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Glyn Collinson and William R. Paterson contributed equally to this work.

Key Points:
- We present the first in situ observations of plasmas in Ganymede's cusp/auroral zones and low-latitude magnetopause boundary
- We observe unambiguous evidence for magnetic reconnection near the intersection between Ganymede's magnetopause and tail plasma sheet
- Field-aligned downflows of ions were observed in the cusp, in a location consistent with auroral observations by the Hubble Space Telescope

Supporting Information:
- Supporting Information S1

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New Results From *Galileo*'s First Flyby of Ganymede: Reconnection-Driven Flows at the Low-Latitude Magnetopause Boundary, Crossing the Cusp, and Icy Ionospheric Escape

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Abstract On 27 June 1996, the NASA *Galileo* spacecraft made humanity's first flyby of Jupiter's largest moon, Ganymede, discovering that it is the only moon known to possess an internally generated magnetic field. Resurrecting the original *Galileo* Plasma Subsystem (PLS) data analysis software, we processed the raw PLS data from G01 and for the first time present the properties of plasmas encountered. Entry into the magnetosphere of Ganymede occurred near the confluence of the magnetopause and plasma sheet. Reconnection-driven plasma flows were observed (consistent with an Earth-like Dungey cycle), which may be a result of reconnection in the plasma sheet, magnetopause, or might be Ganymede's equivalent of a Low-Latitude Boundary Layer. Dropouts in plasma density combined with velocity perturbations afterward suggest that *Galileo* briefly crossed the cusps into closed magnetic field lines. *Galileo* then crossed the cusps, where field-aligned precipitating ions were observed flowing down into the surface, at a location consistent with observations by the Hubble Space Telescope. The density of plasma outflowing from Ganymede jumped an order of magnitude around closest approach over the north polar cap. The abrupt increase may be a result of crossing the cusp or may represent an altitude-dependent boundary such as an ionopause. More diffuse, warmer field-aligned outflows were observed in the lobes. Fluxes of particles near the moon on the nightside were significantly lower than on the dayside, possibly resulting from a diurnal cycle of the ionosphere and/or neutral atmosphere.

Plain Language Summary NASA's *Galileo* spacecraft made the first ever flyby of Jupiter's largest moon, Ganymede, on 27 June 1996, discovering that it is the only moon known to generate a magnetic field. As at Earth, Ganymede's magnetic field projects a magnetic bubble around it called a magnetosphere. *Galileo* carried a package called the Plasma Subsystem (PLS) that was designed to measure charged particles. Although PLS collected data during this first flyby, the results were never published. Resurrecting the original flight software, we processed these data and present them here for the first time, permitting us to go back with a fine detail brush and fill in some of the structure of this complex and exotic magnetosphere. Charged water-based particles were observed escaping from the moon, having been blasted off the icy surface by an energetic rain of particles from Jupiter. We also find that *Galileo* flew just above Ganymede's auroral zones, at the precise location where they have been observed by the Hubble Space Telescope. We also observe evidence for the acceleration of plasmas by magnetic reconnection, wherein magnetic energy is converted into kinetic and thermal energy in space plasmas.

1. Introduction

NASA's *Galileo* was the first spacecraft to explore the icy Jovian satellite of Ganymede: the largest moon in the solar system (larger even than the planet Mercury), orbiting deep within Jupiter's powerful magnetosphere. During its first flyby of Ganymede (orbit "G01"), magnetic and plasma wave observations by the *Galileo* enabled the remarkable discovery that the moon still generates its own internal magnetic field. Kivelson et al. (1996, 2002) reported (and later refined) the direct observation of a magnetic signature consistent with a Ganymede-centered dipole field tilted by 176° to its spin axis, with a surface strength of 719 nT at Ganymede's

