

## Multi-fluid simulations of Ganymede's magnetosphere

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Received 6 August 2004; revised 1 November 2004; accepted 1 December 2004; published 31 December 2004.

[1] Comparative studies of 3D multi-fluid simulations with Galileo magnetometer data are used to develop a quantitative model of the currents and fields within Ganymede's magnetosphere as well as its bulk plasma environment. The model includes contributions from Jupiter's magnetosphere and the flux of different ion species originating from Ganymede's ionosphere. Comparisons between the magnetometer data and the simulation demonstrate good agreement for the strength and structure of Ganymede's magnetosphere. An ionospheric outflow rate of  $\sim 10^{26}$  ions/s was found for the simulation, which is well correlated to the sputtering rate determined for the surface of Ganymede that actively supplies the ionosphere. Qualitative comparisons are made with the Hubble Space Telescope observations of Ganymede's UV aurora. The size and location of regions of Jovian magnetospheric plasma precipitation are similar to the observed UV emissions. Plasma acceleration due to reconnection and the size of Ganymede's cusps are also examined. **INDEX TERMS:** 2736 Magnetospheric Physics: Magnetosphere/ionosphere interactions; 2753 Magnetospheric Physics: Numerical modeling; 2704 Magnetospheric Physics: Auroral phenomena (2407); 5443 Planetology: Solid Surface Planets: Magnetospheres (2756); 6218 Planetology: Solar System Objects: Jovian satellites. **Citation:** Paty, C., and R. Winglee (2004), Multi-fluid simulations of Ganymede's magnetosphere, *Geophys. Res. Lett.*, 31, L24806, doi:10.1029/2004GL021220.

### 1. Introduction

[2] The first indication that Ganymede has its own magnetosphere came from the detection of radio emissions as the Galileo spacecraft approached Ganymede [Gurnett *et al.*, 1996]. The presence of Ganymede's global magnetic field was verified by the Galileo magnetometer data during close flybys of the moon [Kivelson *et al.*, 2002] and its strength and the location of open versus closed field lines were determined from observations of the energetic particles [Williams *et al.*, 1998]. Spherical harmonic extrapolations of the magnetometer observations demonstrated the presence of both an intrinsic and an induced magnetic field, possibly corresponding to a conductive subsurface ocean [Kivelson *et al.*, 2002].

[3] The Jovian magnetosphere drives Ganymede's magnetosphere and both atmospheric oxygen airglow and aurora have been detected at Ganymede using data from Hubble High Resolution Spectrograph [Hall *et al.*, 1998]. The non-uniform spatial emissions on the trailing side (i.e., the side of Ganymede facing into the flow of incident Jovian plasma) were observed by Space Telescope Imaging

Spectrograph (STIS) to have aurora confined at high latitudes [Feldman *et al.*, 2000]. The aurora appear at latitudes  $>|40|^\circ$  over the north and south polar regions corresponding to the predicted location of the separatrix [Neubauer, 1998] and are produced by dissociative electron impact excitation of O<sub>2</sub>. A hydrogen exosphere extending out to 2 Ganymede radii ( $R_G$ ) was also detected in the Feldman *et al.* study, though the dominant component in the near surface atmosphere is believed to be O<sub>2</sub> [cf. Eviatar *et al.*, 2001a]. Ganymede's auroral footprint on Jupiter produced emissions of tens of kilorayleighs in brightness [Clarke *et al.*, 2002]. This indicates a strong interaction between Ganymede's magnetosphere and the Jovian magnetosphere which causes the energization of ions and electrons along connected field lines and the precipitation of particles down to Jupiter's atmosphere.

[4] To fully understand the magnetic signatures of Ganymede and its plasma environment, an understanding of Ganymede's ionospheric density and composition are required. Frank *et al.* [1997] indicated that during Galileo's traversal of Ganymede's polar regions there was a strong outflow of H<sup>+</sup> ions corresponding to  $3 \times 10^9$  gm/yr or about  $10^{26}$  protons/s. Vasylunas and Eviatar [2000] suggested that these ions are actually O<sup>+</sup> ions moving out at a quarter of the 50 km/s velocity reported by Frank *et al.* [1997] and at four times the number density. Eviatar *et al.* [2001b] suggests that the polar ionosphere should be entirely O<sub>2</sub><sup>+</sup> and that the equatorial ionosphere should be O<sup>+</sup>, with H<sup>+</sup> absent from all regions. However, this prediction contradicts the observation of a hydrogen exosphere [Feldman *et al.*, 2000].

