Probing Ganymede's magnetosphere with field line resonances

M. Volwerk, M. G. Kivelson, K. K. Khurana, and R. L. McPherron

Institute of Geophysics and Planetary Physics, University of California, Los Angeles

Abstract. We report on the spectrum of field line resonances identified in data acquired by the Galileo spacecraft within Ganymede's magnetosphere on a relatively low latitude pass. We infer properties of the plasma distribution and its transport from the observed spectrum. The harmonic structure in the spectrum of the magnetometer data agrees very well with the frequencies predicted for resonances of a dipole field. The spectrum implies a density of 2 amu cm$^{-3}$ near the equator on closed field lines of Ganymede's magnetic field inside of 2 $R_G$ (Ganymede radii). This density is significantly reduced relative to the local density of the Jovian plasma sheet near Ganymede ($\leq$ 8 electrons cm$^{-3}$, or $\sim$100 amu cm$^{-3}$ for an average ion mass per charge of 20 amu and average charge of 1.5 electron charges). A shadowing effect of Ganymede for the flow of particles injected at a reconnection layer on the side of the moon downstream relative to the direction of torus plasma flow accounts for the marked density depletion. Implications for conducting paths near Ganymede's surface are considered.

1. Introduction

Ganymede, the largest Galilean satellite of Jupiter, has its own magnetic field [Kivelson et al., 1996] that forms a miniature magnetosphere within the Jovian plasma torus. The magnetic field is reasonably well approximated as a vacuum superposition of a tilted Ganymede-centered dipole and the Jovian magnetic field. Differences between the observations and the model can be interpreted in terms of expected effects of currents flowing in the surrounding plasma [Kivelson et al., 1997, 1998].

Jupiter's Galilean moons are embedded in a torus of magnetized plasma that surrounds Jupiter close to its equatorial plane. The source of the torus plasma is principally Io, so the composition is dominated by heavy ions, principally sulfur and oxygen. The plasma rotates slightly below Jupiter's angular speed, thus orbiting the moons, which move at the much smaller Keplerian orbital speed. For Ganymede, whose Keplerian velocity is $\sim$11 km s$^{-1}$ in a prograde sense, this means that the torus plasma overtakes the moon from its trailing edge at a relative speed of $\sim$140 km s$^{-1}$. Relative to the flow, the trailing edge lies upstream. At Ganymede, the flow speed is smaller than the Alfvén speed, which is in the range 150 - 660 km s$^{-1}$ (F. Bagenal, Plasma parameters near Galilean satellites and during satellite encounters, 1998; available on the Web at http://dosx.colorado.edu/Galileo/encounter.html) (hereinafter referred to as Bagenal, 1998).

Because Ganymede is embedded in a plasma that is both subsonic and sub-Alfvénic, there is no bow shock, and the shape of its magnetosphere differs from the bullet-like configuration typical of planetary magnetospheres [Kivelson et al., 1998]. Figure 1 provides a schematic of the field configuration and the plasma flow paths upstream of and within Ganymede's magnetosphere. The field configuration and the approximate dimensions are consistent both with magnetometer data from four passes [Kivelson et al., 1998] and magnetohydrodynamic simulations [Linker et al., 1998]. In the upstream magnetosphere at low latitudes, Ganymede's magnetic field is opposed to the external field of Jupiter's magnetosphere. The flux tubes are slown reconnecting in this upstream region. The plasma on reconnected flux tubes flows over Ganymede's polar cap [Williams et al., 1998]. These flux tubes must reconnect again at a downstream reconnection point and flow back upstream so that magnetic flux will be conserved [Kivelson et al., 1997, 1998, Linker et al., 1998]. The flow pattern is consistent with an electric field oriented radially away from Jupiter throughout Ganymede's magnetosphere. Note that the field lines include some that arc open in the sense that only one end links to Ganymede and some that are closed in the sense that both ends link to Ganymede.

The first three passes by Ganymede occurred above 30° latitude. There is clear evidence that on those passes Galileo encountered field lines linked to Ganymede at most at one end, with the other end linked to Jupiter's ionosphere [Williams et al., 1997a, 1998]. The final pass (designated G8, as it occurred on Galileo's eighth orbit around Jupiter) cut through the upstream magnetosphere with closest approach at 78.3° Ganymede latitude at an altitude of 1606 km or 0.61 $R_G$, with Ganymede's radius $R_G$ = 2634 km. We believe that on this pass Galileo entered a region of closed magnetic field lines, that is, magnetic field lines connected to the moon on both ends [Williams et al., 1997b, 1998; Kivelson et al., 1998].

