

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

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12 **Key Points**

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

19 **Abstract**

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

33

34 **Plain Language Summary**

35 Ganymede is the largest moon of Jupiter and the only Solar System moon that produces its own
36 magnetic field. Ganymede's magnetic field is surrounded by Jupiter's much larger magnetic
37 field, which flows around the moon like a river flowing around a rock. The boundary where
38 Jupiter's magnetic field first encounters Ganymede's is called the magnetopause. At this
39 boundary, energy and mass can move between the two magnetic fields through a process called
40 magnetic reconnection. Our paper introduces a simple model of Ganymede's magnetopause,
41 and uses this model to show where reconnection can occur on the boundary. We find that
42 reconnection can occur anywhere on the magnetopause for any plausible environmental

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

47

48 **Keywords**

49 Ganymede, magnetic reconnection, magnetopause, modeling

50

51 **1. Introduction**

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

65

66 Ganymede orbits Jupiter at an average distance of $\sim 15 R_J$ in a plane nearly coplanar to Jupiter's
67 spin equator (Bills, 2005; McKinnon, 1997). The orbital plane is $\sim 7^\circ$ inclined with respect to
68 the central plane of a $\sim 3 R_J$ thick, rotating Jovian magnetospheric plasma sheet arising from
69 Io's volcanic activity (Kivelson et al., 2004). Ganymede thus effectively moves up and down
70 through the plasma sheet experiencing large variations in the ambient plasma and magnetic
71 conditions. Under ideal magnetohydrodynamic (MHD) theory, outward radial motions in the
72 plasma sheet leads to stretching of Jovian magnetic field lines, forming a thin current sheet
73 approximately coplanar to the plasma sheet's central plane (Khurana et al., 2004). Hence, the
74 ambient Jovian magnetized plasma conditions at Ganymede are controlled by the distance
75 between Ganymede and the center of Jupiter's current sheet.

76

77 The Jovian plasma rotates with the planet at $\sim 80\%$ of the corotation speed at Ganymede
78 (Williams, Mauk, McEntrie, 1997; Williams, Mauk, McEntrie, Roelof, et al., 1997), which is
79 much faster than Ganymede's Keplerian speed. Hence, the magnetic field frozen into the
80 plasma compresses Ganymede's magnetic field on the upstream side forming a magnetopause
81 boundary (Jia et al., 2008). The Jovian plasma flow is sub-Alfvénic so the magnetic pressure
82 predominantly shapes magnetopause interactions (Neubauer, 1998). Consequently,
83 Ganymede's magnetosphere is cylindrically-shaped with long Alfvén wings and no bow shock
84 preceding the magnetopause (Jia, Kivelson, et al., 2010) - a contrast to planetary
85 magnetospheres which are bullet-shaped due to dynamic pressure dominance in the super-
86 Alfvénic solar wind (Neubauer, 1990). Magnetic field lines near the upstream equator inside
87 the magnetosphere are closed (both ends at Ganymede's magnetic poles) and almost
88 antiparallel (due to 176° dipole tilt) to Jupiter's magnetic field lines, which hints at magnetic
89 reconnection as the dominant mechanism for plasma and energy inflows from Jupiter to
90 Ganymede. Elsewhere, magnetic field lines in Ganymede's large polar caps and magnetotail

91 are open (at least one end at Jupiter), allowing particles entries/escapes from the moon's
92 magnetosphere (Frank et al., 1997; Williams, Mauk, McEntrie, 1997; Williams, Mauk,
93 McEntrie, Roelof, et al., 1997).

94

95 The Ganymede magnetosphere has been modeled by many numerical simulations, some of
96 which discuss magnetic reconnection at the upstream magnetopause. For instance, Jia et al.
97 (2008; 2009) produced a global three-dimensional resistive-MHD simulation of Ganymede that
98 showed transient reconnection signatures spread over large regions of the magnetopause.
99 Subsequent analysis revealed these signals to be consistent with intermittent rope-like flux-
100 transfer events (Jia, Walker, et al., 2010). Recently, modeling work has been extended to
101 include the Hall effect (Dorelli et al., 2015), and to couple with kinetic-ion hybrid (Leclercq et
102 al., 2016) and local particle-in-cell codes (Daldorff et al., 2014; Tóth et al., 2016; Zhou et al.,
103 2019), all of which treat reconnection microphysics more directly. Specifically, the MHD-
104 EPIC (embedded particle-in-cell) model indicated presence of quasiperiodic formation of flux-
105 transfer events consistent with previous resistive-MHD results and Galileo observations.
106 However, these comprehensive numerical modelling studies have not been supported by
107 important assessment of reconnection at Ganymede's magnetopause that apply reconnection
108 onset theory, which is an essential additional element in understanding the physics at work.