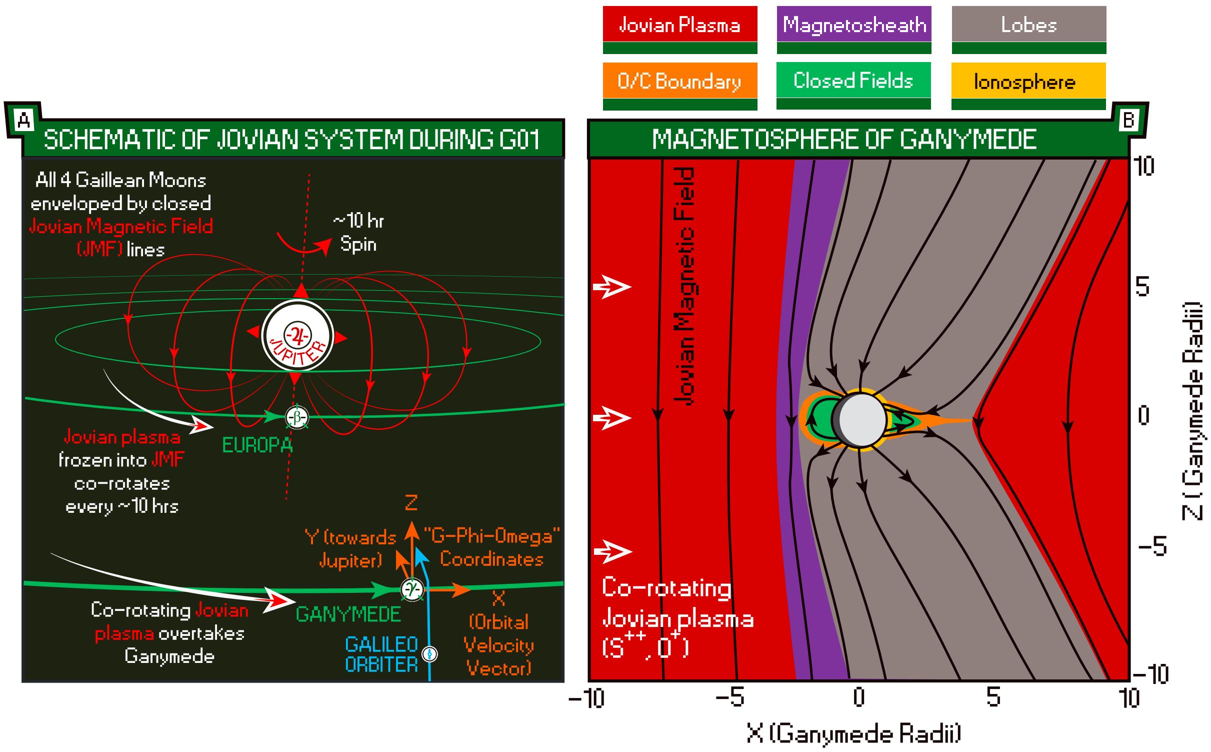

Figure 1. (a) Schematic showing orbits of the four Galilean moons (green), the magnetic field of Jupiter (red), the frozen-in co-rotating plasma (white), the orbit of the *Galileo* (blue), and the Ganymede-centric G-Phi-Omega coordinate system (orange). (b) The regions of Ganymede's magnetosphere including the boundaries between open and closed field lines ("O/C Boundary"), magnetic field lines from a Hall-MHD simulation by Dorelli et al. (2015).

equator. Gurnett et al. (1996), a companion paper, reported intense plasma waves during G01 consistent with such a magnetosphere and found that Ganymede is surrounded by an ionosphere-like plasma with electron densities of approximately 100 cm^{-3}.

Galileo also carried a plasma spectrometer, the Plasma Subsystem (PLS) (Frank et al., 1992) that recorded high-resolution data during the flybys of the moons. However, plasma moments were only ever published for the second (G02) of six flybys of Ganymede (Frank et al., 1997a, 1997b), even though raw counts from all flybys are publicly available. Thus, the actual properties of plasmas encountered by the *Galileo* during the G01 flyby have remained a mystery for over 20 years. In the absence of plasma moments, previous studies of Ganymede's plasma environment from all flybys but G02 have been forced to utilize the raw counts from the uncalibrated data stream (e.g., Jia et al., 2010; Paty et al., 2008).

Resurrecting the original *Galileo* PLS flight software, we processed the raw data from the G01 flyby and here present the plasma moments for the first time, observing a difference between the densities of outflowing ionospheric plasmas on open and closed field lines, and discovering Ganymede's plasma sheet and cross-tail current sheet.

2. Ganymede's Miniature Magnetosphere

Ganymede's magnetosphere is scientifically fascinating and arguably the strangest in the solar system. Specifically, there are four key oddities that are necessary for understanding and interpreting the G01 PLS plasma observations.

1. **Composition of upstream flow:** Whereas all other dynamo magnetospheres are embedded in the H^{+}dominated solar wind, Ganymede orbits within the closed field lines of Jupiter (Figure 1a). The solar wind cannot reach the four Galilean moons, and the dominant upstream ion species at Ganymede are the heavy ($m/q = 16$) O^{+} and S^{++} ions of Jupiter's plasma torus (Bagenal & Sullivan, 1981). The magnetosphere is the smallest known with respect to the local ion gyroradius, and ion-scale effects play a dominant role in its dynamics and structure (Dorelli et al., 2015).

2. **Alfvén wings:** Ganymede does not have a bow shock or heated magnetosheath upstream of its magnetopause. This is because whilst other magnetospheres are embedded within the supersonic solar wind, Ganymede is embedded within the subsonic Jovian plasma torus. The boundaries to Ganymede's magnetosphere are thus subsonic Alfvén wings (Kivelson et al., 1998) (see Figure 1b).
3. **A diurnal cycle:** In Earth's magnetosphere, the terms "dayside" and "nightside" are synonymous with upstream and downstream regions (respectively), with Earth's magnetotail always located on the nightside, extending away from the Sun. Not so at Ganymede. Unlike the anti-sunward flow of the solar wind, the upstream plasma at Ganymede is co-rotating with Jupiter's magnetic field. Since the moon's orbital period is $\sim$ 7 Julian days and the Jovian rotation period is only $\sim$10 hr, the plasma overtakes the moon. Thus, the upstream direction at Ganymede is always the opposite to the orbital direction (Figure 1a). Ganymede is thus a world where the magnetotail is constantly rotating through nightside and dayside as Ganymede orbits Jupiter, presumably resulting in diurnal differences in the local plasma environment as photoionization and photodissociation are switched on and off by the day/night cycle. During the G01 flyby, *Galileo* passed through the magnetotail of Ganymede, almost entirely above the dayside hemisphere (see Figure 1b).
4. **Jovian magnetic background field:** Whereas other magnetospheres are embedded in the weak and turbulent interplanetary magnetic field, Ganymede orbits within the potent and steady Jovian Magnetic Field (JMF). The tilt of Jupiter's magnetic dipole results in a periodic variation in the orientation of the external guide field. During G01, the magnitude of the JMF was 113 nT, with a 42° tilt with respect to the plane of Ganymede's orbit.