Here we will argue that oscillations in the magnetic field observed near closest approach can be interpreted as field line resonances [Kivelson et al., 1998]. These resonances are normal modes of planetary magnetospheres. They are transverse magnetohydrodynamic oscillations of entire flux tubes. Resonant oscillations occur only on flux tubes linked to the planet at both ends, and a magnetic flux tube can oscillate at multiple discrete resonant frequencies. The resonant frequencies depend principally on the length of the flux tube between the ionospheres, the magnitude of the magnetic field, the plasma density near the equator, and the harmonic of the resonance. From the wave spectrum, we can infer some of the plasma properties of the closed field line region of Ganymede's magnetosphere and of the electrical conductivity of Ganymede's ionosphere or outer shell.
2. Field Line Resonances

The magnetometer data of the G8 flyby on May 7, 1998, are plotted versus time in UT in Figure 2. Labels give the location of Galileo in a Ganymede-centered spherical coordinate system referenced to the spin axis. In this system, \( B_z \) is radially outward, \( B_{\theta} \) is along the polar angle measured from the rotation axis, and \( B_{\phi} \) is azimuthal in the right-hand sense. The data include an interval within Ganymede’s magnetosphere [Kivelson et al., 1998] as well as data from both approach and departure when Galileo passed through the plasma torus and observed the magnetic field of Jupiter’s magnetosphere (southward oriented, i.e., \( R_0 > 0 \)) modified by insignificant perturbations related to the nearby moon. The crossing of Ganymede’s magnetopause is revealed by a field rotation from its ambient southward orientation to a largely northward orientation. Large-amplitude, low-frequency compressional waves are evident near both crossings of Ganymede’s magnetopause. These oscillations have been interpreted as Kelvin-Helmholtz waves on Ganymede’s magnetopause [Kivelson et al., 1998]. However, smaller-amplitude transverse waves are also present at higher frequencies in the data taken near closest approach. Such waves were not observed on the other three passes through the magnetosphere.

The frequencies of field line resonances vary across \( L \) shells, so the characteristic frequency spectrum can be expected to emerge clearly only from data acquired at approximately constant \( L \). Fortunately, for several minutes near closest approach the spacecraft remained close to a fixed \( L \) shell, as can be seen in Figure 3. (For the purpose of identifying the \( L \) shell of the trajectory, we mapped to Ganymede’s equatorial plane using dipole field lines and characterized the \( L \) shell by the equatorial radial distance from Ganymede’s center.) Consequently, we select the 3 min around closest approach (1554:47 – 1557:47 UT) for spectral analysis.

A coordinate system aligned with the local magnetic field is useful for revealing the properties of waves standing on the field lines of a magnetosphere. In Figure 4 we present the data rotated into a field-aligned coordinate system with \( \mu \) along the background magnetic field (as determined by a third-order polynomial fit for the 3 min interval near closest approach), \( \phi \) the toroidal component, and \( \nu \) the poloidal component. Compressional waves produce field-aligned fluctuations given by \( \delta B_{\nu} \), the difference between the data and the fit to \( B_{\nu} \). Transverse fluctuations appear in \( \phi \) or \( \nu \).

Using spectral analysis techniques described by McPherron et al. [1972], one can obtain the autospectra, cross correlation, polarization, ellipticity, and azimuthal and poloidal angles. Technical details are provided in the appendix. The autospectra for the field-aligned data are shown in Figure 5. Multiple spectral peaks are evident near locations indicated by downward pointing arrows. The nu component (poloidal) dominates the power, except at the second and sixth harmonics.

The principal axis of the polarization ellipse is always in the \( \nu-\phi \) plane, confirming that these are transverse waves. The azimuthal angle at the spectral peaks varies around an average value of 45° with respect to the \( \nu \) direction of the field aligned coordinate system, indicating that the waves are not purely radial, but somewhat oblique.

Because of the power law background noise characteristic of geophysical spectra, the lowest-frequency peak, which is nominally the fundamental resonant frequency, is hidden in the background. The background noise can be reduced by carrying out the spectral analysis on first differences of the time series data. An eigen-analysis of the differenced data, described fully in the appendix, further sharpens the peaks. In Figure 6 we show the eigenvalues (trace) of the eigen-analysis spectral matrix. The spectral peaks at 0.058, 0.208, 0.346, 0.469, 0.579, 0.711, 0.839, and 0.991 Hz stand out clearly in the plot. Although individual Fourier coefficients are determined at frequencies separated by 0.0037 Hz, we have smoothed the spectra by taking running averages over five frequency estimates. Thus the spacing of independent frequency estimates is 0.0185 Hz. This means that the lowest-frequency peak appears at the third independent estimate and is a real peak in the spectrum.

In order to exclude the possibility that the waves are not resonant oscillations but are propagating in from the boundary, we performed the same spectral analysis on segments of data near both inbound (1547:17–1551:32 UT) and outbound (1557:30–1601:30 UT) magnetopause crossings. Although wave power is substantial in both intervals, spectral peaks do not stand out. This gives us confidence that the spectrum is imposed by the local plasma properties near closest approach.

