M = \frac{P_M}{km_p V_{sw}^2} = 47.5$ cm⁻³, as $P_M = \frac{P_{1AU}}{A_M^2}$, where A_M is the distance from Mercury to the Sun expressed in AU for Mercury located closely in aphelion (0.45 AU). Subsequently, the magnetospheric magnetic field at the magnetopause subsolar point equals to

$$B_{\rm ss} = C_{\rm mp} \frac{B_0}{R_1^3} = 152 \, nT \tag{12}$$

Here the $C_{mp} = 2.44$ coefficient is required to take into account that the magnetic field of dipole and magnetopause currents is 2.44 times the dipole field at the subsolar point [*Mead and Beard*, 1964] to achieve a self-consistent solution of the Chapman-Ferraro problem. From equation (12) we find $R_{ss} = 1.46 R_M$.

Our estimates of the tail current system parameters closely match those made by *Poh et al.* [2017]. In that work, the magnetic field at the inner edge of the tail current $B_t = \mu_0 dj = 110$ nT, where $d = 0.39 R_M$, j = 92 nA/m², and the distance to the inner edge of the tail current system is $1.22 R_M$. In that work, these parameters were computed taking into account the contribution of planetary ions to the stress balance in the central plasma sheet. This important factor lies outside of the immediate scope of the present work; however, we believe that the similarity of the parameters we use to those computed by *Poh et al.* [2017] is a reasonably good sanity check.

The actual solar wind parameters used are somewhat different: $n_{sw} = 23.26 \text{ cm}^{-3}$ and $V_{sw} = 400 \text{ km/s}$ in order to achieve $R_1 = 1.4 R_M$ (value computed by fitting the PMM to magnetic field measurements during the first magnetospheric transit in orbit #418 on 12 October 2011). We then proceed with executing the modeling runs, setting IMF $B_X = B_Y = 0$ nT and initializing B_7 with either of two configurations:

1. $B_Z = -4$ nT as the constant penetrating field and $B_Z = -16$ nT as the left boundary condition.

2. $B_Z = 4 \text{ nT}$ as the constant penetrating field and $B_Z = 16 \text{ nT}$ as the left boundary condition.

These \boldsymbol{b}_0 configurations correspond to IMF B_Z with 20 nT magnitude and a strictly southward or a strictly northward orientation and a κ coefficient of 0.2.

3.2. Difference in the IMF Flow Past Magnetosphere in Cases of Open and Closed Magnetosphere

We now turn to the results of hybrid simulation initialized with magnetic field conditions. Figure 3 presents plasma density in logarithmic scale indicated by false color. Figure 3 (left) displays results for a positive B_Z , and Figure 3 (right) displays results for a negative B_Z . The average lobe density is lower in case of northward IMF. Tail lobe diameter, judging by the plasma population, is smaller in case of northward IMF, which is in agreement with other plots. Both IMF orientations lead to growth of plasma density in magnetopause flanks, tail current sheet, and the nose cone of the magnetopause relative to IMF $B_Z = 0$, but the effect is more pronounced in case of southward IMF. While with northward IMF the density regime changes match the boundaries of the magnetosheath well, with southward IMF we observe that plasma density in the subsolar region of the magnetosheath is depleted by a factor of 5. This can probably be attributed to the pileup of magnetic flux in the equatorial region.

A similar plot of particle velocity distribution cannot be easily built at this time. In some areas of the plot the number of simultaneously present macroparticles is low, so the contribution weight of each one is very high. Despite utilization of techniques like particle splitting inside the PMM region, the resulting number of particles is still insufficient to allow for a realistic picture of velocity distribution.

Let us now examine the superpositions of the magnetic field Z components in northward (B_{ZN}) and southward IMF (B_{ZS}) cases, i.e., $\frac{B_{ZS}-B_{ZN}}{2}$ (Figure 4) and $\frac{B_{ZS}+B_{ZN}}{2}$ (Figure 5) fields. These figures show two cross sections: equatorial (left) and noon-midnight (right).



Figure 3. The XZ cross section of plasma density logarithm ($\log_{10} n[m^{-3}]$, false color) for (left) northward and (right) southward IMF in the CHM. The black lines denote magnetopause and bow shock surfaces.

