GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L10106, doi:10.1029/2005GL025273, 2006

The role of ion cyclotron motion at Ganymede: Magnetic field morphology and magnetospheric dynamics

Carol Paty[1] and Robert Winglee[1]

Received 19 November 2005; revised 23 February 2006; accepted 24 April 2006; published 31 May 2006.

[1] Ion cyclotron motion can play a role in shaping magnetospheres and governing magnetospheric dynamics, particularly in weakly magnetized systems such as the moons of outer planets. However, MHD explicitly neglects such effects. We demonstrate the importance of ion cyclotron motion in the near space environment of Ganymede using 3-dimensional multi-fluid simulations to account for Galileo magnetometer data from several flybys through various regions of Ganymede's magnetosphere. These simulations track several ion species and incorporate ion cyclotron effects through a comprehensive treatment of the plasma dynamics and the generalized Ohm's law equation. In the ideal MHD limit of the multi-fluid formulation the size of Ganymede's magnetosphere is underestimated, while in the full multi-fluid treatment the magnetosphere is shown to be in good agreement with magnetometer measurements from Galileo. The importance of treating the ion cyclotron motion is most noticeable near the magnetopause where magnetic field strengths approach zero. **Citation:** Paty, C., and R. Winglee (2006), The role of ion cyclotron motion at Ganymede: Magnetic field morphology and magnetospheric dynamics, *Geophys. Res. Lett.*, *33*, L10106, doi:10.1029/2005GL025273.

1. Introduction

[2] Ganymede's global magnetic field provides an important example of a magnetosphere embedded within a magnetosphere. The existence of Ganymede's magnetosphere was first indicated by radio emissions observed on the Galileo spacecraft's initial approach to Ganymede [*Gurnett et al.*, 1996]. The dipole field at Ganymede was further quantified and constrained through the cumulative analysis of magnetometer data from multiple flybys of the moon [*Kivelson et al.*, 2002], where it was determined that Ganymede's magnetic signature contains both an intrinsic dipole field and time variable component.

[3] Plasma dynamics have been observed to play a large role in the coupled interaction of Ganymede's magnetosphere with the Jovian magnetosphere through the acceleration of electrons which generate the aurora both at Ganymede [*Feldman et al.*, 2000] and Jupiter [*Clarke et al.*, 2002]. Asymmetries in the magnetometer data and the presence of detectable plasma waves emanating from Ganymede are also indicators of the importance of plasma dynamics for understanding the interaction of Ganymede's magnetosphere with the magnetized plasma of the Jovian magnetosphere. The multi-fluid model was validated by *Paty and Winglee* [2004] demonstrating good correlation to magnetometer observations from the G28 flyby. When using the same incident conditions *Paty and Winglee* [2004] found that regions of energetic particle flux at Ganymede's ionosphere in the model occurred at the same location as aurora observed on Ganymede's upstream facing side [*Feldman et al.*, 2000]. The model used in this investigation differs from *Paty and Winglee* [2004] in two ways which are detailed in the 'Methods' section. First, the numerical algorithm was updated, and most importantly, a higher resolution grid system was implemented which improved the correlation between magnetometer data (G28) and model predictions.

[4] Previously, researchers have used resistive magnetohydrodynamic (MHD) simulations to study Ganymede's magnetosphere [*Kopp and Ip*, 2002]. Magnetic fields generated in the model of *Kopp and Ip* [2002] demonstrated the effects of variations in the incident Jovian magnetic field orientation on Ganymede's magnetic morphology, but the results were not compared to the actual magnetometer data which contained field asymmetries and plasma dynamic perturbations [cf. *Kivelson et al.*, 1998]. The pick-up of ionospheric ions by incident magnetized plasma flows are known to produce asymmetric flows and field morphologies, phenomenon that multi-fluid and hybrid simulations predict [*Harnett et al.*, 2005]. However, these effects are not included in MHD models because the MHD equations average over the gyromotion of the particles and sum together all of the ion components and the electrons into a single bulk fluid. These approximations are valid in settings where all scale lengths are larger than the ion gyroradius, which makes the associated ion drift motions negligible, but this is not the case at Ganymede. In this system, the ion gyroradius of the major ion component O^+ can range from 400 km in the incident plasma flow to thousands of kilometers near the reconnection regions where the magnetic field becomes small. The size of the ion gyroradius is therefore larger than relevant scale sizes in the system such as the scale height of the ionosphere (125 km [*Eviatar et al.*, 2001]), Ganymede's radius (1 R_G = 2631 km), and the average altitude of the magnetopause (.85–1.82 R_G above the surface, based on the G28 flyby in the work by *Kivelson et al.* [2002]).

