Ion energization in Ganymede's magnetosphere: Using multifluid simulations to interpret ion energy spectrograms

C. Paty,[1] W. Paterson,[2] and R. Winglee[3]

[1]   We investigate the ion population and energy distribution within Ganymede's magnetosphere by examining Ganymede's ionospheric outflow as a source of heavy (O^+) and light (H^+) ions and the Jovian magnetospheric plasma as an external source of heavy ions. We develop a method for examining the energy distributions of each ion species in a three-dimensional multifluid simulation in a way directly comparable to the observations of the Plasma Experiment on the Galileo spacecraft. This is used to provide new insight to the existing controversy over the composition of Ganymede's observed ionospheric outflow, and enables further examination of the energetic signatures of the ion population trapped within Ganymede's magnetosphere. The model-predicted ionospheric outflow is consistent with the in situ ion energy spectrograms observed by the Galileo Plasma Experiment at closest approach, and requires that both ionospheric H^+ and O^+ are present in the population of ions exiting Ganymede's ionosphere over the polar cap. The outward flux of ionospheric ions was calculated to be ~10^{26} ions/cm^2/s, which is in agreement with independently calculated sputtering rates of Ganymede's icy surface. The modeled spectrograms define characteristic energy signatures and populations for various regions of Ganymede's magnetosphere, which illustrate the major sources of ions trapped within the magnetosphere are Ganymede's ionospheric O^+ and H^+. The fact that very little plasma was observed inside Ganymede's magnetosphere during the G8 flyby is attributed to the region being shadowed from the sun for ~60 h, which may indicate the importance of photoionization for sustaining Ganymede's ionospheric plasma source.

1.   Introduction

[2]   In order to understand the plasma population and energy distribution in Ganymede's magnetosphere it is important and necessary to account for the various sources of plasma into the system. Previously, researchers have used resistive magnetohydrodynamic (MHD) simulations to study Ganymede's magnetosphere [*Stone and Armstrong*, 2001; *Kopp and Ip*, 2002; *Ip and Kopp*, 2002]. However, those studies focused on the effects of variations in the incident Jovian magnetic field orientation on Ganymede's magnetic morphology and did not incorporate the various ion sources responsible for the observed plasma dynamic perturbations to the magnetic field [cf. *Kivelson et al.*, 1998]. Multifluid simulations enable us to track multiple ion species from different sources as they propagate through the simulation space and interact with electric and magnetic fields. Comparative studies between 3D multifluid simulations and Galileo magnetometer data were performed in order to develop a quantitative model of the currents and fields within Ganymede's magnetosphere [*Paty and Winglee*, 2004, 2006]. The multifluid model demonstrated good agreement with the Galileo magnetometer observations of the strength and structure of Ganymede's magnetosphere for each of the six flybys.

[3]   The plasma population of Ganymede's near space environment has been a source of much debate. The Plasma Experiment on the Galileo spacecraft was designed to observe the low energy plasma population, ranging from as low as ~1 eV up to ~50 keV; a complimentary and slightly overlapping range when compared to the Energetic Particle Detector (EPD). It had the capacity to measure the temperature, density and bulk motion of the low energy ions and electrons. The Plasma Experiment not only characterized the low energy plasma of the Jovian magnetosphere, but was pivotal in observing the polar ionospheric outflow at Ganymede [*Frank et al.*, 1997]. However, the composition of the outflowing ion population can not be directly or uniquely inferred from the observed ion energy spectrograms. *Frank et al.* [1997] interpreted the cold population of ions flowing out of the polar cap as H^+. *Vasyliunas and Eviatar* [2000] developed a different interpretation where they determined the composition of the cold outflow could

[1]Space Science and Engineering Division, Southwest Research Institute, San Antonio, Texas, USA.
[2]Center for Atmospheric Sciences, Hampton University, Hampton, Virginia, USA.
[3]Department of Earth and Space Sciences, University of Washington, Seattle, Washington, USA.

Table 1. Upstream Magnetic Field Observations Near Ganymede

Flyby	Bx, nT	By, nT	Bz, nT	M_{VA}	M_{VS}	Location Relative to Plasma Sheet
G2	17.0	−72.9	−84.7	0.50	1.8	above
G7	−3.00	83.7	−75.6	0.50	1.8	below
G8	−11.0	11.0	−77.6	1.00	1.8	inside

be O^+. An O^+ outflow was somewhat more consistent with the atmospheric models of *Eviatar et al.* [2001] but did not explain the observed Lyman alpha airglow emissions indicating a hydrogen exosphere [*Barth et al.*, 1997].

[4] This study looks to further our understanding of how Ganymede's magnetosphere interacts with the Jovian magnetosphere through the use of multifluid simulations which can describe and account for the Galileo Plasma Experiment observations. Three dimensional multifluid simulations of Ganymede's magnetosphere were performed, and a method for direct comparison between the modeled ion energy environment and the ion energy distributions observed by the Galileo spacecraft was developed. Ion species sourced from the Jovian magnetosphere and from Ganymede's ionosphere were tracked in order to calculate their fluxes into and out of the system and to determine their relative importance to the composition and energy budget of Ganymede's magnetosphere. This enabled further interpretation of the observed ion energy spectrograms and gave new insight to the ionospheric outflow debate.

2. Methods

2.1. The Multifluid Model and Boundary Conditions

[5] A 3D multifluid model was used to examine the magneto-plasma interactions of Jupiter and Ganymede's magnetospheres local to Ganymede. Multifluid simulations explicitly track the various ion species, which enables examination of differential heating and acceleration of each ion species. They also allow us to determine which ion sources make up the population of a given region of the simulation. The multifluid treatment, explained at length for the context of Ganymede magnetospheric simulations by *Paty and Winglee* [2006], keeps track of the different ion species as separate fluids for which the ion gyromotion is not averaged out. This model uses a high resolution nested grid, which makes it possible to resolve the acceleration and drift motion associated with the ion gyromotion. The innermost box has a resolution of 0.45 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. A Cartesian coordinate system is used, where x is defined to be 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). A detailed comparison of the multifluid model to hybrid simulations found that the ion drift motion due to explicitly modeled gyromotion in the hybrid case was comparable to the ion drift motion in the multifluid treatment [*Harnett et al.*, 2005].