The first case (Figure 4) allows us to discard the PMM contribution, as its sign is identical for both runs (in the red area of Figure 2), while retaining the IMF contribution, as $B_{IMF,Z}$ has opposite signs during the two runs (in the blue area of Figure 2). This allows us to observe the effect of northward IMF draping generated as the solar wind plasma flows past the planet's magnetosphere. The contributions of the dipole field and the infinitely thin magnetopause current which confines the dipole field inside the magnetopause are canceled out in this case, and inside the magnetosphere we only have the penetrating b_0 field. Upstream of the bow shock the draped B_{IMF} is uniform and equal to -20 nT. Downstream of the bow shock we see that electric currents connected with ions reflected by the magnetopause form a magnetic barrier. It appears as a jump in IMF after bow shock crossing.

Similarly, the second case (Figure 5) allows us to discard the IMF contribution while retaining the PMM contribution. Here the external boundary of the disturbed region corresponds to the bow shock position.

To further improve our understanding of reconnection properties for northward and southward IMF, we run the combined hybrid model in double-resolution mode and with $\nabla \times B = 0$ condition imposed. On the



Figure 4. The magnitude of $\frac{B_{ZS}-B_{ZN}}{2}$ in the CHM in Teslas: (left) the XY plane and (right) the XZ plane. The PMM contributions, B_{PMM} , have the same sign for closed and open magnetosphere inside the magnetopause and cancel each other in $\frac{B_{ZS}-B_{ZN}}{2}$. Here B_{ZS} and B_{ZN} are the Z components of the total magnetic field in cases of northward and southward IMF.



Figure 5. The magnitude of $\frac{B_{ZS}+B_{ZN}}{2}$ in the CHM in Teslas: (left) the *XY* plane and (right) the *XZ* plane. The IMF contributions, B_{HM} , have opposite signs for closed and open magnetosphere outside the magnetopause and cancel each other in $\frac{B_{ZS}+B_{ZN}}{2}$. Here B_{ZS} and B_{ZN} are the *Z* components of the total magnetic field in cases of northward and southward IMF.

resulting Figure 6 red denotes the negative X component field up to $B_{\chi} = -10$ nT, and blue denotes the positive X component field up to $B_{\chi} = 10$ nT. B_{0z} at the left boundary of the simulation box is set to +16 nT or -16 nT accordingly to maintain the total B_Z in the undisturbed flow equal to 20 nT. The magnetic field reconnection efficiency factor is chosen equal to $\kappa = 0.2$ [Alexeev, 1986]; we will address this issue later in more detail. Our results demonstrate that $\kappa < 1.0$, but for a more precise calculation of κ we need a detailed estimation of the numerical conductivity and to take into account the modeling time scaling ratio to real plasma instability increments. These points lie beyond the scope of the present paper.

We have used the following method to determine magnetopause and bow shock positions in Figures 6 and 3, which describe magnetic field and plasma density for the two modeling runs under discussion.



Figure 6. High-resolution plot of magnetosphere-solar wind interaction for reconnection efficiency value of $\kappa = 0.2$ in case of (left) northward and (right) southward IMF in the CHM. Color denotes the *X* component of the magnetic field in Teslas, and yellow arrows indicate the direction of magnetic field lines. The position of the bow shock and the magnetopause are shown with black lines. The parameters for northward IMF used in the PMM are $R_1 = 1.7 R_M$ and $R_{\rm bs} = 2.4 R_M$. Parameters for southward IMF are $R_1 = 1.42 R_M$ and $R_{\rm bs} = 2.4 R_M$.

The magnetopause position has been chosen for northward IMF so that it lies on the surface dividing the modeled space into two regions, one occupied by IMF field lines and the other one occupied by magnetic field lines connected to Mercury's surface. This boundary surface can be easily determined at the dayside magnetopause. For southward IMF the magnetopause has been chosen so that it passes through the day-side equatorial *X* point separating the area where the magnetic field is dominated by the planetary dipole from the area where the magnetic field is dominated by the IMF. The bow shock position was chosen empirically (similarly to *Kallio and Janhunen* [2003a]) to fit the observed density jump with a paraboloid surface for both IMF directions. It shall be noted that although the subsolar area of the bow shock is poorly described by a paraboloid for southward IMF (likely due to erosion), it describes the flanks of the bow shock well enough.

For southward IMF dayside reconnection occurs in the magnetic field's 2-D neutral point located at the noon magnetopause and coincides with the plasma velocity stagnation point [Sonnerup, 1970]. For northward IMF there are two 3-D magnetic field neutral points in the cusp regions, located approximately at the planet's terminator. Generally, the 3-D neutral points of magnetic field's do not necessarily coincide with velocity stagnation points [Hesse et al., 2014]; however, Nickeler and Karlický [2008] investigated both 2-D and 3-D reconnection sites and found that in the paradigm of ideal MHD, magnetic neutral points indeed should coincide with plasma flow null points. Also, according to Bulanov et al. [2000], the identity of plasma velocity and magnetic field neutral points inevitably follows from the self-consistent dynamics of highly electroconductive plasma.