109

110 We have used an analytical approach to parametrize the magnetopause conditions expected
111 from a typical Jovian plasma flow around Ganymede. This approach provides a
112 computationally cheap way to apply modern kinetic physics of reconnection onset that is
113 challenging to implement in more expensive numerical models. Reconnection onset has been
114 analytically assessed at Earth (Alexeev et al., 1998; Trattner et al., 2007a, 2007b), Jupiter

115 (Desroche et al., 2012; Masters, 2017), Saturn (Desroche et al., 2013; Masters, 2015a), Uranus
 116 (Masters, 2014), and Neptune (Masters, 2015b). In the following sections, we outline the
 117 analytical model of Ganymede's upstream magnetopause followed by the first kinetic
 118 assessment of magnetic reconnection onset and structural properties.

119

120 **2. Analytical Model of Ganymede's Upstream Magnetopause**

121 Maps of conditions immediately either side of Ganymede's magnetopause are essential for
 122 reconnection onset assessment. To achieve this, we must first define the magnetopause surface.
 123 Kivelson et al. (1998) describe Ganymede's magnetosphere as a cylinder with shifting center
 124 points in dynamical Ganymede-at-origin Jovian magnetic field-aligned coordinates (GphiB).
 125 We rewrite the equations for Ganymede's magnetopause surface in Ganymede-at-origin
 126 Cartesian coordinates (GphiO) in which X points along the plasma flow direction, Y points
 127 from Ganymede to Jupiter, and Z points along Jupiter's spin axis (approximately parallel to
 128 Ganymede's spin axis due to small Ganymede orbit inclination) as follow

$$129 \quad f(X, Y, Z) = \frac{(X - X_0)^2}{a^2} + \frac{(Y \cos \theta_r - Z \sin \theta_r - Y_0)^2}{b^2} = 1$$

130 where

$$131 \quad \theta_r = \tan^{-1} \left(\frac{|B_{0,z}|}{B_{0,y}} \right) - 90^\circ$$

$$132 \quad X_0(Y, Z) = X_0(0) + |Y \sin \theta_r + Z \cos \theta_r| \tan \theta$$

$$133 \quad Y_0(Y, Z) = \frac{2}{\pi} Y_{0,max} \sin(\phi - 248^\circ) \tan^{-1} \left(\frac{Y \sin \theta_r + Z \cos \theta_r}{\lambda} \right)$$

134 The angle θ_r describes right-handed rotation angle between GphiB and GphiO coordinates.
 135 $(B_{0,y}, B_{0,z})$ are the ambient Jovian magnetic field components. (X_0, Y_0) denote the center point

136 offsets from the GphiO origin. Kivelson et al. (1998) chose $a = 2.2 R_G$ and $\lambda = 0.5 R_G$, and
137 then used a least squares fit to the Galileo data to calculate $b = 2.90 R_G$, $X_0(0) = 0.544 R_G$,
138 $Y_{0,max} = 0.914 R_G$, and $\theta = 0.298$ radians. This leaves Jupiter's System-III east longitude ϕ
139 as the only free parameter. System-III coordinates describe a stationary Jovian magnetic dipole
140 with Ganymede orbiting quickly through the longitudes, which is equivalent to a rapidly
141 spinning dipole in Ganymede-stationary GphiO coordinates. As the Jovian plasma/current
142 sheets move with the dipole, each ϕ value determines their positions relative to Ganymede thus
143 ambient plasma/magnetic conditions that control reconnection.

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 when Ganymede is in the Jovian current sheet ($\phi = 248^\circ$). Here the magnetopause is north-
149 south symmetric with the standoff distance of $1.65 R_G$ calculated at the subflow point ($Y = 0$
150 R_G , $Z = 0 R_G$). The magnetopause X-coordinate increases away from the subflow point in all
151 directions as the surface curves downstream. The magnetopause gains maximum north-south
152 asymmetries when Ganymede is furthest above/below the current sheet ($\phi = 158^\circ, 338^\circ$).
153 These asymmetries occur in response to changes in ambient Jovian magnetic field orientations
154 (parametrization below). This simple and fixed magnetopause description is sufficient for
155 reconnection onset assessment, as more accurate surface models will not affect the conclusions
156 drawn.