[6] The ions that populate Ganymede's magnetosphere come from two sources: the incident Jovian magnetospheric

plasma (JMP) and Ganymede's ionosphere. The boundary conditions used in the model for these parameters are described in detail by *Paty and Winglee* [2006]. In brief, the JMP is composed of plasma from the Io plasma torus, Jupiter's ionosphere, and to a much lesser extent the solar wind. We chose to model the major constituents of the JMP (mostly O^+ and a few percent H^+) as determined by upstream observations [*Frank et al.*, 1997; *Neubauer*, 1998]. The Jovian magnetic field strength and orientation and the JMP Mach numbers for the three flyby encounters (G2, G7, and G8) studied in the paper were determined from unperturbed spacecraft observations before and after the encounter [*Neubauer*, 1998; *Kivelson et al.*, 2002] and are listed in Table 1.

[7] Ganymede's ionosphere base was set with a density of 5200 ions/cm^3, with a 4:1 ratio of O^+ to H^+ ions, and a scale height of 125 km based on the chemical models of *Eviatar et al.* [2001], sputtering rates of *Ip et al.* [1997] and *Paranicas et al.* [1999], and sputtering products of *Herring-Captain et al.* [2005]. The ionospheric ions at the inner boundary were prescribed temperatures that ranged smoothly from 6.0 to 0.1 eV for the equatorial to polar regions, respectively. The ionospheric density at the inner boundary was held constant on the assumption of a constant source of ionospheric material [*Ip et al.*, 1997; *Paranicas et al.*, 1999], and the base of the ionosphere was given a resistivity of 3800 Ωm to account for collisions. Everywhere else in the simulation the resistivity was set to zero, corresponding to the collisionless plasma environment at Ganymede. In this model we use three ion fluids: the ionospheric O^+, which is tracked separately from the JMP O^+, and an H^+ fluid that combines the ionospheric H^+ and the few percent JMP H^+. The H^+ fluid will be referred to as ionospheric H^+ for simplicity as it only represents a few percent of the JMP.

2.2. Generating Synthetic Ion Energy Spectrograms

[8] In order to determine the energy distributions for each ion species in the simulation for this comparison, the density, temperature, and velocity for each ion species was sampled along the coordinates of a given Galileo flyby. Assuming a Maxwellian distribution for the ions, a probability distribution was determined over an energy (E) range of 10 eV to 10^5 eV (100 keV) to correspond to the sensitivity range of the Plasma Experiment such that

$$\mathcal{P}_i(E, x) = \frac{e^{-\left((V(E,m_i) - V_i(x))^2 / \left(2 V_{Ti}(x)^2\right)\right)}}{V_{Ti}(x)^3 (2\pi)^{3/2}}. \tag{1}$$

Here x corresponds to positions along the spacecraft trajectory, V_{Ti} is the ion thermal velocity at each location (x) along the trajectory, and V_i is the magnitude of the ion velocity at each location. V is the velocity that corresponds to the energy in the range being integrated over and the mass of each ion species (m_i) such that

$$V(E, m_i) = \sqrt{\frac{2E}{m_i}}. \tag{2}$$

To obtain the flux of particles per electron volt (N_i), which is in units of ions/s/eV/cm^2, the probability distribution was multiplied by the number density for each ion and the

square of the velocity V, and divided by the ion mass. This expression

$$
\begin{aligned}
N_i(E, x) &= \frac{n_i(x)V(E, m_i)^2}{m_i} \times \mathscr{P}_i(E, x) \\
&= \frac{1}{(2\pi)^{3/2}} \frac{1}{m_i V_{Ti}(x)^2} \frac{n_i(x)V(E, m_i)^2}{V_{Ti}(x)} \\
&\quad \cdot e^{-\left((V(E,m_i)-V_i(x))^2 / \left(2V_{Ti}(x)^2\right)\right)}
\end{aligned}
\tag{3}
$$

can then be summed over all the ion species to obtain an energy spectrogram that is directly comparable to the observation of the Galileo Plasma Experiment, or it can be plotted separately to examine the contribution of each ion species to the net energy distribution.

3. Results

3.1. Tracking Ion Sources

[9] In tracking the motion of these ion species as the system evolves toward steady state, the model demonstrated that Ganymede's magnetic field provides shielding from most of the bulk flow of the JMP. This leads to Ganymede's magnetosphere being primarily populated by Ganymede's ionospheric constituents. Figure 1 details the density distribution for each of the three modeled ion species throughout the system. In Figure 1 the first row illustrates the morphology of the magnetic field at Ganymede as it encounters the Jovian plasma in Jupiter's magnetospheric lobe as well as the density of each of the three modeled ion species in the x-z and x-y planes. Note that the color bar is consistent for all of the plots. At equatorial latitudes the bulk flow of the JMP is almost completely excluded from Ganymede's magnetosphere. Some of the bulk flow of the JMP on the flow facing side can gain access to Ganymede's ionosphere and surface through the cusps [*Paty and Winglee*, 2004]. Ganymede's ionospheric H$^+$ and O$^+$ dominate the composition of Ganymede's magnetosphere, though the ionospheric O$^+$ is higher in density than the ionospheric H$^+$. Note that this O$^+$ dominance is a reflection of the 4:1 ratio of O$^+$ to H$^+$ at the ionospheric boundary.

[10] The second row in Figure 1 shows the ion density for each species, as well as the flow velocities projected in the x-z plane. The arrows show the direction of the flow and the size of the arrows scale relative to the magnitude of the velocity for each species. The deflection of the JMP in the upstream region where it approaches Ganymede's magnetopause is clearly illustrated. The convection of JMP over the poles and down tail can be seen along with the flow of the ionospheric H$^+$ and O$^+$ ions out of the poles being convected down tail. As the magnetic fields in the tail reconnect, the ion flow is redirected along closed field lines back toward Ganymede. It is through this process that the JMP gains access to Ganymede's magnetotail and a fraction of the polar ionospheric outflow of O$^+$ and H$^+$ ions is trapped into populating Ganymede's magnetosphere. The H$^+$ ion velocities track closely with the boundary between open and closed field lines leading to the tail reconnection region, while the heavy species flow down-tail and are redirected near the equatorial plane. This phenomenon was also noted by *Shay and Swisdak* [2004] when modeling the effects of the presence of heavy ions on reconnection.