Enhancement of the B_Z component upstream of the magnetopause may be connected to a plasma depletion layer (PDL) if the relation $\frac{B^2}{2\mu_0} + p = \text{const holds}$. While Figure 6 does not show clearly whether a plasma depletion layer is created at the magnetopause, it allows us to observe clear differences between closed (left) and open (right) magnetosphere states.

In the case of a closed magnetosphere, closed field lines intersecting the planet's surface can be seen spanning to higher latitudes in case of a closed magnetosphere; we also observe two additional current surfaces with $B_{\chi} = 0$ between layers with strong B_{χ} components of opposing signs. This suggests that in the case of northward IMF, the magnetopause shall be defined as the section at y = 0 of a paraboloid surface focused on the planet's center such that it passes over the last sunward closed field line in the polar region, and in the case of southward IMF, the magnetopause shall be defined as a similar section that passes through the subsolar neutral X point. The expression for the magnetopause is given by equation (13), where all distances are expressed in planetary radii:

$$X(\rho) = R_1 - \frac{\rho^2}{2R_1}$$
(13)

In equation (13) we have used parabolic coordinates, where $\rho^2 = Y^2 + Z^2$ and ρ is the distance from the X axis and R_1 is the subsolar distance from the dipole to the magnetopause. The more generic form of this equation that can be used to describe other surfaces is given by equation (14):

$$X(\rho) = \frac{R_1}{2} \left(1 + \beta^2 - \frac{\rho^2}{R_1^2 \beta^2} \right)$$
(14)

Here $\beta^2 = \frac{x}{R_1} - \frac{1}{2} + \sqrt{\left(\frac{x}{R_1} - \frac{1}{2}\right)^2 + \frac{\rho^2}{R_1^2}}$, equation (14) is reduced to equation (13) by assuming $\beta = 1$, and the surface $\beta = 1$ approaches the magnetopause. To find the correct β value corresponding to the bow shock, we set $\rho = 0$ and express β from $\beta_{bs}^2 = \frac{2R_{bs}}{R_1} - 1$. The subsolar distance to the bow shock R_{bs} is determined by simulation results.

We draw the following conclusions from the resulting Figure 6:

- 1. The magnetopause is located closer to the planet in case of southward IMF. This may be considered as evidence of magnetopause erosion.
- Tail lobe diameter is reduced in case of northward IMF; however, a wide layer of reversed magnetic field polarity arises at the magnetopause flanks.
- 3. Bow shock position relative to the dipole is identical in both cases (open and closed magnetosphere) and does not depend on the IMF orientation or direction and is equal to $R_{bs} = 2.4 R_M$. This is in agreement with ideas discussed earlier by *Winslow et al.* [2013] that bow shock subsolar distance only depends on the Mach number. Thus, magnetosheath thickness varies noticeably between these cases.

AGU Journal of Geophysical Research: Space Physics



Figure 7. Comparison of magnetic field components along MESSENGER orbit no. 418 trajectory as computed by the pure hybrid model (black line), the combined hybrid model (blue line), and experimental observations (red line). The CHM predicts most of the experimentally observed features well; the discrepancy in magnetopause position is explained by the suboptimal manually selected parameters of the PMM.

- 4. For southward IMF there are two equatorial neutral points: one on the dayside magnetopause and the other one in the magnetotail at approximately X = −3.7 R_M.
- 5. For northward IMF there are two neutral points located tailward of the cusps inside the magnetosphere. There are no neutral points at the equatorial plane, and no reconnection is occurring in the subsolar point at the magnetopause.
- 6. Magnetosphere flaring is indeed lower for northward IMF than for southward IMF.
- Neutral lines are located at equatorial latitudes in an open magnetosphere, and cusps (neutral points) are placed at high latitudes in a closed magnetosphere.
- 8. In the terminator plane we observe three areas of decreased velocity for northward IMF: one in the subsolar point and two in the cusp regions where the flow is separated into streams that impact Mercury and pass it.

