

# Favorable Conditions for Magnetic Reconnection at Ganymede's Upstream Magnetopause

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## Key Points

- We create the first analytical model of conditions at Ganymede-Jupiter magnetopause and assess magnetic reconnection onset theory.
- Reconnection may occur anywhere on the magnetopause where Ganymede's closed magnetic field meets the ambient field of Jupiter.
- The average reconnection rate at Ganymede exhibits a Jovian-diurnal variation and hence is driven by Jupiter's rotation.

## **Abstract**

Ganymede is the only Solar System moon known to generate a permanent magnetic field. Jovian plasma motions around Ganymede create an upstream magnetopause, where energy flows are thought to be driven by magnetic reconnection. Simulations indicate Ganymedean reconnection events may be transient, but the nature of magnetopause reconnection at Ganymede remains poorly understood, requiring an assessment of reconnection onset theory. We present an analytical model of steady-state conditions at Ganymede's magnetopause, from which the first Ganymedean reconnection onset assessment is conducted. We find that reconnection may occur wherever Ganymede's closed magnetic field encounters Jupiter's ambient magnetic field, regardless of variations in magnetopause conditions. Unrestricted reconnection onset highlights possibilities for multiple X-lines or widespread transient reconnection at Ganymede. The reconnection rate is controlled by the ambient Jovian field orientation and hence driven by Jupiter's rotation. Future progress on this topic is highly relevant for the JUper ICy moon Explorer (JUICE) mission.

## **Plain Language Summary**

Ganymede is the largest moon of Jupiter and the only Solar System moon that produces its own magnetic field. Ganymede's magnetic field is surrounded by Jupiter's much larger magnetic field, which flows around the moon like a rock in a flowing river. The boundary where Jupiter's magnetic field first collides with Ganymede's is called the magnetopause. At this boundary, energy can move between the two magnetic fields through a process called magnetic reconnection. Our paper introduces a simple model of Ganymede's magnetopause, and use this to show where reconnection can occur on the boundary. We find that reconnection can occur anywhere on the magnetopause for any environmental conditions

around Ganymede, so the locations where these energy release events occur may be particularly unpredictable. The rate of energy release by reconnection meanwhile depends on near-Ganymede conditions, which change significantly as Jupiter rotates. These results will help inform the planning of the JUperiter ICy moon Explorer (JUICE) mission to Ganymede.

## **Keywords**

Ganymede, magnetic reconnection, magnetopause, modeling

## **1. Introduction**

Ganymede (radius  $R_G = 2,634$  km) is the largest moon of Jupiter (radius  $R_J = 71,492$  km) and the Solar System. Unlike all other moons, Ganymede generates a permanent magnetic field as discovered by measurements from both the magnetometer (Kivelson et al., 1997; Kivelson et al., 1996) and the plasma wave subsystem aboard the Galileo spacecraft (Gurnett et al., 1996). The permanent magnetic field is dipolar and likely produced by dynamo action within Ganymede's molten iron core (Anderson et al., 1996; Schubert et al., 1996). The equatorial surface dipole strength is 719 nT,  $\sim 7$  times stronger than the ambient Jovian magnetic field, and the dipole axis typically tilts  $\sim 176^\circ$  from Ganymede's spin axis (Kivelson et al., 2002). The dipole axis orientation varied over the short time scales between Galileo flybys, thought to be due to an additional, induced magnetic field arising from electromagnetic induction in a subsurface ocean (Kivelson et al., 2002). Obtaining detailed knowledge of this potentially life-sustaining water source is the primary objective for the upcoming JUperiter ICy moon Explorer (JUICE) mission, which will be the first spacecraft to orbit a non-Earth moon (Grasset et al., 2013).

Ganymede orbits Jupiter at an average distance of  $\sim 15 R_J$  in a plane nearly coplanar to Jupiter's spin equator (Bills, 2005; McKinnon, 1997). The orbital plane is  $\sim 7^\circ$  inclined with respect to the central plane of a  $\sim 3 R_J$  thick, rotating Jovian magnetospheric plasma sheet produced by Io's volcanic activities (Kivelson et al., 2004). Hence, Ganymede effectively moves up and down through the plasma sheet experiencing large variations in the ambient plasma and magnetic conditions. Under ideal magnetohydrodynamic (MHD) theory, the presence of rotating plasma sheet leads to outward stretching of Jovian magnetic field lines, forming a very strong ( $> 160$  MA) but thin current sheet approximately coplanar to the plasma sheet's central plane (Khurana et al., 2004). Hence, the ambient Jovian magnetized plasma conditions at Ganymede are controlled by the distance between Ganymede and the center of Jupiter's current sheet.