Let us now consider whether the wave structure near closest
approach is characteristic of field line resonances like those observed in the Earth’s magnetosphere [Cummings et al., 1969; Orr, 1984; Takahashi and McPherron, 1984; Engebretson et al., 1986]. We first consider whether the range of frequencies observed is reasonable. The approximate value of the fundamental period of field line resonances based on a time-of-flight approximation is given by:

\[ T = \frac{\delta s}{v_A} = \frac{2}{3} B_0^2 \left( \mu_0 m_i m_p \right)^{1/2} \]  

(1)

where \( v_A \) is the Alfvén velocity, \( \delta s \) is the length of the field line, \( m_i \) (\( m_p \)) is the ion (proton) mass, and \( B_0 \) and \( n_0 \) are the magnetic field magnitude and the ion number density at the flux tube equator. For \( B_0 = 160 \) nT, and \( \delta = 4 \) \( R_J \), the period is \( T(\text{seconds}) = 6 \left( \frac{n_0 m_i}{m_p} \right)^{1/2} \). The lowest frequency in our spectrum has a period of 17 s, so the identity is satisfied for a mass density of 8 amu cm\(^{-3}\). For a proton plasma this would imply \( n_0 = 0(8\times10^6 \text{ m}^{-3}) = 0(8 \text{ cm}^{-3}) \). For typical torus plasma the ion mass is \( \sim 20 \) \( m_p \), and the observed 17 period yields an estimated number density: \( n_0 = n_e = 0.4 \) ions cm\(^{-3}\) (\( n_e \) = electrons cm\(^{-3}\)). In the surrounding torus plasma, \( n_e = 2 - 8 \) cm\(^{-3}\) and the average ion charge is \( 1.5 e \), with \( e \) being the magnitude of the electron charge (Bagenal, 1998). This means that the frequencies observed are plausible field line resonance frequencies, provided the density within Ganymede’s magnetosphere is much lower than that in the ambient plasma.

As there are reasons to believe that access of torus plasma to the closed field line region within Ganymede’s magnetosphere is indirect, the required low density is not unreasonable and the interpretation of the oscillations as field line resonances is plausible.

Next consider the wave polarization. In the Earth’s case the principal axis of the polarization ellipse usually is along the phi component [Engebretson et al., 1986]. However, radially polarized harmonic structure has also been observed [Hughes et al., 1978]. In our case the polarization is oblique, which is
Figure 4. An expanded view of the data from the 3 min around closest approach of the Ganymede G8 flyby. The top two and the bottom plot show the components of the field rotated into a field-aligned coordinate system. The vectors mu, nu, and phi are orthogonal, with mu at time t parallel to a polynomial fit ($B(t)$) to the magnetic field, phi close to azimuthal, and nu close to radial. (The system is precisely defined in the appendix.) By construction, $B_{mu}$ and $B_{phi}$ have zero means during the critical 3 min, and the field amplitude appears in $B_{nu}$. A dashed curve in the bottom plot is a polynomial fit to $B_{nu}$, and the next to bottom plot shows the difference ($\Delta B_{mu}$) between the measured and fitted fields.

Figure 5. Power spectrum of the 3 min of data around closest approach in field-aligned coordinates $B_{mu}$ (dashed), $B_{nu}$ (thick solid), and $B_{phi}$ (thin solid). Visible are multiple harmonics, principally in the poloidal ($nu$) component. Arrows show the frequencies determined from an eigen-analysis described fully in the appendix.
Figure 6. Spectral eigenvalues (maximum, intermediate, and minimum from top to bottom) of the first difference of field-aligned data obtained as discussed in the appendix. Arrows indicate weighted peak frequencies. These are the frequencies used for Figure 5 and in Table 1.

Theoretically predicted for resonant oscillations detected slightly away from the resonant L shell [Chen and Hasegawa, 1974].

Although it is useful to estimate the wave period from (1), the approximation can be improved by turning to the numerical results of Cummings et al. [1969] for waves standing on dipole field lines. Cummings et al. assume that the number density varies with radial distance as

\[ n = n_0 (L/r)^m \]  

Here \( n_0 \) is the equatorial density at radial distance \( L \). A notable feature of the spectra that they obtained is the frequency spacing. The higher harmonics are separated by roughly constant frequency differences, \( \Delta f \), but the lowest harmonics are nonuniformly spaced (see Table 1). Furthermore, the fundamental frequency is less than or roughly equal to half the frequency separation of the higher harmonics.

In columns 4 and 6 of Table 1 we show the frequencies inferred for the different harmonics of radially polarized resonant oscillations in a dipole field for the cases \( m = 0 \) and \( m = 2 \). The frequencies have been normalized to the frequency of the observed fundamental spectral peak. The normalization is achieved by identifying \( L = 2 \) as the magnetic shell on which the oscillations were present and using a mass density of \( (m/m_p)n_{eq} = 7 \times 10^{3} \text{ cm}^3 \). (Here the waves were observed at 28.5° latitude and \( r = 1.6 R_E \) which places them on the \( L = 2 \) magnetic shell.) The observed frequencies roughly match the model frequencies, the frequency separations are close to constant for the higher harmonics, and the fundamental is less than 0.5 \( \Delta f \), just as for the model. To within the uncertainty in the frequency of the fundamental frequency (20.004 Hz), the inequality is robust. We therefore believe that the harmonic order has been correctly established.

