Properties of Ganymede’s magnetosphere inferred from improved three-dimensional MHD simulations

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We describe a three-dimensional single-fluid MHD simulation of Ganymede’s magnetosphere that accords extremely well with the Galileo particles and fields measurements. Major improvements to our previously published model involve the modification of the inner boundary condition and the implementation of an anomalous resistivity model. The improved model couples the moon’s ionosphere (with finite Pedersen conductance) with the magnetosphere self-consistently. The previous model applied only in the limit of unreasonably high ionospheric conductivity. We illustrate in detail the global convection pattern inferred from the new model and demonstrate some features of the convection that differ from that of the Earth’s magnetosphere because Ganymede lacks a corotation electric field. Our new model does a better job of reproducing magnetic field and plasma observations from multiple Galileo passes, which sampled different external conditions and different regions of the magnetosphere. In particular, for a critical upstream pass (G8) during which the Galileo spacecraft entered onto closed field lines, the simulated magnetosphere provides an excellent fit to the measurements without the need for tuning the spacecraft trajectory. In comparison with the plasma measurements of the G2 flyby, our model also yields good agreement with the Galileo PLS observations and supports the conclusion reached by Vasyliūnas and Eviatar (2000) that the observed ionospheric outflow consists of oxygen ions. For constant external conditions, dynamic variations associated with magnetic reconnection on timescales of the order of tens of seconds are found over a large region near the magnetopause in the simulations. Future applications of our model, such as test particle tracing and investigating the behavior of the cross polar cap potential under different external and ionospheric conditions, will provide a more comprehensive understanding of Ganymede’s magnetospheric environment.


1. Introduction

Ganymede, the largest Galilean satellite of Jupiter, has its own magnetosphere, which forms due to the interaction between the moon’s intrinsic magnetic field and Jupiter’s magnetospheric environment [Kivelson et al., 1996, 1997]. The internal magnetic field of Ganymede, whose equatorial surface strength is ~7 times larger than the ambient Jovian field, stands off the incident Jovian plasma at a distance of about 1 R_G upstream from the moon’s surface (R_G, radius of Ganymede = 2634 km). At Ganymede’s orbit ~15 R_J (R_J, radius of Jupiter = 71,492 km), the corotating plasma overtakes the moon from the moon’s trailing edge because its speed is greater than Ganymede’s Keplerian speed. The typical flow speed of the ambient plasma relative to Ganymede is less than the magnetosonic speed. Under such circumstances, the corotating plasma directly impinges on and interacts with Ganymede’s magnetosphere without being modified by a bow shock such as those form upstream of planetary magnetospheres. Since Ganymede’s intrinsic field is nearly antiparallel to the external field near the equator, magnetic reconnection couples the minimagnetosphere of Ganymede with Jupiter’s giant magnetosphere. In contrast to the highly fluctuating solar wind with unpredictable variations in plasma and magnetic field, the plasma at Ganymede’s orbit imposes external field and plasma conditions that vary slowly (with the nearly 10.5 hour synodic period of Jupiter’s rotation) and the magnetic field remains in a favorable orientation (southward in this case) for reconnection. Therefore Ganymede’s magnetosphere provides us with a good opportunity to investigate the reconnection process in a relatively stable external environment.
MHD simulations have been extensively carried out for decades to study the interaction between plasma flow and various obstacles with and without intrinsic magnetic fields, such as the interaction between the solar wind and planets, comets [Gombosi et al., 1996] and Io’s interaction with the Jovian magnetosphere [Linker et al., 1998]. Ganymede’s magnetosphere has been modeled by several groups using MHD simulations [Kopp and Ip, 2002; Ip and Kopp, 2002; Paty and Winglee, 2006; Jia et al., 2008; Paty et al., 2008]. Kopp and Ip [2002] and Ip and Kopp [2002] conducted the first simulation of Ganymede’s magnetosphere using a resistive MHD model, which was adapted from the one used to model Titan’s interaction with Kronian plasma [Kopp and Ip, 2001]. They studied the variation of Ganymede’s magnetospheric configuration and current systems for different background field orientations. To validate their model, they compared the measured magnetic field with the simulation results for only one flyby (G2). However, the quality of their model is difficult to evaluate based on their published results [Kopp and Ip, 2002, Figure 2]. Their simulation domain appears to be rather small, covering only about 10 R\(_G\) surrounding Ganymede. As a result, Ganymede’s magnetosphere is comparable in size to their simulation box. Such a small simulation domain could lead to boundary effects having significant influence on model results. Possible boundary effects include reflections at the outer simulation boundaries. Their flow boundary condition at the inner boundary near Ganymede’s surface was adapted from their Titan model [Kopp and Ip, 2001] in which the plasma flow velocity is set to zero. One consequence of this flow boundary condition is that the global convection inside of Ganymede’s magnetosphere is nearly stagnant. Such a flow pattern is inconsistent with the flow measurements from the Galileo Plasma Subsystem (PLS). Paty and Winglee [2006] used multifluid MHD rather than single fluid MHD to account for the magnetic field observations acquired by the Galileo spacecraft. They found that the upstream magnetopause location in their single fluid simulation lies significantly (~36%) closer to the surface than that it does in their multifluid simulation. The latter simulation predicts magnetospheric dimensions that correspond to the Galileo magnetic field observations. Jia et al. [2008] demonstrated that the Galileo magnetic field observations including the upstream magnetopause location for all six close encounters can be reproduced by their single fluid MHD model provided that the resolution of the computational grid is sufficiently high. The results presented in Jia et al. [2008], however, required a small (~0.1 R\(_G\)) shift of the trajectory to match the data from the G8 flyby. This pass is crucial for validating the MHD model because the spacecraft trajectory goes through the closed field line region near the upstream cusp, a region in which magnetic gradients are large. Jia et al. [2008] attributed the discrepancy to such factors as the possible inaccuracy of Ganymede’s internal field model [Kivelson et al., 2002] and/or numerical uncertainties within one or two grid cells. In the present work, we have improved our MHD model and find that we can reproduce the magnetometer observations without shifting the spacecraft trajectory, even for the G8 pass. The good fit of simulation results to the Galileo measurements suggests that single fluid MHD incorporates the most important aspects of the physics of Ganymede’s magnetosphere.

In this section we briefly review some basics of our MHD model, which has been described at length by Jia et al. [2008]. Our code solves the three-dimensional resistive MHD equations in spherical coordinates. Temporal derivatives are advanced with leapfrog time differencing combined with a semi-implicit method, while centered differencing is used for the terms involving spatial derivatives. The semi-implicit scheme enables the time step to exceed the Courant-Friedrichs-Lewy (CFL) limit for Alfven and magnetosonic waves by removing short-wavelength high-frequency oscillations that are beyond the scope of this study. The increased time step greatly reduces the overall cost of the calculation, as has been found in computations of the solar corona [Miki et al., 1994; Linker et al., 1999]. The code uses a nonuniform spherical mesh (131 × 132 × 128 (r, θ, φ) grid points) covering the simulation domain from 0.5 R\(_G\) to 40 R\(_G\) with Ganymede being located at the center. The nonuniform mesh allows grid points to be distributed finely in regions of interest, which is the region of the magnetosphere within several R\(_G\) in radial distance in the case of Ganymede. The grid in the runs presented here provides fine resolution within Ganymede’s magnetosphere and around the low latitude magnetopause (~2 R\(_G\) to 3 R\(_G\)). The finest grid resolution in the radial direction is of order 0.01 R\(_G\) ≈ 26 km and the average spatial resolution within the magnetosphere is about 0.04 R\(_G\) ≈ 100 km. High grid resolution is necessary to capture the signature of plasma currents that produce sharp rotations in the observed magnetic field near the magnetospheric boundaries, as discussed in the work of Jia et al. [2008].