The Jovian plasma rotates with the planet at  $\sim 80\%$  of Jupiter's rotation speed (Williams, Mauk, McEntrie, 1997; Williams, Mauk, McEntrie, Roelof, et al., 1997), which is much faster than Ganymede's Keplerian speed. Hence, the magnetic field-carrying plasma compresses Ganymede's magnetic field on the upstream side forming a magnetopause boundary (Jia et al., 2008). The Jovian plasma is sub-Alfvénic so the magnetic pressure predominantly shapes magnetopause interactions (Neubauer, 1998). As a result, Ganymede's magnetosphere is cylindrically-shaped with long Alfvén wings and no bow shock preceding the magnetopause (Jia, Kivelson, et al., 2010) - a contrast to planetary magnetospheres which are bullet-shaped due to dynamic pressure dominance in the super-Alfvénic solar wind (Neubauer, 1990). Magnetic field lines near the upstream equator inside the magnetosphere are closed (both ends at Ganymede's magnetic poles) and almost antiparallel (due to  $176^\circ$

dipole tilt) to Jupiter's magnetic field lines. The nearly antiparallel configuration hints that magnetic reconnection may be the dominant mechanism for plasma and energy inflows from Jupiter to Ganymede. Elsewhere, magnetic field lines in Ganymede's large polar caps and magnetotail are open (at least one end at Jupiter), allowing particles to enter and escape from the moon's magnetosphere (Frank et al., 1997; Williams, Mauk, McEntrie, 1997; Williams, Mauk, McEntrie, Roelof, et al., 1997).

The Ganymede magnetosphere has been modeled by many numerical simulations, some of which discuss magnetic reconnection at the upstream magnetopause. For instance, Jia et al. (2008; 2009) produced a global three-dimensional resistive MHD simulation of Ganymede that showed transient reconnection signatures spread over large regions of the magnetopause. Subsequent analysis revealed these signals to be consistent with intermittent rope-like flux-transfer events (Jia, Walker, et al., 2010). Recently, modeling work has been extended to include the Hall effect (Dorelli et al., 2015), and to couple with kinetic-ion hybrid (Leclercq et al., 2016) and local particle-in-cell codes (Daldorff et al., 2014; Tóth et al., 2016; Zhou et al., 2019), all of which treat reconnection microphysics more directly. The Hall-MHD model predicted local ion accelerations from reconnection, while the MHD-EPIC (embedded particle-in-cell) model suggested particle heating from reconnection and presence of quasiperiodic formation of flux-transfer events consistent with previous resistive MHD results and Galileo observations. However, these comprehensive numerical modelling studies have not been supported by important assessment of reconnection at Ganymede's magnetopause that apply reconnection onset theory, which is an essential additional element in understanding the physics at work.

We have used an analytical approach to parametrize the magnetopause conditions expected from a typical Jovian plasma flow. This approach provides a computationally cheap way to apply modern kinetic physics of reconnection onset that is challenging to implement in more expensive numerical models. Reconnection onset has been analytically assessed at Earth (Alexeev et al., 1998; Trattner et al., 2007a, 2007b), Jupiter (Desroche et al., 2012; Masters, 2017), Saturn (Desroche et al., 2013; Masters, 2015a), Uranus (Masters, 2014), and Neptune (Masters, 2015b). In the following sections, we outline the analytical model of Ganymede's upstream magnetopause followed by the first kinetic assessment of magnetic reconnection onset and structural properties.

## 2. Analytical Model of Ganymede's Upstream Magnetopause

Maps of conditions immediately either side of Ganymede's magnetopause are essential for reconnection onset assessment. To achieve this, we must first define the magnetopause surface itself. Kivelson et al. (1998) describe Ganymede's magnetosphere as a cylinder with shifting center points in a dynamical Ganymede-centered Jovian magnetic field-aligned coordinates (GphiB). This is converted to a Ganymede-centered Cartesian coordinates (GphiO) for our model in which X points along the plasma flow direction, Y points from Ganymede to Jupiter, and Z points along Jupiter's spin axis (approximately parallel to Ganymede's spin axis due to the moon's small orbit inclination). The shape of Ganymede's magnetopause surface follows

$$f(X, Y, Z) = \frac{(X - X_0)^2}{a^2} + \frac{(Y \cos \theta_r - Z \sin \theta_r - Y_0)^2}{b^2} = 1$$

where

$$\theta_r = \tan^{-1} \left( \frac{|B_{0,z}|}{B_{0,y}} \right) - 90^\circ$$

$$X_0(Y, Z) = X_0(0) + |Y \sin \theta_r + Z \cos \theta_r| \tan \theta$$

$$Y_0(Y, Z) = \frac{2}{\pi} Y_{0,max} \sin(\phi - 248^\circ) \tan^{-1} \left( \frac{Y \sin \theta_r + Z \cos \theta_r}{\lambda} \right)$$

135 The angle  $\theta_r$  describes right-handed rotation angle between GphiB and GphiO coordinates  
 136 where  $(B_{0,y}, B_{0,z})$  are the ambient Jovian magnetic field components.  $(X_0, Y_0)$  denote the  
 137 center point offsets from the GphiO origin. Kivelson et al. (1998) chose  $a = 2.2 R_G$  and  
 138  $\lambda = 0.5 R_G$ , and then used least square fit to the Galileo data to calculate  $b = 2.90 R_G$ ,  
 139  $X_0(0) = 0.544 R_G$ ,  $Y_{0,max} = 0.914 R_G$ , and  $\theta = 0.298$  radians. This leaves Jupiter's east  
 140 longitude  $\phi$ , which captures north-south asymmetry of Ganymede's magnetosphere in  
 141 response to the ambient Jovian magnetic field orientation, as the only free parameter. Each  $\phi$   
 142 value importantly corresponds to a unique position of Ganymede with respect to the Jovian  
 143 current sheet.