3.3. MESSENGER Orbit 418 Simulation Run

While the presented hybrid model plots allow us to draw a number of interesting conclusions, their resolution is insufficient to clearly establish the possibility of magnetic barrier formation or absence thereof. To investigate this matter further, we used another simulation run with a different set of parameters. We now set n = 5.87 cm⁻³ and V = 400 km/s. IMF components are $B_{\chi} = 4.0$ nT in the whole simulation box; $B_{\gamma} = -2.31$ nT inside the magnetopause, and $B_{\gamma} = -7.69$ nT in the solar wind; $B_Z = 2.31$ nT inside the magnetopause, and $B_{\chi} = -7.69$ nT in the solar wind; $B_Z = 2.31$ nT inside the magnetopause, and $B_Z = 7.69$ nT in the solar wind. We use 30 macroparticles per cell; total simulation time t = 320 s unless noted otherwise, and simulation time step t = 0.00125 s. The parameters of the interplanetary medium were chosen based on the position of the planet and the general knowledge of solar wind properties at that distance from the Sun; PMM parameters were chosen by running a fitting procedure against magnetometer data collected in process of transit of MESSENGER through Mercury's magnetosphere during that orbit.

In other words, the magnetic field vector is directed to the top left in the YZ plane and to the top right in the XZ plane. With such an IMF vector orientation we observe a shell of higher plasma density around the magnetosphere with a notable hollow region diametrically opposed to the region where the IMF impacts the magnetospheric obstacle normally. This result is only obtained when using the CHM; the original hybrid model does not produce a similar effect.

We use these values to build profiles of magnetic field components computed by the combined hybrid model along MESSENGER's orbit (Figure 7). On this series of plots, the CHM resulting field is denoted by a blue line; original MESSENGER data (wherever available) are denoted by a red line, and pure hybrid simulation results are denoted by a black line. We can see that in this scenario it is possible to clearly observe small regions of enhanced magnetic field at the magnetopause on the 4 h mark and the 5.7 h mark. The exact size of these regions is hard to determine as the resolution of the simulation run was limited to $0.1 R_M$. However, we observe signs of a reduced plasma density region positioned in the immediate vicinity of the inbound magnetopause crossing, where the number density is decreased by over 25%. We believe that the signature of this region matches the one of a magnetic barrier and an associated plasma depletion layer. We observe no similar PDL signature corresponding to the outbound magnetic barrier; this fact may or may not be explained by the insufficient resolution of our simulation.

We shall also note that in the region with extraordinarily high velocity values inside the magnetosphere the number density is very low; i.e., only a small number of particles actually participated in the simulation. Due to this fact, we cannot consider our simulation results of flux kinetic properties in this region reliable.

Finally, let us compare similar profile plots of magnetic field produced by the original hybrid model, the CHM, and MESSENGER measurements (Figure 7). We observe that the new CHM demonstrates a marked improvement in accuracy when describing magnetic field behavior in the magnetosheath and inside the magnetosphere. There are certain discrepancies in the position of the outbound magnetopause crossing which are most likely connected to the fact that these particular simulation runs were executed with solar wind density of about a quarter of the theoretically estimated value. It is worth noting that MESSENGER observations do not confirm the existence of a magnetic barrier and a plasma depletion layer in the predicted locations. Thus, the question of their existence in Mercury's magnetosphere and the reason for such a substantial difference between a number of analytical predictions and numeric simulation is, for now, left unanswered.

4. Discussion

Let us discuss our choice of the IMF penetration coefficient κ . According to Alexeev et al. [1993] and Heyner et al. [2016], the penetration coefficient depends on the magnetic Reynolds number $R_m = \mu_0 \sigma V_{sw} R_1$, where μ_0 is vacuum permeability, σ is electric conductivity, and R_1 is the subsolar distance to the magnetopause. For Mercury's environment, $R_m = 574$. We are only interested in the IMF component normal to the solar wind flow velocity, $\kappa = 1.8 R_m^{-\frac{1}{4}} = 0.26$, as the parallel component is not used in the induction equation. To further investigate this issue, we offer Figure 8, where we present results of simulation with κ assuming values of 1.0, 0.5, 0.1, and 0.0 (left to right). In Figure 8 (first row) we can observe for northward IMF that the IMF disturbance outside the bow shock is virtually nonexistent and that the magnetotail appears to be quite short, with no neutral point in the simulation box. For southward IMF we observe that the nightside neutral point is located very close to the surface of Mercury and that dayside closed field lines exist although they are limited almost exclusively to subequatorial latitudes. Figure 8 (bottom row) presents the opposite extreme case, where the IMF does not penetrate the magnetosheath at all. Here the subsolar foreshock bulge is more pronounced for northward IMF, while being less pronounced for southward IMF. Field lines originating at the nightside of the terminator behave nearly identically in both cases.

