Ganymede's magnetosphere: Magnetometer overview

M. G. Kivelson,1,2 J. Warnecke,1 L. Bennett,1 S. Joy,1 K. K. Kurumaa1
J. A. Linker,2 C. T. Russell,1 R. J. Walker,1 and C. Polanskey1

Abstract. Ganymede presents a unique example of an internally magnetized moon whose internal magnetic field excludes the plasma present in its magnetotail, thereby forming a
magnetospheric cavity. We describe some of the properties of this mini-magnetosphere, embedded in a sub-Alfvénic flow and formed within a planetary magnetosphere. A vacuum
superposition model (obtained by adding the internal field of Ganymede to the field imposed by Jupiter) organizes the data acquired by the Galileo magnetometer on four close passes in a
useful, intuitive fashion. The last field line that links to Ganymede at both ends extends to ~2
Ganymede radii, and the transverse scale of the magnetosphere is ~5.5 Ganymede radii. Departures from this simple model arise from currents flowing in the Alfvén wings and
elsewhere on the magnetopause. The four passes give different cuts through the magnetosphere
from which we develop a geometric model for the magnetopause surface as a function of the
System III location of Ganymede. On one of the passes, Ganymede was located near the center
of Jupiter’s plasma disk. For this pass we identify probable Kelvin-Helmholtz surface waves on
the magnetopause. After entering the relatively low-altitude upstream magnetosphere, Galileo
apparently penetrated the region of closed field lines (ones that link to Ganymede at both ends),
where we identify predominantly transverse fluctuations at frequencies reasonable for field line
resonances. We argue that magnetic field measurements, when combined with flow
measurements, show that reconnection is extremely efficient. Downstream reconnection,
consequently, may account for heated plasma observed in a distant crossing of Ganymede's
wake. We note some of the ways in which Ganymede’s unusual magnetosphere corresponds to
familiar planetary magnetospheres (viz., the magnetotail topology and an electron ring
current). We also comment on some of the ways in which it differs from familiar planetary
magnetospheres (viz., relative stability and predictability of upstream plasma and field
conditions, absence of a magnetotail plasma sheet and of a plasmapause, and probable
instability of the ring current).

1. Introduction

The Galileo Orbiter has completed its reconnaissance of
Jupiter’s largest moon, Ganymede. The existence of an internally
generated magnetic field large enough to surround Ganymede
with a minimagnetosphere carved out of Jupiter’s magnetosphere
has been confirmed [Kivelson et al., 1996, 1997, Frank et al.,
1997; Guenter et al., 1996, Williams et al., 1997a, b]. Here we
focus on the properties of this unique magnetosphere. First
passes at significantly different locations both relative to the
Moon’s surface and relative to the magnetosphere itself, suggest
that there is a distinct excretion of Ganymede’s wake. Flowing
plasma of Jupiter’s magnetosphere, capable to present a model
of its bounding surface, the magnetopause. Near Ganymede’s orbit
(at a distance of 14.97 RJ from Jupiter, with Jupiter’s radius (RJ = 71,492 km), the Alfvén Mach number of Jupiter, magnetic plasma is < 1, implying that it is
predominantly magnetically pressure rather than dynamic pressure
that confines Ganymede’s magnetosphere (see plasma parameters
tabulated by F. Bagenal and F. Cairns at URL:
http://dssdx.colorado.edu/Galileo/Ganet.html). As Ganymede’s
magnetosphere provides an example, thus far unique, in which the interaction between a magnetized body and a flowing plasma is dominated by the magnetic energy density, there is considerable incentive to describe its features quantitatively. Of particular importance are the plasma currents that flow in the interaction region, principally on the magnetopause. A first step in understanding these currents is to establish the shape of the magnetopause on which they flow. Knowledge of magnetopause currents will ultimately enable us to improve estimates of the internal field of Ganymede and possibly to identify some of the higher order multipole moments. At present, we fit Ganymede’s internal magnetic field to lowest order as a centered dipole whose north pole is tilted 10° from the spin axis toward 200° Ganymede east longitude and whose equatorial surface field strength is 750 nT [Kivelson et al., 1996]. By convention, the longitude is measured from 0° in the Jupiter-facing meridian plane through Ganymede and Jupiter. Ganymede’s field, northward-oriented near the equator, is strong enough to stand off the jovian magnetospheric field and the plasma in which it is embedded at an equatorial distance of roughly 2 RJ (RJ radius of Ganymede = 2643 km). Because Jupiter’s magnetic moment tilts 10° from its spin axis, the orientation and magnitude of the field and the plasma properties near Ganymede’s orbit vary with the ~0.5-hour synodic period of Jupiter’s rotation. Correspondingly, Ganymede’s magnetospheric changes shape in a periodic and predictable manner, unlike the unpredictable variation that the solar wind impinges on a planetary magnetosphere. By adding Ganymede’s dipole field to the magnetic field of Jupiter’s magnetosphere at Ganymede’s position (obtained from a field model), we obtain a simple and useful, though incomplete, representation. The model background field is taken from Kuznetov [1997]; it represents Jupiter’s internal field with the O6