144

145 From these equations we can generate Ganymede's upstream ( $X < 0 R_G$ ) magnetopause grid  
 146 surface between  $-4.0 R_G < Y < 4.0 R_G$  and  $-1.0 R_G < Z < 1.0 R_G$  with  $0.01 R_G$  resolution  
 147 in both dimensions. The magnetopause is projected onto a Y-Z plane as shown in Figure 1A  
 148 specifically when Ganymede is in the Jovian current sheet ( $\phi = 248^\circ$ ). Here the  
 149 magnetopause is north-south symmetric with the standoff distance of  $1.65 R_G$  calculated at  
 150 the subflow point ( $Y = 0 R_G, Z = 0 R_G$ ). The magnetopause X-coordinate increases away  
 151 from the subflow point in all directions as the surface curves downstream. The magnetopause  
 152 will gain maximum north-south asymmetries when Ganymede is furthest above/below the  
 153 current sheet ( $\phi = 158^\circ, 338^\circ$ ). This simple and fixed magnetopause description is sufficient

for reconnection onset assessment, as more accurate surface models will not affect the conclusions drawn.

Next, we describe the Jovian-side (external) conditions at the magnetopause. The ambient Jovian plasma mass density is  $\rho_0 = 56 \text{ amu/cm}^3$  when Ganymede is in the current sheet and  $\rho_0 = 28 \text{ amu/cm}^3$  when Ganymede is furthest above/below the current sheet (Jia et al., 2008). The plasma is compressed near Ganymede's magnetopause increasing its mass density. We employ a simple compression formula  $\rho_J = A_1 \cos(\alpha) + \rho_0$  where  $\alpha$  is the flaring angle between the X-axis and the local magnetopause normal vector. The cosine of flaring angle is adapted from results at Earth's magnetopause (Petrinec & Russell, 1997) and captures spatial density variations expected from plasma flows around a cylindrical magnetosphere. A more complex compression description is again possible but unlikely to affect main conclusions drawn. The typical compression amplitude  $A_1 = 4 \text{ amu/cm}^3$  is estimated from numerical simulations (Jia et al., 2008; Tóth et al., 2016) and the added ambient mass density  $\rho_0$  forbid plasma decompression. Figure 1B shows the Jovian-side mass density variation when Ganymede is in the current sheet. The density peaks near the subflow point where Jovian plasma collides head-on with the magnetopause and decreases toward the flanks where plasma glances off the surface.

The ambient Jovian plasma pressure is  $P_0 = 3.8 \text{ nPa}$  when Ganymede is in the current sheet and  $P_0 = 1.9 \text{ nPa}$  when Ganymede is furthest above/below the current sheet (Jia et al., 2008; Kivelson et al., 2004). Figure 1C shows plasma pressure at the Jovian-side magnetopause when Ganymede is in the current sheet. Like mass density, a cosine relation  $P_{J,p} = A_2 \cos(\alpha) + P_0$  parametrizes the pressure compression. The amplitude  $A_2 = 1.0528 \text{ nPa}$  is



approximated from the pressure relation at Earth's magnetopause for slow plasma flow speeds (Petrinec & Russell, 1997).

The ambient Jovian plasma flows along the X-axis at speed  $v_0 = 140$  km/s in Ganymede's reference frame (Jia et al., 2008). Figure 1D shows the plasma flow velocity at the Jovian-side magnetopause when Ganymede is in the current sheet. Unlike mass density and pressure, we parametrize the flow speed by a sine relation  $v_J = v_0 \sin(\alpha)$  as the ambient plasma is most stagnated by direct collision near the subflow point. The Jovian-side flow directions (denoted by arrows normalized in the Y-Z plane) are constrained parallel to the magnetopause surface and coplanar to the ambient plasma flow vector.

The ambient Jovian magnetic field has been computed at Ganymede using a mathematical model (Jia et al., 2008; Khurana, 1997). The magnetic field strength is a function of Jupiter's east longitude and hence Ganymede's orbital position, with minimum of  $B_0 \sim 70$  nT when Ganymede is in the current sheet and maximum of  $B_0 \sim 105$  nT when Ganymede is furthest above/below the current sheet. We assume negligible x-component  $B_{0,x}$  and parametrize the remaining two components by  $B_{0,y} = 84 \sin(\phi - 248^\circ)$  nT and  $B_{0,z} = 3 \cos(\phi) - 79$  nT. Since  $B_{0,z}$  is always negative, the ambient Jovian magnetic field points southward in the Y-Z plane between  $135^\circ$ - $225^\circ$  clock angles. We quantify magnetic field compression at the Jovian-side magnetopause using the fact that the sum of magnetic, plasma, and dynamic pressures must be equal before and after the compression. The total pre-compression pressure can be calculated from ambient plasma/magnetic values. Using data from Figures 1C and 1D, we derive post-compression plasma pressure and magnetopause-parallel dynamic pressure component. We subtract these values from the total pressure to obtain the post-compression

magnetic pressure  $P_{J,b}$  (which also contains the magnetopause-normal dynamic pressure component) and convert this into Jovian-side magnetic field strength  $B_J$  shown in Figure 1E when Ganymede is in the current sheet. The plasma compression also constrains magnetic field directions onto the magnetopause surface, which we denote by normalized arrows.