We draw the following conclusions from Figure 8:

- We observe magnetopause erosion for southward IMF. Higher IMF penetration coefficients result into somewhat stronger erosion, but this effect is not as pronounced as for other planets.
- 2. The layer of reversed polarity is much more extensive for northward IMF for all κ values.
- 3. We observe a magnetic barrier upstream of the magnetopause; its magnetic field pileup appears to be more intensive for northward IMF.



Figure 8. High-resolution plot of magnetosphere-solar wind interaction for different reconnection efficiency values ($\kappa = 1.0, 0.5, 0.1, and 0.0$ from left to right) and different magnetospheric states: (top row) closed and (bottom row) open. Color denotes the *X* component of the magnetic field in teslas, and vectors indicate the direction of magnetic field lines.

- 4. For southward IMF magnetopause flaring is higher. Magnetopause is located closer to the planet in the subsolar point, but in the terminator plane its size is larger.
- 5. Both IMF orientations lead to creation of a plasma sheet; however, with $B_Z < 0$ its density appears to be higher.

We must also pay special attention to the inevitable discrepancies introduced by the approach used by both the original and combined hybrid models. As we use massive macroparticles instead of protons to reduce computation time necessary while preserving pressure balance, our kinetic solutions become unreliable in cells visited only by a few macroparticles. We provide relevant notices whenever necessary and discard plots that we consider affected too significantly to discuss them.

4.1. Comparison With Earlier Research

Gershman et al. [2013] state that their observations show reconnection in cusps and resulting flux transfer event showers [*Slavin et al.*, 2012] transporting more flux at Mercury than at the Earth. This might be connected with the domination of the B_X component in the IMF at Mercury's orbit, which leads to intensification of the cusp reconnection [e.g., *Belenkaya et al.*, 2013].

Summarizing previous findings supporting our simulation results, we can conclude that as a consequence of magnetic tension during plasma flow past the magnetosphere, two layers are formed: a depletion layer close to the magnetopause and an accelerated plasma flow at the flanks of the magnetosphere.

Some of the most widely accepted models by *Erkaev et al.* [2011] ignore plasma conductivity and use frozen-in magnetic field conditions; as a consequence, they ignore magnetic reconnection effects. In our calculation the magnetic field component normal to magnetopause does exist, and we take violations of the frozen-in condition and magnetic reconnection into account. We can also detect plasma acceleration along magnetospheric flanks.

According to *Erkaev et al.* [2011], the physical mechanism behind PDL formation under northward IMF conditions relies on magnetic tension and total pressure gradient forces acting on the flow associated with magnetic field lines draping around the magnetosphere. For lower M_A plasma depletion is stronger,

and thus, the acceleration produced by the pressure gradient is higher. An additional acceleration is produced by magnetic tension; this acceleration is stronger for lower M_A values.

At the dayside the pressure gradient and magnetic tension forces act in the same direction but tailward of the terminator magnetic tension starts to act in the direction opposite to that of the pressure gradient. The highest plasma speeds are attained whenever the total acting force turns to zero. However, a plasma depletion layer forms at Mercury as a result of magnetic flux pileup draped around the magnetosphere. The low average upstream Alfvénic Mach number ($M_A \sim 3-5$) in the solar wind at Mercury often results in large-scale plasma depletion in the magnetosheath between the subsolar magnetopause and the bow shock. Flux pileup is observed to occur downstream under both quasi-perpendicular and quasi-parallel shock geometries for all orientations of the interplanetary magnetic field. Furthermore, little to no plasma depletion is seen during some periods with stable northward IMF. The consistently low ratio of plasma pressure to magnetic pressure at the magnetopause associated with low average upstream M_A is believed to be the cause for a high average reconnection rate at Mercury, reported to be nearly triple of that observed at the Earth. Finally, the characteristic depletion length, D, outward from the subsolar magnetopause is found to be $D \sim 300$ km at Mercury.

Compared to the depletion layer, plasma in the accelerated flow layer at the magnetosheath side of the magnetopause is characterized by an increased flux of energetic electrons and involvement of magnetosheath ions reflected off the magnetopause. Density, temperature, and magnetic field changes, as well as the presence of leaked magnetospheric protons in the plasma depletion layer, are consistent with draping and pileup of the magnetic field in the sunward vicinity of the dayside magnetopause. Changes in ion distributions in the accelerated flow layer are consistent with dayside magnetic reconnection. There are also other important effects that require consideration, such as Kelvin-Helmholtz instability at Mercury's magnetopause discussed, for example, in *Liljeblad et al.* [2016]. However, they are out of scope of the present paper because such a study would require us to model fine structure of the magnetosheath flow, and the numerical step of our grid is too coarse for that purpose.