The density (2 amu cm\(^{-3}\)) determined from the dipole model is even smaller than that estimated from the time-of-flight calculation and far lower than the \( 100 \text{ amu cm}^3 \) density in the surrounding torus (electron number density \( \approx 8 \text{ cm}^3 \) and ion number density \( \approx 5.3 \text{ cm}^3 \)). Here we have taken the upper limit estimate given by Bagenal [1998] because the G8 encounter occurred close to the center of the plasma sheet where the density should be greatest. For an average ion mass equal to that of the torus \( (m_i = 20 m_p) \), the number density at the equatorial portion of the \( L = 2 \) flux tube is 0.1 cm\(^{-3}\). However, in the next section we

<table>
<thead>
<tr>
<th>Harmonic Number</th>
<th>( f_{obs} )</th>
<th>( \Delta f_{obs} )</th>
<th>( f_{op} (m = 0) )</th>
<th>( \Delta f_{op}(m=0) )</th>
<th>( f_{op} (m = 2) )</th>
<th>( \Delta f_{op} (m = 2) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.059</td>
<td>0.149</td>
<td>0.0588</td>
<td>0.151</td>
<td>0.0588</td>
<td>0.145</td>
</tr>
<tr>
<td>2</td>
<td>0.208</td>
<td>0.138</td>
<td>0.710</td>
<td>0.134</td>
<td>0.204</td>
<td>0.122</td>
</tr>
<tr>
<td>3</td>
<td>0.346</td>
<td>0.123</td>
<td>0.344</td>
<td>0.131</td>
<td>0.326</td>
<td>0.122</td>
</tr>
<tr>
<td>4</td>
<td>0.469</td>
<td>0.110</td>
<td>0.475</td>
<td>0.130</td>
<td>0.448</td>
<td>0.117</td>
</tr>
<tr>
<td>5</td>
<td>0.579</td>
<td>0.130</td>
<td>0.605</td>
<td>0.130</td>
<td>0.565</td>
<td>0.123</td>
</tr>
<tr>
<td>6</td>
<td>0.709</td>
<td>0.130</td>
<td>0.735</td>
<td>0.130</td>
<td>0.688</td>
<td>0.123</td>
</tr>
</tbody>
</table>

The model frequencies from Cummings et al. [1969] use two different power law exponents \( (m = 0, m = 2) \) for the dependence of density on radial distance from the Earth.
will suggest that within Ganymede's upstream magnetosphere the plasma source is likely to be Ganymede's exospheric ionosphere and that the inferred 2 amu cm\(^{-3}\) implies a number density close to 2 ions cm\(^{-3}\).

3. Implications for Plasma Sources and Transport in Ganymede's Low-Latitude Magnetosphere

The density inferred from analysis of the resonant spectrum is low relative to the density of Jupiter's plasma torus at Ganymede's location. This may be partly because at most a small fraction of the upstream plasma is expected to cross the magnetopause and enter Ganymede's low-latitude magnetosphere. The mechanism of transport across the magnetopause is principally reconnection. Reconnection appears to be efficient for Ganymede's magnetosphere, with 30-100% of the incident flux tubes reconnecting at the upstream boundary [Kivelson et al., 1998]. As described in the discussion of Figure 1, the torus plasma enters the magnetosphere on the newly reconnected flux tubes and convects over Ganymede's polar cap on the reconnected flux tubes (see Figure 1). Some plasma is lost through precipitation before the open flux tubes reconnect at the downstream neutral line. After crossing the downstream reconnection line, plasma flows back upstream on the closed field lines. There is no need to compensate for compression or expansion of flux tubes as the plasma crosses the reconnection line because the cross sections of flux tubes (proportional to the field magnitude) change little across the magnetopause.

After the plasma enters the magnetosphere at the downstream reconnection site, it begins to drift back toward Ganymede under the influence of a cross-magnetosphere electric field and the gradient of the magnetic field (see Figure 1). The analogy to particles drifting toward the Earth from the distant neutral line in the magnetotail may be helpful in understanding this aspect of the flow. The cross-magnetosphere electric field \(E_0\) is a fraction \(\varepsilon\) of the corotational electric field of Jupiter's magnetosphere (of order 18 mV m\(^{-1}\) near Ganymede's orbit), that is, \(E_0 = 18 \varepsilon\) mV m\(^{-1}\), where \(\varepsilon\) is the reconnection efficiency factor previously discussed. Because Ganymede is tidally locked to Jupiter, it does not rotate with respect to the plasma flow around it, and hence the corotational electric field that affects particle motion in the frame of Earth's magnetosphere is absent at Ganymede. We calculate particle trajectories in the return flow by injecting particles of different energies in the equatorial plane along a line \(\sim 2.5 R_E\) downstream of Ganymede. We take the magnetic field as the superposition of a Ganymede-centered dipole and a mirror dipole 8 times stronger at \(6 R_E\) upstream. Within the magnetopause this model approximates the compression of the magnetic field at the upstream side by the plasma pressure. Both the field model and the nominal distance to the reconnection line are roughly consistent with the magnetohydrodynamic simulation of Linker et al. [1998].