Simulation results shown in this paper are displayed in a Ganymede-centered Cartesian system (referred to as “GphiO”) based on the direction of Jupiter’s convective flow. In the GphiO system, X is along the incident flow direction, Y is along the Ganymede-Jupiter vector, positive toward Jupiter, and Z is parallel to Jupiter’s spin axis.

The initial setup of the simulation contains a uniform flow with a specified plasma density, pressure and flow velocity, and a uniform background field superposed on Ganymede’s internal field given by Kivelson et al. [2002]. The upstream external conditions are inferred from Galileo observations for each of the passes. The internal field consists of two parts, a permanent dipole and a time-varying component due to induction that varies in response to
changes of the external field. Plasma with the assumed upstream properties flows into the simulation sphere from the upstream boundary \((X < 0)\) hemisphere and propagates in the direction parallel to the \(X\) axis. Details can be found in the work of Jia et al. [2008].

2.1. Boundary Conditions

Solutions to the MHD equations depend on the specified boundary conditions. As shown in Figure 1, there are three boundaries appearing in the simulation: (1) the core boundary (green circle), (2) the inner boundary (yellow circle), and (3) the outer boundary (black circle).

Figure 1. A cartoon showing the three boundaries in the simulation: (1) the core boundary (green circle), (2) the inner boundary (yellow circle), and (3) the outer boundary (black circle).

modified the conditions imposed at the inner boundary \((r = 1.05 \, R_G)\) of the plasma flow. The inner boundary at \(1.05 \, R_G\) roughly represents the location of the peak ionospheric conductivity. In the work of Jia et al. [2008] (hereinafter referred to as Jia2008), the conductance of the moon’s interior was set very high. This led to a total conductance (sum of interior and ionospheric conductances) that was too high, although the ionospheric contribution used was only 2S. Our previous model (Jia2008) used a so-called “fixed boundary” condition in which the plasma density and pressure are uniformly specified with fixed values and flow velocity is set to be zero at the inner boundary. Forcing the ionospheric flow velocity to be zero is a reasonably good approximation for a highly conducting obstacle. However, the moon’s mantle is most likely to be quite weakly conducting and the conductance of Ganymede’s ionosphere is quite uncertain. Kivelson et al. [2004] give a Pedersen conductance of 2S while Eviatar et al. [2001] estimate the conductance to be \(~100\) S due to ion pickup. The “fixed boundary” condition, applicable to an obstacle with high conductance, does not provide us the freedom of studying the magnetosphere under different ionospheric conditions, i.e., different ionospheric conductances. In this paper we adopt inner boundary conditions that allow us to model self-consistently the coupling of ionosphere with the magnetosphere.

Next we describe how we modify the inner boundary conditions. First, the ionosphere can, to a good approximation, be considered as a reservoir populated with cold and dense plasma. Therefore the boundary condition in which plasma density and pressure were held constant in time in Jia2008 is still applicable and needs no modification. Second, several different boundary conditions can be applied for the flow velocity. One plausible boundary condition requires the component of flow velocity normal to the inner boundary (i.e. the radial component \(V_r\) in the spherical simulation coordinates) to vanish while the tangential components \((V_\theta, V_\phi)\) are continuous. This can be done by using the zeroth order extrapolation, i.e. \(V_{r1} = V_{r2}\) and \(V_{\theta1} = V_{\theta2}\), where subscript “1” denotes the point on the inner boundary and “2” denotes the neighboring point in the calculation domain. This condition (referred to hereafter as BC1) allows the boundary to act as a hard wall with respect to the flow and prevents the plasma from penetrating the boundary. Obviously, not allowing the flow go through the boundary, or in other words, deflecting all the flow moving toward the boundary is not appropriate for an ionosphere with finite conductance. This boundary condition also causes other problems, for example, if the flow has a field-aligned component at point “2” and is not tangential to the boundary, it is forced by this boundary condition to move tangentially along the boundary at point “1” which may give rise to an artificial component transverse to the local magnetic field.

In MHD, a more appropriate boundary condition can be constructed by taking the magnetic field into account. In some global MHD simulations of the Earth [Raeder et al., 1998; Lyon et al., 2004; Hu et al., 2007], the inner boundary is placed at a radial distance of about 2 to 4 Earth radii in order to avoid the strong magnetic field close to the Earth. The magnetosphere and ionosphere are then coupled through field-aligned currents. These field-aligned currents
are calculated in the magnetosphere near the inner numerical boundary and then mapped into the ionosphere along dipole field lines. Owing to the continuity of electric currents, field-aligned currents must close through perpendicular currents in the ionosphere, which is approximated by a resistive and infinitesimally thin layer. Closure currents in the ionosphere are used to derive the distribution of the electric potential and, in turn, the convection pattern in the ionosphere for a given distribution of the ionospheric conductance. Finally, the ionospheric convection pattern, which represents the perpendicular flow velocity relative to the magnetic field, is mapped back along the Earth’s dipole field lines from the ionosphere to the magnetosphere under the ideal MHD assumption that magnetic field lines are equipotentials, the mapped flows set the transverse velocity components at the inner numerical boundary of the global MHD simulations. In our Ganymede simulation, the inner simulation boundary is placed at $r = 1.05 R_G$ as close as possible to the moon’s ionosphere at an acceptable cost of computational time. It is assumed that the ionospheric conductance peaks at this altitude ($0.05 R_G$). Instead of mapping the field-aligned currents and solving the potential distribution in the ionosphere as in most MHD simulations of the Earth, we directly solve the whole set of MHD equations in the domain between the inner ($r = 1.05 R_G$) and the outer boundary ($r = 40 R_G$). To organize the MHD flow based on the magnetic field, we apply a boundary condition (referred to hereafter as BC2) that requires the component of the flow velocity perpendicular to the local magnetic field to be continuous at the inner boundary, i.e., $V_{\text{perp}}^1 = V_{\text{perp}}^2$, where $V_{\text{perp}} = V - v_{\text{Alf}} b$, $b$ is a unit vector along the local magnetic field and subscripts “1” and “2” denote the points on the inner boundary and the neighboring point in the calculation domain, respectively. For the sake of numerical stability and simplicity, at the boundary we use a zeroth-order extrapolation instead of higher order schemes. As will be demonstrated below, the BC2 boundary condition provides a more believable physical picture of magnetospheric convection and produces magnetic configurations and plasma conditions more consistent with the Galileo observations for multiple passes than the fixed boundary condition used in Jia2008.