2.1. The *Galileo* Plasma Subsystem (PLS)

Due to the failure of the *Galileo* high-gain antennae (Johnson, 1994), telemetry rates were significantly lower than planned, and thus high-resolution 3-D PLS data were only telemetered during the flybys of the moons. PLS was designed to measure electron velocity distributions, ion composition, and ion velocity distributions. Unfortunately, only the latter element was successful, the electron sensors being damaged by the harsh Jovian environment, and the ion composition sensors not having sufficient sensitivity to obtain adequate counting statistics. PLS (Frank et al., 1992) employed a series of fan-shaped curved-plate electrostatic analyzers to sample energies and physically span in order to scan through 4π. PLS sampled plasmas over its full energy range of 10 eV to 52 keV on every spin, but individual energy steps were interleaved such that it took two spins to cover the full energy table: Every other energy being sampled on the first spin, with the gaps being filled in by the second spin. This paper uses single-spin data, taking advantage of the maximum possible time resolution of 20 s. Note that occasional periodic data gaps are visible in the moments, which are a result of PLS going into special modes such as attempting to use its mass spectrometers or the use of special low-energy tables, which are data products not examined here.

3. *Galileo* PLS Observations During the G01 Flyby

Figure 2 shows a map of the G01 flyby in the Ganymede-centric "G-Phi-Omega" coordinate system (see Figure 1a), wherein X points in the direction tangent to the orbit of Ganymede around Jupiter (i.e., in the rough direction of co-rotating Jovian plasma), Y points inward toward Jupiter, and Z completes the right-handed set, pointing upward out of the orbital plane of the moon. Units of distance are in Ganymede radii ($1R_\gamma = 2631.2$ km). Figure 2a (right) shows the flyby in the Y versus X plane (with $+Z$ into the page, i.e., as if viewed from below the south pole of Ganymede), and Figure 2b (left) shows the Y versus Z plane (with $+X$, co-rotating plasma, out of the page). Overlaid onto Figure 2b are magnetic field lines (green arrows) according to a simplified vacuum superposition model by Kivelson et al. (1997) of Ganymede's dipole and the JMF during the G01 flyby to provide a rough approximation of the magnetospheric regions *Galileo* passed through. For a 3-D visualization of the G01 flyby together with an MHD model of the magnetic field, see Jia et al. (2009), Figure 5.

PLS began recording high-resolution data at 06:07 GMT, approximately $3.5R_\gamma$ above the equator of Ganymede, with Jupiter eclipsed on the far side of the moon. The spacecraft was flying toward Jupiter on a trajectory that would take it through the downstream plasma wake and to within 835 km of the moon's surface at a latitude of 30.4° north. Of the six flybys of Ganymede by the *Galileo*, G01 was the only voyage through this central plasma wake.

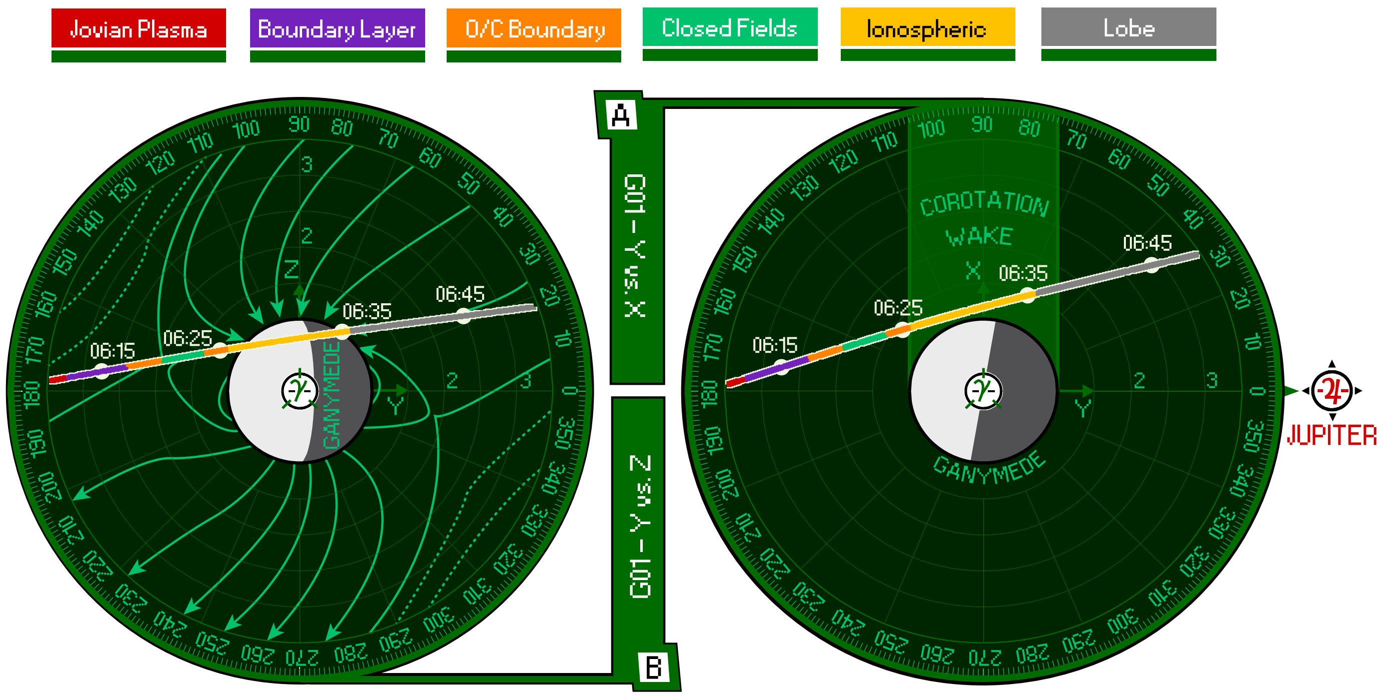

Figure 2. Map of the "G01" flyby of Ganymede by the *Galileo*, color-coded by magnetospheric regions encountered, in the G-Phi-Omega coordinate system. (a, right) *Y* versus *Z*, overplotted over the Kivelson et al. (1997) vacuum superposition model of Ganymede's magnetosphere. (b, left) *Y* versus *X*.