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1 Institute of Geophysics and Planetary Physics, University of
California, Los Angeles.
2 Department of Earth and Planetary Sciences, University of California,
Los Angeles.
3 Schriever Applications International Corporation, San Diego,
California.
4 The Jet Propulsion Laboratory, Pasadena, California.
field model of Connerney [1993] and uses a Euler potential to represent the external magnetic field. Figure 1 shows modeled field lines and the Galileo trajectory projected into the yoz plane at 180° at the meridian plane in this vacuum superposition model for the four passes G1, G2, G7, and G8. The numbers reflect the radial or inner, which close passes of Ganymede (G) occurred. The direction of upstream plasma flow is out of the plane of the figure. Although the schematic magnetosphere, confined within a separatrix surface that corresponds to a magnetopause, differs in shape from representations of the magnetospheres of Earth and other planets, the topology corresponds closely. Outside the magnetopause, field lines that do not connect to the interior. For the interior of the magnetosphere, such field lines would be solar wind flow. Here they are field lines connected to Jupiter's ionosphere at high latitudes. Within the magnetosphere field lines, i.e., ones connected to Ganymede at both ends, and lines of the low-latitude field lines in the terrestrial magnetosphere. Finally, there are field lines that connect to Ganymede only at one end and to Jupiter at the other end. They link to Ganymede's polar caps like the polar cap field lines in the terrestrial magnetosphere, and they form a region topologically equivalent to the lobes of the terrestrial magnetosphere. In an orthogonal view of the model in the meridian plane through Ganymede and Jupiter, the vacuum superposition model magnetosphere is roughly symmetric about the direction of the Moon's spin axis. Evidently, the presence of plasma produces departures from the simple model shown here, especially on scale sizes small compared with the diameter of the Moon.

2. Magnetometer Measurements From the Ganymede Passes

In order to optimize science return, Galileo's field and particles instruments normally return data directly at relatively low rates whenever tracking is available. However, for roughly 1 hour at each satellite encounter, the data are stored on the spacecraft only. The upper limit, at best, is 1 hour at each Ganymede pass. Magnetometer vectors are acquired every 0.5 s. The three components of the magnetic field and the field magnitude measured on the G1 (June 27, 1996) [Kivelson et al., 1996], G2 (September 6, 1996) [Kivelson et al., 1997], G3 (April 5, 1997), and G8 (May 7, 1997) passes are shown in Figure 2. The coordinate system is defined in the legend. In each plot, shading emphasizes the relatively abrupt field variations that occur with the spacecraft crossing the Ganymede magnetopause.

A difference in the field signatures on the different passes is obvious in the plots of Figure 2. The orientation of the unperturbed background magnetic field varies with the system III longitude of the spacecraft. The amplitude of the signature varies principally with the distance of approach. Times and locations of closest approach for each pass are given in Table 1. In G2 the pass with closest approach at 11.6 R J (measured from the center of Ganymede) at 70° G3, the background external field was ~113 nT and the maximum field measured within the magnetosphere reached 1167 nT. In the G7 pass with closest approach at 21.8 R J at 55.8° Ganymede latitude, the background external field was ~105 nT, and the maximum field measured within the magnetosphere was only ~220 nT. The vacuum superposition model, also plotted for all of the passes in Figure 2, provides a fair estimate of the magnetic field farther from the boundary crossings, particularly for the high-latitude passes (G2 and G7). For these latter passes the difference between the measured and model components is systematically negative. We can account for this feature of the data in terms of an Alfvén wing interaction [Neubauer, 1980; Scheible, 1989]. Currents in the Alfvén wing field back the flux tubes linked to the moon in the direction of the plasma flow both above and below, thereby introducing a negative (positive) B perturbation above (below) Ganymede. (The Alfvén wing currents can also contribute to B.) As the G2 and G7 passes occurred well above Ganymede's equator, the Alfvén wing contributed negative B perturbations.