[5] The multi-fluid treatment, explained at length for the context of Earth magnetospheric simulations by *Winglee* [2004] and below for the case of Ganymede, keeps track of the different ion species as separate fluids for which the ion gyromotion is not averaged out. A detailed comparison of the multi-fluid model to hybrid simulations for Pluto found that the ion drift motion due to explicitly modeled gyromo-

---

[1] Earth and Space Sciences, University of Washington, Seattle, Washington, USA.

0094-8276/06/2005GL025273

tion in the hybrid case was comparable to the ion drift motion in the multi-fluid treatment [*Harnett et al.*, 2005].

[6] This study looks to further our understanding of how Ganymede's magnetosphere interacts with the Jovian magnetosphere through the use of multi-fluid simulations which can describe and account for the Galileo magnetometer observations for several flybys and at various locations with a single, consistent model and set of parameters. We examine the role of ion cyclotron motion, particularly for heavy ions such as O^+, in governing the size, shape and dynamics of Ganymede's magnetosphere. Two sets of simulations were performed; the first using a modified multi-fluid treatment where the ion gyromotion is neglected (hereafter referred to as the NG, or Non-Gyromotion, treatment), and the second using the full multi-fluid treatment which includes ion cyclotron effects. The size and shape of the observed and modeled magnetospheres and the location of the magnetopauses are explored to determine the relative importance of ion cyclotron motion in governing Ganymede's magnetospheric dynamics.

2. Methods

2.1. Multi-Fluid Treatment

[7] In tracking several ion species the conservation of mass and momentum and pressure are calculated separately for each ion species; here α denotes the ion species, n is number density, $\vec{v}$ is velocity, q is ion charge, and ρ is mass density.

$$\frac{\partial \rho_\alpha}{\partial t} + \nabla \cdot (\rho_\alpha \vec{v}_\alpha) = 0 \qquad (1)$$

$$\rho_\alpha \frac{d\vec{v}_\alpha}{dt} = n_\alpha q_\alpha \left(\vec{E} + \vec{v}_\alpha \times \vec{B}\right) - \nabla P_\alpha - \left(\frac{GM_G}{R^2}\right)\rho_\alpha \hat{r} \qquad (2)$$

$$\frac{\partial P_\alpha}{\partial t} = -\gamma \nabla \cdot (P_\alpha \vec{v}_\alpha) + (\gamma - 1)\vec{v}_\alpha \cdot \nabla P_\alpha. \qquad (3)$$

The evolution of the magnetic field is given by the induction equation,

$$\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E}. \qquad (4)$$

The current, $\vec{J}$, is

$$\vec{J} = e\left(\sum_\alpha n_\alpha \vec{v}_\alpha - n_e \vec{v}_e\right) = \frac{1}{\mu_o} \nabla \times \vec{B}. \qquad (5)$$

Equation (5) can be solved for the electron velocity, $\vec{v}_e$ to obtain the following expression

$$\vec{v}_e = \sum_\alpha \frac{n_\alpha \vec{v}_\alpha}{n_e} - \frac{\vec{J}}{en_e}. \qquad (6)$$

Solving the conservation of momentum equation of the electron population (assuming $\frac{d\vec{v}_e}{dt}$ is small on the ion cyclotron timescales and the gravitational term is negligible) for the electric field, and substituting the formulations for $\vec{v}_e$ from equation (6) gives a modified Ohm's Law

$$\vec{E} = -\sum_\alpha \frac{n_\alpha \vec{v}_\alpha \times \vec{B}}{n_e} + \frac{\vec{J} \times \vec{B}}{en_e} - \frac{\nabla P_e}{en_e} + \eta(\vec{x}_i)\vec{J}. \qquad (7)$$

A resistivity term is added to the Ohm's Law in order to account for the collisional resistivity present in the ionosphere. The resistivity, $\eta(\vec{x}_i)$, is applied only in the ionosphere where collisions produce a finite conductivity, the rest of the simulation space is assumed to be a collisionless space plasma with $\eta = 0$.

[8] In dimensionless units, the ratio of the Hall and ∇P_e terms in equation (7) relative to the convection term is the order of the ratio of the ion skin depth to the grid spacing. Hence the MHD limit represented in the NG treatment is obtained by setting this ratio to zero. For Ganymede the ratio is of order of unity for our model resolution, indicating the need for the full multi-fluid treatment.