157

158 Next, we describe the Jovian-side (external) conditions at the magnetopause. The ambient
159 Jovian plasma mass density is $\rho_0 = 56 \text{ amu/cm}^3$ when Ganymede is in the current sheet and

160 $\rho_0 = 28 \text{ amu/cm}^3$ when Ganymede is furthest above/below the current sheet (Jia et al., 2008).
161 The plasma is compressed near Ganymede's magnetopause thus increasing its mass density.
162 We employ a simple compression formula $\rho_J = A_1 \cos(\alpha) + \rho_0$ where α is the flaring angle
163 between the X-axis and the local magnetopause-normal vector. The cosine of flaring angle is
164 adapted from results at Earth's magnetopause (Petrinec & Russell, 1997) and captures spatial
165 density variations expected from plasma flows around a cylindrical magnetosphere. A more
166 complex compression description is again possible but unlikely to affect main conclusions
167 drawn. The typical compression amplitude $A_1 = 4 \text{ amu/cm}^3$ is estimated empirically from
168 numerical simulations (Jia et al., 2008; Tóth et al., 2016) and the added ambient mass density
169 ρ_0 prevents plasma decompression. Figure 1B shows the Jovian-side mass density variation
170 when Ganymede is in the current sheet. The density peaks near the subflow point where Jovian
171 plasma collides head-on with the magnetopause and decreases toward the flanks where plasma
172 flows near-parallel to the surface.

173

174 The ambient Jovian plasma pressure (thermal and energetic) is $P_0 = 3.8 \text{ nPa}$ when Ganymede
175 is in the current sheet and $P_0 = 1.9 \text{ nPa}$ when Ganymede is furthest above/below the current
176 sheet (Jia et al., 2008; Kivelson et al., 2004). Figure 1C shows plasma pressure at the Jovian-
177 side magnetopause when Ganymede is in the current sheet. Like mass density, a cosine relation
178 $P_{J,p} = A_2 \cos(\alpha) + P_0$ parametrizes the pressure compression. The amplitude $A_2 = 1.05 \text{ nPa}$ is
179 approximated from the pressure relation at Earth's magnetopause for slow plasma flow speeds
180 (Petrinec & Russell, 1997). This method provides slightly smaller Jovian-side plasma pressures
181 ($\sim 1 \text{ nPa}$ difference) compared to numerically simulated values. However, larger pressures are
182 found to cause unrealistic Jovian magnetic field decompression at the magnetopause (discussed
183 below).

184

185 The ambient Jovian plasma flows along the X-axis at speed $v_0 = 140$ km/s in Ganymede's rest
186 frame (Jia et al., 2008). Figure 1D shows the plasma flow velocity at the Jovian-side
187 magnetopause when Ganymede is in the current sheet. Unlike mass density and pressure, we
188 parametrize the flow speed by a sine relation $v_J = v_0 \sin(\alpha)$ as the ambient plasma is most
189 stagnated by direct collision near the subflow point. The Jovian-side flow directions
190 (normalized arrows) are constrained to be parallel to the magnetopause surface and orthogonal
191 to cross products of magnetopause-normal vectors and ambient plasma flow vectors.

192

193 The ambient Jovian magnetic field has been computed at Ganymede using a mathematical
194 model (Jia et al., 2008; Khurana, 1997). The magnetic field strength has minimums of $B_0 \sim 70$
195 nT when Ganymede is in the current sheet and maximums of $B_0 \sim 105$ nT when Ganymede is
196 furthest above/below the current sheet. Following Jia et al. (2008), we assume negligible x-
197 component $B_{0,x}$ and parametrize the remaining two components by $B_{0,y} = 84 \sin(\phi - 248^\circ)$
198 nT and $B_{0,z} = 3 \cos(\phi) - 79$ nT. Hence, the ambient Jovian magnetic field always points
199 southward in the Y-Z plane between 135° - 225° clock angles. We quantify magnetic field
200 compression at the Jovian-side magnetopause using conservation of combined magnetic,
201 plasma, and dynamic pressures before and after the compression. The total pre-compression
202 pressure can be calculated from ambient plasma/magnetic values. Using data from Figures 1C
203 and 1D, we derive post-compression plasma pressure and magnetopause-parallel dynamic
204 pressure component. We subtract these values from the total pressure to obtain the post-
205 compression magnetic pressure $P_{J,b}$ (which includes the magnetopause-normal dynamic
206 pressure component) and convert this into Jovian-side magnetic field strength B_J shown in

207 Figure 1E when Ganymede is in the current sheet. The plasma compression also constrains
208 magnetic field directions (normalized arrows) onto the magnetopause surface.