[11] In row three the view is shifted to look down upon the equatorial plane and show the density and flow for each modeled ion species. Again the deflection of the upstream JMP is noticeable as the vectors indicate the motion of the flow around Ganymede's magnetosphere. Ganymede's flow facing magnetosphere shields out the bulk JMP flow in the equatorial plane. In the magnetotail region the JMP gains access through reconnection and the flow of JMP appears quite asymmetric. Down-tail flows of JMP on the anti-Jupiter flank of the magnetotail are shown directly next to distinct inward moving flows. The inward transport of JMP tapers in magnitude as you move across the magnetotail in the y-direction as well as in the negative x direction where the JMP stops short of convecting completely into the inner magnetosphere from down-tail. Asymmetries in the equatorial magnetotail are visible in the ionospheric H$^+$ and O$^+$ as well, and are due to the ion cyclotron motion and finite Larmor radius effects. The mass difference between the ionospheric H$^+$ and O$^+$ makes the O$^+$ Larmor radius a factor of 16 larger than that of H$^+$, and is responsible for the differences in flow and density asymmetries in the equatorial flow figures. For example, the heavy ionospheric ions in the tail are deflected in the negative y-direction, an effect quite noticeable in the O$^+$ but not significant in the H$^+$ ionospheric ions. Such flow and density asymmetries between heavy and light ions have been shown in hybrid models for other moons [*Simon et al.*, 2007] but would not be present in an ideal MHD model where the ion cyclotron motion is averaged out and the ions and electrons are collapsed into a single fluid.

3.2. Interpreting Ionospheric Outflow

[12] In order to better understand the flow of ionospheric ions away from Ganymede, the net flux of each ion species was determined. The flux of the ionospheric H$^+$ and O$^+$ ions was calculated at a distance of 24 R$_G$ in order to determine the amount of ionospheric ions lost from the system and picked up by the Jovian magnetosphere. This ensured that the flux was determined further down the magnetotail than the location of reconnection (which occurs at ~7 R$_G$, ± 2 R$_G$ as upstream conditions vary), and that the ions flowing out of the system would not become trapped on newly closed field lines and be redirected back toward Ganymede. At 24 R$_G$ it was calculated that Ganymede was losing on average 4×10^{26} ions/s of ionospheric O$^+$ and 1×10^{26} ions/s of ionospheric H$^+$. The 4:1 ratio in the fluxes of O$^+$ and H$^+$ being directly linked to the choice of the ionospheric composition at the inner boundary.

[13] The flux of ionospheric H$^+$ and O$^+$ was also determined near the surface of Ganymede, at a distance of 3 R$_G$. The factor of ~4 difference between the rate of O$^+$ and H$^+$ ions flowing out of Ganymede's ionosphere was still present, however some of the outflow at this distance would become trapped in Ganymede's magnetosphere. The difference in outflow rates is evident when examining the ion population of Ganymede's magnetosphere in the first row of Figure 1. Here the ionospheric O$^+$ density is shown to be the dominant species in Ganymede's magnetosphere by a factor of 2 to 8, with the highest density ratios occurring along closed field lines. Since the ionospheric outflow supplies Ganymede's magnetosphere with plasma, the difference in
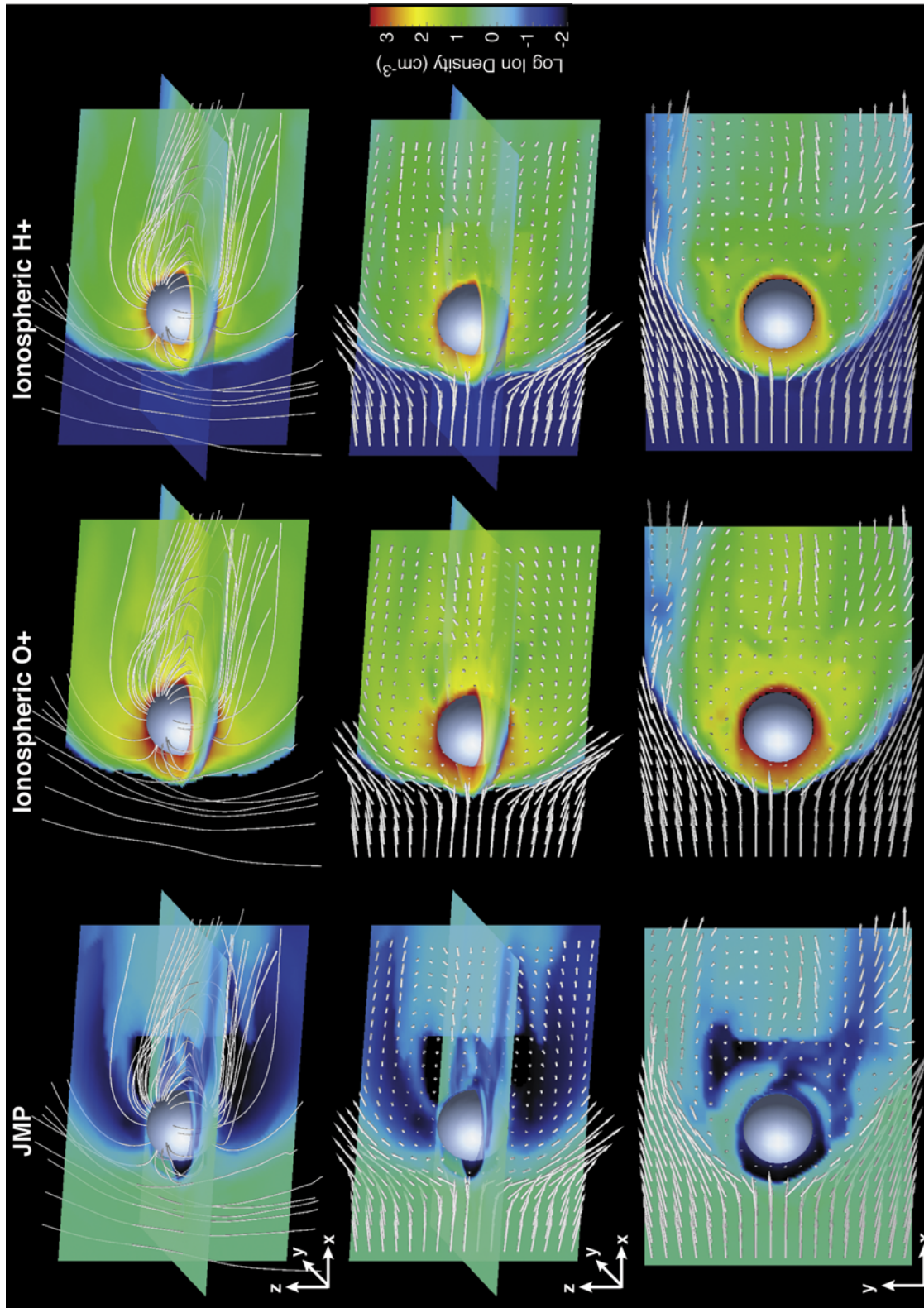
Figure 1. The field morphology, ion density and flow patterns for each ion species are shown for the verticle (x-z) and equatorial (x-y) planes. Axis are labeled in GPHIO coordinates.
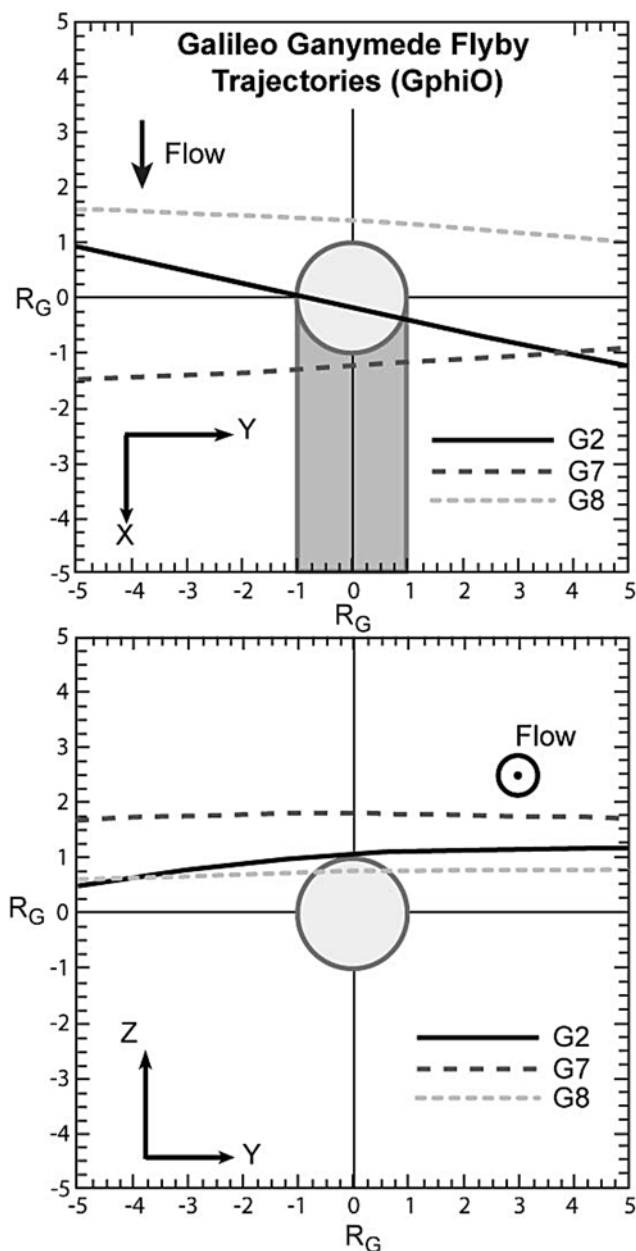
Figure 2. The spatial distribution of three of Galileo's flybys of Ganymede: G2, G7, and G8.