[5] This study looks to further our understanding of how Ganymede's magnetosphere interacts with the Jovian magnetosphere through the use of multi-fluid simulations that include the interactions of different ion species. Resistive MHD simulations [Kopp and Ip, 2002] and models incorporating the effects of external field sources [Stone and Armstrong, 2001] have been performed, however this is the first time such a novel approach to modeling will be used to resolve the heating and interaction of different ion species and sources with Ganymede's magnetosphere. The multi-fluid approach is particularly useful because it incorporates particle drift motions which become noticeable and important in the weak-field limit where ion cyclotron radii are no longer small; Ganymede represents such a limit, with cyclotron radii ranging from hundreds to thousands of kilometers [Neubauer, 1998].

[6] The simulation will be benchmarked against Galileo magnetometer results for the G28 flyby to ensure agreement between the model and directly comparable measurements. We will also compare the rate of ionospheric outflow generated in the simulation with rates of surface sputtering calculated by Paranicas *et al.* [1999] and Ip *et al.* [1997].

Qualitative comparisons will then be made to the HST (Hubble Space Telescope) observations of the trailing side aurora [Feldman *et al.*, 2000] in an attempt to understand how and where the plasma is accelerated to keV energies and allowed to precipitate to Ganymede's atmosphere. Finally the overall population of Ganymede's magnetosphere by its ionospheric  $H^+$  and  $O^+$  and the Jovian magnetospheric plasma (JMP) will be shown, illustrating the importance of using multi-fluid simulations and accounting for heavy versus light ion interaction in such a weak field environment.

## 2. Methods

[7] The simulations presented here use the same numerical algorithm as Winglee [2004] used for modeling multi-fluid ( $H^+/O^+$ ) interactions in the terrestrial magnetosphere. The 3D simulations incorporate a nested grid scheme, which allows the highest resolution in areas of important boundary layers while the coarsest resolution is 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).

[8] The innermost box has a resolution of 1 Ganymede radii ( $R_G$ ) or about 263 km, and extends from  $-3$  to  $6 R_G$  in  $x$ ,  $-3$  to  $3 R_G$  in  $y$  and  $-3$  to  $3 R_G$  in  $z$ . Each consecutive box in the simulation increases in size and grid spacing by a factor of two out to five boxes, leaving the largest simulation volume dimensions  $144 R_G$  in  $x$  and  $96 R_G$  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 Courant condition is based on the highest resolution box.

[9] There are both inner and outer boundary conditions to consider in this simulation. The outer boundary conditions enable the motion of the JMP from the corotational magnetosphere into the simulation volume along the left hand boundary. The inner boundary lies along the base of the ionosphere, which is held constant on the assumption of a constant source of ionospheric and exospheric material from surface sputtering [Ip *et al.*, 1997; Paranicas *et al.*, 1999; Cooper *et al.*, 2001]. Plasma incident on this boundary is lost to the simulation since we do not incorporate the chemical effects associated with generation of aurora or surface sputtering.

[10] The speed, average composition and density of the JMP at Ganymede's orbital location were compiled by Neubauer [1998] from measurements made by both the Voyager 1 and Galileo spacecrafts. In keeping with this, we chose the JMP to have a flow velocity of 180 km/s and a bulk density of  $30 \text{ amu/cm}^3$ , generating an incident flow with sonic and Alfvén Mach numbers of 1.8 and .41 respectively. Though using the multi-fluid method enables us to track individual ion species in the simulation, we chose as a first approximation to represent the bulk density of the JMP as light ions since the exact composition of the bulk flow at Ganymede is not known due to the inherent difficulties in interpreting the data [cf. Frank *et al.*, 1997; Vasylunas and Eviatar, 2000].

[11] Ganymede's ionosphere was also difficult to parameterize due to the contradictory interpretations of observations on Galileo. However, with the additional information garnered from the Hubble observations described above, we chose to use ionospheric densities of  $O^+$  suggested by Eviatar *et al.* [2001b] and Vasylunas and Eviatar [2000] but incorporate a 2:1  $H^+$  to  $O^+$  ratio corresponding to the sputtering of water ice as the source mechanism [Paranicas *et al.*, 1999] as well as the observed hydrogen exosphere [Feldman *et al.*, 2000]. The base of the ionosphere was given a density of  $\sim 2000 H^+$  ions/cm<sup>3</sup> and  $\sim 1000 O^+$  ions/cm<sup>3</sup> with a scale height of 263 km and temperatures of 9.0 to 0.1 eV for the equatorial to polar regions. The resistivity,  $\eta$ , was set to be  $1.2 \times 10^{-4}$  ohm-meters at the ionosphere and zero everywhere else in the simulation.