The departures from the vacuum field model are less readily interpreted for G1 and G8. Both of these passes traversed regions close to the boundary between closed and open field lines (see Figure 1). The G8 pass occurred near the center of the plasma torus, and the ambient plasma was probably denser than on the other passes. Closest approach occurred at 1.6 R J at 28.3° Ganymede latitude; the background external field was only ~100 nT, and the maximum field encountered within the magnetosphere was ~170 nT. The model field differs considerably from the measured field. The magnetopause encounters occurred ~10 min later inbound and earlier outbound than the times predicted from the vacuum superposition model. By contrast, for G1, G2, and G7, which all occurred well off the center of the plasma torus where the plasma density was

Figure 1. Field lines in a vacuum superposition of an external magnetic field from a model of Jupiter's magnetospheric magnetic field [Ko, 1987] and the field of a Ganymede-centered magnetic dipole with equatorial surface field strength of 750 nT tilted 10° inward from +z, the direction antiparallel to Jupiter's spin axis. The view is a projection into the meridional plane of Jupiter through Ganymede's center. The four passes G1, G2, G7, and G8 are shown in panels as labeled. The orientation of the external field differs for the different passes. For the G1 (downstream) pass and G2 (parallel) pass, the external field is ~120° and is tilted by ~50° outward from z. For the G7 (parallel) pass, the external field is again ~120° and but is tilted inward by ~50°. For the G8 (upstream) pass, the external field is ~75° and nearly due southward. For each case the projected trajectory of Galileo are shown with start and end times indicated and dots at 5-min intervals along the trajectory. Dashed field lines are those connected to Jupiter at both ends. Solid lines are connected to Ganymede at one or both ends. A surface separates these two classes of field lines, and its intersection with the plane of the figure is shown as a thick line. This surface provides a low-order approximation to the location of the magnetopause.
Figure 2. Components and magnitude of the magnetic field in nT measured by the Galileo magnetometer [Kivelson et al., 1992] on Ganymede passes (a) G1 on June 27, 1996, (b) G2 on September 6, 1996, (c) G7 on April 5, 1997, and (d) G8 on May 7, 1997. The data are plotted as heavy lines in a Ganymede-centered coordinate system with z aligned with Jupiter’s spin axis, x azimuthal and positive along the corotation direction, and y radially inward toward Jupiter. Data are plotted versus UT at the spacecraft. Rotations that we identify as magnetoquasie crossings are shaded. The components and magnitude along the orbit from the vacuum superposition model are plotted as thin lines. The figures are labeled with distances in Rp.

Table 1. Times and Locations Relative to Ganymede and to Jupiter of Closest Approach for the Four Galileo Passes

<table>
<thead>
<tr>
<th>Pass</th>
<th>G1</th>
<th>G2</th>
<th>G7</th>
<th>G8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date and time</td>
<td>June 27, 1996</td>
<td>Sept 6, 1996</td>
<td>April 5, 1997</td>
<td>May 7, 1997</td>
</tr>
<tr>
<td>Altitude</td>
<td>383</td>
<td>264</td>
<td>3105</td>
<td>1599</td>
</tr>
<tr>
<td>Latitude</td>
<td>30.40</td>
<td>79.30</td>
<td>55.79</td>
<td>28.31</td>
</tr>
<tr>
<td>East longitude</td>
<td>247.5</td>
<td>237.5</td>
<td>271.3</td>
<td>85.8</td>
</tr>
<tr>
<td>Local time</td>
<td>1116</td>
<td>1046</td>
<td>1944</td>
<td>0807</td>
</tr>
<tr>
<td>Jupiter east longitude</td>
<td>185</td>
<td>302</td>
<td>340</td>
<td>73</td>
</tr>
</tbody>
</table>

Passes are labeled G1, G2, G7, and G8, the numbers identifying the orbit on which the encounter occurred. Altitude is given in kilometers, latitude and longitude relative to Ganymede’s surface in degrees, local time in hours. Longitudes <180° are upstream of Ganymede relative to the direction of magnetostric plasma flow. Ganymede’s location relative to Jupiter is given by its east longitude in degrees (relative to the origin of System III) and the local time of the encounter in hours and minutes.
relatively low, the magnetopause crossings occurred within ~2 min of the times inferred from the vacuum-superposition model. Fluctuations were small within the magnetosphere for all passes other than G8.