Figure 3 shows *Galileo* observations during the G01 flyby: 3a shows a timeline of the encounter, color coded to the six distinct plasma environments encountered; 3b shows data from the *Galileo* magnetometer for context; 3c presents data from the PLS ion channels, showing a time-energy spectrogram where color denotes the particle count rate, and the following panels show the derived particle density and temperature, four components of velocity in G-Phi-Omega coordinates (in the orbital frame of the moon), and the angle between magnetic field and plasma velocity vector. In order to calculate moments, a mass must be assumed. We chose to plot data assuming a dominant mass per charge of 16 (solid lines), consistent with the O^+ and S^{++} dominated Jovian plasma torus, and the presumed O^+ rich Ganymede plasma (Eviatar et al., 2001). However, other studies (Frank et al., 1997a; Paty et al., 2008) have proposed that the dominant Ganymede plasma species in the energy range of PLS (> 10 eV) is H^+. For this initial (albeit overdue) observational report, our conclusions are based only on relative (not absolute) moments, and thus a single species approximation is adequate. However, to aid any future studies requiring absolute moments, or investigating the composition of plasma outflowing from Ganymede, full sets of moments calculated for mass 1, 2, 16, and 32 are included in the supporting information accompanying this paper: Table S0 contains the single-spin data presented in this paper; Tables S1 to S4 show double-spin data for the G01 flyby, and Tables S5 to S8 show double-spin data for the G02 flyby. Supporting information Figure S09 shows a plot of the G02 data comparable to that of Figure 3 for G01.

Observations by PLS show that *Galileo* passed through six distinct plasma environments during G01, which will now be discussed.

3.1. Jovian Co-rotating Plasma

The G01 flyby began when *Galileo* was still firmly in the co-rotating Jovian plasma torus, dominated by O^+ and S^{++}, with a secondary lower-energy population of protons (H^+) (Frank et al., 1997a). Since these two populations are co-rotating at the same velocity but different mass per charge, they appear as two distinct mono-energetic distributions in the PLS ion spectrogram in Figure 3, with the O^+ and S^{++} comingled at ≈4 keV, and a more diffuse distribution of protons at ≈300 eV.

Given that these two populations are both of known species and well separated in energy, we may perform further analysis to confidently report absolute plasma moments in this region. Following Frank et al. (1997a), we isolated the primary distribution of O^+ and S^{++} and recomputed moments, finding that the plasma was

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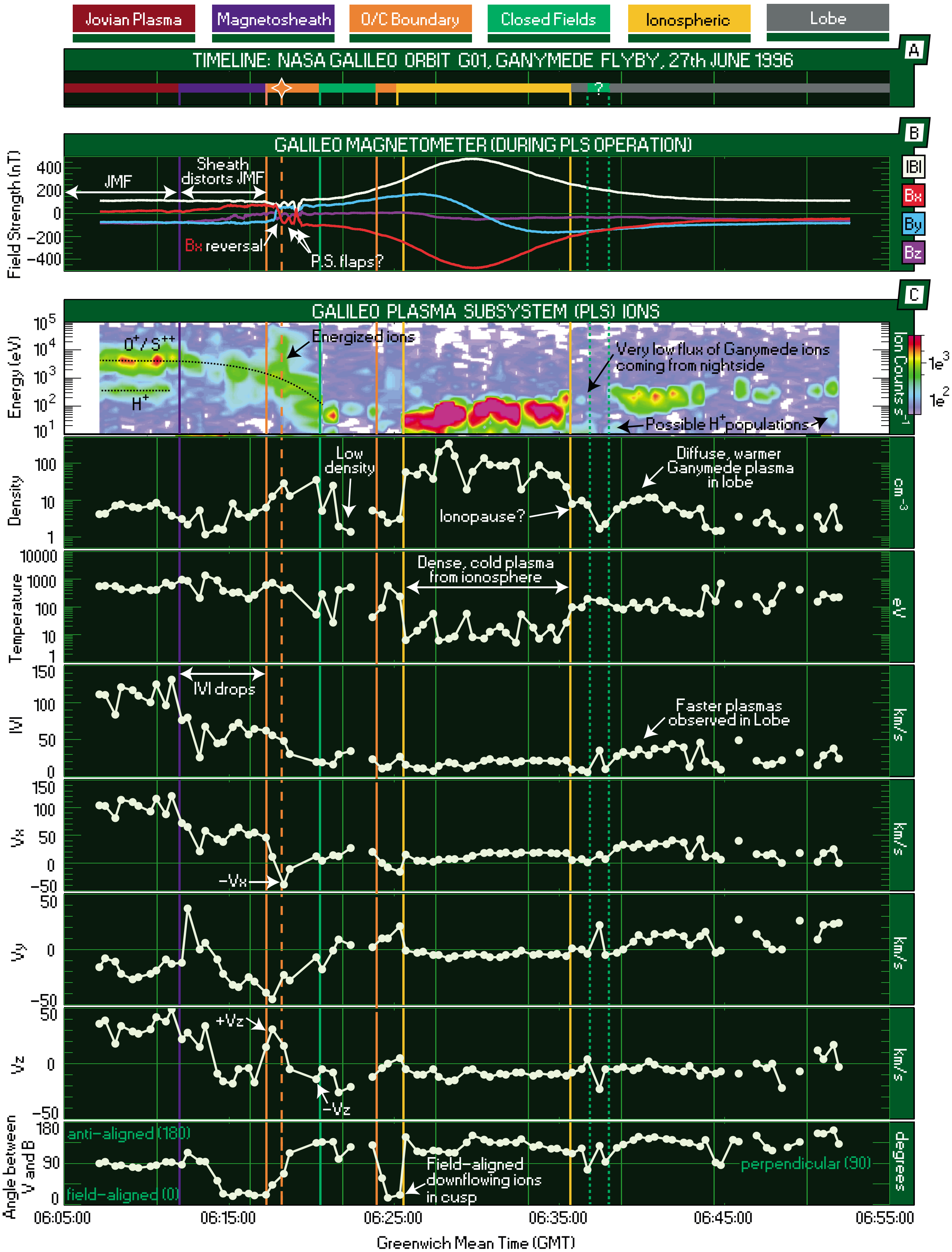