The Jovian-side plasma and magnetic pressures together exert force on Ganymede's magnetopause, which is balanced by magnetic pressure from Ganymede's magnetic field given negligible plasma pressure inside the moon's magnetosphere (Jia et al., 2008). Hence, we can derive the magnetic field strength at the Ganymede-side magnetopause  $B_G$  as shown in Figure 1F when Ganymede is in the current sheet. Magnetic field directions (normalized arrows) have no azimuthal component (consistent with dipolar field) and lie parallel to the magnetopause surface. The magnetic field points northward in the “closed-field region” defined by  $|Z| < 0.63 R_G$  and southward elsewhere. The closed-field region is bounded by two horizontal red dashed lines which we retroactively add to all Figure 1 subplots. Otherwise, the Ganymede-side plasma density and flow speed are set to uniform values  $\rho_G = 20 \text{ amu/cm}^3$  and  $v_G = 0 \text{ km/s}$  respectively - the latter approximates a relatively slow plasma flow inside Ganymede's magnetosphere compared to the external Jovian flow.

### 3. Magnetic Reconnection Assessment at Ganymede

Having obtained maps of conditions on both sides of Ganymede's magnetopause, we can assess reconnection onset specifically for the closed-field region where particle transport is not expected under MHD theory. Reconnection onset requires three conditions to be satisfied. First, the magnetopause current sheet separating Jupiter's and Ganymede's magnetic fields must be thinner than approximately an ion inertial length to break the MHD frozen-in flux

condition and allow collisionless plasma diffusion (Phan et al., 2011). The Galileo data analysis revealed the magnetopause current sheet thickness to be <400 km (Kivelson et al., 1998), similar to the ~426 km ion inertial length calculated from magnetopause conditions in Figure 1. Hence, we can assume a sufficiently thin magnetopause current sheet irrespective of Ganymede's position relative to the Jovian current sheet.

The remaining two onset conditions effectively limit local plasma flows to below the characteristic Alfvén speed associated with reconnection, with suppression of reconnection above this limit. The second onset condition concerns the diamagnetic drift between plasma electrons and ions within the magnetopause current sheet, leading to a condition involving the magnetic shear angle

$$\theta_{\text{sh}} > 2 \tan^{-1} \left( \frac{d_i \Delta \beta}{L} \right) = 2 \tan^{-1} (\Delta \beta)$$

where  $\theta_{\text{sh}}$  is the smaller shear angle between the Jovian and Ganymedean magnetic fields in a magnetopause-tangent plane at each grid point (Swisdak et al., 2003; 2010). If this condition is unsatisfied, the diamagnetic drift is too fast and reconnection is suppressed. The system length scale ( $L$ ) is the magnetopause current sheet thickness, which from the first onset condition is approximately equal to the ion inertial length ( $d_i$ ), so the shear angle minimum threshold depends only on the beta difference ( $\Delta \beta = \beta_J - \beta_G$ ) across the magnetopause. As Ganymede contributes negligible plasma pressure ( $\beta_G = 0$ ), the beta difference is equal to the Jovian-side beta  $\beta_J = P_{J,p}/P_{J,b}$ . The third onset condition concerns the flow shear between Jovian and Ganymedean bulk plasmas adjacent to the magnetopause current sheet along reconnection outflow direction. Each magnetopause location has two outflow vectors parallel/antiparallel to the cross product of the vector bisecting the smaller shear angle

between Jovian and Ganymedean magnetic field lines and the local surface normal vector (Masters, 2017). We choose the southward-pointing primary outflow vector following the Jovian field lines, and define the flow shear condition

$$v_{sh} = \frac{|v_1 - v_2|}{2} < v_{out} \left( \frac{\rho_1 B_2 + \rho_2 B_1}{2(\rho_1 B_2 \rho_2 B_1)^{1/2}} \right)$$

$$v_{out} = \left( \frac{B_1 B_2 (B_1 + B_2)}{\mu_0 (\rho_1 B_2 + \rho_2 B_1)} \right)^{1/2}$$

where symbol definitions are  $v$  = flow velocity,  $\rho$  = mass density,  $B$  = magnetic field strength, and  $\mu_0 = 4\pi \times 10^{-7}$  H/m (Doss et al., 2015). Subscripts 1 and 2 indicate parameter projections along the outflow vector on Jovian-side and Ganymedean-side respectively. The flow shear is  $v_{sh} = |v_1 - v_2|/2$  and the outflow speed is  $v_{out}$ . Reconnection is suppressed if the flow shear exceeds its maximum threshold.

We first assess these two onset conditions for a specific case when Ganymede is in the Jovian current sheet, and then consider two extreme cases when Ganymede is furthest above/below the current sheet. Figure 2 assesses the diamagnetic drift condition when Ganymede is in the current sheet. Beta differences in Figure 2A have the average of 2.02 in the closed-field region, with largest discrepancies along the magnetopause flanks where the Jovian-side magnetic field is weakest. The resulting shear angle minimum thresholds ( $\theta_{sh,min}$ ) in Figure 2B have the average of  $90.3^\circ$  with largest values along the flanks. Figure 2C shows magnetic shear angles calculated using data from Figures 1E and 1F. The average  $\theta_{sh}$  is  $175^\circ$  with largest values in columns nearest to the subflow point and toward the flanks, with smaller values in-between. Comparing Figures 2B and 2C indicates that  $\theta_{sh} > \theta_{sh,min}$  at every point

in the closed-field region, so the second onset condition is satisfied everywhere on Ganymede's magnetopause.