the outflow rates of O^+ and H^+ is represented in the ion density distribution.

[14] While the net ionospheric loss was calculated to be on average 1×10^{26} and 4×10^{26} ions/s of H^+ and O^+ ions respectively, these values were variable depending on the location of Ganymede with respect to the Jovian plasma sheet. In the Jovian plasma sheet, where the magnetic field strength is weaker, we see a drop in the ionospheric outflow by a factor of 2 relative to when Ganymede resides outside the Jovian plasma sheet. The average ionospheric outflow rate from the simulations can be compared to the sputtering rate independently determined from observations made by the Energetic Particle Detector and Plasma Experiment on Galileo. *Paranicas et al.* [1999] determined that the sputter-

ing rate should be $\sim 2 \times 10^{26}$ water molecules/s in agreement with calculations by *Ip et al.* [1997]. Hence the multifluid simulations produce ionospheric outflows that are consistent with the sputtering rate assumed to supply the base of the ionosphere in the model.

[15] JMP ions lost to Ganymede were also calculated for the simulation, with $\sim 2 \times 10^{26}$ ions/s passing into the ionosphere. This value varies by nearly an order of magnitude depending on where Ganymede is located relative to the Jovian plasma sheet, with fluxes as small as 5×10^{25} in the lobe. The JMP density is higher and its gyroradius larger in the Jovian plasma sheet relative to in the lobes; these characteristics are responsible for the higher fluxes of JMP to Ganymede's surface while its orbit resides in the plasma sheet. This bulk flux into Ganymede is important for it drives processes like sputtering, excitation of aurora and airglow. We do not expect this number to be exactly balanced by the net ionospheric loss rate, since not all sputtering products are lost or even populate the ionosphere. A fraction of sputtering related products recombines and precipitates back to the surface as a water frost layer. In addition, processes like sputtering and aurora can be driven by electron precipitation and the precipitation of the energetic tails of the ion distributions not incorporated in the above flux calculation. Keep in mind that ions and electrons that pass into the ionosphere are lost to the simulation; the physics and chemistry associated with generating aurora, dissociation, ion-neutral interactions, and surface sputtering are not yet included in the formulation driving the simulation.