[9] The incident plasma from Jupiter's magnetosphere at Ganymede has an average mass per ion of 13.7 amu [*Neubauer*, 1998], and is composed of a variety of plasma species sourced from the Io plasma torus, Jupiter's ionosphere, and sputtering of the icy Galilean moons. Ganymede's ionosphere and exosphere are believed to be produced from sputtering of its icy surface by the incident Jovian magnetospheric plasma (JMP), causing it to be composed of neutral and ionized hydrogen and oxygen [*Ip et al.*, 1997; *Eviatar et al.*, 2001], hence the importance of keeping track of the different ion species. In these simulations we consider three ion species: Ganymede's ionospheric H^+ and O^+ and the incident Jovian magnetospheric plasma. One limitation of the model, which is also applicable to MHD, is that it assumes an isotropic temperature distribution and cannot incorporate the high energy tails of the ion and electron distributions, though *Harnett et al.* [2005] shows these to be second order effects.

2.2. Numeric Algorithms and Boundary Conditions

[10] The 3D simulations incorporate a nested grid scheme, allowing the highest resolution in areas of important boundary layers, and the coarsest resolution well outside the magnetopause, extending out to tens of Ganymede radii. A Cartesian coordinate system is used where x is in the flow direction of the Jupiter's corotational velocity at Ganymede, y points in the Ganymede-to-Jupiter look direction, and z is along the rotational axis of Ganymede (GPHIO coordinates). We solved the above equations using a 2nd order Runge-Kutta, and used flux correction on each grid cell at every time-step to reduce numerical noise.

[11] The innermost box has a resolution of .045 R_G or about 120 km, and extends from approximately -3 to 3 R_G in x, -2 to 2 R_G in y and -2 to 2 R_G in z. The simulation has a grid spacing that increases by a factor of two between consecutive boxes, with the largest simulation volume of dimension 48 R_G in x and 32 R_G in y and z. Information from the inner boxes is passed to the outer boxes at a corresponding resolution, and information from the outer boxes is interpolated and passed inward along the inner box edges at every time-step. The time-step size, Δt, is determined after each time-step as a fraction of the time-scale prescribed by the Courant condition, which is based on the

Table 1. Simulation Parameters

Flyb	Bx, nT	By, nT	Bz, nT	M_{va}	M_{vs}
G2	0.00	−72.9	−84.7	0.75	1.8
G8	0.00	0.00	−77.6	0.95	1.8
G28	0.00	77.9	−75.6	0.75	1.8

fastest speeds in highest resolution box and ensures that no information is lost when the boxes communicate. Therefore Δt varies for each time-step and is on the order of .01 s.

[12] The outer boundary conditions involve the motion of the JMP from the corotational magnetosphere into the simulation volume along the upstream boundary. Our simulations represented the bulk density of the JMP with mostly O^+ and a few percent H^+ based on the upstream plasma observations from *Frank et al.* [1997] and the mean mass per ion, speed and mach numbers compiled by *Neubauer* [1998], with the incident magnetic fields corresponding to the upstream Jovian field orientations for each of the Galileo flybys. The upstream Jovian field orientations used in the simulations and resultant sonic and Alfvén Mach conditions for the three flybys (G2, G8 and G28) examined in this paper are indicated in Table 1. The other 5 sides of the simulation have open boundary conditions to allow the plasma to escape. The inner boundary lies along the base of the ionosphere and is set at 5,200 ions/cm^3, with a 4:1 ratio of O^+ to H^+ and a scale height of 125 km [*Eviatar et al.*, 2001]. The ionospheric density is held constant on the assumption of a constant source of ionospheric material [*Ip et al.*, 1997; *Paranicas et al.*, 1999], and the resistivity $\eta(\vec{x}_i)$ is set to 3800 ohm-meters at the base of the ionosphere and zero everywhere else.

3. Results

[13] We begin by comparing the results of the multi-fluid simulation with full treatment of ion cyclotron motion to the NG treatment for the G8 flyby. We chose this flyby because the spacecraft was at low latitude, placing it within close proximity of the flow-side neutral point for the upstream field configuration at that time. This location should experience the greatest influence of ion cyclotron motion because of the extremely weak fields local to the spacecraft. Note also that at the time of the G8 flyby Ganymede was located in the center of the Jovian plasma sheet, which places it in a flow regime closer to an Alfvén Mach number of one (see Table 1) due to the weaker magnetic field and enhanced density of the JMP in the plasma sheet.