2.2. Other Adjustments

[12] In MHD simulations, resistivity is a particularly important property of the plasma and of the body onto which it flows. The solutions of numerical models differ greatly depending on the resistivity used. It has been suggested that Ganymede’s interior is most likely composed of a metallic core of radius $0.15 R_G$ that sustains the moon’s internal magnetic field and a silicate mantle [Anderson et al., 1996; Schubert et al., 1996]. This implies that the interior of Ganymede and its ionosphere together with the ambient space plasma have different electrical conductivity or resistivity. We take this structure into account when specifying the numerical resistivity in our resistive MHD model. A typical resistivity profile used in our present model is shown in Figure 2 as a function of radial distances. To include the effect of the moon’s interior, the innermost simulation boundary, i.e., the core boundary, is placed at $r = 0.5 R_G$, the maximum of the inferred core radius. Between the core boundary ($0.5 R_G$) and the moon’s surface ($1 R_G$) is the insulating rocky mantle whose electrical conductivity is extremely low. Note that there is no plasma flowing in this region so our model solves only a diffusion equation for the magnetic field. As shown in Figure 2, we impose high numerical resistivity corresponding to a Lundquist number (ratio of the diffusion time to the Alfvén traveltime) of 0.2 in this region. The flowing plasma outside the ionosphere is regarded as

![Figure 2](image-url)

**Figure 2.** A snapshot of the resistivity profile, including both the background (fixed in time) and anomalous resistivity, in normalized units used in the MHD simulations as a function of radial distances measured from the moon’s center. It is plotted along a radial path coinciding with the $-\hat{X}$ axis on the upstream side of the magnetosphere. The spike-like structure corresponds to the anomalous resistivity, which is introduced only outside the ionosphere and varies in space and in time according to the model described by equations (1) and (2) in the text.
infinitely conducting. Therefore we set the background resistivity outside the ionosphere to an extremely small value corresponding to a Lundquist number of 4000. In terms of conductivity, the ionosphere, whose finite conductivity arises from neutral-ion collisions, can be considered as a transition layer between the insulating mantle and the highly conducting magnetosphere. We let the ionospheric resistivity decrease monotonically from its value in the mantle to its background value outside the ionosphere. Because the Hall conductance is estimated to be much smaller than the Pedersen conductance in Ganymede’s ionosphere [Kivelson et al., 2004], only the Pedersen conductance is included in our model. For the sake of simplicity, the Pedersen conductance is uniformly distributed in the ionosphere and fixed in time. Day-night asymmetry and possible localized changes in the ionospheric conductance caused by energetic particle precipitation are neglected in the present model. Note that the entire resistivity profile described above is spherically symmetric, depending only on radial distance, and is fixed throughout the run.

[13] In ideal MHD, because of the infinite conductivity of plasma magnetic reconnection does not take place. For reconnection to occur, the frozen-in condition \( \vec{E} = -\vec{V} \times \vec{B} \) must be violated and neglected terms in the generalized Ohm’s law, such as those proportional to the resistivity \( \eta \), must play an important role. In numerical simulations, reconnection often takes place as a result of numerical effects equivalent to resistivity that are inherent in finite-differencing schemes. Numerical diffusion has often been invoked in the literature in order to interpret the presence of magnetic reconnection but its role is not easily quantified because it varies from one cell to another and from one time step to another depending on various factors, such as the detailed algorithm used in finite-differencing and the grid spacing, etc. Fedder et al. [2002] has suggested that numerical diffusion tends to lead to numerical reconnection where oppositely oriented magnetic field components are present. A good numerical scheme should confine significant effects of numerical diffusion to regions such as the magnetopause and the magnetotail, where conditions leading to reconnection are present, and be negligible elsewhere. As described above, the uniform background resistivity used in our resistive MHD gives a Lundquist number \( >10^3 \), which approximates ideal MHD. This means that an enhanced resistivity (called anomalous resistivity) is needed to enable fast reconnection to occur in regions where magnetic shear is strong. Here we adapt an anomalous resistivity model from a terrestrial global MHD code by Raeder et al. [1998]. The anomalous resistivity is introduced only outside the ionosphere and is turned on only at locations where the local current density exceeds some specified threshold. The total resistivity, including both the background and anomalous resistivity, is described by:

\[
\eta = \begin{cases} 
\eta_0 \alpha^2, & \text{if } f \geq f_0 \\
\eta_0, & \text{otherwise}
\end{cases}
\]

(1)

\[
f = \frac{|B| \Delta}{|B| + \epsilon}
\]

(2)

where \( \eta_0 \) is the background resistivity, \( \alpha \) is a constant coefficient that controls the absolute value of the anomalous resistivity and \( f_0 \) is the normalized current density threshold. In equation (2), \( j \) and \( B \) are the local current density and magnetic field, respectively and \( \Delta \) is the grid spacing. \( \epsilon \) is a small number \((10^{-5})\) introduced to avoid dividing by zero. The normalized current density also can be written as \( f = \frac{|B| \Delta}{|B| + \epsilon} = \frac{1}{\eta_0} \), where \( l \) is the scale length over which magnetic field changes. As can be seen, \( f \) is equivalent to the ratio between the local grid size and the scale length of the local magnetic field gradient. The anomalous resistivity is switched on when the magnetic shear in a localized region is so strong that the inherent diffusion introduced by the numerical scheme is not enough to smooth strong field gradients. In such unstable conditions, the resistivity needs to be enhanced. The localized resistive region not only stabilizes the numerical code but also enables reconnection to occur at a rate similar to that found in simulations that include kinetic effects such as those in the GEM Reconnection Challenge [Birn et al., 2001]. In the example given by Figure 2, the anomalous resistivity (shown as a spike around 2 \( R_G \)) is turned on by the algorithm at the upstream magnetopause where the magnetic shear between oppositely oriented magnetic fields on the two sides is quite strong and consequently magnetic reconnection is anticipated. Note that the threshold \( f_0 \) is adjusted such that anomalous resistivity is introduced only at a very few grid points. In the simulation, the location of anomalous resistivity varies in time according to equations (1) and (2).

3. Simulation Results

3.1. Comparison of Different Boundary Conditions

[14] In this part, we describe the differences in the simulations using the fixed, BC1 and BC2 inner boundary conditions described in the previous section. We compare simulations run for the G8 conditions because the background field during this pass is mainly along the \( Z \) axis and the approximate symmetries of the magnetosphere around the \( Z \) axis and the \( XY \) plane make it easier to identify the effects related to the boundary conditions. All three runs shown here use the external plasma and field conditions for the G8 flyby as listed in Table 2 of Jia2008. The ionospheric conditions at the inner boundary \((r = 1.05 R_G)\), including the plasma density and temperature, are identical in all three runs. However, the anomalous resistivity is used only in the BC1 and BC2 cases but not in the fixed boundary case. As we will discuss below, the anomalous resistivity affects the configuration of the magnetopause but it does not affect the overall convection pattern. Instead, it is the inner boundary condition that greatly influences the global convection. We start by comparing the plasma flow because the modifications of the boundary condition greatly affect the velocity. Figure 3 shows the \( x \) component \((V_x)\) of the plasma flow velocity as color contours with the superposed unit vectors indicating the flow direction. The top row shows the results in the \( XZ \) plane at \( Y = 0 \) for the three cases using different boundary conditions while the bottom row gives the results in the \( XY \) plane at \( Z = 0 \). Since the time required for the system to reach a similar state varies depending on the boundary conditions, we choose to compare the results at time steps when strong reconnection begins in each of the three simulations. In general, it is expected that the incident
flow is brought into the magnetosphere mainly through reconnection on the upstream side and in turn convects over the polar cap into the downstream region. This can be best illustrated in the XZ plane. The simulation case using the fixed boundary condition in Figure 3a shows a convection pattern in the polar cap with some flows moving downstream while others are moving back into the upstream cusp region. The flow speed is fairly small within the entire polar cap. This odd convection pattern results mainly from the imposed $V=0$ inner boundary condition, which forces the flux tubes attached to the ionosphere to be stagnant. On the contrary, the flow pattern in the BC1 simulation (shown in Figure 3b) in which the tangential component of the flow was continuous, gives a picture in the XZ plane that appears physically plausible and is closer to our expectations. However, near the inner boundary (represented by the green circle), artificial tangential flows introduced by the boundary condition are noticeable. The third case (BC2) shown in Figure 3c provides what we regard as a more physical picture of the convection. In particular, the artificial tangential flow components in the BC1 case are absent because of the method of associating the flux tube motion with the magnetic field. It also is useful to examine the flow circulation is the XY plane, which is nearly perpendicular to the background magnetic field in the three cases presented here. The plasma that convects from upstream to downstream over the polar cap is expected to partially return toward the moon and upstream at low latitudes. Figure 3d shows the corresponding convection pattern in the XY plane for the case of the fixed boundary condition. Figure 3 shows that near the inner boundary the flow is nearly stagnant and the direction of flow vectors is disordered. Outside the stagnation region, the flow returns from the downstream to the upstream side of the magnetosphere through flanks. This is consistent with the result found in the XZ plane (Figure 3a) that also can be attributed to the imposed boundary condition. Figures 3e and 3f show the convection patterns for the BC1 and the BC2 cases, respectively. In general, these results differ greatly from those in Figure 3d in the sense that the plasma flow is not stagnant near the inner boundary. However, some differences can be noticed between the two cases. In the BC1 case (Figure 3e), the radial component of the flow disappears at the inner boundary and consequently those flows moving toward the inner boundary are forced to move tangentially with respect to the boundary while, in the BC2 case, flows are