5. Summary and Conclusions

The analysis shown in this paper implies that a new combined hybrid simulation allows us to study magnetosheath structure, in particular, to identify the location and shape of both the magnetopause and the bow shock. As follows from our results, Mercury's magnetosheath geometry has the following properties:

- 1. The magnetopause is located closer to the planet in case of southward IMF. This may be considered as evidence of magnetopause erosion.
- 2. Bow shock offset is identical in both cases and does not depend on magnetic field orientation and is equal to $R_{\rm hs} = 2.4 R_{\rm M}$.
- 3. Magnetosphere flaring is lower for southward IMF than for northward IMF.
- 4. In the terminator plane we observe three areas of decreased velocity for northward IMF: one in the subsolar point and two in the cusp regions where the flow is separated into streams that impact Mercury and pass it. For southward IMF these cusp areas are less pronounced, plasma flow is somewhat closer to a uniform one, and there is no significant velocity decrease in cusp regions.

We also have come to the following conclusions regarding general magnetospheric features:

- 1. Cusps are located at lower latitudes in an open magnetosphere than in a closed magnetosphere.
- 2. For southward IMF there are two equatorial neutral points: one on the dayside magnetopause and the other one in the magnetotail at approximately $X = -3.7 R_M$.
- 3. For northward IMF there are two neutral points located in cusps inside the magnetopause, i.e., inside the magnetosphere. There are no neutral points in the dayside or the nightside.

We observe that although numerical simulations successfully confirm the theoretically predicted existence of a thin magnetic barrier with an associated plasma depletion layer, in situ measurements by MESSENGER do not confirm this prediction, showing a strong change in magnetic field near the magnetopause to values that fluctuate only slightly for most of the trajectory through the magnetosheath. The cause behind this discrepancy calls for further modeling and data analysis.

Acknowledgments

This work uses the MESSENGER data archive [Korth, 2015] and was partially supported by the Ministry of Education and Science of the Russian Federation grant 14.616.21.0084 and by the Austrian NFN project S116 "Pathways to Habitability" of the Austrian Science Foundation (FWF) and its related subprojects S11606-N16 and S11607-N16. M.L.K. also acknowledges the support of the FWF projects I2939-N27, P25587-N27, and P25640-N27 and Leverhulme Trust grant IN-2014-016.

References

- Alexeev, I. I. (1986), The penetration of interplanetary magnetic and electric fields into the magnetosphere, J. Geomag. Geoelectric, 38(11), 1199–1221.
- Alexeev, I. I., and V. V. Kalegaev (1995), Magnetic field and plasma flow structure near the magnetopause, J. Geophys. Res., 100(A10), 19,267–19,275.

Alekseev, I. I., and V. P. Shabansky (1972), A model of a magnetic field in the geomagnetosphere, *Planet. Space Sci.*, 20(1), 117–133.
Alexeev, I. I., E. S. Belenkaya, V. V. Kalegaev, and Y. G. Lyutov (1993), Electric fields and field-aligned current generation in the magnetosphere, *J. Geophys. Res*, 98(3), 4041–4051.

Alexeev, I. I., E. S. Belenkaya, V. V. Kalegaev, Y. I. Feldstein, and A. Grafe (1996), Magnetic storms and magnetotail currents, J. Geophys. Res., 101(A4), 7737–7747.

Alexeev, I. I., D. G. Sibeck, and S. Y. Bobrovnikov (1998), Concerning the location of magnetopause merging as a function of the magnetopause current strength, J. Geophys. Res., 103(A4), 6675–6684.

Alexeev, I. I., E. S. Belenkaya, J. A. Slavin, and M. Sarantos (2008), Paraboloid model of Mercury's magnetosphere, J. Geophys. Res., 113, A12210, doi:10.1029/2008JA013368.

Alexeev, I. I., et al. (2010), Mercury's magnetospheric magnetic field after the first two MESSENGER flybys, *Icarus*, 209(1), 23–39.
Belenkaya, E. S., I. I. Alexeev, J. A. Slavin, and M. S. Blokhina (2013), Influence of the solar wind magnetic field on the Earth and Mercury magnetospheres in the paraboloidal model, *Planet. Space Sci.*, 75, 46–55.