Figure 3 assesses the flow shear condition when Ganymede is in the current sheet. Reconnection outflow speeds in Figure 3A have the average of 327 km/s in the closed-field region with largest values along columns near the subflow point, where magnetic fields are most strongly aligned with outflow vectors. The resulting maximum flow shear thresholds ( $v_{sh,max}$ ) in Figure 3B have the average of 443 km/s with largest values near the subflow point. Figure 3C shows flow shears calculated from the Jovian plasma flow in Figure 1D. The average  $v_{sh}$  is 13.7 km/s with largest values near the subflow point from outflow-aligned magnetic fields. A zero-shear strip is present along  $Z = 0$  where the Jovian plasma flow stagnates. Comparing Figures 3B and 3C indicates that  $v_{sh} < v_{sh,max}$  at every point in the closed-field region, so the third onset condition is satisfied everywhere on Ganymede's magnetopause.

Consequently, magnetic reconnection can occur anywhere on Ganymede's magnetopause when Ganymede is in the current sheet. The electric field associated with reconnection follows (Doss et al., 2015)

$$E = 2k \left( \frac{B_1 B_2}{B_1 + B_2} \right) v_{out} \left( 1 - \frac{(v_1 - v_2)^2}{(v_{out})^2} \frac{\rho_1 B_2 \rho_2 B_1}{(\rho_1 B_2 + \rho_2 B_1)^2} \right)$$

Where  $k = 0.1$  is the reconnection efficiency factor (Paschmann et al., 2013). Figure 4A shows the electric field when Ganymede is in the current sheet with average magnitude 3.2 mV/m. Strongest field magnitudes are found along near-subflow columns corresponding to

largest outflow speed locations. We also track (following Cooling et al., 2001) parcels of plasma in reconnection outflows from three equatorial reconnection sites – one at the subflow point and two others at mid-flanks ( $Y = \pm 1.5 R_G$ ). All outflows travel bidirectionally north/south away from Ganymede's equator. However, the subflow site's outflows remain on the magnetopause symmetry axis ( $Z = 0$ ) while the mid-flank sites' outflows shift toward their nearest flanks due to influence from the Jovian-side plasma flow.

Figures 4B and 4C respectively show reconnection assessment when Ganymede is furthest above and below the current sheet, with magnetopause asymmetries and ambient parameters adjusted accordingly. Despite condition changes, the electric fields remain non-zero throughout closed-field regions, so reconnection is possible anywhere on the magnetopause when Ganymede is furthest above/below the current sheet. The electric field varies symmetrically north/south of the current sheet and becomes stronger along the flanks where Jupiter's and Ganymede's magnetic fields are now most strongly antiparallel. The average electric field also increases from 3.2 mV/m to 5.1 mV/m at extreme Ganymede positions. Small discontinuities are observed across lines containing the subflow point, reflecting sharp turns on the magnetopause arising from the surface equations. A more realistic magnetopause surface would be smoother, and so the discontinuities should disappear.

#### **4. Discussion**

There appears to be no restrictions for reconnection onset when Ganymede's magnetosphere is symmetric (Figure 4A) and most asymmetric (Figures 4B and 4C). Hence, we can generalize that reconnection is favorable anywhere on the magnetopause for all magnetospheric asymmetries i.e. all positions along Ganymede's orbit of Jupiter. This result

is consistent with widespread reconnection events observed in global simulations (e.g. Jia, Walker, et al., 2010; Tóth et al., 2016)

The electric field magnitude range (2.6 – 5.6 mV/m) observed are much larger compared to at Earth's (<0.01 – 0.2 mV/m) and Jupiter's (<0.1 mV/m) upstream magnetopauses (Paschmann et al., 2013; Masters, 2017), indicating significant reconnection rates at all Ganymedean magnetopause locations. Although a dominant X-line is possible, this electric field configuration highlights possibilities for less ordered reconnection site distributions, such as multiple X-lines or transient flux-transfer events (seen in global simulations), at Ganymede's magnetopause.

The electric field equation is found most sensitive to changes in magnetic parameters  $B_1$  and  $B_2$ . Due to the model's fixed magnetopause surface, both  $B_1$  and  $B_2$  increase with stronger ambient Jovian magnetic field as Ganymede moves away from the Jovian current sheet. The average electric field increases in Figure 4 are therefore monotonic and functions of Ganymede's orbital position and Jupiter's east longitude similar to the ambient Jovian magnetic field strength. As each longitude value also corresponds to distinct time-of-day on Jupiter, magnetic reconnection rate at Ganymede exhibits a Jovian-diurnal variation and is effectively driven by Jupiter's rotation. The conclusion has been independently supported by remote observations of Jovian radio emissions associated with Ganymede (Zarka et al., 2018).

Multiplying the average electric fields by the magnetopause width ( $\sim 6 R_G$ ) gives 50-80 kV reconnection voltage estimates at Ganymede's magnetopause, which may be used to

constrain reconnection rate in the magnetotail via open magnetic flux conservation. We also calculate reconnection-induced electron and ion temperature increases of 250-560 eV and 2,000-4,200 eV respectively using empirical methods from Earth-based studies (Phan et al., 2013; 2014), with the maximum (minimum) value corresponds to when Ganymede is furthest above/below (in) the Jovian current sheet. These numbers far exceed ambient temperatures for electrons and ions of 300 eV and 60 eV respectively (Kivelson et al., 2004), hence reconnection should provide heated particle signatures observable by the upcoming JUICE mission.