Figure 3. Color contours of the $\hat{X}$ component of the flow velocity ($V_x$) superposed with unit flow vectors in (top row) the XZ plane and (bottom row) the XY plane for the case of (a and d) fixed boundary conditions, (b and e) BC1 boundary conditions, and (c and f) BC2 boundary conditions. The green circle in each plot shows the inner boundary of the simulation ($r = 1.05 R_G$).
allowed to move in and out through the inner boundary. One noticeable difference between Figure 3d and Figures 3e and 3f is that fast flows produced by reconnection at downstream appears mostly near the flanks in the fixed boundary condition case while they extend over a larger cross tail region for the other two cases (BC1 and BC2).

[15] As shown above, the BC2 boundary condition, which organizes the plasma flow based on the local magnetic field, provides the most convincing picture of the plasma convection in Ganymede’s magnetosphere and thus should be a more appropriate boundary condition for our simulation than either the fixed boundary condition that is appropriate only for extreme ionospheric conditions or the BC1 condition, which constrains the flow based on the spherical form of the moon’s surface without regard to the magnetic configuration.

3.2. Global Convection Pattern

[16] Ganymede is phase locked to Jupiter and as a consequence there is no corotation electric field in the rest frame of the plasma. The absence of a corotation electric field combined with the large ratio of the scale of the moon to the transverse scale of the tiny magnetosphere makes the circulation of the plasma flow and the return of the magnetic flux to upstream differ greatly from the Earth’s case. In this section we describe in detail the global convection in the magnetosphere and in the ionosphere based on our run using the BC2 boundary condition. Again, results shown here are extracted from the G8 simulation because of the approximate symmetry in this case. Figure 4a shows the side view (XZ plane at Y = 0) of magnetospheric convection in a square area ranging from −12 R_G to 12 R_G in the X direction. The incident flows merge with the plasma flows on the magnetospheric side through the upstream reconnection and subsequently convect over the polar cap until they reach the downstream reconnection site. High-speed horizontal flows, ranging from a few hundred to 1000 km/s as observed in the simulation, are ejected out of the downstream site both toward the moon and down tail. In contrast to the results shown in Figure 3b in Jia2008, we now find that open flux tubes connected to Ganymede’s high latitude ionosphere move at a finite transverse velocity, which increases with altitude, instead of being nearly stagnant in the fixed boundary case. A zoomed-in view of the convection pattern shown in Figure 4b, which covers the region from −4 R_G to 4 R_G, shows that outflows with speed on the order of a few km/s originating from the ionosphere on the upstream hemisphere supply plasma and magnetic flux to the upstream reconnection site. Note that the color scale is adjusted in this plot in order to show the relatively small flow speed within the magnetosphere. In addition, plasma and magnetic flux also are being transported from the downstream to the upstream magnetopause through the flanks of the magnetosphere at low latitudes. This is indicated by the convection plot shown in Figure 3f and also can be seen in the other plots of Figure 4.

[17] In order to draw a complete global convection picture, we also show the convection pattern in the ionosphere near the inner simulation boundary. Color contours of \( V_x \) are plotted on a sphere of radius = 1.08 R_G in Figure 4b. Since the ionosphere is coupled to the magnetosphere, ionospheric convection reflects the global convection in the magnetosphere. In the plot, one can easily recognize that the polar cap contains open flux tubes moving tailward while the low latitude ionosphere contains return flow on closed field lines. The separatrix between the tailward and the return flow also represents the open-closed field line boundary in the ionosphere. It clearly shows that the whole polar cap is shifted toward the downstream side due to the upstream magnetopause and tail currents. The convective speed perpendicular to the magnetic field depends on the ionospheric conductance, i.e., higher conductance leads to slower convection. In the case shown here, which corresponds to an ionospheric conductance of \( \sim 2 \) S, the tailward convective flow speed in the polar cap ionosphere ranges from several km/s near the center of the polar cap to 15 km/s near the separatrix. As will be shown in section 3.3.2, such a convective flow speed is consistent with the measurements from both the Galileo Energetic Particle Detector (EPD) and the Galileo PLS during a polar flyby (G2). In order to associate the convection with the current distribution in the ionosphere, we enlarge the ionospheric part and plot the field-aligned current density on the anti-Jupiter side of Ganymede as color contours superposed with unit flow vectors (Figure 4d). Green solid lines on both hemispheres are contours of \( V_x = 0 \) delimiting the flow regions. It is expected that the flow shear along the magnetopause drives field-aligned currents into and out of the ionosphere. Indeed, one can see that the field-aligned currents intensify near the flow separatrix (green lines). For instance, in the northern hemisphere the most intense upward field-aligned currents (negative \( J_{paur} \) in the north and positive \( J_{paur} \) in the south) are localized near the flow separatrix, which is also the strongest flow shear region in the ionosphere. On the Jupiter-facing side of Ganymede, the field-aligned currents near the flow separatrix are downward toward the moon. A pair of field-aligned currents with opposite polarities is found at lower latitudes. These field-aligned currents flowing on closed field lines are analogous to the Region 2 currents in the Earth’s magnetosphere. They result mainly from the strong gradients of plasma thermal pressure and flux tube volume within the magnetosphere.

[18] The width of the magnetosphere is apparent in Figure 4c, which shows the cross-section of the magnetosphere (YZ plane) at X = 0 with color giving the flow velocity \( (V_x) \) contours and white curves representing the projection of field lines. The magnetosphere extends to about 6 R_G in this plane as indicated by both the topology of field lines and the sharp transition of the convective flow speed at the magnetopause. The return flows (with negative \( V_x \)) are indicated by red colors at low latitudes. The return flows are on closed field lines that eventually participate in upstream reconnection and thereby complete the global circulation of plasma and magnetic flux.

[19] One aspect dramatically different from the global convection pattern at Earth is that the return flows within the range of the moon’s diameter (−1 R_G < Y < 1 R_G) do not necessarily divert around the moon. Because there is no corotation electric field, the plasma may flow into the ionosphere and be absorbed. The fraction of the flow that is diverted or absorbed depends on the ionospheric conductance. If the ionosphere is weakly conducting, the return flow will primarily be absorbed as it encounters the ionosphere, while the magnetic field will continue to diffuse...
through the moon’s ionosphere and interior. If the ionosphere is highly conducting, which is unlikely to be the case for Ganymede, return flows carrying magnetic flux would divert fully around the obstacle returning to the upstream side.

Our MHD model is assumed to describe the bulk motion of low energy plasma, for which the gradient and curvature drift is not important. For studying the motions of energetic particles, gradient and curvature drifts must be taken into account. Future work involving tracing test particles in the MHD electromagnetic fields will help us to comprehensively understand the energetic particle behavior for comparison with the Galileo EPD observations acquired during multiple flybys.