The geometry of all four passes is illustrated in Figure 3. The trajectories have been projected into Ganymede’s equatorial plane (x-y plane) and the Galileo-Jupiter meridian plane (z=x plane). G1 woke pass occurred downstream in the flow. G2 and G7 were poster passes with G2 at very low altitude (closest approach of 0.1\text{R}_J altitude) and G7 at higher altitude. G8 was an upstream pass relative to the direction of the corotating magnetospheric plasma.

In the top pairs of panels, projections of measured magnetic field vectors (1 min averages) are shown as arrows rooted at successive locations along the trajectory. In the middle pair of panels the background field has been subtracted, and just the Ganymede-associated perturbations remain. In the bottom pair of panels the model field perturbations along the trajectory are plotted as filled circles. In the middle panels and the model (bottom panel) are in agreement except for the bend-back in the z component. This effect, attributed to Alfven-wing currents, is apparent for G2 and is extreme for the most distant pass, G7, where the internal field contribution is comparatively small and the Alfven-wing current system is well developed. Additional discrepancies (local rotations) are evident at magnetopause crossings.

As we noted above, the vacuum-superposition model is less satisfactory for the G8 pass (Figure 3d) than for the other passes. We have attributed this, in part, to the locations of the different encounters relative to Jupiter’s plasma sheet. Encounters G1, G2, and G7 occurred in a low-\text{ plasma} B environment (\text{B} is the ratio of plasma thermal pressure to magnetic pressure) where the vacuum-superposition model provides useful guidance. The G8 encounter occurred in a higher plasma B environment where the center of the plasma sheet where the vacuum-superposition model depends considerably from observations. The dynamic pressure of the plasma, neglected in the vacuum-superposition model, compresses the magnetosphere, moving the magnetopause inward. The Alfven-wing currents (middle panel) and the effective magnetopause in the vacuum superposition model. This compression accounts for the large shift between the predicted and actual times of magnetopause crossings on this pass. In addition, the G8 trajectory lay just within the magnetopause at relatively low altitude. The Alfven-wing currents, magnetopause current enhance the z component of the field inside the boundary and decrease the x component. Figure 4 shows schematically how the dayside magnetopause currents at Earth modify a dipole field. This type of distortion predicted by the location’s position at 5-min intervals along the trajectory past Ganymede. Figure 4 shows schematically how the dayside magnetopause currents at Earth modify a dipole field. This type of distortion predicted by the location’s position at 5-min intervals along the trajectory past Ganymede. Figure 4 shows schematically how the dayside magnetopause currents at Earth modify a dipole field. This type of distortion predicted by the location’s position at 5-min intervals along the trajectory past Ganymede. Figure 4 shows schematically how the dayside magnetopause currents at Earth modify a dipole field. This type of distortion predicted by the location’s position at 5-min intervals along the trajectory past Ganymede. Figure 4 shows schematically how the dayside magnetopause currents at Earth modify a dipole field. This type of distortion predicted by the location’s position at 5-min intervals along the trajectory past Ganymede. Figure 4 shows schematically how the dayside magnetopause currents at Earth modify a dipole field. This type of distortion predicted by the location’s position at 5-min intervals along the trajectory past Ganymede. Figure 4 shows schematically how the dayside magnetopause currents at Earth modify a dipole field. This type of distortion predicted by the location’s position at 5-min intervals along the trajectory past Ganymede. Figure 4 shows schematically how the dayside magnetopause currents at Earth modify a dipole field...
Figure 4. Schematic of field of view in which the pressure of flowing plasma (flowing from the left) affects the form of an initially dipole magnetic field configuration. The trajectory of Galileo during the OS encounter is shown schematically. Note the trajectory for effect of dynamic pressure is to decrease $B_r$ and increase $B_\theta$, as occurred in the GS pass. As the pass skimmed the boundary between closed and open field lines in the model shown in Figure 3, these situations should cause Galileo’s trajectory to penetrate into the region of field lines closed at both ends at Ganymede. In the region downstream of the dipole source, the field lines stretch along the flow direction.

The diagram presents in Figure 5 applies when Ganymede is above Jupiter’s current shadow. When Ganymede is below Jupiter’s current shadow, as for GD, the magnetic northward of Ganymede is opposite that of Jupiter.