3.3. Energy Distribution in Ganymede's Magnetosphere

[16] In this section we will examine 3 of the Ganymede flybys, which represent the three different regions of Ganymede's magnetosphere: the polar cap region (G2), the flowfacing or upstream region (G8) and the magnetotail (G7). Figure 2 shows the trajectories of these three flybys. The simulations keep track of enough information to generate the synthetic spectrograms described in section 2.2; they also enable us to split the full ion spectrogram into its individual ion components. Figure 3 illustrates this; the top panel reproduces the ion spectrogram from the Plasma Experiment during the G2 flyby, beneath it is the synthetic ion spectrogram determined using equation (3) along the G2 trajectory through the simulation. The bottom three panels split the full model produced spectrogram into the individual components corresponding to the JMP, ionospheric H^+ and ionospheric O^+ ions respectively. The y axis plots the log of the energy ranging from 10 eV up to 10^5 eV, and the x axis is the radial distance from Ganymede through the G2 flyby. The color bar is the same for all of the model produced spectrograms, and maps the log of the ion flux per eV (or, ions/s/eV/cm^2).

[17] Starting from the left hand side in Figure 3, the spacecraft is outside of Ganymede's magnetosphere and measures the upstream JMP conditions. The horizontal dotted black lines in the observed spectrogram represent the mean energies for two ion masses determined for the velocity of the Jovian rotational magnetosphere. The top line represents 16 amu O^+ ions, while the bottom line indicates the energy of 1 amu H^+ ions for a given ram velocity of the JMP. These lines are meant as guides for
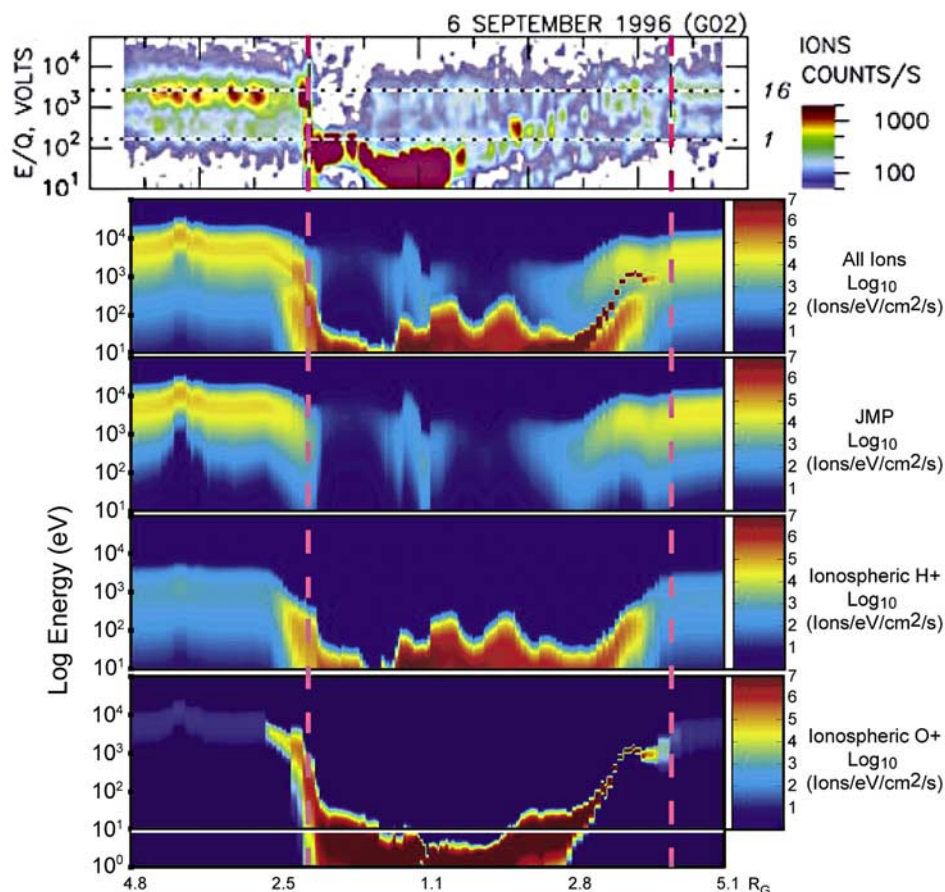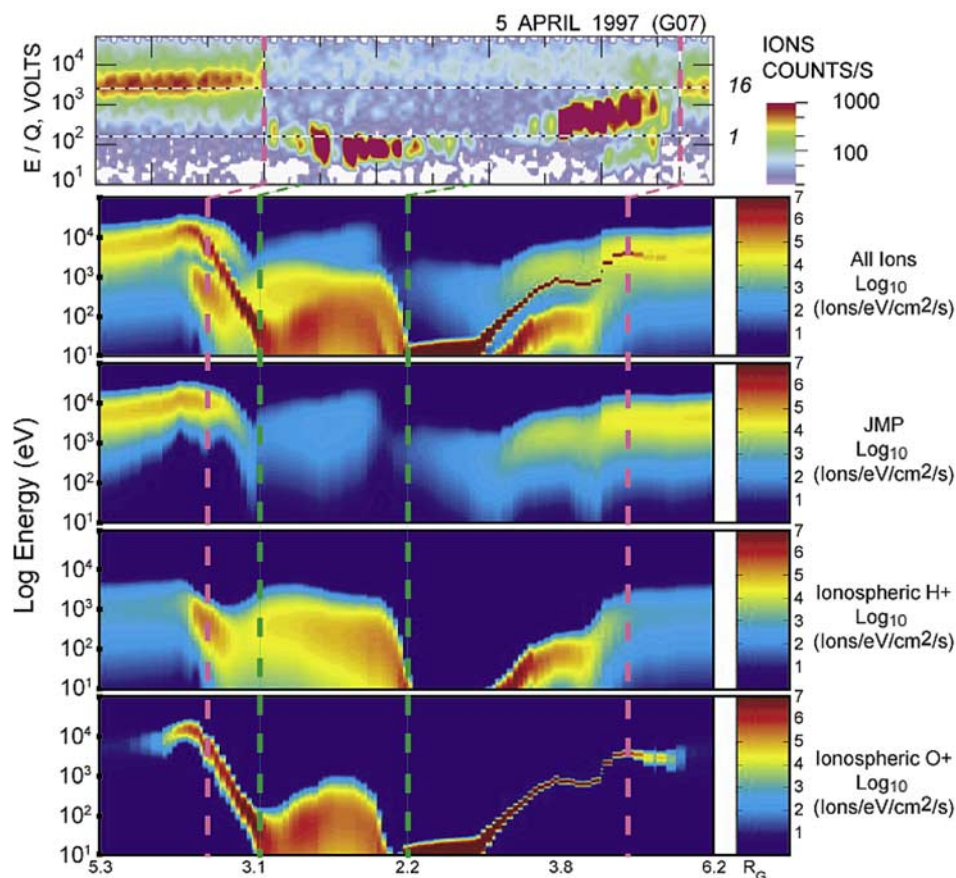
Figure 3.   Comparison between the ion energy spectrogram observed by the Plasma Experiment on the G2 flyby, which flew over the polar cap and was also the closest approach trajectory, and those predicted by the model. The dashed lines indicate observed magnetopause crossing locations, and the white line in the bottom plot indicates the instrument detection threshold.