209

210 The Jovian-side plasma and magnetic pressures together exert force on Ganymede's
211 magnetopause, which is balanced by magnetic pressure from Ganymede's magnetic field given
212 negligible plasma pressure inside the moon's magnetosphere (Jia et al., 2008). Hence, we can
213 derive the magnetic field strength at the Ganymede-side magnetopause B_G as shown in
214 Figure 1F when Ganymede is in the current sheet. Magnetic field directions (normalized
215 arrows) have no azimuthal component (consistent with dipolar field) and lie parallel to the
216 magnetopause surface. The magnetic field points northward in the "closed-field region"
217 defined by $|Z| < 0.63 R_G$ and southward elsewhere (Jia et al. 2009). The closed-field region
218 is bounded by two horizontal red dashed lines which we retroactively add to all Figure 1
219 subplots. Otherwise, the Ganymede-side plasma density and flow speed are set to uniform
220 values $\rho_G = 20 \text{ amu/cm}^3$ (Jia et al. 2008, 2009) and $v_G = 0 \text{ km/s}$ (approximating relatively
221 slow plasma flows inside Ganymede's magnetosphere) respectively.

222

223 **3. Magnetic Reconnection Assessment at Ganymede**

224 With maps of conditions on both sides of Ganymede's magnetopause, we can assess
225 reconnection onset specifically for the closed-field region where particle transport is not
226 expected under MHD theory. Reconnection onset requires three conditions to be satisfied. First,
227 the magnetopause current sheet separating Jupiter's and Ganymede's magnetic fields must be
228 thinner than approximately an ion inertial length to break the MHD frozen-in flux condition
229 (Phan et al., 2011). The Galileo data analysis revealed the magnetopause current sheet
230 thickness to be $< 400 \text{ km}$ (Kivelson et al., 1998), similar to the $\sim 426 \text{ km}$ ion inertial length

231 calculated from magnetopause conditions in Figure 1. Hence, we can assume a sufficiently thin
232 magnetopause current sheet irrespective of Ganymede's position relative to the Jovian current
233 sheet.

234

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

$$240 \quad \theta_{\text{sh}} > 2 \tan^{-1} \left(\frac{d_i \Delta\beta}{L} \right) = 2 \tan^{-1}(\Delta\beta)$$

241 where θ_{sh} is the smaller shear angle between the Jovian and Ganymedeian magnetic fields in a
242 magnetopause-tangent plane at each grid point (Swisdak et al., 2003; 2010). If this condition
243 is unsatisfied, the diamagnetic drift is too fast and reconnection is suppressed. The system
244 length scale (L) is the magnetopause current sheet thickness, which from the first onset
245 condition is approximately equal to the ion inertial length (d_i), so the shear angle minimum
246 threshold depends only on the beta difference ($\Delta\beta = \beta_J - \beta_G$) across the magnetopause. As
247 Ganymede contributes negligible plasma pressure ($\beta_G = 0$), $\Delta\beta$ is equal to the Jovian-side beta
248 $\beta_J = P_{J,p}/P_{J,b}$. The third onset condition concerns the flow shear between Jovian and
249 Ganymedeian bulk plasmas adjacent to the magnetopause current sheet along the reconnection
250 outflow direction. Each magnetopause location has two outflow vectors parallel/antiparallel to
251 the cross product of the vector bisecting the smaller shear angle between Jovian and
252 Ganymedeian magnetic field lines and the local magnetopause-normal vector (Masters, 2017).

253 We choose the southward-pointing primary outflow vector following the Jovian field lines, and
 254 define the flow shear condition

$$255 \quad v_{\text{sh}} = \frac{|v_1 - v_2|}{2} < v_{\text{out}} \left(\frac{\rho_1 B_2 + \rho_2 B_1}{2(\rho_1 B_2 \rho_2 B_1)^{1/2}} \right)$$

$$256 \quad v_{\text{out}} = \left(\frac{B_1 B_2 (B_1 + B_2)}{\mu_0 (\rho_1 B_2 + \rho_2 B_1)} \right)^{1/2}$$

257 where symbol definitions are v = flow velocity, ρ = mass density, B = magnetic field strength,
 258 and $\mu_0 = 4\pi \times 10^{-7}$ H/m (Doss et al., 2015). Subscripts 1 and 2 indicate parameter projections
 259 along the outflow vector on Jovian-side and Ganymede-side respectively. The flow shear is
 260 $v_{\text{sh}} = |v_1 - v_2|/2$ and the outflow speed is v_{out} . Reconnection is suppressed if the flow shear
 261 exceeds its maximum threshold.