Figure 7 shows the paths along which electrons drift at constant first adiabatic invariant \(\mu = W/B\) [cf. Chen, 1970]. The drift orbits are plotted for electrons with several different values of \(\mu\) for \(\varepsilon = 0.1\) and 0.5. Low-energy electrons (initially 100 eV, black curves) are little influenced by the gradient \(B\) drift and convect onto the moon. Higher energy electrons (initially 10 keV for the dark gray lines and 100 keV for the light gray curves) are affected by the gradient \(B\) drift and avoid colliding with the moon but do not drift fully around it. Closed drift orbits (lightest gray curves encircling Ganymede) exist for particles that do not link to the connection line. Examples of such orbits are illustrated. For the \(\varepsilon = 0.5\) case these orbits correspond to 100 keV electrons starting close to the moon at \(x = 0\) on the Jupiter side. Moving at constant \(B\), the energy of these particles is \(\sim 10\) keV near \(L = 2\) on the anti-Jupiter side of the moon. These orbits may contain ring current electrons on closed field lines reported by Williams et al. [1998]. Ring current ions would be expected to also be affected by the electric fields and would be expected to reduce the asymmetry of the orbits for both ions and electrons.
Recalling that the temperature of torus plasma is ~100 eV [Bagenal, 1994], one concludes from Figure 7 that only the high-energy tail of the plasma distribution can return to the upstream side of the magnetosphere. Thus the low latitude upstream magnetosphere is populated principally by the energetic particles that enter near the downstream reconnection line. As in Earth’s dayside magnetosphere, some energetic particles that enter the low latitude upstream magnetosphere on newly reconnected field lines may drift onto closed field lines, but their density will be low. This scenario accounts for the low densities inferred from the spectrum of field line resonances on the upstream pass.

However, the explanation poses a new problem: if the return flow does not yield the required upstream density, what is the source of the 2 amu cm⁻³ plasma? Particles of > 20 keV measured by the Galileo Energetic Particle Detector [Williams et al., 1992] provide roughly two orders of magnitude less density than inferred (A. Eviatar, personal communication, 1998). Some scattering could diffuse particles onto closed drift orbits where they could remain for extended intervals of time, but it is hard to see what could produce the required scattering. At Earth, diffusion of plasma is achieved principally as a result of the temporal variation of both electric and magnetic fields. The temporal variations relate to geomagnetic activity and, in turn, arise because of the varying orientation of the magnetic field of the solar wind. At Ganymede the plasma and field conditions change slowly and predictably at the synodic period of Jupiter’s rotation, roughly 10 hours. Field orientation never reverses. The time scale for change is slow with respect to the time for particles to drift through Ganymede’s magnetosphere, so only adiabatic responses, which do not produce scattering, are expected. Nonadiabatic transport arising from finite gyroradii effects can be relevant to the higher-energy heavy ions, and some scattering can result from the very types of waves that we have analyzed here [Southwood and Kivelson, 1997]. Such scattering has been shown to be relevant to the outward transport of ring current ions at Earth [Li et al., 1993]. These effects have not yet been evaluated quantitatively for an initial particle distribution of the type likely to apply to Ganymede’s magnetosphere.

Other possible sources of plasma in the Ganymede’s upstream low-latitude magnetosphere are the ionosphere and locally ionized neutrals. If the convection electric field penetrates into Ganymede’s ionosphere, it will pull ionospheric flux tubes into the upstream magnetosphere. Expansion of such a flux tube will carry ionospheric plasma into the magnetosphere. In order to estimate the density at \( L = 2 \) if the source is the ionosphere, we assume that an emerging flux tube starts very close to the surface at \( L = 1.01 \) in the ionosphere. Flux conservation in a dipole field demands that the flux tube volume increase by approximately a factor of 100 if it is transported to \( L = 2 \). Hence the density at \( L = 2 \) will be down by two orders of magnitude compared with the ionospheric density. However, the ionospheric density is not known. D. P. Hinson (personal communication, 1998), using the type of radio occultation measurements that revealed an ionosphere at Europa [Kivelson et al., 1997], does not detect an ionosphere at Ganymede. This sets an upper limit to the ionospheric electron density of 2000 cm⁻³, which is not inconsistent with the requirements that we describe. Some of the plasma near \( L = 2 \) could be directly introduced by ionization of neutrals, but local ionization is not likely to be the dominant source. An ion density of ~200 cm⁻³ in the topside ionosphere would produce a density of ~2 amu cm⁻³ on the \( L = 2 \) flux tube through direct transport. Barth et al. [1997] report a neutral hydrogen density of 1.5 x 10⁶ cm⁻³ above the surface of Ganymede. Thus the ionospheric density required to account for the inferred magnetospheric plasma density at \( L = 2 \) could be satisfied if 1% of the neutral exosphere is ionized. We cannot confirm the suggestion of this level of ionization, as neither the atmospheric structure nor the ionization mechanisms have been worked out for Ganymede, but the requirement appears not unreasonable. The suggestion that the plasma inferred from the wave spectrum is a proton plasma that has convected up out of the ionosphere cannot be ruled out, and there seems to be no alternative source.