## 5. Summary

Ganymede's permanent magnetic field and its resulting magnetosphere present a unique opportunity to study magnetic reconnection in a sub-Alfvénic plasma flow environment. We present an analytical model of steady-state conditions at Ganymede's upstream magnetopause, from which we conduct the first assessment of reconnection onset theory at this boundary. The model shows that reconnection may occur anywhere on the magnetopause where Ganymede's closed magnetic field encounters Jupiter's ambient field, and the onset appears largely unaffected by Ganymede's position relative to the Jovian current sheet. This result is consistent with previous global MHD simulations of Ganymede's magnetosphere, and highlights possibilities for less orderly reconnection structures (multiple X-lines, widespread flux-transfer events) at Ganymede's magnetopause.

The average reconnection rate is shown to be a function of Ganymede's position along its orbit around Jupiter, which approximately corresponds to the time-of-day on Jupiter. Hence, the reconnection rate exhibits a Jovian-diurnal variation and is effectively driven by Jupiter's



rotation. The reconnection process should heat up surrounding plasma particles producing signatures detectable by spacecraft instruments. Our steady-state model currently does not capture orientation changes of Ganymede's magnetic field due to the moon's subsurface ocean. Future integration of ocean effects will allow more accurate predictions of reconnection structures in preparation for the JUICE space mission.