interpreting the JMP composition and are not applicable when the spacecraft passes into Ganymede's magnetosphere. The vertical magenta lines represent the magnetopause boundary crossings as confirmed by the coincident magnetometer data. The low energy population in the center of the observed spectrogram has contributed to the outflow debate; without also knowing the mass or the velocity of the observed ion outflow, extrapolations to obtain ion composition from the energies in the spectrogram could not be uniquely interpreted [cf. *Frank et al.*, 1997; *Vasyliunas and Eviatar*, 2000]. The following discussion of the model results provides new insights into this controversy.

[18]   The magnetopause crossings in the synthetic spectrograms are well correlated to those observed by the Galileo spacecraft. The upstream population in the synthetic spectrograms is comparable to the observed upstream population, with the peak flux corresponding to energies defined by the modeled rotational flow velocity of the Jovian magnetosphere and the ion mass. The low energy population situated near the closest approach in the modeled spectrogram has the same energy range as the observed ionospheric outflow population. Further examination of the low energy population is performed by probing each of the constituent ion species and their contribution to the ionospheric outflow, shown in Figure 3 in the bottom three plots.

Notice that very little of the JMP is present over Ganymede's polar cap, the low energy population is entirely composed of ions sourced at the ionosphere. The ionospheric H^+ appears to makes up the bulk of the low energy population between 10 and 100 eV, however, most of the ionospheric O^+ is just below the threshold of the instrument's sensitivity (~10 eV). This is show in the bottom plot in Figure 3, where the portion of the ionospheric O^+ spectrogram below the white line represents the modeled O^+ fluxes below the instruments lower energy limit. The simulation tracks the energy range of the ionospheric O^+ over the polar cap to range from 2 to 12 eV depending on the spacecraft altitude. The modeled spectrograms from multifluid simulations provide interesting possibilities for reinterpreting the ionospheric outflow, which address some of the concerns raised by both *Frank et al.* [1997] and *Vasyliunas and Eviatar* [2000].

[19]   Some of the major concerns raised by *Frank et al.*'s [1997] interpretation of the Ganymede's ionospheric outflow were due to the lack of O^+ interpreted to be present in outflow observations [*Vasyliunas and Eviatar*, 2000]. The first concern raised was that the ionization rate required to support the outflow of H^+ was not feasible, and the second dealt with oxygen accumulation at the surface *Vasyliunas and Eviatar* [2000]. The assumption that Ganymede's
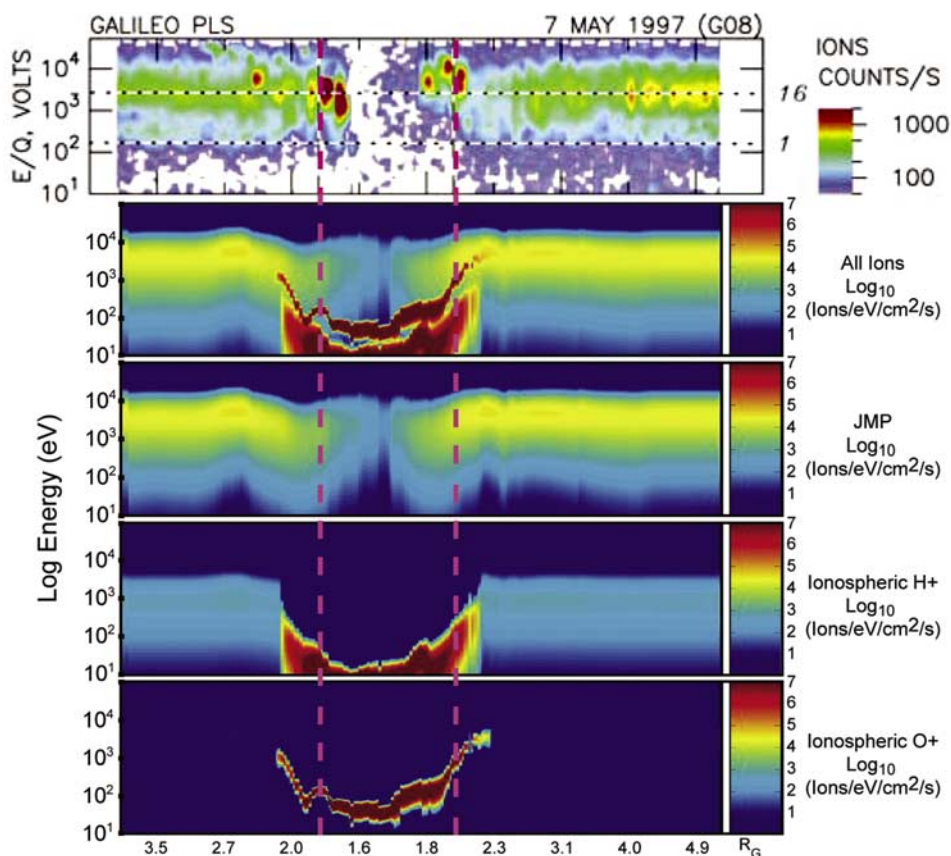
Figure 4. Comparison between the ion energy spectrogram observed by the Plasma Experiment on the G7 flyby, which traversed through the magnetotail at high latitudes, and those predicted by the model. The green dashed lines indicate the model-predicted transitions into the reconnected magnetotail (3.1 R_G) and back out to the open, stretched, tail-ward convected field (2.2 R_G) before the outbound magnetopause crossing.

ionosphere is composed almost entirely of O^+ and O_2^+ ions comes from the hypothesis that sputtering of surface ice and dissociation of water group molecules imparts enough energy on neutral H and H_2 that it escapes before becoming ionized [*Eviatar et al.*, 2001], hence the concern over *Frank et al.*'s [1997] identification of the outflow as H^+. However, recent laboratory studies have demonstrated that surface sputtering may produce more H^+ and H_2^+ than initially thought [*Herring-Captain et al.*, 2005], especially at the low temperatures present on Ganymede's surface. The second concern stated that if the outflow consisted of H^+ ions it would leave behind an accumulation of meters of oxygen on the surface, a feature not found in any surface spectral analysis. *Vasyliunas and Eviatar* [2000] argue that to solve both of these concerns the outflow population should be reinterpreted as a low energy population of O^+, moving at a quarter of the speed noted for the H^+ interpretation. This would keep with the observed energy range of the outflow population, solve the H^+ ionization rate issue and make sure that meters of oxygen were not left accumulating on Ganymede's surface.