3.3. Comparisons With the Galileo Observations

3.3.1. Magnetic Field and Magnetospheric Configuration

The inner boundary condition affects not only the convection pattern, as shown above, but also the magne-
spheric fields as will be shown in the following. Here we
mainly focus on comparing the fixed and the BC2 boundary
conditions because the BC1 boundary condition leads to
unrealistic flows near the surface. The external plasma and
field conditions and the ionospheric plasma density and
temperature remain the same in the two models. We choose
the G1 and G8 passes as examples to illustrate in detail the
differences between the two models. Shown in Figure 5a are
comparisons of the magnetic field between the Galileo
measurements [Kivelson et al., 1992] and the simulation
results from two different models, one using the fixed inner
boundary condition and the other using the BC2 boundary
condition. The two model results appear to be similar and
both show good agreement with the observations in terms of
the overall trend of individual traces and the magnetopause
locations identified as the sharp rotations in the
$B_x$ and $B_y$ components. However, there are some differences that can
be noticed in the $B_z$ component within the magnetosphere,
especially on the G1 pass between 06:20UT and 06:40UT.
Because $B_z$ is a minor component compared to the other two
components ($B_x$ and $B_y$) during this interval, the differences
between the two model runs are not evident on the scale
used for the other two components. To better illustrate
differences between the two simulation runs, an expanded
plot of $B_z$ is shown in Figure 5b. It clearly shows that the
model using the fixed boundary condition gives an unsatis-
factory estimate of the $B_z$ component compared to the
measurements while the model using the BC2 boundary
condition provides a more satisfactory agreement with the
observations. The fact that $B_z$ remains similar in the two
models while $B_y$ differs between the two certainly suggests
that the geometry of the magnetic field lines is different in
these two cases. Figure 5c shows the magnetic field lines
traced along the spacecraft trajectory in the two model runs.
In the downstream region inside the magnetosphere, the
yellow field lines (extracted from the model with the fixed
inner boundary condition) are carried toward the equatorial plane
for some distance downstream of Ganymede. In this case the footprints of the flux tubes are
fixed in the ionosphere because of the boundary condition,
while the more distant parts of the flux tubes are still in
motion. As a result, the flux tubes appear to be bent. On the
contrary, the red field lines that are extracted from the BC2
case appear less bent than in the previous case, which
-corresponds to a small $B_z$ component. The boundary
condition used in the BC2 case causes the differences in the
field line geometry because the BC2 boundary condition
allows the flux tube footprints in the ionosphere to move
together with the higher altitude parts of the flux tubes at a
rate that depends on the ionospheric conductance. The

Figure 5. (a) Magnetic field components and magnitude along the spacecraft trajectory of the G1 flyby.
Black solid lines represent the Galileo observations, green dashed lines show the results traced along the
spacecraft trajectory in a simulation run that uses the fixed inner boundary condition, and red solid lines
show the results extracted from a simulation run that uses the BC2 inner boundary condition. (b) An
expanded version of the third panel in Figure 5a for the $B_z$ component. (c) A three-dimensional display of
magnetic field lines sampled along the spacecraft trajectory (shown as white scattered dots) from the
MHD simulation results. Yellow lines show the result for the case of fixed inner boundary condition, and
red lines represent that of the BC2 boundary condition case. Color contours of the $B_z$ component are
shown in the equatorial plane ($XY$ plane at $Z = 0$) for reference, and the centered sphere in cyan represents
the inner boundary of the simulation.
differences between the two cases also can be understood in terms of the current flowing in the ionosphere. The closure current through the ionosphere produces a positive $B_z$ perturbation in the region of the G1 trajectory. For a given cross polar cap potential, higher ionospheric conductance sustains stronger ionospheric current and therefore enhances $B_z$ in the downstream midlatitude region. The fixed boundary case corresponds to a perfectly conducting ionosphere and therefore produces a more positive $B_z$ than produced in the BC2 case, for which the ionospheric conductance is finite.

As discussed in Jia2008, the G8 flyby is a crucial pass for validating the simulation model because during this flyby the Galileo spacecraft flew through the upstream region very close to the cusp and the magnetic field and energetic particle measurements within the magnetosphere provide critical constraints on the magnetospheric configuration [Kivelson et al., 1998; Williams et al., 1997a]. In Figure 6 we compare results from our improved model that uses the BC2 boundary condition with the simulation results published in Jia2008 for the G8 pass. Note that the simulation results shown here are extracted along the original spacecraft trajectory for both model runs. As can be seen, all three components along with the magnitude of the magnetic field extracted from the BC2 case match the observations much better than those from the fixed boundary case. In Jia2008, the simulation results from the fixed boundary case show good agreement with the observation when the trajectory along which the field is traced is shifted by about 0.1 $R_G$. In contrast, the simulated field from the BC2 case gives satisfactory agreement with the Galileo observations without the need of shifting the spacecraft trajectory, which suggests that the scale of the magnetosphere produced in the BC2 case is larger and more consistent with the one inferred from the measurements than that from the fixed boundary case. It further indicates that if boundary conditions are appropriately selected a single fluid MHD model is capable of providing a realistic representation of Ganymede’s magnetosphere that is consistent with the observations.

The size and the shape of a simulated magnetosphere depend on the boundary conditions of the simulation. In Figure 7, we directly compare the magnetospheric configuration for the G8 flyby conditions for the fixed case and the BC2 case by illustrating magnetic field lines and plasma thermal pressure in the XZ plane. Because the spacecraft moved primarily along the direction of the $+\hat{Y}$ axis in this flyby, we also mark the intersection of the spacecraft trajectory with the XZ plane for reference. Figures 7a and 7b, corresponding to the two boundary conditions, differ noticeably. First of all, near closest approach the virtual spacecraft encounters the cusp region, the transition between

Figure 6. Magnetic field comparisons between the simulation results and the Galileo observations for the G8 flyby. Black solid lines are the spacecraft measurements, green dashed lines are results extracted from the run using fixed boundary conditions, and red solid lines are from the run using BC2 boundary conditions. The locations where large amplitude magnetic fluctuations are observed during both inbound and outbound magnetopause crossings are marked.
closed and open field lines in the fixed boundary case as described in Jia2008. A magenta cross in Figures 7a and 7b represents the place where Galileo crossed the XZ plane. Both $B_x$ and $B_z$ vary rapidly with $Z$ in this region, so the data from this pass provides a sensitive test of the details of a simulation model. In Jia2008, we “tuned” the spacecraft trajectory shifting it slightly in order to obtain agreement with measurements. However, the BC2 case needs no tuning, it predicts that the spacecraft passes through a region of closed field lines inside of the upstream magnetosphere. The pitch angle distributions of energetic electrons measured by the EPD onboard Galileo show butterfly distributions in the magnetosphere, also consistent with a closed field line geometry. The field geometry in the BC2 case is more consistent with that inferred by the Galileo observations from the magnetometer and the energetic particle detector. It is evident that the simulation results are greatly improved when the BC2 boundary condition is applied.

Secondly, the standoff distance and the whole magnetosphere on the upstream side in the BC2 case appear to be larger than that in the fixed boundary case. A more quantitative illustration is given by Figure 7c, which shows the $B_z$ component traced along the $-X$ axis on the upstream in the fixed boundary case (blue solid lines) and the BC2 boundary case (red solid lines).