[14] Figure 1 illustrates the importance of fully treating the ion cyclotron motion. The full multi-fluid treatment simulation compares well with the observed magnetic field signature, while the NG treatment does not capture the observed field. Without the ion cyclotron motion, Ganymede's resultant magnetosphere is comparatively small to that observed by Galileo. This is due to the increased temperature, and therefore pressure, produced by the ion gyromotion terms on Ganymede's magnetospheric plasma. In the full multi-fluid treatment, the ionospheric H^+ and O^+ that support Ganymede's magnetosphere can exert more outward pressure to balance the incident flow of the Jovian magnetosphere, allowing the magnetopause to form further from Ganymede's surface on the flow facing hemisphere (see Figure 2). In Figure 1 it is clearly shown that in the NG simulation the spacecraft barely crossed into the magnetosphere, whereas in the actual flyby and in the full multi-fluid simulation the spacecraft spent a significant amount of time inside the magnetosphere. Note that during the G8 flyby the B_y component of the local Jovian magnetosphere varied from ~ -25 nT to 25 nT, so for this simulation the average (B_y = 0.0 nT) was used in order to run the simulation to a steady state. This produces the discrepancy in the simulated upstream conditions in Figure 1.

[15] Figure 2a further illustrates the differences between the full multi-fluid and NG treatments by comparing the magnetopause locations in the x−y plane of the two simulations, black for the full multi-fluid treatment and magenta for the NG simulation. The magnetopause in 2a–b is determined by projecting the location where the B_z component of the magnetic field goes to zero in the equatorial plane; a reasonable approximation due to the fact that in the G8 flyby the orientation of the incident Jovian magnetic field and Ganymede's magnetosphere were anti-parallel in the z direction and nearly zero in x and y. Notice that the size and symmetry differ significantly, with the magnetopause altitude of the full multi-fluid treatment residing at an altitude of $\sim$1.1 R_G while the magnetopause in the NG simulation was at $\sim$0.7 R_G. Since the full multi-fluid simulation was well correlated to the observed magnetic signature, the lower altitude modeled in the NG simulation corresponds to a 36% smaller magnetosphere than that observed by Galileo on the G8 encounter. Figures 2c and 2d demonstrate the 3-D shape of the modeled magnetospheres for the full multi-fluid treatment and NG treatment respectively. Again the spacecraft trajectory is mapped in blue. It is apparent that without the ion gyromotion effects included in the simulations (2d), the resultant magnetosphere is noticeably smaller than when fully treated (2c).

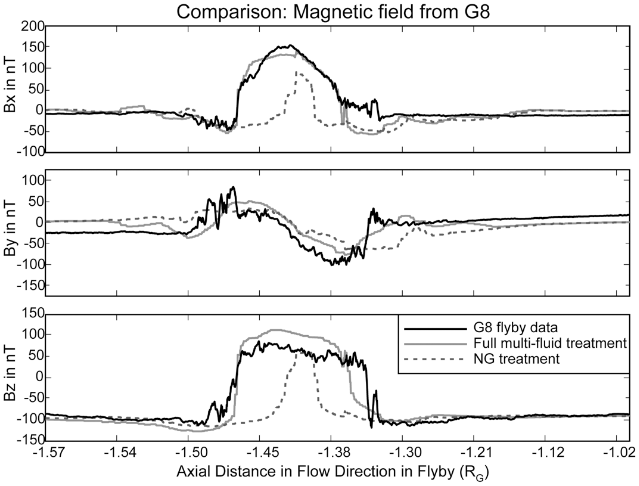

Figure 1. A comparison of the 3 components of the magnetic field measured by Galileo's magnetometer data from the G8 flyby (black) to the full multi-fluid treatment (grey) and the NG treatment (grey dashed). The axial distance in the flow direction is the x-direction in GPHIO coordinates.