262

263 We first assess these two onset conditions for a specific case when Ganymede is in the Jovian
 264 current sheet, and then consider two extreme cases when Ganymede is furthest above/below
 265 the current sheet. Figure 2 assesses the diamagnetic drift condition when Ganymede is in the
 266 current sheet. Beta differences in Figure 2A have the average of 2.02 in the closed-field region,
 267 with largest $\Delta\beta$ along the magnetopause flanks where the Jovian-side magnetic field is weakest.
 268 The resulting shear angle minimum thresholds ($\theta_{\text{sh,min}}$) in Figure 2B have the average of 90.3°
 269 with largest values along the flanks. Figure 2C shows magnetic shear angles calculated using
 270 data from Figures 1E and 1F. The average θ_{sh} is 175° with largest values in columns nearest
 271 to the subflow point and toward the flanks. Comparing Figures 2B and 2C indicates that $\theta_{\text{sh}} >$
 272 $\theta_{\text{sh,min}}$ at every point in the closed-field region, satisfying the second onset condition
 273 everywhere on Ganymede's magnetopause.

274

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

285

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

$$289 \quad E = 2k \left(\frac{B_1 B_2}{B_1 + B_2} \right) v_{out} \left(1 - \frac{(v_1 - v_2)^2}{(v_{out})^2} \frac{\rho_1 B_2 \rho_2 B_1}{(\rho_1 B_2 + \rho_2 B_1)^2} \right)$$

290 where the near-Earth reconnection efficiency factor $k = 0.1$ is adopted as it has no known β -
291 dependence (e.g. Paschmann et al., 2013, Masters 2017). Figure 4A shows the electric field
292 when Ganymede is in the current sheet with average magnitude 3.2 mV/m. Strongest field
293 magnitudes are found along near-subflow columns corresponding to largest outflow speed
294 locations. We also track (following Cooling et al., 2001) parcels of plasma in reconnection
295 outflows from three equatorial reconnection sites – one at the subflow point and two others at
296 mid-flanks ($Y = \pm 1.5 R_G$). All outflows travel bidirectionally north/south away from

297 Ganymede's equator. However, the subflow site's outflows remain on the magnetopause
298 symmetry plane ($Z = 0$) while the mid-flank sites' outflows shift toward their nearest flanks
299 due to influence from the Jovian-side plasma flow.

300

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

312

313 **4. Discussion**

314 Since there appears to be no restrictions for reconnection onset when Ganymede's
315 magnetopause is symmetric and most asymmetric, we can generalize that reconnection is
316 favorable anywhere on the magnetopause for all magnetopause asymmetries i.e. all positions
317 along Ganymede's orbit of Jupiter. This result is consistent with widespread reconnection
318 events observed in global simulations (e.g. Jia, Walker, et al., 2010; Tóth et al., 2016)

319

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

327

328 The electric field equation is found most sensitive to changes in magnetic parameters B_1 and
329 B_2 . As Ganymede moves further away from the Jovian current sheet, the ambient Jovian
330 magnetic field becomes stronger, increasing both B_1 and B_2 (the latter due to the model's fixed
331 magnetopause surface).. The average electric field increases in Figure 4 are therefore
332 dependent on Ganymede's position and controlled by Jupiter's east longitude ϕ . As the Jovian
333 dipole rotates rapidly, each ϕ value also corresponds to a distinct time-of-day on Jupiter. Hence
334 magnetic reconnection rate at Ganymede exhibits a Jovian-diurnal variation and is effectively
335 driven by Jupiter's rotation. The conclusion has been independently supported by remote
336 observations of Jovian radio emissions associated with Ganymede (Zarka et al., 2018).

337

338 Multiplying the average electric fields by the magnetopause width (~6 R_G) gives 50-80 kV
339 reconnection voltage estimates at Ganymede's magnetopause, which may be used to constrain
340 reconnection rate in the magnetotail via open magnetic flux conservation. We also calculate
341 reconnection-induced electron and ion temperature increases of 250-560 eV and 2,000-4,200
342 eV respectively using empirical methods from Earth-based studies (Phan et al., 2013; 2014),
343 with the maximum (minimum) value corresponding to when Ganymede is furthest

344 above/below (in) the Jovian current sheet. These numbers far exceed ambient temperatures for
345 electrons and ions of 300 eV and 60 eV respectively (Kivelson et al., 2004), hence reconnection
346 should result in particle heating signatures observable by the upcoming JUICE mission.