Our fits in Table 3 are empirical functions that depend on the external field orientation and $\delta_{fl}$, which is the actual source location of the Alfven-wing flow, and the north-south asymmetry. We define the source as

$$f(X, Y, Z) = \left(\frac{X - X_0}{r} \right)^2 + \left(\frac{Y - Y_0}{r} \right)^2 + \left(\frac{Z - f_{\delta_{fl}}}{r} \right)^2 = 1$$

where the vector $(X_0, Y_0)$ is the center of the line source and $Z_0$ is the Z-axis location of $(X_0, Y_0)$ in the field frame.

We take

$$f_{\delta_{fl}}(Z) = X_0(Y_0 - Z)$$

with $\delta_{fl}$ characterizing the bend-back of the magnetopause. In the Alfven-wing description, this angle should satisfy tan $\delta_{fl} = M_{fl}$, but we take it as a parameter to be determined. We adopt a form of the $Y$-offset that depends on the $X$-offset $\delta_{fl}$, such that $d_{r} = \delta_{fl}$ to allow the two-asymmetry parameters to vary with the external field orientation.

$$Y(Z) = \frac{X_{fl}}{X_{fl}} - \delta_{fl} - 2\delta_{fl}$$

This offset is nearly constant for $\theta > 85^\circ$ and is greatest at $\theta = 90^\circ$ (Ganymede above the current sheet) and $\theta = 90^\circ$ (Ganymede below the current sheet).

The two tables in Table 3 are summary relevant algorithms for all six parameters in $X_0, Y_0, Z_0, X_{fl}, Y_{fl}$, and $Z_{fl}$ and provide the locations of the six magnetopause crossings. However, the last two columns crossing near $X = 0, Z > 0$ introduce uncertainties into the flux, yielding values that inflate the magnetopause similarly relative to the simulation values. By setting $a = 2.5, R_{0}$, and $\lambda = 0.05 R_{0}$, and calculating the remaining parameters by the least-squares method, we obtain a surface that falls similar to that of the simulation.

The calculated parameters are $X_{fl} = 0.544, X_0 = 0.004, Y_0 = 0.016$, and $Z_{fl} = -0.018$. Table 3 gives the size of the fragment (10) of each crossing. For $\delta_{fl}$ from 0 to 1, the $Y$-offset is good. The only two crossings for which $\delta_{fl}$ differs from 0 by more than 1% are identified as GD and residual GD, both of which occurred near the polar cap (see Figure 7), where the surface location is a sensitive function of position, and large errors are expected.

A satisfactory representation of the magnetopause should predict the nominal distances reasonably accurately. Table 3 gives the errors between the model normals and the measured normals for each crossing. The measured normals are entered in Table 2. They were obtained by rotating the data for each magnetopause crossing into a minimum variance coordinate system. The quality of the results is also indicated. If the normal direction is 0.995, it is clear that the field normal to the minimum eigenvalues of the current matrix is not less than 0.995 of the normal direction, or it is difficult to identify the boundary location in the data, the quality of the normal is poor. The angle between the model and measured normals is large for GD, residual GD, and GI outflow. For GI, the normal is generally in the plane of the boundary again can be applied to the source of the discrepancy because the definition of the magnetopause changes rapidly with distance along the surface in this region. For GI, residual GD, and GI outflow, the normals are poorly defined, and the discrepancy between the model and the minimum variance normal may result from a poorly constrained observation.

The data of the Table 2 and the model normal estimate considerably from the form of Earth's

### Table 2. Magnetopause Crossing Positions for the Four Ganymede Passes

<table>
<thead>
<tr>
<th>Event</th>
<th>X_{G} (R_{J})</th>
<th>Y_{G} (R_{J})</th>
<th>Z_{G} (R_{J})</th>
<th>Charge</th>
<th>Current UT</th>
</tr>
</thead>
<tbody>
<tr>
<td>GI in</td>
<td>251.47</td>
<td>4.01</td>
<td>2.43</td>
<td>0.30</td>
<td>0.30</td>
</tr>
<tr>
<td>GI out</td>
<td>252.34</td>
<td>1.54</td>
<td>1.16</td>
<td>0.67</td>
<td>0.56</td>
</tr>
<tr>
<td>GI in</td>
<td>362.36</td>
<td>0.20</td>
<td>0.31</td>
<td>0.14</td>
<td>0.15</td>
</tr>
<tr>
<td>GI out</td>
<td>288.38</td>
<td>3.021</td>
<td>2.617</td>
<td>0.35</td>
<td>0.15</td>
</tr>
<tr>
<td>GI in</td>
<td>243.64</td>
<td>3.115</td>
<td>2.656</td>
<td>0.35</td>
<td>0.15</td>
</tr>
<tr>
<td>GI out</td>
<td>352.32</td>
<td>1.899</td>
<td>0.893</td>
<td>0.36</td>
<td>0.15</td>
</tr>
<tr>
<td>GI in</td>
<td>75.83</td>
<td>-0.061</td>
<td>-0.031</td>
<td>0.14</td>
<td>0.01</td>
</tr>
<tr>
<td>GI out</td>
<td>76.24</td>
<td>-0.036</td>
<td>0.203</td>
<td>0.14</td>
<td>0.01</td>
</tr>
</tbody>
</table>