Bulanov, S. V., T. Y. Echkina, Inovenkov B. N., F. Pegoraro, V. V. Pichushkin, and D.-I. Sakai (2000), Formation and evolution of the current sheets in plasma, in *Proceedings of the P.N. Lebedev Physical Institute, Cosmic Physics and Plasma Physics, Moscow*, pp. 48–67, P.N. Lebedev Phys. Inst. of the Russian Acad. of Sci., Russian.

Delcourt, D. C., T. E. Moore, S. Orsini, A. Millilo, and J. A. Sauvaud (2002), Centrifugal acceleration of ions near Mercury, Geophys. Res. Lett., 29(12), 1591, doi:10.1029/2001GL013829.

Erkaev, N. V., C. J. Farrugia, B. Harris, and H. K. Biernat (2011), On accelerated magnetosheath flows under northward IMF, Geophys. Res. Lett., 38, L01104, doi:10.1029/2010GL045998.

Gershman, D. J., J. A. Slavin, J. M. Raines, T. H. Zurbuchen, B. J. Anderson, H. Korth, D. N. Baker, and S. C. Solomon (2013), Magnetic flux pileup and plasma depletion in Mercury's subsolar magnetosheath, J. Geophys. Res. Space Physics, 118, 7181–7199, doi:10.1002/2013JA019244.

Hesse, M., N. Aunai, D. Sibeck, and J. Birn (2014), On the electron diffusion region in planar, asymmetric, systems, *Geophys. Res. Lett.*, 41, 8673–8680, doi:10.1002/2014GL061586.

Heyner, D., C. Nabert, and E. Liebert (2016), Concerning reconnection induction balance at the magnetopause of Mercury, J. Geophys. Res. Space Physics, 121, 2935–2961, doi:10.1002/2015JA021484.

Ip, W. H. (1987), Dynamics of electrons and heavy ions in Mercury's magnetosphere, Icarus, 71(3), 441-447.

Jia, X., J. A. Slavin, T. I. Gombosi, L. K. Daldorff, G. Toth, and B. Holst (2015), Global MHD simulations of Mercury's magnetosphere with coupled planetary interior: Induction effect of the planetary conducting core on the global interaction, J. Geophys. Res. Space Physics, 120, 4763–4775, doi:10.1002/2015JA021143.

Johnson, C. L., et al. (2012), MESSENGER observations of Mercury's magnetic field structure, J. Geophys. Res., 117, E00L14, doi:0.1029/2012JE004217.

Kabin, K., T. I. Gombosi, D. L. DeZeeuw, and K. G. Powell (2000), Interaction of Mercury with the solar wind, Icarus, 143(2), 397-406.

Kallio, E., and P. Janhunen (2003a), Modelling the solar wind interaction with Mercury by a quasi-neutral hybrid model, *Ann. Geophys.*, 21(11), 2133–2145.

Kallio, E., and P. Janhunen (2003b), Solar wind and magnetospheric ion impact on Mercury's surface, Geophys. Res. Lett., 30(17), 1877, doi:10.1029/2003GL017842.

King, J. H., and N. E. Papitashvili (2005), Solar wind spatial scales in and comparisons of hourly Wind and ACE plasma and magnetic field data, J. Geophys. Res., 110, A02104, doi:10.1029/2004JA010649.

Kobel, E., and E. O. Flückiger (1994), A model of the steady state magnetic field in the magnetosheath, J. Geophys. Res., 99(A12), 23,617–23,622.

Korth, H., N. A. Tsyganenko, C. L. Johnson, L. C. Philpott, B. J. Anderson, M. M. Al Asad, S. C. Solomon, and R. L. McNutt (2015), Modular model for Mercury's magnetospheric magnetic field confined within the average observed magnetopause, J. Geophys. Res. Space Physics, 120, 4503–4518.

Korth, H. (2015), MESSENGER MAG reduced data archive. NASA Planetary Data System. [Available at https://pds-ppi.igpp.ucla.edu/search/?sc=Messenger&i=MAG.]

Liljeblad, E., T. Karlsson, T. Sundberg, and A. Kullen (2016), Observations of magnetospheric ULF waves in connection with the Kelvin-Helmholtz instability at Mercury, J. Geophys. Res. Space Physics, 121, 8576–8588, doi:10.1002/2016JA023015.

Marquardt, D. W. (1963), An algorithm for least-squares estimation of nonlinear parameters, J. Soc. Indust. Appl. Math., 11(2), 431–441. Mead, G. D., and D. B. Beard (1964), Shape of the geomagnetic field solar wind boundary, J. Geophys. Res., 69(7), 1169–1179.