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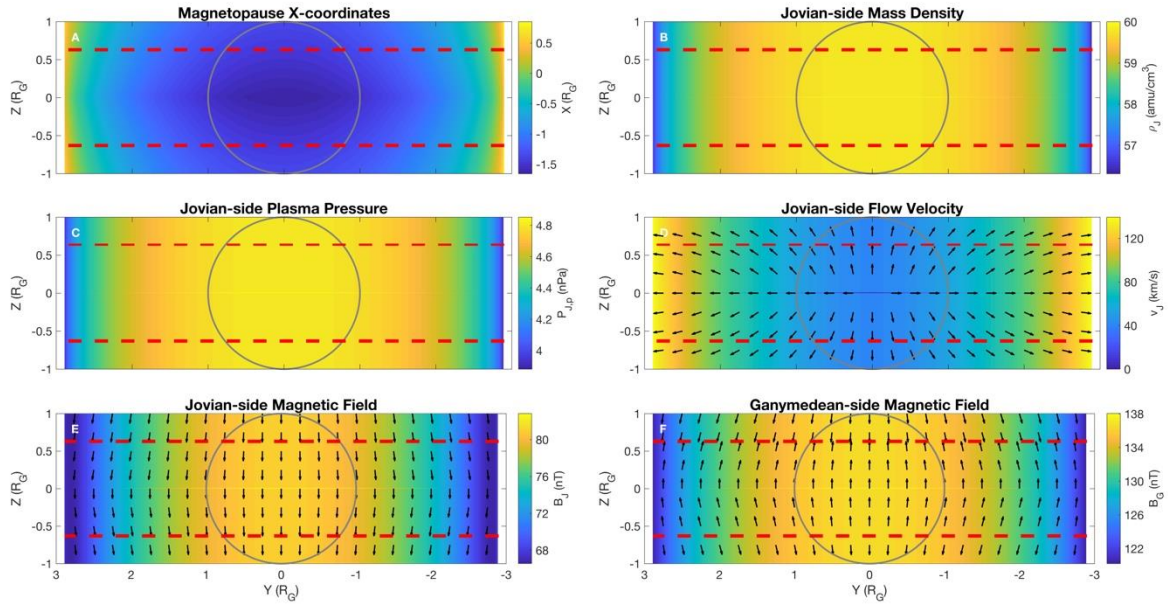
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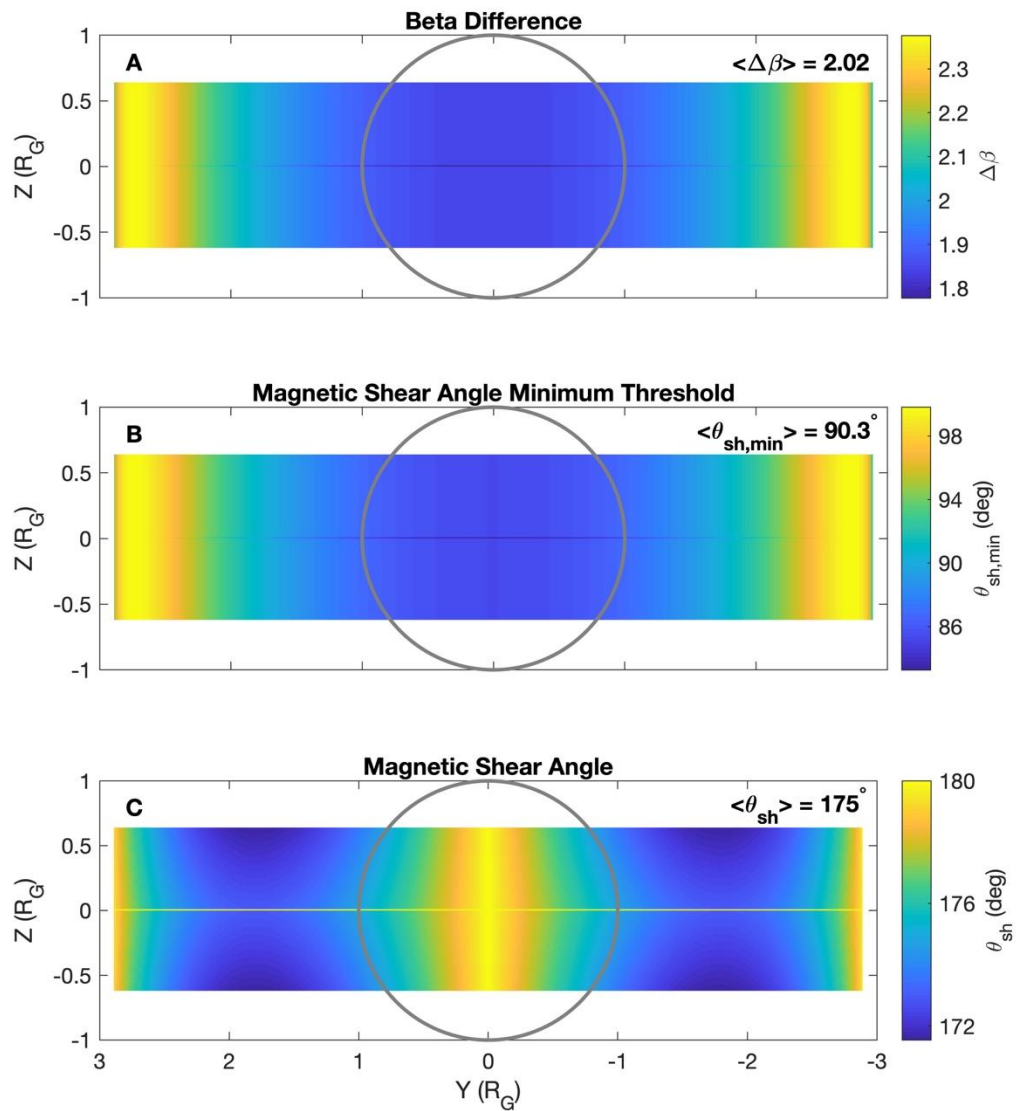
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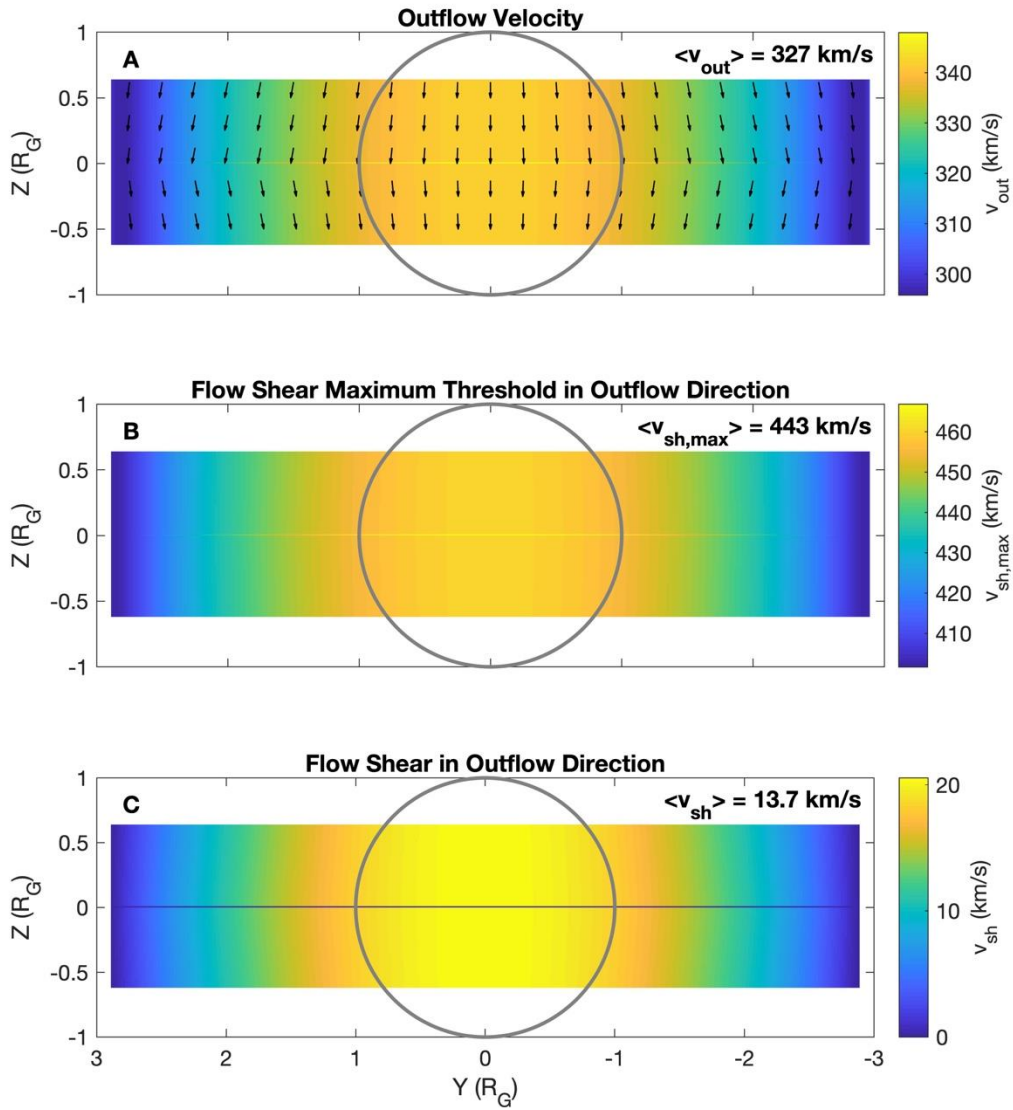
517 Figure 1: Magnetopause conditions projected onto a two-dimensional plane with the Jovian  
 518 plasma flowing into the page when Ganymede is in the Jovian current sheet. Parameters  
 519 shown are (A) X-coordinates on the magnetopause surface, (B) Jovian-side mass density, (C)  
 520 Jovian-side plasma pressure, (D) Jovian-side flow velocity, (E) Jovian-side magnetic field,  
 521 and (F) Ganymede-side magnetic field. Ganymede is outlined in grey and the closed-field  
 522 region is defined between two red dashed lines.