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The data of the Table 2 and the model normal estimate considerably from the form of Earth's
magnetopause as anticipated from the representations of Figure 1. Whereas Earth's magnetopause is roughly symmetric about the flow direction because the solar wind dynamic pressure confines it, both the dynamic pressure and the magnetic pressure of the external field control Ganymede's magnetopause. This imposes a small but distinct anisotropy about the flow direction. The bend-back angle of $0.298^\circ$ radians is $-17.1^\circ$ away from the equatorial plane is constrained predominantly by data from encounters G1, G2, and G7, all of which occurred at relatively high Ganymede magnetic latitudes. The value is consistent with an Alfvén Mach number of 0.31, a reasonable value for the encounters away from the center of the plasma sheet (the range 0.23-0.93 is given by F. Bagenal and F. Crany, http://dxsax.cs.colorado.edu/ Galileo/encounter.html).

It must be emphasized that the closure of the magnetopause in the wake was forced to correspond to simulation and may be greatly oversimplified in the model presented here. Indeed, a substantial magnetic signature recorded as Galileo passed through Ganymede's wake at a downstream distance of 30 $R_G$ on June 26, 1997, suggests that plasma at pressures above ambient, possibly heated by reconnection in the downstream Ganymede magnetosphere, was present in the distant wake (A. K. Kuranova et al., Ganymede's distant wake, submitted to Journal of Geophysical Research, 1997).

4. Ultralow Frequency Waves on the Magnetopause

On all four Ganymede passes the power in field fluctuations increased near magnetopause crossings, but on most passes even near the boundary the amplitude of the waves remained small (see, for example, the G7 pass shown in Figure 5a). On the G8 pass that occurred near the center of the jovian plasma sheet, waves of 10-30 mT with periods of 15-20 s were present near both the inbound and outbound magnetopause crossings (Figure 2d). An appropriate coordinate system for examining waves near the boundary is a principal axis system with $l$, along the direction of maximum variance across the boundary, $N$ along the direction of minimum variance, and $M$ orthogonal to the other two. The data for the inbound G8 magnetopause in this boundary normal coordinate system are plotted in Figure 5b. This is a clean crossing with a well-defined normal direction. Waves are evident just outside the boundary. They are predominantly transverse, with smaller amplitude in the field magnitude than the components. The waveforms are irregular, but the $M$ and $N$ components vary in-phase with each other, while the $L$ component varies in quadrature (90° out of phase) with other components. Such phase relations are expected for a surface wave propagating along the $M$ direction on a tangential discontinuity. Displacement of the magnetopause boundary could result from pressure-density fluctuations in the ionos sheet, but the perturbations are periodic, as would be expected if they arise from the instability of a surface in a shear flow. The wavelength can be estimated by noticing the spacecraft velocity and recalling that the phase velocity of a Kelvin-Helmholtz wave is half the relative flow velocity on the two sides of the boundary.

With the plasma sheet plasma flow at 150 km/s relative to Ganymede (Williams et al., 1997a), the wavelength is 1125 km, or roughly 0.5 $R_G$, which is a plausible scale size for a surface wave perturbation on magnetopause at 2 $R_G$ from the central body.

The amplitude of surface waves is larger on the G8 pass than on the other passes of the same pass. The pass discussed herein occurred near the center of Jupiters plasma sheet. G8 was the only pass for which the flow kinetic energy incident on Ganymede's magnetopause was large, and it is flow energy of the external plasma that drives the surface waves. The appearance of Kelvin-Helmholtz surface waves at Ganymede is of particular theoretical interest because it extends the study of such waves into a regime...
in which the thickness of the crustal boundary is in the order of the rotation period in one of the boundary plasma.