Figure 7. Comparison of the magnetospheric configuration for conditions of Galileo’s G8 flyby for (a) the fixed boundary case and (b) the BC2 boundary case. In each plot, projected field lines are shown in white in the XZ plane at $Y = 0$ superposed on color contours of plasma thermal pressure. The intersection of the spacecraft trajectory with the XZ plane is represented by the magenta cross near the northern cusp. The inner boundary of the simulation is represented as a centered sphere. (c) The $B_z$ component traced along the $-X$ axis on the upstream in the fixed boundary case (blue solid lines) and the BC2 boundary case (red solid lines).
magnitude of $B_z$ inside the magnetosphere is determined in part by perturbations produced by closure currents in the ionosphere and the moon’s interior. These perturbations weaken the field on the upstream side and consequently allow the magnetopause to move inward toward the moon. Assuming a fixed reconnection rate at the upstream magnetopause, an ionosphere with higher conductance can sustain stronger closure current and thus weaken the upstream magnetospheric field. The fixed boundary case corresponds to a perfectly conducting ionosphere and, therefore, results in a smaller magnetosphere than that produced by the BC2 case, which corresponds to a finite ionospheric conductance. The mechanism is the same as described in interpreting the G1 flyby results. Similar findings have been noted by Lavraud and Borovsky [2008] in studying the response of the Earth’s magnetosphere to different ionospheric Pedersen conductances. In short, they show that higher ionospheric Pedersen conductance weakens the dayside magnetospheric field and leads to a smaller dayside magnetosphere for a fixed dayside reconnection rate.

Figures 7a and 7b show that the magnetospheric configuration on both the upstream and the downstream sides differs between the two cases. Compared with the BC2 case the current sheet is more elongated and thinner in the fixed boundary case. This is due to the anomalous resistivity model (described in section 2.2) that was applied in the BC2 case (but not in the fixed case). In the region of strong localized currents such as the upstream and downstream magnetopause, the anomalous resistivity model implemented in the BC2 case switches on and enhances reconnection when the current intensity exceeds the threshold. In the fixed boundary case without anomalous resistivity, the current density in the current sheet becomes extremely large. Reconnection begins only when the current sheet becomes so thin that numerical resistivity inherent in the computational scheme can initiate it. We would like to point out that both the inner boundary condition and the anomalous resistivity affect the form and the size of the magnetosphere. However, global convection is controlled principally by the inner boundary condition although the anomalous resistivity controls the reconnection process near the magnetopause and magnetotail.

We also have conducted simulations for the remaining four flybys (G2, G7, G28 and G29) using the improved model. Simulation results are shown in Figure 8. It is found that for the external conditions listed in Table 2 of Jia2008,
the model results with the BC2 boundary condition improve agreement with the Galileo MAG observations compared to those produced in the fixed boundary case, shown in Figure 5 of Jia2008 and repeated in Figure 8. In particular, for these passes the field magnitude near closest approach in the BC2 case is enhanced and more consistent with the measurements than previous results. In order to view clearly the differences between the two models (the fixed and the BC2 cases), we also show the residuals between the modeled and observed fields for the two cases in Figure 9. The residuals are smaller in the BC2 case than in the fixed boundary case. Moreover, the biggest discrepancies occur near the magnetopause crossings where small differences of spatial locations translate to large residuals. One thing that needs to be pointed out is that for the G29 pass (Figure 8d), during which Ganymede was located near midnight in Jupiter’s magnetosphere, the simulation results from the improved model are similar to previous results and do not improve the agreement with measured values of the magnetic field near closest approach or the location of the inbound magnetopause boundary. As noted in Jia2008, these discrepancies may have resulted from some departures from the corotation direction in the ambient flow that twisted the magnetosphere and displaced the magnetopause. Since both the original (fixed boundary) run and the BC2 case shown here use the same external flow condition and assume strict corotational flow, it should not be a surprise that those discrepancies persist.

3.3.2. Comparison With Plasma Measurements

[25] While in the previous section we compare our simulation results mainly with the magnetometer data, in this section we continue to compare simulation results with plasma measurements from the Galileo PLS. Because plasma moments derived from the PLS experiments are not available for most of Ganymede flybys except for the G2...
flyby [Frank et al., 1997], we focus on the comparison for the G2 flyby. Figure 10 shows the measured ion energy spectrogram and the plasma bulk flow velocities calculated from the PLS measurements. Magnetic field magnitude from the Galileo magnetometer and the MHD model. (b) Ion energy spectrogram measured by the PLS. The color-coded ion count rate represents the maximum response from all available sensors at a given E/Q during one spacecraft spin period. Data are provided by the Planetary Data System (PDS). (c) EPD ion count rates from the lowest energy channel (A0: 22–42 keV) for the G2 flyby. This panel is reproduced from Figure 1 in Williams et al. [1997b]. (d–g) Three components and the speed of the plasma bulk flow of the G2 flyby in GphiO coordinates. In each panel, the blue dots represent bulk flows derived from the PLS measurements for heavy ions with mass-per-charge (M/Q) = 16. The gray dots are the calculated moments assuming M/Q = 1, and the black dots represent bulk flows if M/Q = 16. The PLS moments are from Frank et al. [1997]. Red traces are the bulk flow velocity output from the MHD simulation. The three vertical dashed lines mark the inbound and the outbound magnetopause crossings identified from the magnetic field data and the location of closest approach, respectively.

Figure 10. Plasma, energetic particle, and magnetic field measurements of the G2 flyby. (a) Magnetic field magnitude from both the Galileo magnetometer and the MHD model. (b) Ion energy spectrogram measured by the PLS. The color-coded ion count rate represents the maximum response from all available sensors at a given E/Q during one spacecraft spin period. Data are provided by the Planetary Data System (PDS). (c) EPD ion count rates from the lowest energy channel (A0: 22–42 keV) for the G2 flyby. This panel is reproduced from Figure 1 in Williams et al. [1997b]. (d–g) Three components and the speed of the plasma bulk flow of the G2 flyby in GphiO coordinates. In each panel, the blue dots represent bulk flows derived from the PLS measurements for heavy ions with mass-per-charge (M/Q) = 16. The gray dots are the calculated moments assuming M/Q = 1, and the black dots represent bulk flows if M/Q = 16. The PLS moments are from Frank et al. [1997]. Red traces are the bulk flow velocity output from the MHD simulation. The three vertical dashed lines mark the inbound and the outbound magnetopause crossings identified from the magnetic field data and the location of closest approach, respectively.

Flyby [Frank et al., 1997], we focus on the comparison for the G2 flyby.
to the flow energy of ions with a convective flow speed of 150 km/s are plotted for M/Q = 16 and = 1, respectively. Plasma bulk flows of heavy ions (M/Q = 16) calculated from the PLS measurements are shown as the blue dots in Figures 10d to 10g. On the other hand, inside of the magnetosphere around closest approach (from 18:51 to 19:13 UT), the PLS measurements show that the ambient heavy ions are largely excluded and instead, cold ions originating from Ganymede’s ionosphere are present. However, there is only one noticeable energy peak in the observed spectrogram. In order to calculate plasma moments, the plasma composition (M/Q) must be assumed. Frank et al. [1997] assumed that the observed plasma near closest approach is composed of hydrogen ions (M/Q = 1) and the calculated flow velocities assuming hydrogen ions are shown as the gray dots in Figures 10d to 10g. It is shown in Figure 10g that the averaged flow speed inside of the magnetosphere (between 18:51 and 19:13 UT) is around 70 km/s. Figure 10c shows the Galileo EPD ion count rates of the lowest energy channel (A0: 22 ~ 42 keV), which has been used by Williams et al. [1997b] to infer the upper limit of the convective flow speed. As shown in Figure 10c, the Galileo EPD shows no detectable flow anisotropies inside of the magnetosphere, which results in an upper limit of ~25 to 45 km/s for the convection speed [Williams et al., 1997b]. Vasyliunas and Eviatar [2000] pointed out that the observed ions inside of the magnetosphere are not protons but instead oxygen ions with M/Q = 16 and the resulting plasma density and convective flow speed should differ by factors of 4 and 1/4 from those calculated by Frank et al. [1997], respectively. Consequently, the derived PLS moments assuming oxygen ions are more consistent with the electron density measurements from the Plasma Wave instrument (PWS [Gurnett et al., 1996]) and the flow measurements inferred from the EPD [Williams et al., 1997b] during this pass. The resulting bulk flow velocities inside of the magnetosphere assuming oxygen ions are represented by the black dots in Figures 10d to 10g.