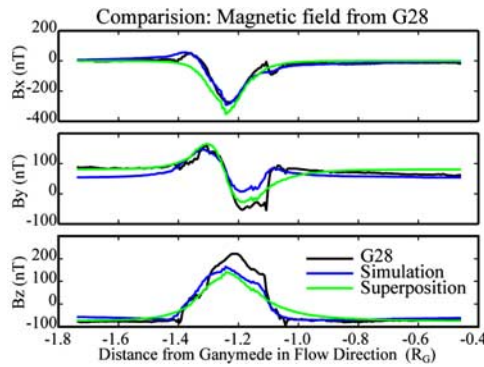
[12] The orientation and strength of the field was determined from Galileo magnetometer data for the G28 flyby before the influence of Ganymede's magnetic field was detected, where  $B_y \sim 78$ ,  $B_z \sim -76$  nT and  $B_x$  was comparatively small and therefore set to zero [Kivelson *et al.*, 2002]. The magnetic field of Ganymede was set as a dipole of 740 nT at the equatorial surface, approximately the strength of the intrinsic non-variable component of Ganymede's field determined by Kivelson *et al.* [2002].

## 3. Results

[13] Benchmarking the simulation for the Ganymede system was performed through comparison with the Galileo magnetometer data from the G28 flyby. The time dependent magnetic field is a function of the electric fields generated by motion of the plasma, coupling of the currents to the magnetic field, electron pressure gradients, and currents flowing in the ionosphere [Winglee, 2004]. We compare the Galileo magnetometer data from the G28 flyby to both the static superposition of the assumed dipole and Jovian field as well as the multi-fluid simulation results. The satellites trajectory is mapped through both the 3D superposition and 3D simulation, which are at the same resolution for consistency. The comparison of the  $x$ ,  $y$  and  $z$  components of the magnetic field are show in Figure 1. The variation in the incident Jovian magnetic field, observable as the decrease in  $B_y$  strength from the far left to the far right in Figure 1, was not taken into account in our simulation. This causes the discrepancy in the  $B_y$  comparison to the left of where the spacecraft encountered Ganymede's magnetosphere.

[14] Both the superposition and the dynamic case show reasonable agreement with the magnitude of the magnetic field measurements, which is expected since the magnetic field strengths used in the study were extrapolated from spherical harmonic reduction of the flyby data [Kivelson *et al.*, 2002]. However, more of the observed structure is obtained in the dynamic case. For example, the sharp boundaries observed by the spacecraft when crossing into and out of Ganymede's magnetosphere are accommodated in the dynamic case as the inflowing plasma compresses the magnetosphere and generates a bow wave. In contrast, the static superposition yields gradual and unrealistic transitions between the flow and inside the magnetosphere.

[15] Another way of benchmarking the simulation was to compare the amount of ionospheric loss generated in the simulation to the sputtering rate determined from observa-