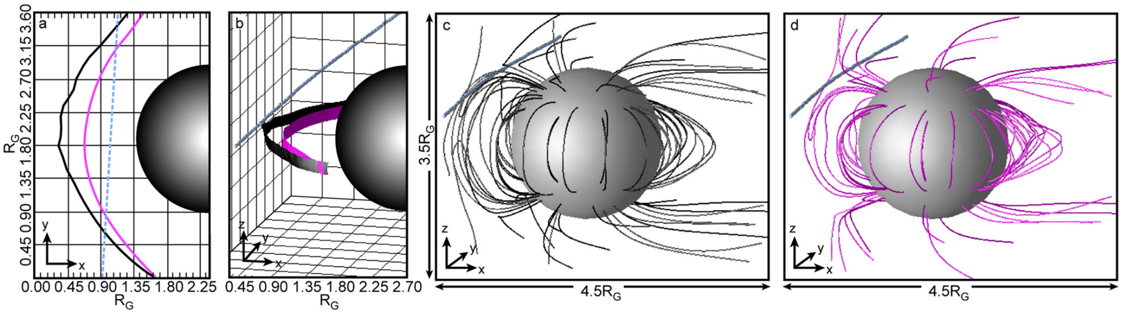

Figure 2. (a) A 2-dimensional projection in the x–y plane (GPHIO coordinates) of the equatorial magnetopause from the full multi-fluid (black) and the NG (magenta) treatments. The G8 spacecraft trajectory is projected into the plane in blue. (b) Similar except the view is rotated to see all 3 dimensions and latitude information from the flyby. (c and d) Magnetic field configuration for the multi-fluid and NG treatments respectively.

[16] A more comprehensive test of the simulations is to investigate other flybys which provide different cuts through Ganymede's magnetosphere. At the time of the G2 flyby Ganymede was located well above the Jovian plasma sheet, and during the G28 flyby it was below the plasma sheet. Figure 3 shows the results of the full multi-fluid simulations for the G2 and G28 flyby conditions and trajectories respectively. The only differences between these two simulations and the one performed and compared to the G8 flyby was the strength and orientation of the incident magnetic field from Jovian magnetosphere (see Table 1). The density and possibly composition of the incident Jovian plasma could also be varied to represent Ganymede's location in the plasma sheet (G8) versus in the lobe (G2, G28) of Jupiter's magnetosphere, which could result in better correlation for the G28 flyby. However, the variability of these parameters are not well constrained so it was held constant so as not to introduce another free parameter.

[17] For all three flybys discussed in this paper, the multi-fluid model accurately describes the three component magnetic field strengths and magnetopause crossings observed by the Galileo magnetometer. This indicates that the physics and assumptions included in the full multi-fluid treatment model are accurate for the weak field/heavy ion conditions present at Ganymede (and several other icy moons at Jupiter and Saturn). Simulations for the other three Galileo flybys (with Ganymede located similarly as in G2 and G28 relative to the Jovian plasma sheet) were also performed, all with comparably good correlations to the observed magnetic signatures.

4. Conclusion

[18] We found that the multi-fluid model containing the full treatment of the ion cyclotron motion consistently describes the magnetic field configuration detected by the Galileo magnetometer at the location of the Galileo spacecraft. This holds true for each of the possible incident Jovian field configurations, i.e., for Ganymede being located above (G2), below (G28) or inside (G8) the Jovian plasma sheet, with representative flybys shown specifically in this paper. This demonstrates the importance of treating the ion cyclotron motion when describing the Ganymede interaction with the surrounding Jovian magnetosphere.

[19] The fact that the near space environment of Ganymede includes several heavy ion species and weak magnetic fields invalidates a general assumption for using ideal or resistive MHD models. Without including the physics associated with the gyromotion of these heavy ions, the simulated magnetosphere of Ganymede is significantly smaller than that observed by the Galileo spacecraft. The full multi-fluid simulation of the magnetosphere, which