Figures 10d–10g shows the comparison between the PLS data and the bulk flow velocity output from the MHD simulation. Outside of Ganymede’s magnetosphere, the modeled flow velocity in general agrees well with the PLS observations. However, the PLS data shows a significant northward component of flow (as large as 70 km/s in the inbound leg). There is a nearly constant difference (+Va) of about 50 km/s between the modeled and the observed data in these regions. Because the external flow condition used in the model assumes a strict rotational flow direction, such a northward flow is not included presently. After the inbound magnetopause crossing at ~18:50 UT, the MHD simulation predicts that plasma flow is greatly slowed down from about 150 km/s outside of the magnetosphere to about 15 km/s inside. Inside of the magnetosphere, the plasma flow speed is of the order of 15 km/s with a minimum value of about 6 km/s at closest approach. In this region, the modeled flow velocity in general agrees much better with the calculated flow velocity for oxygen ions than with that calculated for hydrogen ions. During the outbound magnetopause crossing at ~19:23 UT, the model predicted flow speed gradually increases to the external flow speed, which is consistent with the PLS observations.

[28] However, there are large deviations between the model and the PLS data present in some regions. In particular, during the interval between 19:12 and 19:21 UT, the MHD simulation significantly underestimates the Va and Vz components compared to the PLS observations. Since the MHD model mainly describes the convective flow velocity that is perpendicular to the magnetic field, in order to understand the discrepancy, it is useful to decompose plasma flow into components that are parallel and perpendicular to the local magnetic field. Figures 11a to 11c shows the comparison between the model results and the PLS observations for the plasma flow in field-aligned coordinates. It can be seen in Figure 11b that the perpendicular flow in the MHD model is quite consistent with that calculated from the PLS measurements during the entire close flyby when the observed ionospheric outflow is assumed to be oxygen ions. Between 19:12 and 19:21 UT (yellow shaded interval), when the modeled flow velocity deviates considerably from the PLS observations, there are substantial parallel flows with a peak speed over 100 km/s. In this region, the MHD model also shows some parallel flows that are in the right direction and at the right location compared to the observations. However, the outflow speed (with a peak value of ~30 km/s) along the field line produced in the model is smaller than the observed value. It is these strong parallel flows that are not fully captured by the model and then lead to the deviation seen in Figures 10e to 10g. In MHD, parallel flows can result only from localized pressure gradients along field lines. As shown in Figure 11d, during this interval the spacecraft went into regions of open field lines near the magnetopause where strong field-aligned currents are present. The observed large parallel flows could have resulted from strong field-aligned currents and the associated parallel electric fields, which are not fully described by an MHD model.

[29] Paty et al. [2008] interpreted the PLS measurements of the G2 flyby by using a multifluid MHD simulation. Their model included multiple ion fluids: oxygen ions from both Jupiter’s magnetosphere and Ganymede’s ionosphere, and protons mainly from Ganymede’s ionosphere. The bulk motions of different ion species were then traced separately in their simulation. However, we have not been able to determine how their simulation treated the ionospheric properties other than as a source of plasma. They extracted ion energy spectrograms from their simulation assuming Maxwellian distributions of the ions and compared the results with spectrograms of the measured PLS ions. Plasma bulk properties were not reported in their paper. They concluded that both ionospheric hydrogen and oxygen ions are present inside of the magnetosphere, however, because the energy of most of the ionospheric oxygen ions observed in their simulation were below the threshold of the instrument sensitivity (~10 eV), they concluded that the observed populations are mostly hydrogen ions. If this is the case, then both hydrogen and oxygen ions that originate from the ionosphere should move together across field lines at roughly the same E × B drift velocity because their thermal energies are both quite low (~several eV). The magnetic field in the polar region is strong, implying only insignificant effects due to the different gyroradii of the two species. Therefore if the ions observed by PLS indeed are hydrogen ions, then the convective speed over the polar cap
Figure 11. (a) Parallel and (b) perpendicular components of the plasma bulk flow velocities relative to the magnetic field. The flow speed is shown in Figure 11c. In Figures 11a–11c, the legends are the same as those defined in Figure 10. The two vertical dashed lines mark the inbound and the outbound magnetopause crossings identified from the magnetic field data, respectively. (d) The projection of the modeled field lines in the YZ plane (orthogonal to the incident flow direction) and color contours of the modeled $V_x$ in the YZ plane and on a sphere of radius $r = 1.08R_G$. Note that in the $V_x$ color contours, the color scale is adjusted in order to show the relatively small flow speed within the magnetosphere and consequently the color of the ambient flow (~150 km/s) is saturated. The black lines with arrows are some field lines traced along the Galileo G2 trajectory (red trace), and the dark gray traces are some arbitrarily chosen field lines within Ganymede’s magnetosphere plotted for reference. Note that the bendback of those open field lines in the polar cap caused by the Alfvén wing currents is not indicated in this plane. The locations where the PLS observed large field-aligned plasma flows are marked with yellow color in Figures 11a–11d.
for both oxygen and hydrogen ions would have to be \( \sim 70 \text{ km/s} \), which is still higher than the upper limit of the convection speed (\( \sim 25 \) to 45 km/s) inferred from the EPD measurements by a factor of \( \sim 2 \). Such rapid convective flows in the polar cap imply an unreasonable reconnection efficiency on the upstream magnetopause. Based on equation (7) by Kivelson et al. [1998], the upstream reconnection efficiency is estimated to be \( \sim 150\% \). On the other hand, our MHD model predicts that the convection in Ganymede’s polar cap is significantly slowed down and the convection speed is much smaller than that originally derived by Frank et al. [1997] assuming the ion \( M/Q = 1 \). Instead, our simulation results are more consistent with the cold ions observed near closest approach being oxygen ions and therefore confirm the conclusion drawn by Väisälä and Eviatar [2000].

4. Discussion

[30] The ambient Jovian field and plasma conditions at Ganymede’s orbit vary slowly with the nearly 10.5 hour synodic period of Jupiter’s rotation. Jia et al. [2008] has shown that Ganymede’s magnetospheric configuration changes in response to variation of the ambient field and plasma conditions as the moon orbits around Jupiter. Although the results shown there are extracted from simulations using fixed boundary condition, we find that the response of field-aligned current system to different background field conditions in our improved model (the BC2 boundary case) remains qualitatively similar to the earlier results and the general conclusions drawn in the previous paper still remain valid. However, as expected, the amount of total current that closes through Ganymede and its ionosphere reduces in the case of a finite ionospheric conductance. In the case shown in this paper, the total field-aligned currents in each Alfvén wing at high latitudes are found to be \( \sim 1.2 \times 10^6 \text{ A} \), which is about a half of the value (\( \sim 2 \times 10^6 \text{ A} \)) estimated in Jia2008.