Figure 3. Observations by the *Galileo* Plasma Subsystem (PLS) during the G01 flyby. (a) Color-coded timeline of encounter. (b) Magnetometer data for context. (c) PLS ion observations, showing a spectrogram, density, temperature, four-component velocity, and the angle between **B** and **V**. JMF = Jovian Magnetic Field.

co-rotating at 176.5 ± 14 km/s. This is in perfect agreement with the 175.6 km/s velocity expected for an object at this distance from Jupiter (9.98×10^8 m), rigidly co-rotating with the planet (0.10076 revolutions per hour).

The mean density of this primary O^+ and S^{++} distribution was 2.75 cm^{-3}, and its temperature was 521 eV ($6.05 \times 10^6 K$). This is faster, denser, and cooler than the O^+ and S^{++} population reported on the G02 flyby, which had a mean velocity of 147.8 ± 3.98 km/s, a density of 0.92 cm^{-3}, and a temperature of 726 eV (8.43×10^6 K) (Frank et al., 1997a). As one would expect, this Jovian plasma was moving at 90° to the closed Jovian Magnetic Field lines (which are dragging it around the planet). It is important to note that the moments presented in Figure 3 (assuming a single mass of 16) did not exclude this lower-energy population of H^+, and thus the apparent velocity of the total bulk moment appears lower (≈120 km/s—dragged down by the lower-energy population), and the total density appears higher (≈5 cm^{-3}—propped up by the extra particles in the H^+ population).

3.2. Magnetosheath/Alfvén Wing

The transition between fast-moving Jovian plasma and slowly outflowing Ganymede plasma occurred as a gradual transition across a boundary layer, which we refer to as the "*magnetosheath*," as reported during the G02 flyby (Frank et al., 1997a) and later reproduced in resistive MHD (Jia et al., 2008) and Hall-MHD (Dorelli et al., 2015) simulations. Consistent with this picture, the co-rotating (*Vx* dominated) flow gradually slowed from its steady co-rotation velocity to a mean of 60 km/s (assuming mass 16) at the outer edge of the boundary between open and closed magnetic fields. Plasma in this region was highly dynamic, with reversals in *Vy* and *Vz*, suggesting the Alfvén wings of Ganymede are turbulent and complex.

Entry into the magnetosheath (purple on timeline, Figure 3a) began at ∼06:12 GMT. As expected, plasma temperatures remained roughly constant. However, plasma density decreased to a minimum of 1.6 cm^{-3}. The gradual change in plasma velocity is accompanied by a gradual change in the direction (but not the magnitude) of the magnetic field, resulting from Ganymede's Alfvén wings (Dorelli et al., 2015; Jia et al., 2008, 2009, 2010). Throughout this boundary layer, the angle between **V** and **B** changed from perpendicular flow (90°) to parallel field-aligned flow (0°), with velocity vectors consistent with Jovian plasma flowing along the magnetopause and around the magnetosphere of Ganymede.

Curiously, entry into the magnetosheath co-coincided with an apparent switch-off of the secondary population of lower-energy Jovian protons. Only the mass 16 population was observed in the transition boundary layer, gradually decreasing in energy as it is decelerated to flow around the moon's magnetosphere.

3.3. Reconnection-Driven Flows at the Low-Latitude Magnetopause Boundary

Inside the magnetosheath lies the magnetopause (crossed at ∼06:17:45) (Gurnett et al., 1996; Kivelson et al., 1996), inside of which every magnetic field line connects with the moon on least one end. Particle observations may now finally be added to that of waves and fields, permitting us to add to and partially reinterpret the story of the first-ever crossing of Ganymede's magnetopause.

To the zeroth order, plasma convection throughout Ganymede's magnetosphere is driven by an Earth-like Dungey cycle (Dungey, 1959; Kivelson, 2004). The polarity of the JMF and magnetic dipole of Ganymede is always reversed, such that they meet in opposition at the upstream magnetopause stagnation point (left blue "X-line," Figure 4a), where they break and reconnect (field lines from MHD simulation by Jia et al., 2008). Just as at Earth, the convection flow around Ganymede (orange arrows, Figure 4a, Jia et al., 2009) drag the open field lines downstream and into the magnetotail. There these opposing field lines are pressed together into a narrow layer that requires a current to form to support it. As at Earth, we shall refer to this as the "cross-tail current sheet," or simply the *current sheet*, which we expect to be surrounded by layers of hot (keV) plasma, which (again consistent with terrestrial nomenclature) we shall refer to as the *plasma sheet*.

The original (Kivelson et al., 1996, 1997) vacuum superposition model predicted that *Galileo* entered the magnetosphere of Ganymede at the flanks, at low magnetic latitudes, and at the location where the magnetopause is intersected by the tail plasma sheet (Figure 2a, orange trajectory crossing magnetopause at the point where closed field lines reverse direction back toward the moon). At Earth, this region is referred to as the "Low-Latitude Boundary Layer" (Eastman, 2003; Hones et al., 1972).

Simultaneous to crossing the boundary between open and closed field lines, *Galileo* observed numerous signatures consistent with magnetic reconnection. While they appear to be consistent with plasma sheet-driven flows, this interpretation should be regarded as preliminary, and a full understanding would require 3-D global modeling, which lies outside the scope of this report.