5. Ultraviolet Frequency Waves in the Upstream Magnetosheath

Both the field orientation and the angular distribution of energetic electrons (Williams et al., 1997a) suggest that Galileo encountered aligned-like Cmereyke field lines (with both axis linked to Cmereyke) on the G8 pass. Analogous to Earth's magnetopause suggests that transient field perturbations in the base of frequencies imposed by field line resonances may be detectable. However, the rapid motion of Galileo across Cmereyke labels would broaden narrow-band frequency peaks, so truly wave-like fluctuations are unlikely. A much estimate of the fundamental period \( T \) of standing shear Alfven waves can be made as follows:

\[
F = k_B^2 \frac{\rho}{\mu} \leq 2 \left( \frac{\rho}{\mu} \right)^{1/2} \sqrt{\frac{1}{B}}
\]

where \( F \) is a distance along the field line, \( \rho \) is the Alfven speed, \( L \) is the length of the field line, \( \mu \) is the ion mass, and \( \rho \) is the ion density. As Cmereyke is icy and ion sources within the magnetosheath are proton-rich compared with the plasma term, we take \( \rho = 10 \mu \), \( \rho \) is the proton mass. With \( F = 4L \) and \( B = 150 \text{ nT} \), the fundamental period is of the order of \( 300 \text{ s} \). Special analysis of the fluctuations within the magnetosheath reveals transient power at periods larger than 4 on a frequency below \( 1 \text{ Hz} \) at levels significantly above the convectional power. This signature is consistent with generation by low harmonics of standing field line resonances. However, the question of frequency of ions with \( \rho_{ \rho 2 } = 8 \text{ s} \) falls in the same frequency band as the proposed field line resonances. More extensive wave analysis is needed to interpret the source of observed power in field fluctuations.

6. Reconstruction

In an earlier report on the G8 and G2 passes (Kivelson et al., 1997), we discussed the relation between the flow velocity near the polar cap and the reconnection rate at the nose of the magnetopause. Reconnection imposes some fraction of the upstream potential drop across Cmereyke's magnetopause, and the convection flow speed is directly proportional to the imposed potential drop. Velocity measurements (Frank et al., 1991; Williams et al., 1997b) thus constrain the reconnection efficiency, by which we mean the ratio of the imposed potential drop to the full possible potential drop across the width of the magnetopause. For G2, Frank et al. (1997) report that the ambient plasma flows at 180 km/s and that the bulk flow velocity over the polar cap is 70 km/s. Williams et al. (1997b) report that the ambient plasma flows at 150 km/s and gives an upper limit to the flow speed over the polar cap of 22–45 km/s. The data repeats the implications of these measurements for the reconnection efficiency of Cmereyke's magnetopause. We have previously noted (Kivelson et al., 1997) that at high altitudes within the lobes of Cmereyke's magnetosphere, the convective flow speed \( V_c \) is.
\[ v_x = E_x / B_0 = eE_z / B_0 \]  

(5)

Here \( E_0 \) is the convection electric field in the high-latitude lobe where the magnetic field strength does not differ from the external field magnitude \( B_0 \), and \( E_z \) is the convective electric field in the unperurbed plasma that is flowing onto Ganymede's magnetosphere. The measured quantity \( \text{Frank et al., 1997} \) provides the flow speed at the low altitude of the second Ganymede pass. \( \text{Kivelson et al., 1997} \) invoke an approximate form of flux-tube compression in a dipole field to show that along the 62 trajectory of Galiloo, the flow is approximately

\[ \tau_{\text{f}} = (E_x / B_0)(B_0 / B_{\text{eq}})^{1/2} \times (\epsilon eR_0 / B_{\text{eq}})^{1/2} \]  

(6)

hence

\[ \epsilon = \left( \frac{eR_0}{\tau_{\text{f}} B_{\text{eq}}} \right)^2 \]  

(7)

Near the center of the polar cap \( B_0 \) is \( 10^8 \). The measured flows (selecting the upper limit when using the measurements of \( \text{Williams, 1997} \)) imply that \( \epsilon = 1 \), an unexpectedly large value that should be taken as an upper limit. The high reconnection efficiency requires most of the plasma flowing onto Ganymede's magnetosphere to cross the magnetopause. Some plasma must be diverted around the magnetosphere because there is clear evidence of flow divergence on the flanks of the magnetosphere (\( \text{Frank et al., 1997} \)), but our analysis suggests that a large fraction of the incident flow penetrates the boundary. In a steady state the flux tubes that reconnected at the upstream boundary must discontinue after they have convected to the downstream boundary. For this reason, we expect that a downstream neutral line, analogous to Earth's distant neutral line in the magnetosheath, must be continuously active. Heated plasma must be ejected from this downstream neutral line, and we believe that it is this heated plasma that forms the sheath detected on the distant wake crossing of June 26, 1997, as discussed by \( \text{Kaurismaki et al., 1997} \).  