4. Implications for the Electrical Conductivity of Ganymede or Its Ionosphere

Field line resonances similar to those we report were found in Mercury’s magnetosphere [Russell, 1989], the other magnetosphere whose scale is close to Ganymede’s. Mariner 10 penetrated deeply into the magnetosphere of Mercury on March 16, 1975. Russell [1989] identified narrowband waves with a period of ~2 s in the magnetic data. The wave was very coherent and highly linearly polarized. Estimating the length of the field lines (1.6 Mercury radii) and the electron density (3 cm⁻³) and assuming that the ions were protons, Russell found that this wave could be the fourth harmonic of a field line resonance. However, no other harmonics were detectable in the data. In analyzing this wave, considerable attention has been paid to the boundary conditions at the planetary ends of the flux tubes. Russell [1989] and Southwood [1997] suggested that the magnetic field lines are more likely to be anchored in Mercury’s core than in its ionosphere. Southwood [1997] concluded that there are two possibilities: (1) reflection at the perfectly conducting core of Mercury or (2) reflection at the insulating or weakly conducting surface of Mercury.

What boundary conditions are likely to pertain to the field line resonances observed at Ganymede? In the analysis of the wave spectrum we used a model of the field line resonances that assumes perfect reflection at a highly conducting ionospheric boundary. However, it is possible that the boundary layer, whether at the ionosphere or below it, may not be highly conducting. Newton et al. [1978] evaluated the effects on field line resonances of finite resistivity of the ionosphere. Hughes and Southwood, 1976; Allan and Knox, 1979; Orr 1984. Remarkably, although the waveforms depend on the ionospheric boundary conditions, the resonant frequencies are quite insensitive (<20% variation) to the boundary conditions, providing that the waves do not damp in less than one cycle [Newton et al., 1978]. Thus the full range of reasonable assumptions for the boundary conditions produces an uncertainty in the plasma density of <40%, which does not affect the basic analysis that we have provided.

When the ionospheric Pedersen conductivity \( \Sigma_p \) is infinite, the field line resonances have fixed-end boundary conditions and the electric field has a node at the ionosphere. Newton et al. [1978] showed that the waves have free-end boundary conditions and the electric field has an antinode at the ionosphere for zero conductivity. In neither of these extreme cases does coupling to the ionosphere damp the waves. (This is because the Joule losses to the ionosphere are proportional to \( \Sigma_p E^2 \), a quantity that vanishes in one extreme because \( \Sigma_p = 0 \) and in the other extreme because \( E = 0 \).) Maximum damping occurs for intermediate \( \Sigma_p \).

We argue that losses to the ionosphere must maximize when \( \Sigma_p \) matches the Alfvén conductance, \( \Sigma_A = (\mu_0 n_A)^{1/4} \), of the magnetosphere just above the ionosphere. a point not mentioned...
5. Conclusions

Galileo entered a region of closed magnetic field lines (i.e., both ends are connected to the moon) during the G8 flyby. The data from the magnetometer show strong transverse wave activity near closest approach. The waves, with principally poloidal polarization, are identified as harmonics of field line resonances and are well described by the harmonic spectrum for a dipole field. The power spectrum is highly dependent on the interval around closest approach. Shifting the interval to 1 min earlier or later blurs the frequency peaks. This is consistent with direct evidence (Figure 3) that the interval during which Galileo is on relatively constant L shell is limited. The mainly poloidal polarization of the waves observed is not typical of such waves in the terrestrial magnetosphere (e.g., Takahashi and McPherron, 1984), but such poloidal polarization has been reported. Examples include the events at geostationary orbit reported by Cummings et al. (1969) and by Hughes et al. (1978). In the latter event the lowest frequency in the spectrum was the second harmonic, and only even harmonics were present. The wave growth was attributed to a bounce-drift resonance with energetic (10-100 keV) protons. In the Ganymede case, both odd and even harmonics are present, and the bounce-drift resonant mechanism does not explain the wave growth. It will be of interest in the future to test other models of resonant wave generation in relation to the observations reported here.

The density in Ganymede's upstream magnetosheath inferred from the field line resonances is 2 amu cm\(^{-3}\). This is low compared with the density of plasma surrounding the Ganymede magnetosphere. We propose that the low-density results from the shadowing effect of Ganymede for particles injected into the closed field line region downstream. In the case of steady reconnection around Ganymede, fluctuations in the magnetic field will be small, and diffusion of plasma onto the closed orbits will be small. Thus a ring current around Ganymede is expected to be quite weak. A probable source of the plasma in the region probed by the G8 pass is the ionosphere, a source of an H\(^+\) plasma with an inferred electron density of ~200 cm\(^{-3}\).