[31] Besides the variations over the synodic period of hours, temporal variations on much shorter timescales on the order of a few tens of seconds, which is a fraction of the time that the ambient plasma takes to convect across the magnetosphere, are also observed in our new simulations that implement the BC2 boundary condition and introduce anomalous resistivity. Drastic variations take place in the vicinity of the magnetopause on both the upstream and the downstream boundaries. For instance, if a virtual spacecraft remains at a fixed spatial point located on the upstream magnetopause slightly off the equator, it will observe abrupt changes in plasma conditions, such as enhancement of flow speed and plasma pressure, accompanied by changes in the magnetic field. Such changes frequently take place periodically, with periodicities between 20 to 50 seconds. The dynamic changes in plasma and field conditions, which are manifestations of reconnection, appear to occur almost everywhere on the magnetopause. On the two low latitude passes on the upstream side, the G8 and G28 flybys, the spacecraft detected what appeared to be large amplitude waves in the magnetic field at the magnetopause crossings. For example, as marked by the yellow area in Figure 6, magnetic field fluctuations were present both prior to the entry and after the exit from the magnetosphere during the G8 pass. Whether the observed oscillations were spatial structures or resulted from temporal variations of the magnetopause is not clear although it has previously been proposed that they resulted from surface waves caused by the Kelvin-Helmholtz instability on the magnetopause [Kivelson et al., 1998]. Our improved model provides a description of the magnetospheric fields that matches the observations so faithfully that we believe it is capable of representing realistically the behavior at the magnetospheric boundary. Time sequences of the traced magnetic field along the spatially fixed Galileo trajectory in the simulations clearly indicate that the location of the magnetopause oscillates in time and the structure of the magnetopause is highly variable even under steady external conditions. By comparing the observed fluctuations with our simulation results, we attribute the observed boundary oscillations to temporal variations arising from intermittent magnetic reconnection at the magnetopause. Detailed analysis of the magnetopause dynamics will be presented in a subsequent paper.

[32] We note that the dynamic behavior of the magnetopause on short timescales develops only when anomalous resistivity is used in the simulation. In an ideal MHD run with only the numerical resistivity arising from finite differencing, reconnection on the magnetopause occurs less often with a relatively low reconnection rate. In a resistive MHD run with uniformly distributed resistivity, reconnection on the magnetopause tends to be steady and the high resistivity causes the magnetopause to become more diffusive. These results are not consistent with the Galileo magnetic field observations. Although the anomalous resistivity model used here is an oversimplified one that attempts to mimic the dissipation in the diffusion region around the reconnection site, it provides a representation of the magnetopause configuration in good agreement with the observations and may reflect the physical process occurring in Ganymede’s magnetosphere. Recently Kuznetsova et al. [2007] has developed an approach based on a physically motivated dissipation model that incorporates nongyrotropic corrections in the diffusion region into the global MHD model. Their simulations with nongyrotropic corrections show dynamic quasiperiodic responses of the Earth’s magnetotail to steady driving solar wind conditions and present encouraging results in comparison with the observations. Implementing such a diffusion model in our code may provide useful insights into the reconnection process occurring in the Ganymede system. However, this approach requires the identification of reconnection sites that may vary at each time step and currently is applied only in a north-south symmetric magnetotail case. Additional development of an algorithm to search for reconnection sites in a more realistic magnetospheric geometry is needed and will be worth undertaking in the future.

[33] One of our future goals is to improve Ganymede’s internal magnetic field model by extracting the field perturbations arising from the magnetospheric currents self-consistently calculated in the MHD simulations. Evidently, the ionospheric conductance largely determines the intensity of the closure currents through the ionosphere and this, in turn, affects the magnetic field measured in space, especially at low altitudes. In the present study, a uniform Pedersen conductance of \( \sim 2 \text{ S} \) is assumed for Ganymede’s iono-
sphere. However, because the ionospheric conductance is not well constrained observationally, the effect of the ionospheric conductance on the total measured field needs to be assessed by exploring a wide range of conductance values, possibly from a few to tens of Siemens when ion pickup effects are considered [Kivelson et al., 2004; Eviatar et al., 2001].

Moreover, saturation of cross polar cap potential in the Earth’s magnetosphere is an important issue in the solar wind magnetosphere coupling. The physical mechanism of the saturation is not fully understood yet although several explanations have been proposed [Hill et al., 1976; Siscoe et al., 2002]. Recently, by invoking the Alfvén wing arguments [Kivelson and Ridley, 2008] demonstrated that for the case of strong solar wind electric field, as the Alfvén conductance of the solar wind ($\sum A = \frac{1}{\nu_A v_A}$, where $\nu_A$ is the upstream Alfvén speed) decreases and becomes much less than the Pedersen conductance in the ionosphere, the increasing efficiency of wave reflection off the ionosphere leads to the saturation of cross polar cap potential. Because of the sub-Alfvénic interaction Ganymede’s magnetosphere provides a natural analog for studying the saturation phenomenon. Examining the dependence of the cross polar cap potential in Ganymede’s magnetosphere on the ionospheric conductance by using our simulations may shed light on the understanding of the saturation process in the Earth’s magnetosphere.

5. Summary and Conclusions

In this paper, we demonstrate how we improved our three-dimensional MHD simulations of Ganymede’s magnetosphere by modifying the ionospheric boundary condition at the simulation inner boundary by taking the local magnetic field into account. The improved boundary condition enables convection in the ionosphere to couple with that in the magnetosphere in a relatively self-consistent way. The property of the electric conductivity in different regions included in the simulation domain also is updated to reflect a realistic condition suitable for Ganymede. An anomalous resistivity model, which is switched on only in regions with strong localized currents, has been implemented in order to obtain fast reconnection on the magnetopause where oppositely oriented magnetic fields on both sides generate strong magnetic shear. Our previous model was appropriate only for highly conducting obstacles. The new boundary condition provides a physical picture of global plasma convection and is applicable for a body surrounded by an ionosphere with finite Pedersen conductance. Our Ganymede model differs from the Earth’s magnetospheric convection not only in the nature of the external plasma environment but also in the reduced diversion of the return flows (within the moon’s diameter) from the downstream reconnection sites owing to the absence of a corotation electric field. Depending upon the ionospheric conductance, return flows moving toward the downstream ionosphere are partly absorbed and lost at the inner boundary. However, in this situation magnetic flux can still return upstream by diffusing through the moon’s ionosphere and interior. In addition, plasma and magnetic flux are constantly being returned by convection of closed field lines through the flank magnetosphere at low latitudes.

Our new model yields results in good agreement with the magnetic field measured on six Galileo flybys of Ganymede and corresponds more closely to the observations than did our earlier model (Jia2008). In particular for the G8 pass, which is critical for validating the numerical model because its trajectory penetrated the closed field line region of the upstream magnetosphere, the simulated magnetic fields are in a good agreement with the observed field without the need of tuning the spacecraft trajectory. The new model produces a magnetosphere whose size and configuration are quite consistent with the form inferred from the observations. This further demonstrates that a single-fluid MHD model can provide a realistic description of Ganymede’s magnetospheric fields, given appropriate boundary conditions. In comparison with the Galileo low-energy plasma measurements obtained during the G2 flyby, the only flyby for which plasma moments are presently available, our new model agrees reasonably well with the overall variation of the measured plasma flow when heavy ions were clearly identified. However, inside of the magnetosphere near closest approach where the ion composition is not clearly identified, the modeled plasma flow is significantly smaller than the flow velocity derived from the PLS measurements if the observed ions are protons. Rather, our model is in good agreement with the measurements if the observed ions are oxygen. Therefore our simulation results support the view that the outflowing ionospheric ions observed by the Galileo PLS inside of the magnetosphere are oxygen ions instead of protons.

The simulated magnetopause exhibits dynamic behavior on short timescales of the order of tens of seconds. The location of the magnetopause appears to oscillate and bursty flows along with rapid changes in the field and other plasma properties appear in the vicinity of the magnetopause. The dynamics observed in the simulations provide useful hints in understanding the strong magnetic field fluctuations seen by the Galileo spacecraft during several magnetopause crossings. Details will be discussed elsewhere.

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