347

348 **5. Summary**

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

359

360 The average reconnection rate is shown to be a function of Ganymede's position along its orbit
361 around Jupiter, which approximately corresponds to the time-of-day on Jupiter. Hence, the
362 reconnection rate exhibits a Jovian-diurnal variation and is effectively driven by Jupiter's
363 rotation. The reconnection process should heat up surrounding plasma particles producing
364 signatures detectable by spacecraft instruments. Our steady-state model currently does not
365 capture orientation changes of Ganymede's magnetic field due to the moon's subsurface ocean.
366 Future integration of ocean effects will allow more accurate predictions of reconnection
367 structures in preparation for the JUICE space mission.

368

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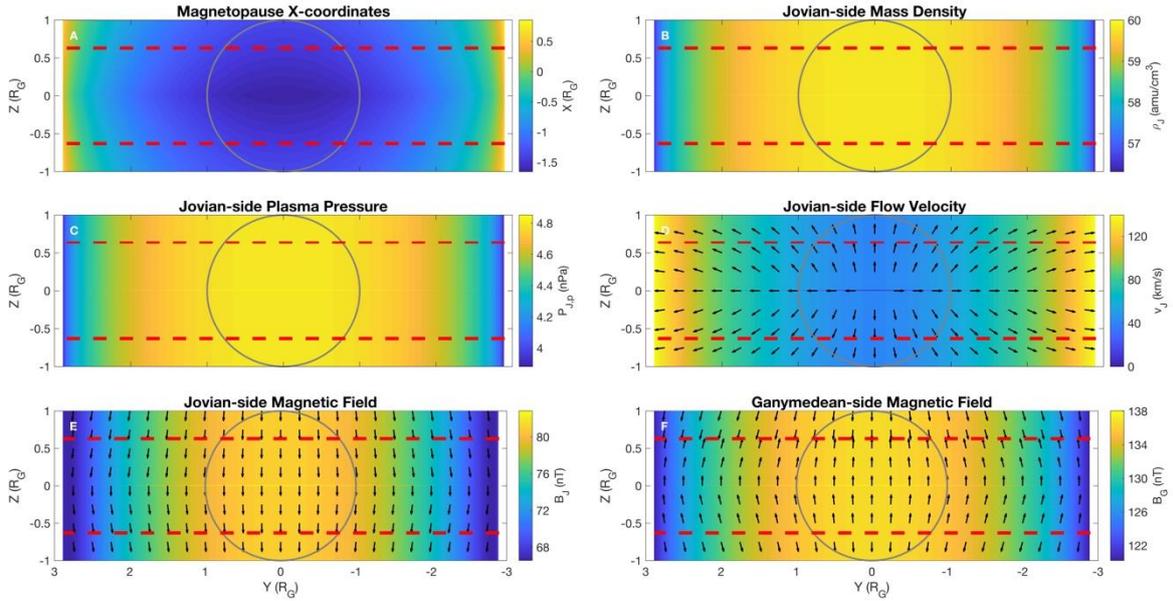
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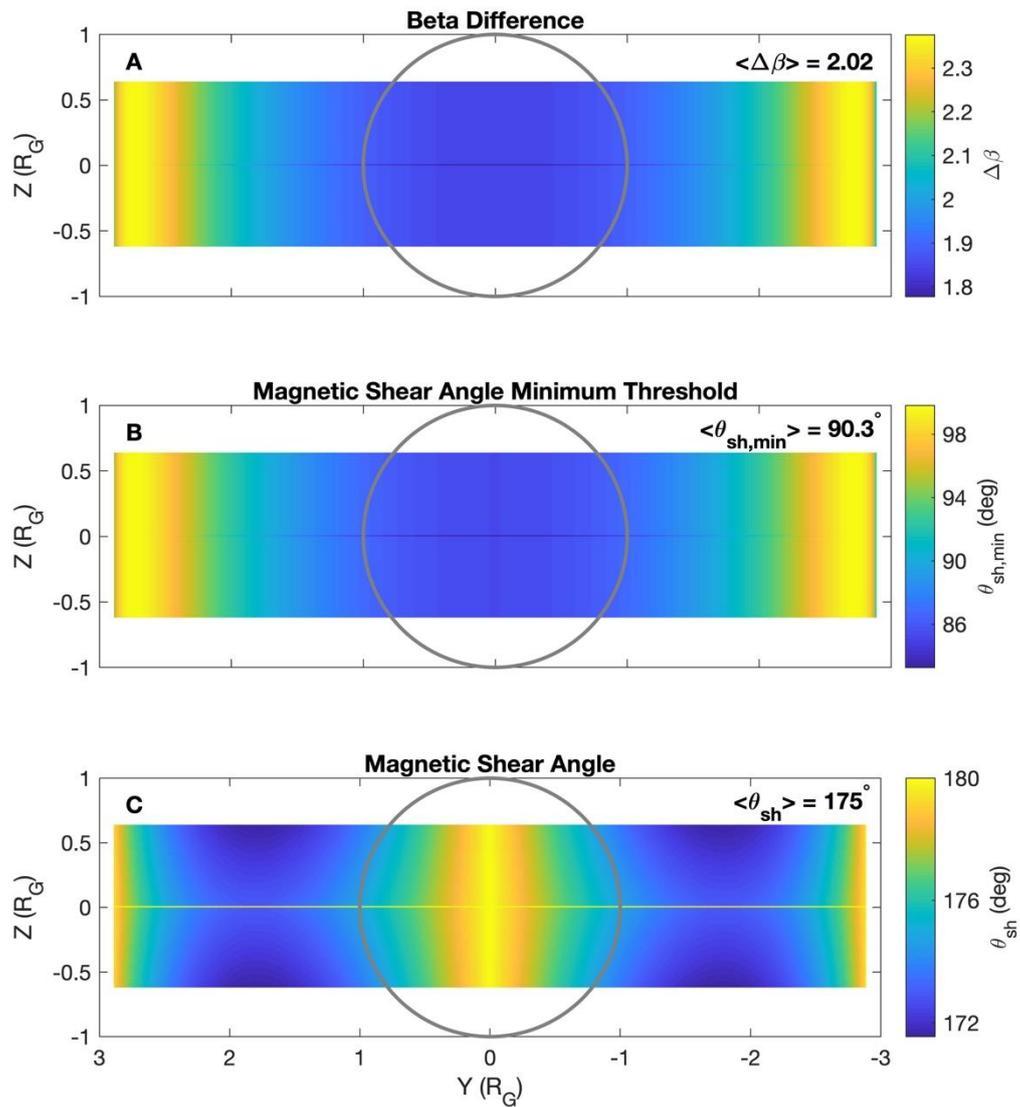
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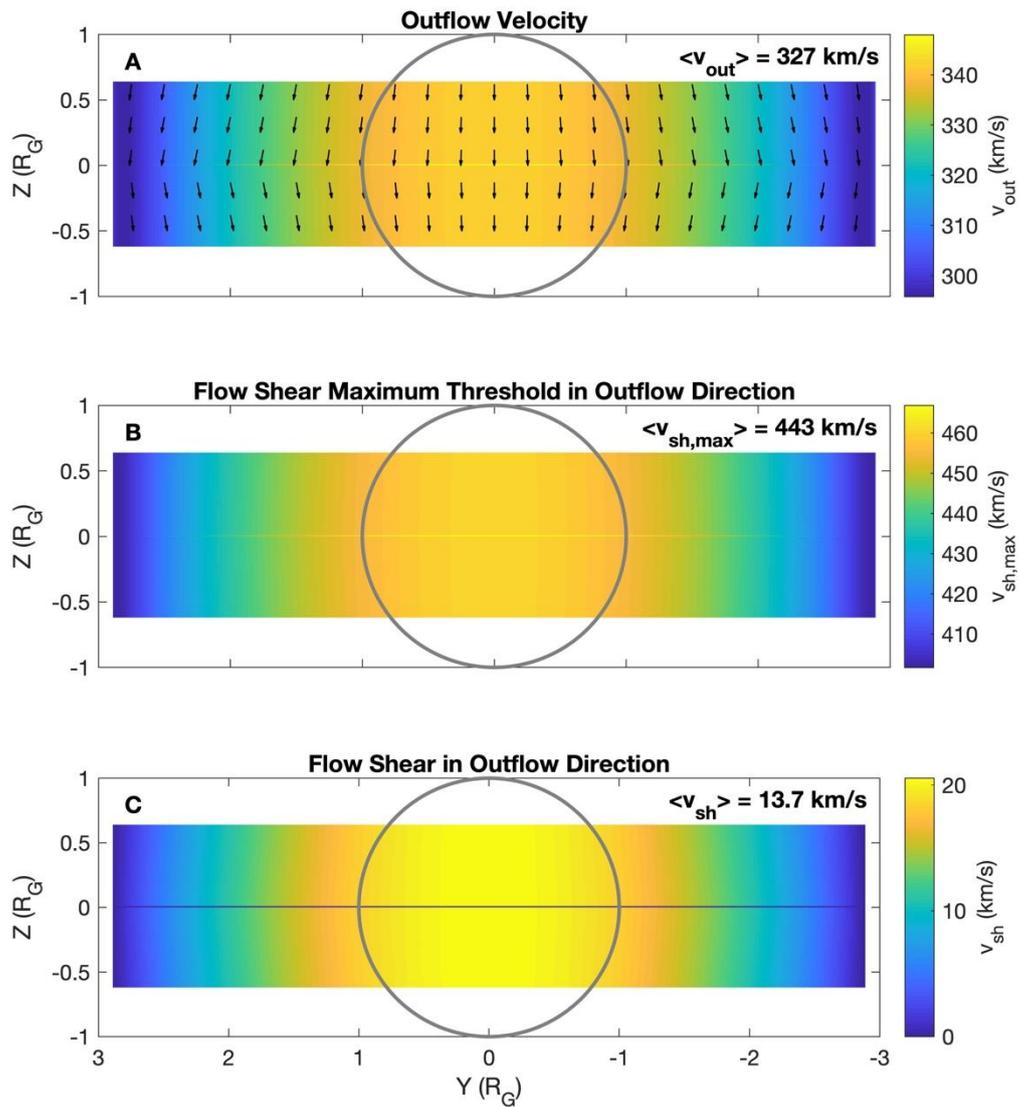
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521 Figure 1: Magnetopause conditions projected onto a two-dimensional plane with the Jovian
 522 plasma flowing into the page when Ganymede is in the Jovian current sheet. Parameters shown
 523 are (A) X-coordinates on the magnetopause surface, (B)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