The existence of field line resonant waves that do not damp quickly implies either a conducting layer (\(\Sigma_e > 1\)) near the surface of Ganymede or an insulating crust (\(\Sigma_e < 10^{-3}\)). Arguments that favor the low conductivity limit appear most plausible. Better estimates of the ionospheric and crustal conductivity are relevant to the full interpretation of standing waves in the magnetosphere of Ganymede.

Appendix: Data Analysis

The components and magnitude of the magnetic field measured by Galileo on the G8 pass are plotted in Ganymede-centered spherical coordinates in Figure 2. Light shading defines the interval during which Galileo was inside Ganymede's magnetosphere. Dark shading identifies a 3 min interval roughly centered on the time of closest approach during which Galileo's L value changed very slowly. This portion of the data is optimum for identification of resonant pulsations of magnetic field lines.

An initial analysis of the spectrum of the three spherical components of the field revealed weak spectral peaks separated by constant intervals suggestive of resonant field line oscillations.
Encouraged by this result, we proceeded to enhance the sharpness of the spectral peaks by using standard analysis techniques described in this appendix. We first transformed the data to a field-aligned (FA) coordinate system. The FA coordinate system is obtained by fitting the vector components plotted in Figure 2 to third-order polynomials, which define a reference background magnetic field. The data are then rotated into FA coordinates defined by the three unit vectors \((\mathbf{u}, \mathbf{p}, \mathbf{m})\). At each time step the unit \(\mathbf{u}\) vector is parallel to the reference field. The \(\mathbf{p}\) vector is perpendicular to the cross product of \(\mathbf{u}\) with the radius vector, \(\mathbf{u}\). Nu completes the system and is positive radially outward in a magnetic meridian plane. The results of the transformation are plotted in Figure 4. In the FA coordinate system both the \(\mathbf{u}\) and \(\mathbf{p}\) components have zero mean, and the total field magnitude is the \(\mathbf{m}\) component. The bottom plot of Figure 4 shows both the \(\mathbf{u}\) component and a third-order polynomial (dashed line) fitted to it. The first three plots show the \(\mathbf{u}\), \(\mathbf{p}\), and \(\mathbf{m}\) difference between the measured \(\mathbf{u}\) component and the polynomial fit to it. Vertical lines identify the interval during which the spacecraft remained approximately on a constant \(L\) shell. The time of closest approach (1556:10 UT) is shown with an arrow in the bottom plot.

Vector data in the FA coordinate system \((\mathbf{d}B_{\text{rms}}, \mathbf{u}, \mathbf{p})\) were fast Fourier transformed \((\mathcal{F}^T)\) with a fundamental frequency \(f_0 = 1/360\) Hz for the 3 min interval (540 points with 0.33 s resolution) centered on the time of closest approach. The transforms of the three components were then used to calculate the full 3 by 3 Fourier spectral matrix

\[
G_{ij}(f) = [\mathcal{F}^T[B_j]]^* \times [\mathcal{F}^T[B_j]]^T
\]

\((A.1)\)

\(G_{ij}\) is a Hermitian matrix defined at each frequency in the Fourier transform. Its real part is a symmetric matrix with six independent elements, while its imaginary part is antisymmetric with three independent elements. The elements of this matrix were then smoothed with a low-pass filter that averages the signal power over a band of width five complex Fourier coefficients and also normalized to obtain power spectral density. The separation of completely independent spectral estimates is thus \(\Delta f = 3.6 = 0.043778\ Hz\).

The autospectra obtained for \(B_u\) (thick line), \(B_p\) (thin line), and \(B_m\) (dashed line) are plotted in Figure 5. It is obvious that the power in the field-aligned component is almost an order of magnitude lower than the power in the two transverse components. Equally evident is the organization of the spectrum into a series of nearly equally spaced peaks. Such spectral peaks are characteristic of resonant oscillations of field lines in the Earth’s magnetosphere and suggest a similar origin at Ganymede. It should be noted that over most of the spectrum the power is greater in the \(\mathbf{u}\) component (radial) than in the \(\mathbf{p}\) component. However, the second peak has equal power in both components, while the sixth peak is dominated by the \(\mathbf{p}\) component. This suggests that the waves are not purely radially polarized but are elliptical with their major axis of polarization at a substantial angle to the radial direction.