[20] However, the idea that O^+ could be flowing out of Ganymede's polar ionosphere at energies just below the threshold of the Plasma Experiment was not considered.

The model predicts that O^+ ions are accelerated to energies of 3 to 12 eV over the polar cap (at G2 flyby altitudes), energies just at or below the detection threshold of the Plasma Experiment. H^+ ions from the ionosphere reach energies of 10 to 100 eV at the same altitudes and under the same model conditions. With this in mind, an alternate interpretation of the Plasma Experiment observation is presented. The ionosphere over Ganymede's polar cap, assumed to be composed of mostly O^+ ions and some H^+ ions, produces an ionospheric outflow of H^+ and lower energy O^+. The number fluxes of these species were calculated in the previous section, and it was determined that their relative abundance in the ionosphere was proportional to their relative outflow rates. While it appears necessary to have a measurable H^+ component in Ganymede's ionosphere to account for the ion energies observed by the Plasma Experiment, the ratio of H^+ relative to O^+ is not well constrained. More research is currently underway to determine to relative abundance of H^+ in Ganymede's ionosphere resultant from direct ionization from energetic particle interactions with the icy surface. However, regardless of the exact composition, the presence of a strong O^+ ionospheric population is generally agreed upon [*Eviatar et al.*, 2001; *Cooper et al.*, 2001] and the outflow of iono-

Figure 5. Comparison between the ion energy spectrogram observed by the Plasma Experiment on the G8 flyby, which was a low latitude flyby that crossed into the flow-facing magnetosphere, and those predicted by the model.

spheric O^+ helps in addressing the issue of oxygen building up on Ganymede's surface. H^+ may be escaping in the observable range of 10 to 100 eV, but O^+ is also obtaining energies corresponding to velocities greater than escape velocity of 2.74 km/s, where $v_{escape} = \sqrt{\frac{2GM_G}{R_G}}$. Hence oxygen is likely not building up on Ganymede's surface; it is escaping at energies just below the detection range of the Plasma Experiment.

[21] Another way to test the accuracy of the modeling is to undertake a comparative study with the data from other flybys. Figure 4 compares the observed ion energies from the G7 (magnetotail) flyby to those derived from the model along the same trajectory, while Figure 5 compares the observations and model predictions from the flow facing magnetosphere flyby (G8) (cf. Figure 2 for flyby locations). It is first evident when comparing the G7 (Figure 4) and G8 (Figure 5) Plasma Experiment observations that the ion energy distributions are significantly different in the magnetotail versus on the flow facing side. The ions in Ganymede's magnetotail (Figure 4) are observed to have much higher energies than the trapped ions in the flow facing magnetosphere. In the G7 flyby, the spacecraft crosses the magnetopause boundary at approximately 3.1 R_G, indicated by the dashed magenta line in Figure 4. The ion energy distribution changes significantly after the crossing; the bulk energy at the peak flux drops to ~100 eV. There is a short dropout in the flux near closest approach, after which the

ions increase in energy as the spacecraft approaches the outbound magnetopause crossing. A second population is noticeable at lower energies during the outbound portion of the flyby, before the spacecraft passes back into the Jovian magnetosphere.

[22] The structure in the energy distribution in Ganymede's tail is mostly predicted by the simulation and shown in the bottom panels of Figure 4. The duration the spacecraft spends within the magnetotail is well predicted by the model, as is the general morphology of the energy distribution within the magnetopause crossings. Both the observed spectrogram and the modeled spectrogram in Figure 4 show a relatively small flux of keV ions inside Ganymede's magnetosphere. This diffuse population is at energies near those of the incident JMP, and by separating out the ion species (bottom three panels of Figure 4) the model indicates that the composition is in fact sourced from the JMP. This diffuse population is present in all three flybys presented here, but was most noticeable in the Galileo data in the high latitude wake flyby (G7). In the outbound portion of the flyby two ion populations are clearly visible; the ratio of their mean energies corresponds approximately to a factor of 16 difference in mass indicating that they are moving at the same velocity. Again, decomposing the modeled spectrogram into the constituent ion species, it becomes apparent that both populations are sourced from Ganymede's ionosphere.

[23] The main noticeable difference between the observed and the model predicted spectrograms is that the predicted spectrogram shows the spacecraft passing into the closed field region of Ganymede's magnetotail between 3.1 and 2.2 R_G, the area between the dashed green lines in Figure 4. The closed field line interpretation for this region of the model comes from combining 3-dimensional renderings (similar to those in Figure 1, but for the G7 flyby conditions) and the synthetic spectrogram technique. The descending energy region directly after the magnetopause crossing in the modeled G7 flyby can be interpreted as the spacecraft encountering Ganymede's open field lines which are stretching tail-ward. The spacecraft then passes into the reconnected magnetotail (at the first green dashed line in Figure 4), where the ions have been heated as illustrated by the broadened energy distributions between the green dashed lines. The observed spectrogram does not appear to show the spacecraft passing into the closed field line region. This is confirmed by further examination of the plasma data. During the G7 encounter the flow of ions was uniformly tailward, an observation confirmed by the fact that the cold ions in the spectrogram only appear in sensors P6 and P7 (the spectrograms presented in the paper average over all of the sensor look directions). This uniform tailward flow is inconsistent with the spacecraft flying through closed field lines in the tail.