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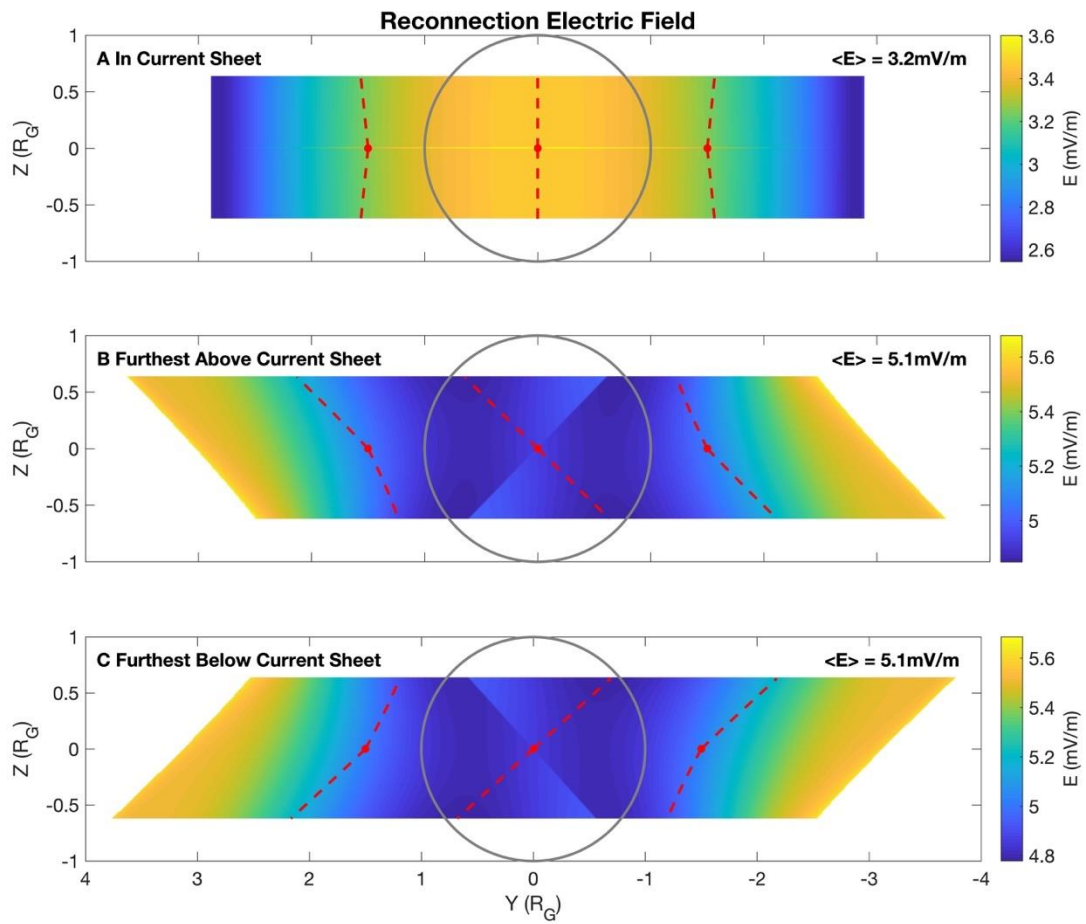
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525 Figure 2: Evaluation of the diamagnetic drift onset condition in Ganymede's closed-field  
 526 region when Ganymede is in the Jovian current sheet. Parameters shown are (A) beta  
 527 difference across the magnetopause, (B) magnetic shear angle minimum threshold, and (C)  
 528 shear angle calculated from magnetopause conditions. Ganymede is outlined in grey and  
 529 average parameter values are shown at top right.



530

531 Figure 3: Evaluation of the bulk plasma flow shear onset condition in Ganymede's closed-  
 532 field regions when Ganymede is in the Jovian current sheet. Parameters shown are (A)  
 533 reconnection outflow velocity, (B) flow shear maximum threshold, and (C) flow shear  
 534 calculated from magnetopause conditions. The format is the same as Figure 2.



535

536 Figure 4: Electric field at potential reconnection sites in Ganymede's closed-field regions  
 537 computed when Ganymede is (A) in, (B) furthest above, and (C) furthest below the Jovian  
 538 current sheet. Red dashed lines indicate plasma outflow tracks from selected reconnection  
 539 sites. The format is the same as Figure 2.

540