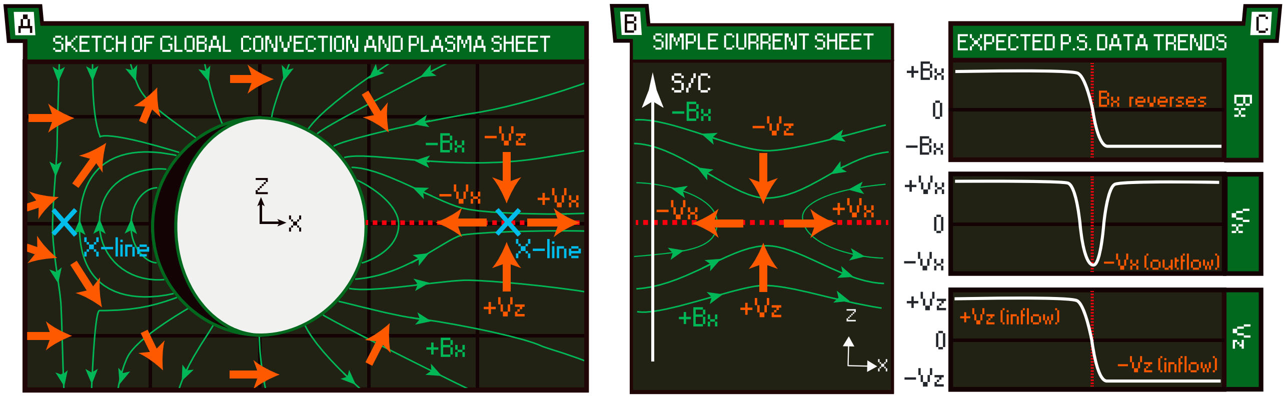

Figure 4. (a) Sketch of Ganymede's Dungey-cycle-driven global plasma convection and formation of the tail current sheet; green lines, magnetic field (based on MHD simulation by Jia et al., 2008); orange arrows, plasma velocity vector (from Jia et al., 2009); blue crosses, magnetic reconnection points; red dashed line, tail current sheet; white arrow, simplified spacecraft trajectory. (b) Cartoon of reconnection at a plasma sheet. (c) Qualitative sketch of the expected general trends of magnetic field and ion velocity perturbations resulting from plasma sheet reconnection.

3.3.1. Ion Energy Spectrogram

Consistent with reconnection outflows, an abrupt burst of energized ions was observed, from 50 eV to 50 keV. This is also consistent with Hall-MHD simulations by Dorelli et al. (2015) who predicted that the Hall effect produces an ion jet in Ganymede's magnetotail current sheet. In addition to bursty reconnection-driven acceleration processes (Payan et al., 2015), we expect additional ion energization to arise from the $\mathbf{J} \times \mathbf{B}$ force resulting from the magnetic shear in the reconnecting current sheet.

3.3.2. Ion Flows

During the rest of the flyby, the plasma velocities are largely dominated by a downstream ($+Vx$) flow, consistent with the co-rotating Jovian plasma torus and outflowing Ganymede ions escaping down the plasma wake. However, ion velocities briefly reversed near the magnetopause, flowing toward the moon ($-Vx$) and at ≈90° to the magnetic field, consistent with reconnection-driven outflow somewhere tailward of the spacecraft. Curiously, flow patterns throughout the low-latitude magnetopause boundary are consistent with flows driven by reconnection in the plasma sheet (Figure 4), where ions are driven toward the moon by magnetic reconnection as part of an Earth-like Dungey cycle (Dungey, 1959). Vz reversed on either side of the $-Vx$ outflow, consistent with inflow toward a current sheet (Figure 4). The strong $-Vy$ components throughout this interval are also consistent with the $-Vy$ flows predicted throughout the tail plasma sheet in Hall-MHD simulations by Dorelli et al. (2015).

3.3.3. Magnetic Reversals

Another feature associated with reconnection is a reversal in the direction of the magnetic field (Figure 4b and top of 4c). Consistent with this picture, the Bx and By components of the field flip at the moment the burst in keV ions was observed. Shortly after the reversal in magnetic field, Bx twice approached zero again before returning to its original value. This is consistent with observations of "flapping" current sheets at Earth (Speiser & Ness, 1967), Venus (Rong et al., 2015), and Mars (DiBraccio et al., 2015), suggesting that if these flows are a result of the return flow from the plasma sheet, the magnetotail of Ganymede may be similarly turbulent and dynamic.

3.4. Properties of Ions Inside Ganymede's Magnetosphere

Four distinct plasma populations were encountered inside the magnetopause, each associated with a different region of the magnetosphere.

3.4.1. Diffuse Ionospheric Plasma on Closed Field Lines

As shown in Figure 1b, close to the moon in the tail, the Open/Closed Boundary (orange) will wrap around a region of closed magnetic field lines (as at Earth). As with the two later flybys through closed field lines on the upstream side (G08 and G28) (Jia et al., 2010), Jovian plasma cannot enter this region, and the spacecraft is magnetically connected to the surface of the moon on both ends of the field lines on which it is situated. Thus, any plasma observed here can only come from Ganymede below, and a decrease in plasma density would thus be expected when on magnetic flux tubes disconnected from Jupiter.

Consistent with entry into such an expected region of closed magnetic fields, the character of the local plasma abruptly changed at ~06:20:30. Densities dropped precipitously, plasmas cooled from the ≈1 keV observed in Jovian plasma to ≈100 eV, and ion flows slowed to 18 km/s presuming O^+ (shown in Figure 3c) or 78 km/s presuming H^+.