Mead, G. D., and D. H. Fairfield (1975), A quantitative magnetospheric model derived from spacecraft magnetometer data, J. Geophys. Res., 80(4), 523–534.

Müller, J., S. Simon, Y. C. Wang, U. Motschmann, D. Heyner, J. Schüle, W. H. Ip, G. Kleindienst, and G. J. Pringle (2012), Origin of Mercury's double magnetopause: 3D hybrid simulation study with AIKEF, *Icarus*, 218(1), 666–687.

Nakamura, T. K. M., H. Hasegawa, and I. Shinohara (2010), Kinetic effects on the Kelvin-Helmholtz instability in

ion-to-magnetohydrodynamic scale transverse velocity shear layers: Particle simulations, Phys. Plasmas, 17(4), 42119.
Nickeler, D. H., and M. Karlický (2008), On the validity of ideal MHD in the vicinity of stagnation points in the heliosphere and other astrospheres, Astrophys. Space Sci. Trans., 4(1), 7–12.

Parunakian, D., A. Efitorov, and V. Shirokii (2016), Analysis of Mercury's Magnetosphere States based on MESSENGER data by Kohonen Neural Network and other Clustering Algorithms, Proc. Comput. Sci., 88, 499–504.

Poh, G., J. A. Slavin, X. Jia, J. M. Raines, S. M. Imber, W.-J. Sun, D. J. Gershman, G. A. DiBraccio, K. J. Genestreti, and A. W. Smith (2017), Mercury's cross-tail current sheet: Structure, X-line location and stress balance, *Geophys. Res. Lett.*, 44, 678–686, doi:10.1002/2016GL071612.

Shue, J. H., J. K. Chao, H. C. Fu, C. T. Russell, P. Song, K. K. Khurana, and H. J. Singer (1997), A new functional form to study the solar wind control of the magnetopause size and shape, J. Geophys. Res., 102(A5), 9497–9511.

Slavin, J. A., et al. (2012), MESSENGER observations of a flux-transfer-event shower at Mercury, J. Geophys. Res., 117, A00M06, doi:10.1029/2012JA017926.

Sonnerup, B. U. (1970), Magnetic-field re-connexion in a highly conducting incompressible fluid, J. Plasma Phys., 4(01), 161-174.

Töth, G., et al. (2016), Extended magnetohydrodynamics with embedded particle-in-cell simulation of Ganymede's magnetosphere, J. Geophys. Res. Space Physics, 121, 1273–1293, doi:10.1002/2015JA021997.

Trávníček, P., P. Hellinger, and D. Schriver (2007), Structure of Mercury's magnetosphere for different pressure of the solar wind: Three dimensional hybrid simulations, *Geophys. Res. Lett.*, 34, L05104, doi:10.1029/2006GL028518.

Tsyganenko, N. A. (1987), Global quantitative models of the geomagnetic field in the cislunar magnetosphere for different disturbance levels, *Planet. Space Sci.*, 35(11), 1347–1358.

Tsyganenko, N. A. (1989), A magnetospheric magnetic field model with a warped tail current sheet, *Planet. Space Sci.*, 37(1), 5–20. Tsyganenko, N. A. (1995), Modeling the Earth's magnetospheric magnetic field confined within a realistic magnetopause, *J. Geophys. Res.*, 100(A4), 5599–5612.

Tsyganenko, N. A. (2002), A model of the near magnetosphere with a dawn-dusk asymmetry: 1. Mathematical structure, J. Geophys. Res., 107(A8), 1179, doi:10.1029/2001JA000219.

Tsyganenko, N. A. (2013), Data-based modelling of the Earth's dynamic magnetosphere: A review, Ann. Geophys., 31(10), 1745–1772. Copernicus GmbH.

Tsyganenko, N. A., and A. V. Usmanov (1982), Determination of the magnetospheric current system parameters and development of experimental geomagnetic field models based on data from IMP and HEOS satellites, *Planet. Space Sci.*, 30(10), 985–998.

Vulpetti, G. (2012), Fast Solar Sailing: Astrodynamics of Special Sailcraft Trajectories, vol. 30, Springer, Dordrecht, Netherlands. Winslow, R. M., B. J. Anderson, C. L. Johnson, J. A. Slavin, H. Korth, M. E. Purucker, D. N. Baker, and S. C. Solomon (2013), Mercury's

magnetopause and bow shock from MESSENGER Magnetometer observations, J. Geophys. Res. Space Physics, 118, 2213–2227, doi:10.1002/jgra.50237.