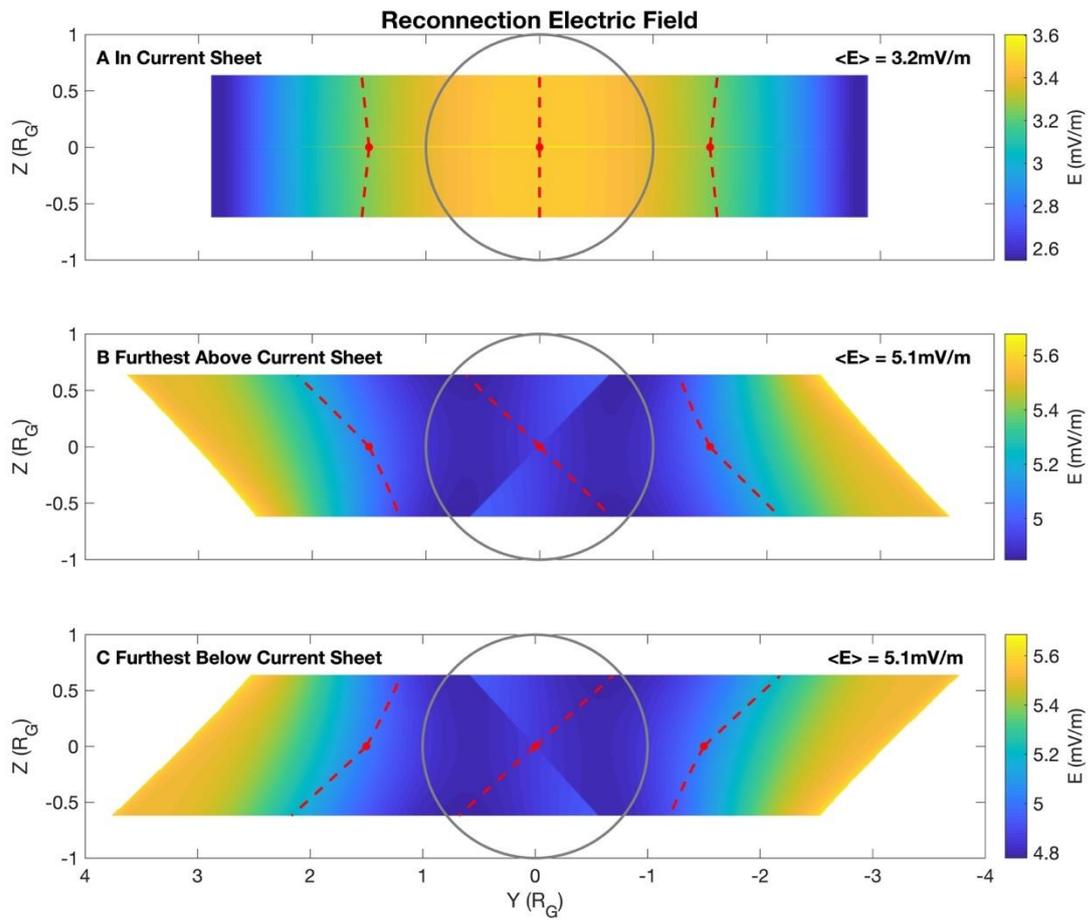
527

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



533

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



538

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