3.4.2. Precipitating Ions in the Cusp

When crossing from closed equatorial field lines to open polar field lines at such low altitudes (~1650 km → ~1150 km), one would expect *Galileo* to pass through another open/closed field line boundary, equivalent to Earth's cusps and auroral oval. Consistent with passage through the cusp, just prior to entering the polar cap, ion flow velocities shifted to become highly field aligned, flowing down toward the surface of the moon, and the energy spectrogram shows signs of energized (~ keV) precipitating ions. The location of this proposed cusp crossing (18.7° → 23.7° latitude, 149.2° → 137.8° longitude, G-Phi-Omega) is consistent with the of Ganymede's auroral oval in both three-dimensional multifluid simulations by Payan et al. (2015) and observations by the Hubble Space Telescope (McGrath et al., 2013).

3.4.3. Dense Ionospheric Outflow

At closest approach (06:25:10 to 06:35:40, gold in Figure 3a), a striking population of cold (10 eV), very dense plasma was observed outflowing from Ganymede, with velocities consistent with that measured on closed field lines. Assuming mass 16 (as shown in Figure 3c), the maximum density observed was 242 cm^{-3}, the average was 86 cm^{-3}, and the mean velocity was 17 km/s. If mass 1 is assumed (as suggested by Paty et al., 2008), the maximum density observed was 60 cm^{-3}, the average was 21 cm^{-3}, but the mean velocity was 77 km/s. A $-Vy$ bias was observed during all ionospheric outflow.

This population is entirely consistent with the high-density ionospheric outflows reported by Frank et al. (1997a) from the G02 flyby of Ganymede (Frank et al., 1997a). The highest density reported by Frank et al. (1997a) (near closest approach of 261 km) was 76 cm^{-3} (assuming H^+), slightly higher than that on G01 (60 cm^{-3} at 831 km). We therefore conclude that the most plausible explanation is that these cold, dense plasmas (likely H^+) are the same ionospheric population reported by Frank et al. (1997a) during G02. It is interesting that comparable maximum densities were observed on both G01 and G02 despite very different altitudes at closest approach (831 km versus 261 km) and a similar solar zenith angle. We posit this may be due to a variation in the ionosphere of Ganymede, but further analysis and modeling would be required for an accurate intercomparison between the two flybys.

3.4.4. Lobes

At 06:35:40 GMT, the characteristics of the plasmas abruptly changed again, suddenly dropping in density to < 10 cm^{-3} and increasing an order of magnitude in temperature (≈100 eV). We posit that this may represent (a) *Galileo* crossing an altitude-dependent boundary layer (such as an ionopause) and abruptly leaving the ionosphere proper, or (b) may be a diurnal effect (since field lines in this region should connect to the nightside ionosphere), or (c) a combination of both.

After crossing this boundary, densities, temperatures, and velocities very briefly returned to values consistent with those observed on closed field lines. Given the similarity in plasma moments and spectra, we posit that this may also be due to a second (brief) crossing onto closed field lines, although this is highly speculative.

After ~06:38:00, warm, diffuse plasmas were observed, consistent with those reported by Frank et al. (1997a) in Ganymede's lobes. A secondary low-energy plasma population was observed once near to the moon, and again shortly before PLS stopped recording, which we posit may represent an outflow of protons, whereas the primary population may be an outflow of heavier ions (O^+/O^{++}), although further research is required to investigate this. PLS stopped recording high-resolution data when it was still in the magnetic lobe of Ganymede and before crossing back into Jovian plasma. As observed on G02 (Frank et al., 1997a), the lobe was populated by diffuse (10 cm^{-3}) and warm (100 eV) plasma from Ganymede escaping along the open field lines. The density of this population decreased with distance from Ganymede (as on G02). The velocity of plasma in the lobe is twice as fast as the polar ionospheric outflow discussed above (30 km/s versus 17 km/s).

4. Discussion and Conclusions

On 27 June 1996, NASA's *Galileo* Jupiter orbiter made humankind's first close flyby of Ganymede (during orbit G01), the largest Galilean moon, discovering that it generates its own internal magnetic dipole field. Ganymede is thus a "magnetosphere within a magnetosphere," a moon-magnetosphere interaction currently