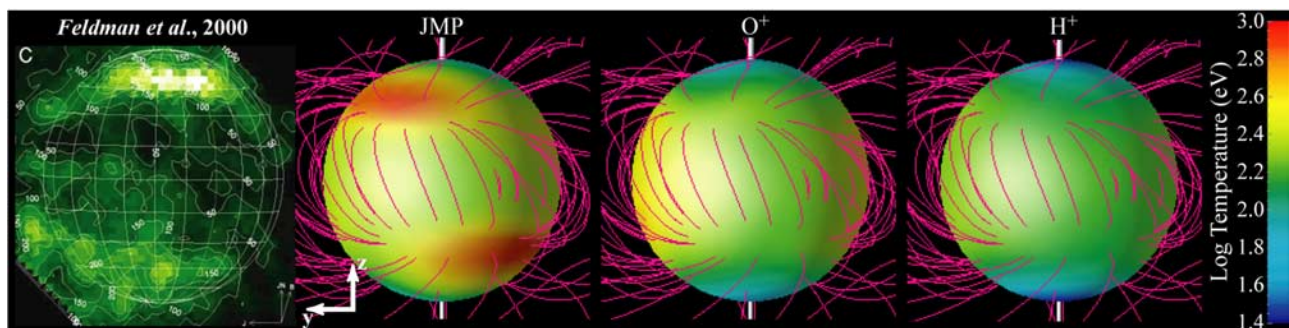


**Figure 1.** The 3 components of the magnetic field measured by Galileo's magnetometer (black) are compared to a static superposition of Ganymede's dipole field with the incident field from Jupiter (green) and our dynamic multi-fluid simulation (blue). The distance from Ganymede is in the flow direction (the x-direction in GPHIO coordinates).

tions made by experiments on Galileo. Since sputtering of surface ice is the main source for Ganymede's tenuous atmosphere, it is important to demonstrate agreement between source rates and the loss rates produced in our simulation. *Paranicas et al.* [1999] determined a sputtering rate should be  $\sim 2 \times 10^{26}$  water molecules/s in agreement with calculations by *Ip et al.* [1997]. The multi-fluid simulations are in good agreement with the sputtering rate, demonstrating stable ionospheric loss rates of  $\sim 4 \times 10^{26}$   $H^+$  ions/s and  $\sim 1 \times 10^{26}$   $O^+$  ions/s. These rates are calculated on the tail side of Ganymede at  $\sim 24 R_G$  so that ion fluxes trapped or returning to the surface are not counted. The flux calculations occur at instants in time, which cannot fully illustrate the loss due to quasi-periodic reconnection events driven in the magnetotail. An increase in the flux of  $O^+$  ions is seen in our simulations during these events, with the above numbers representing a nominal loss flux. JMP lost to Ganymede was also calculated for the simulation, with  $\sim 1.5 \times 10^{27}$  amu/s passing into the ionosphere. This bulk flux into Ganymede is important for it indicates that higher energy ions and electrons which drive processes like sputtering, excitation of aurora and airglow will also gain access.

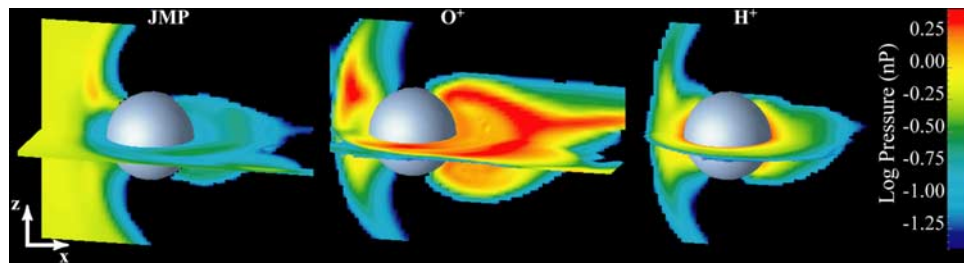
[16] Note that fluid simulations only directly model the bulk or average properties of the plasma with protons obtaining a few keV bulk energies and heavy ions a few  $10^2$ 's of keV. The location and strength of the JMP population penetrating through the ionosphere should correspond to plasma precipitation events. Figure 2 illustrates the temperature (in log eV) for each of the ion species mapped at the altitude of the ionosphere on the trailing hemisphere of Ganymede compared to the *Feldman et al.* [2000] auroral observations. The incident JMP not only has access down through the ionosphere in some flow side regions, it also experiences heating to the keV range associated with flow side reconnection. The access area corresponds to the location of Ganymede's cusps, also visible in Figure 2, which are significantly larger relative to the size of the satellite than those at the Earth or Jupiter. This is due to comparable strengths of the incident Jovian magnetic field and Ganymede's surface field as well as the shock free sub-Alfvénic interaction. The cusps occur at high latitudes and have significant latitudinal and longitudinal extent. Their exact location is dependant on the orientation of the incident Jovian magnetic field. Though the JMP is heated through magnetic reconnection and permitted to penetrate down through the cusps, relatively little heating was observed in either of the ionospheric plasma species on the flow side of Ganymede, and both the  $O^+$  and  $H^+$  appear warmer in the closed field line region than in the open ones.