7. Ganymede's Internal Magnetic Field and the Polar Cap Boundary

- The combined data set from four passes provides good support for our earlier estimates of the internal magnetic moment of Ganymede (\( \text{Kivelson et al., 1996} \)). The vacuum superposition model that we have used to orient and interpret our data does not and should not match the measurements in every detail. We have explained some of the departures from the simple model in terms of predictable effects of interaction with the ambient plasma. Furthermore, the internal field model (\( \text{Kivelson et al., 1997} \)) predicts loss cones that are in generally good agreement with the loss cones observed in the energetic electron fluxes after correction for instrument response (\( \text{Williams et al., 1997} \)). With lower energy electron loss cones do not follow predictions of the vacuum superposition model (\( \text{Frank et al., 1997} \)) in measurements made immediately after the inbound magnetopause crossing and before the outbound crossing. However, the plasma in these regions, like boundary layer plasma in Earth's magnetosphere, is controlled by source and loss mechanisms different from those that act deeper in the magnetosphere. Thus their properties do not provide a useful test of the magnetospheric field configuration.  

8. Discussion

Ganymede provides an example of a magnetospheric interaction that cannot be found at Earth or other planets. In which the upstream conditions are steady over times long compared to the time with the convected plasma through the system and these stable conditions are predictable. The upstream conditions allowed us to define a boundary shape despite the limited data set available for analysis. In future data analyses, there may be lessons relevant to the study of magnetic activity at Earth. It remains a challenge to determine if Ganymede's activity is intermittent or if the steady upstream conditions correspond to the development of bursty activity. Analysis of data from all Ganymede wake crossings may help resolve this question.  

Ganymede's magnetosphere is different from Earth's for reasons other than the predictable nature of its environment. Its spatial structure differs greatly because of the low Alfvén Mach number of the plasma streams. Despite its unfamiliar spatial form, there are features such as the magnetic topology (closed and open) that are similar to other planet's magnetospheres. Major differences are apparent and must not be overlooked. For example, the shape of the magnetosphere is determined by the development of the polar cap by discharge from Earth's plasmasheet. As well, the slow rotation of Ganymede precludes the development of a plasma sheet in the same way as it does at Earth. The velocity of corotation within Ganymede's magnetosphere (radius \( R_g \)) is \( 4 \times 10^5 \text{ km/s} \) or \( 172 \text{ hours} \). The convective flow speed at low altitude above the polar cap is of the order of \( 70 \text{ km/s} \) (\( \text{Frank et al., 1997} \)), so much larger than the velocity of rotation about Ganymede that plasma will be convected from upstream to downstream everywhere, and no plasmasphere will form. On the other hand, energetic particles of tens of keV will drift in the magnetic field gradient and speed that can exceed the convection speed. Such plasma and energetic plasma and energetic particles, which may have large bending radii on trapped ring current particles have been reported (\( \text{Williams et al., 1997} \)). However, the gyroadi of the ion of high energy to develop closed drift orbit would be \( 4550 \text{ m} \text{s}^{-1} / (eBv) \) or \( 10 \text{ km/s} \), a scale large compared with the characteristic lengths for field variances. Then it seems likely that the ring current would not be able to decay through violation of the adiabatic invariants. Further analysis of Ganymede's magnetosphere may show how the absence of stable plasma boundaries affects its dynamics.  

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L. J. Kivelson, S. J. Joy, K. K. Khurana, M. G. Kivelson, C. T. Russell, R. J. Walker, and J. A. Slavin, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, Los Angeles, CA 90095-1567. (e-mail: rukiveno@igpp.ucla.edu)

J. A. Linker, Science Applications International Corporation, 10260 Campana Point Drive, MS C-2, San Diego, CA 92126-1778

C. Polanskey, Jet Propulsion Laboratory, 4800 Oak Grove Avenue, Pasadena, CA 91109.

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