With the objective of improving the identification of the spectral peaks, particularly the lowest harmonic, we performed two additional steps in the analysis. First, we prewhitened the spectra by taking first differences of the time series data. This effectively multiplies the spectrum by the factor \(f^2\), forcing the power to zero at zero frequency. Next, we performed an eigen-analysis of the spectral matrix as a function of frequency. In this procedure we take the real part of the spectral matrix and, at each frequency, determine a coordinate rotation \(R(f)\) that diagonalizes the real part, placing the minimum diagonal element at \(i = j = 3\). The resulting orthogonal transformation matrix \(R(f)\) is then used to perform a similarity transformation of both the real and imaginary parts of the spectral matrix to obtain a rotated matrix \(S_{ij}\) defined by

\[
S_{ij} = R^T G_{ij} R
\]

\((A.2)\)

The transformed spectral matrix has a diagonal real part and an imaginary part with most of the power in the upper left (2 by 2) submatrix. If the waves are truly transverse to the background field and are highly polarized, one eigenvalue will be much smaller than the other two.

A plot of the eigenvalues of the real part of the spectral matrix for the first difference data is presented in Figure 6. The spectrum is much flatter than that of the field-aligned data shown in Figure 5. In addition, the eigen-analysis has concentrated the power at each frequency into a principal axis coordinate system that better defines the spectral peaks, particularly the lowest harmonic. From this spectrum we identify the frequencies of the spectral peaks interactively by centering a crosshair on each peak. The frequencies thus determined to an accuracy of 0.004 Hz are listed in Table 1 and indicated with arrows in Figures 5 and 6.

It is difficult to assign error bars to the final spectral estimates. The original spectrum of the field-aligned data has estimates with 10 degrees of freedom (five harmonics). For random data with power \(P_0\) at frequency \(\omega\) we would expect the 95% confidence interval to be defined by points 1.8 \(P_0\) above and 0.4 \(P_0\) below each estimate. It can be seen that the range between peaks and troughs in the FA coordinate spectrum (Figure 5) slightly exceeds this range. To approximate the errors in the eigen-spectrum, we subjected Gaussian random data to the same analysis procedure. We obtained a flat spectrum with a root-mean-square deviation of 0.31. Then we fit a third-order polynomial to the principal eigenvalue in Figure 5 and calculated the root-mean-square deviation of the residuals from the fit. Again, the deviations are larger than expected by chance. Also, we determined that the average ratio of maximum to minimum eigenvalues of the random spectrum was 1.5, whereas for the FA coordinate spectrum of the measured fluctuations (Figure 5), the average ratio is 4.5. Again, the ratio is larger than expected for random data.

The rows of the transformation matrix \(R(f)\) determined by the eigen-analysis are the unit vectors of the principal axis coordinate system expressed in the FA coordinate system. The angles these vectors make with respect to the original coordinate system define the principal axes of the wave polarization ellipse at each frequency. These directions are more variable than the eigenvalues. Nonetheless, we find that direction of maximum variance is uniformly orthogonal to the average field across the entire spectrum. For most of the spectrum this direction is oriented near 45° to the radial direction. The \(\epsilon\) axis (minimum variance direction) is, on average, tilted by about 20° from the field, mostly in the direction of positive \(\phi\).

In the plane transverse to the minimum eigenvalue (represented by the upper left (2 by 2) submatrix in \(S_{ij}\)), we can determine the percent polarization of the signal and its ellipticity [Born and Wolf, 1964; Fowler et al., 1967]. We find that at each peak the average percent polarization exceeds 90%. This should be compared to the average value of 50% obtained with random data. The ellipticity is nearly uniformly ~0.5, indicating left elliptical (with respect to direction of background field) polarization.

The frequencies of the spectral peaks are listed in the second
column of Table 1. The proposed harmonic number of each peak is given in column 1. The difference between adjacent frequencies are given in column 3. The average separation of the harmonic numbers 2-6 is 0.125 Hz.

The identification of the fundamental frequency is the least certain, but our analysis determines a peak with period 17 s (f = 0.058 Hz). This value must be regarded as less certain than the higher-frequency estimates, as the detrending process that removes the background field significantly affects the shape of the spectrum at the low-frequency end and 0.058 Hz corresponds to only the third completely independent spectral estimate. However, its uncertainty is of order 0.018.

Acknowledgments. The authors wish to acknowledge helpful discussions of this topic with Christophe Zimmer and Arko Eviatar. This research was supported by the National Aeronautics and Space Administration through Jet Propulsion Laboratory under contract JPL 958694, UCLA Institute of Geophysics and Planetary Physics Publication 5105.

Janet L. Gilmann thanks Ian R. Mann and Richard W. McIntire for their assistance in evaluating this paper.

References


Newton, R. S., D. J. Southwood, and W. J. Hughes, Damping of geomagnetic pulsations by the ionosphere, Planet. Space Sci, 26, 201-209, 1978.

Orr, D., Magnetospheric hydromagnetic waves: Their eigenperiods, amplitudes and phase variation, a tutorial introduction, J. Geophys.., 55, 76-84, 1986.


K. K. Kuruzha, M. G. Kivelson, R. L. McPherron, and M. Volwinkel, Institute of Geophysics and Planetary Physics, University of California, 6843 Stichter Hall, 405 Hilgard Avenue, Los Angeles, CA 90024-1567.

(Received November 19, 1998; revised February 26, 1999; accepted March 25, 1999.)