[24] The discrepancy between the observed and modeled spectrograms is due to the fact that the size and shape of the magnetotail is highly susceptible to the upstreamflow conditions of Jupiter's rotating magnetosphere which varies throughout the flyby as Jupiter's plasma sheet wobbles over Ganymede's orbital location [cf. *Kivelson et al.*, 2002]. The simulation is run to a quasi-steady state with the upstream conditions held constant, which could account for the slight discrepancy between the morphology of the modeled and the observed magnetotail. By shifting the spacecraft location 1 grid space in the +Z direction in the simulation, we find that it does not encounter the closed field line region. One grid space is equivalent to 0.045 R_G, which demonstrates how slight the difference is between the modeled and observed morphology of Ganymede's magnetosphere. Also, mapping the spacecraft trajectory onto Cartesian grid has inherent uncertainty since modeled quantities are explicitly calculated on the grid point, hence a difference on of 1 grid space in mapping the trajectory is reasonable within the uncertainty of this method.

[25] The energy distribution observed on the flow facing part of Ganymede's magnetosphere was much different than that observed in the magnetotail (or wake) region. Figure 5 compares the G8 Plasma Experiment observation, which occurred on the upstream side of Ganymede at low latitudes, to model predicted energy spectrograms in the same manner as Figures 4 and 5. The spacecraft observed enhancements in the ion counts per second around the keV energy range directly after crossing into Ganymede's magnetosphere and just before exiting, likely the result of moving through Ganymede's magnetosheath. The central region of the spectrogram, which corresponds to the spacecrafts closest approach to Ganymede and is located well within Ganymede's magnetosphere, shows almost no ion counts in the >100 eV energy range. There appears to be some flux in the range of 10 to 100 eV near closest

approach (~1.6 R_G), however that borders on the lower limit of the instruments sensitivity.

[26] In the modeled spectrogram (second panel in Figure 5), there is a significant ion signature between the magnetopause crossings. In the bottom three panels it is shown that the modeled signature at closest approach is representative of ionospheric H^+ and O^+ ions trapped along closed field lines in Ganymede's magnetosphere. The energy of the ionospheric O^+ in this region is at higher energies than the ionospheric H^+, and the ratio of energies implies that they have similar velocities. The lack of ions near closest approach in the observation is not reproduced in the simulation. While the model predicts the location, energies and densities of multiple ion species, it does not take into account the chemistry corresponding to photoionization and recombination in Ganymede's ionosphere. At the time of the G8 flyby, the upstream hemisphere had been shadowed from the sun for ~40 h, hence much of its ionosphere would have recombined causing the dropout of ions observed at closest approach. The model did not incorporate such ionospheric asymmetries as it had not been reported in the literature or existing ionospheric models for Ganymede. The model should accurately depict the ion energy distribution at low latitudes in a sunlit upstream magnetosphere, however no such flyby exists in the six performed by Galileo for comparison. The observation combined with the model prediction raises new questions regarding the importance of photoionization for Ganymede's atmosphere and ionosphere, the effects of which may also be noticeable in the G2 flyby (cf. Figure 3, top panel). The ion signature measurements after closest approach during the G2 flyby are substantially weaker than those from the inbound portion of the flyby. The weaker particle fluxes correspond to the Galileo spacecraft crossing the terminator into the shaded night-side region in the outbound portion of the flyby, where photoionization would not contribute to the ionospheric density.

4. Conclusions

[27] This paper addressed the ion population, ionospheric outflow and ion energy distributions within Ganymede's magnetosphere. In order to understand the plasma population and distribution within Ganymede's magnetosphere, it was important to account for the various sources of plasma into the system. While Ganymede's magnetosphere is small in size and strength relative to the magnetic field of the rotating Jovian magnetosphere, it still provides enough shielding to exclude much of the JMP at low latitudes (<45°). The JMP gains access through two processes: some precipitates through Ganymede's cusps and some convects down tail and becomes trapped along reconnected field lines. Ganymede's magnetospheric plasma is composed of mostly ionospheric O^+ and H^+ ions. These ions originate in the ionosphere, flow out at the polar cap regions, are convected down tail and a fraction of the outflow is eventually trapped on reconnected field lines. The escaping flux rate of the ionospheric O^+ and H^+ was calculated to be on the order of 10^{26} ions/s for the simulation, which is well correlated to the independently determined sputtering rate for the surface of Ganymede that actively supplies the

atmosphere and ionosphere [*Ip et al.*, 1997; *Paranicas et al.*, 1999].

[28]　While examining the density distribution and flow of ions was useful for understanding how various ion species populate different regions of Ganymede's near space environment, it was not directly comparable to observational data. A method for comparing the model to the observations of the Plasma Experiment was developed and was used in conjunction with ion energy spectrograms from 3 representative Galileo flybys: the polar cap flyby (G2), one of the wake flybys (G7), and one of the upstream flybys (G8). This provided a means for reinterpreting the ionospheric outflow observed on the G2 flyby. The energy characteristics of the modeled spectrogram are shown to be consistent with the observed energy distributions. The model required that both ionospheric H^+ and O^+ were flowing out of the polar cap region, with O^+ occasionally below the detection threshold of the Plasma Experiment.

[29]　The predicted energy spectrograms were also well correlated to the observed ion spectrograms from the wake and upstream flybys, and enabled the identification of ion species and representative energy signatures for different regions of Ganymede's magnetosphere. For example, the modeled energy signature along the open convected field lines was consistent with the energies and populations observed during the wake flyby (G7). The model also predicted a population of heated ionospheric H^+ and O^+ along newly reconnected field lines in the magnetotail. While the spacecraft closely missed passing through closed field lines during the G7 encounter, the predicted signature was useful in illustrating the process of how ionospheric plasma is heated and fills Ganymede's magnetosphere. Model-produced spectrograms were shown to be useful for interpreting various ion sources and populations in the Plasma Experiment observations as well as suggestive of important physical processes (such as photoionization) which have been to date neglected in magnetospheric and atmospheric models of Ganymede.

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W. Paterson, Center for Atmospheric Sciences, Hampton University, Hampton, VA 23668, USA.

C. Paty, Space Science and Engineering Division, Southwest Research Institute, P.O. Drawer 28510, San Antonio, TX 78228-0510, USA. (cpaty@swri.edu)

R. Winglee, Department of Earth and Space Sciences, University of Washington, Box 351310, Seattle, WA 98195-1310, USA.