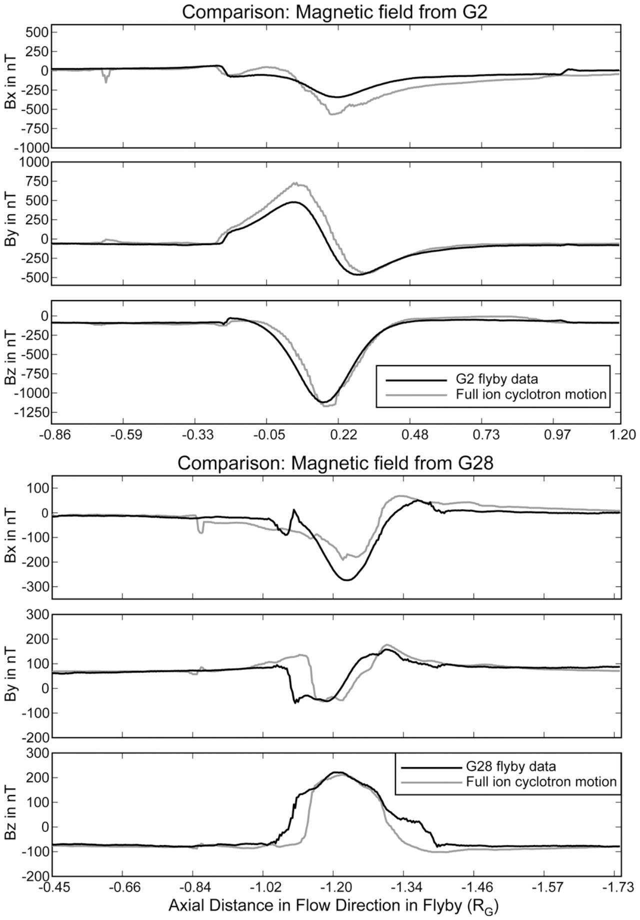

Figure 3. A comparison of the 3 components of magnetometer data from the G2 and G28 flybys (black) to multi-fluid simulations (grey).

includes ion-cyclotron effects, predicts hotter ion populations relative to the NG simulations. As a consequence, the predicted magnetopause is ~58% further from the surface than in the NG simulations and in good agreement to spacecraft observations. This multi-fluid model is the first simulation of Ganymede's magnetosphere that includes the ion gyromotion in the governing physical equations, and it consistently describes the field configuration observed by the Galileo spacecraft for several locations of Ganymede relative to the Jovian plasma sheet.

[20] **Acknowledgment.** This research was supported by NASA grants NNG05GM39G, NNG05GL59G, and NSF grant ATM 0105032 to the University of Washington.

References

Clarke, J. T., et al. (2002), Ultraviolet emissions from the magnetic footprints of Io, Ganymede and Europa on Jupiter, *Nature*, *415*, 997–999.

Eviatar, A., et al. (2001), The ionosphere of Ganymede, *Planet. Space Sci.*, *49*, 327–336.

Feldman, P. D., et al. (2000), HST/STIS ultraviolet imaging of polar aurora on Ganymede, *Astrophys. J.*, *535*, 1085–1090.

Frank, L. A., et al. (1997), Outflow of hydrogen ions from Ganymede, *Geophys. Res. Lett.*, *24*, 2151–2154.

Gurnett, D. A., et al. (1996), Evidence for a magnetosphere at Ganymede from plasma-wave observations by the Galileo spacecraft, *Nature*, *384*, 535–537.

Harnett, E. M., et al. (2005), Three-dimensional multi-fluid simulations of Pluto's magnetosphere: A comparison to 3D hybrid simulations, *Geophys. Res. Lett.*, *32*, L19104, doi:10.1029/2005GL023178.

Ip, W.-H., et al. (1997), Energetic ion sputtering effects at Ganymede, *Geophys. Res. Lett.*, *24*, 2631–2634.

Kivelson, M. G., et al. (1998), Ganymede's magnetosphere: Magnetometer overview, *J. Geophys. Res.*, *103*(E9), 19,963–19,972.

Kivelson, M. G., et al. (2002), The permanent and inductive magnetic moments of Ganymede, *Icarus*, *157*, 507–522.

Kopp, A., and W.-H. Ip (2002), Resistive MHD simulations of Ganymede's magnetosphere: 1. Time variabilities of the magnetic field topology, *J. Geophys. Res.*, *107*(A12), 1490, doi:10.1029/2001JA005071.

Neubauer, F. M. (1998), The sub-Alfvén is interaction of the Galilean satellites with the Jovian magnetosphere, *J. Geophys. Res.*, *103*, 19,843–19,866.

Paranicas, C., et al. (1999), Energetic particle observations near Ganymede, *J. Geophys. Res.*, *104*, 17,459–17,469.

Paty, C., and R. Winglee (2004), Multi-fluid simulations of Ganymede's magnetosphere, *Geophys. Res. Lett.*, *31*, L24806, doi:10.1029/2004GL021220.

Winglee, R. M. (2004), Ion cyclotron and heavy ion effects on reconnection in a global magnetotail, *J. Geophys. Res.*, *109*, A09206, doi:10.1029/2004JA010385.

C. Paty and R. Winglee, Earth and Space Sciences, University of Washington, Seattle, WA 98195, USA. (cpaty@u.washington.edu)