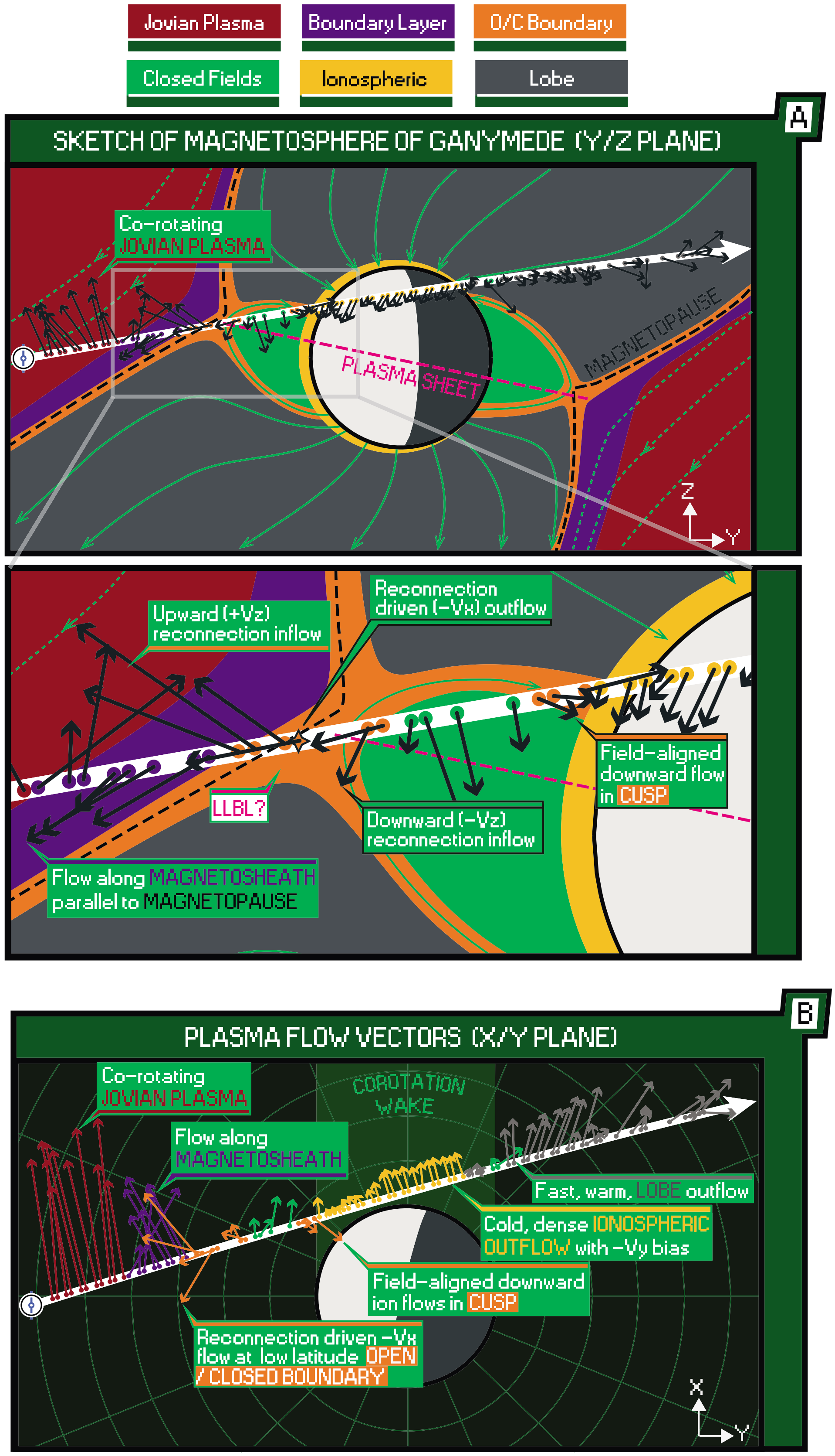

Figure 5. Flow vectors measured by GO1: (a) *Y-Z* plane overlaid onto a sketch of the structure of the magnetosphere and a close-up of magnetopause boundary crossing. (b) *X-Y* plane with key features labeled.

unique in the solar system (Kivelson, 2004). Although *Galileo* carried a PLS (Frank et al., 1992), plasma moments were only ever published for one of the six flybys (on G02), and thus the plasma environment encountered has remained a mystery for over 20 years. Restoring the original PLS data-processing software, plasma moments (density, temperature, and velocity) have been calculated for G01 and presented here. Figure 5 shows PLS plasma flow vectors, overplotted on a revised picture of Ganymede's magnetosphere based on these new results.

The G01 flyby carried *Galileo* through the downstream wake of Ganymede, during daytime. Upstream Jovian plasma (red, Figure 5) began decelerating 7 min prior to entry into Ganymede's magnetosphere (at a position of [−0.5, −5.1, −0.2] R_γ). Flow gradually slowed as *Galileo* flew through Ganymede's subsonic Alfvén Wings/Magnetosheath (purple, Figure 5). In this region, flow was approximately parallel to the magnetopause and consistent with the bulk flow of Jovian plasma around the magnetosphere.

Galileo then crossed the magnetopause of Ganymede at low magnetic latitudes, on the flanks of the magnetosphere, at the predicted location of the intersection between the magnetopause and tail plasma sheet. At this location, *Galileo* observed three signatures consistent with magnetic reconnection: simultaneous burst of energetic ions, a reversal in magnetic field direction, and flow patterns consistent with inflow to and outflow from reconnection somewhere further downstream (although it is not believed that the spacecraft passed directly through the X-line). This may be a result of plasma sheet reconnection (which the data are most consistent with), flank magnetopause reconnection, or may be the Ganymede equivalent of Earth's "Low-Latitude Boundary Layer" (Eastman, 2003; Hones et al., 1972), wherein the $+Vx$ flow around the magnetopause meets $-Vx$ return flow from the plasma sheet. Given the complexity of Ganymede's magnetosphere, we leave closure on this question as a mystery for future studies.

Having crossed the Open/Closed Field Boundary (orange, Figure 5), *Galileo* emerged onto closed magnetic field lines (green, Figure 5), where a new type of plasma population was observed (not encountered on the polar G02 flyby reported by Frank et al., 1997a), flowing tailward at a few tens of kilometers per second with very low densities. Around closest approach to Ganymede, the densities of cold plasmas abruptly increased a hundredfold (yellow, Figure 5). This sudden increase in the densities of Ganymede ions occurred near noon (i.e., nowhere near the terminator) and is thus highly unlikely to be a result of a change in photoionization rates. Given that the location of this abrupt transition is close to where models predict the boundary between open and closed field lines should be, we interpret this abrupt change to be a result of crossing the cusp onto open field lines in the polar cap.

In the cusp, energetic (~keV) precipitating ions were observed, and plasma flows became strongly field-aligned, flowing downward into the surface of the moon. The location of the cusp crossing is consistent with both multifluid simulations by Payan et al. (2015) and observations by the Hubble Space Telescope by McGrath et al. (2013).

Outbound from Ganymede, *Galileo* observed a second region of very low density plasmas, flowing down-tail at very low velocities. This abrupt change may be a second encounter with closed field lines, may be an altitude effect, or represent some sort of transitional altitude boundary such as an ionopause. However, at present we must be cautious in our interpretations due to the paucity of data, but these observations strongly motivate further PLS data analysis.

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