[17] The HST aurora observations [*Feldman et al.*, 2000] allow for a qualitative comparison between remote measurements and the simulation, shown in Figure 2. While the orientation of the Jovian magnetic field in the simulation was not consistent with that in the observation, due to choosing the G28 flyby orientation for the quantitative magnetometer comparison, the simulation produces key characteristics in agreement with those observed with HST. Namely, the longitudinal variability and a lack of limb brightening over the poles indicated by *Feldman et al.* [2000] are present in the simulation. While it was originally thought that both polar caps would be completely illuminated by aurora due to open field lines allowing direct access of JMP, Ganymede's magnetospheric behavior restricts the region of acceleration and access for precipitation. Changing the orientation of the incident Jovian magnetic field in the simulation within the range provided by the tilt of the magnetic axis with respect to the spin axis of



**Figure 2.** An HST observation of Ganymede's UV aurora [*Feldman et al.*, 2000] (left hand-side, reprinted with permission) compared to the temperature of each ion species for the trailing hemisphere of Ganymede; magnetic field line configuration is included to demonstrate the shape of the magnetosphere and location and size of the cusps.





**Figure 3.** A side view ( $y$ -look-direction in GPHIO) of the pressure of each ion species. The sphere is representative of the surface of Ganymede, and the colored slabs are located in the  $x$ - $z$  plane and the  $x$ - $y$  plane. Notice little JMP penetrates into the magnetosphere except for what is lost through the cusps. Any parts of the slabs in black indicate negligible pressure.

Jupiter, allows the location of the cusps to move, possibly providing for the observed variability in longitude between observations [Feldman *et al.*, 2000].

[18] The multi-fluid treatment allows us to examine the bulk properties of each plasma species in populating and controlling the dynamics of Ganymede's entire magnetosphere. Figure 3 demonstrates the pressure of each ion species in Ganymede's magnetosphere. While the JMP has access to the ionosphere via the cusps, it has very little access to Ganymede's magnetosphere except for a small population of highly energetic ions that can directly penetrate the magnetosphere due to very large gyroradii. The strong influence the heavy ionospheric  $O^+$  has on the entire magnetosphere is quite visible. The  $O^+$  comprises most of the plasma present in Ganymede's magnetotail as well as providing an energetic population for the inner magnetosphere. The ionospheric  $H^+$  significantly populates the inner magnetosphere, accounting for 75–85% of the ion number density, but is not energetic and has little influence on the magnetotail.

#### 4. Conclusions

[19] Ganymede's weak field environment coupled with the population of heavy ions necessitates the use of multi-fluid simulations. The multi-fluid treatment enables us to track the motion and energization of several ion species, and incorporates the drift motion of these ions which plays an important role in generating currents and electric fields that govern the structure of Ganymede's magnetosphere and the characteristics of the bulk plasma environment. We have demonstrated the validity of the simulation by comparing it to observed and extrapolated quantities such as magnetic field strength, sputtering rates and location of aurora. Both the strength and the structure of Ganymede's magnetosphere measured by the Galileo spacecraft's magnetometer were captured in the multi-fluid simulation. The surface sputtering rates calculated from Galileo observations were in agreement with the ionospheric loss rates predicted in our simulations at approximately  $10^{26}$  ions/s. Finally, the location of ion, and therefore electron, precipitation in the simulations was found to be coincident with the observed location of Ganymede's ultraviolet aurora by the HST.

[20] The trailing hemisphere aurora appears to be associated with reconnection of the incident Jovian magnetosphere with Ganymede's magnetosphere, which causes acceleration of the incident JMP. This energetic population has access to Ganymede's ionosphere through the enhanced

cusps, which are a result of Ganymede's magnetic field and Jupiter's incident magnetosphere having similar strength and opposite alignment. The protons pulled from Ganymede's ionosphere are shown to populate the inner magnetosphere, but have relatively low energy. Ganymede's heavy ionospheric population ( $O^+$ ) plays a major role in governing the size and shape of the magnetotail, and possesses the most energy of the three bulk ion species modeled in Ganymede's magnetosphere. It is clear from these preliminary results that the coupled Jupiter-Ganymede interaction is significantly complex and requires even more rigorous treatment to fully appreciate the importance of surface processing and possible conductive subsurface layers of Ganymede. A diverse ion population in the incident JMP needs to be considered to account for differences in how incident heavy ion species will interact with Ganymede's magnetosphere and sputter the surface.

[21] **Acknowledgments.** This research was supported by NASA grant NAG5-11869 and NSF grant ATM 0105032 to the University of Washington. A special thanks to P. Feldman.

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