Evidence for a magnetosphere at Ganymede from plasma-wave observations by the Galileo spacecraft

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On 27 June 1996 the Galileo spacecraft[1,2] made the first of four planned close fly-bys of Ganymede, Jupiter's largest moon. Here we report measurements of plasma waves and radio emissions, over the frequency range 5 Hz to 5.6 MHz during the first encounter. Intense plasma waves were detected over a region of space nearly four times Ganymede's diameter, which is much larger than would be expected for a simple wake arising from Ganymede's passage through Jupiter's rapidly rotating magnetosphere. The types of waves detected (whistler-mode emissions, upper hybrid waves, electrostatic electron cyclotron waves and escaping radio emission) strongly suggest that Ganymede has a large, extended magnetosphere of its own. The data indicate the presence of a strong ($B > 400$ nT) magnetic field, and show that Ganymede is surrounded by an ionosphere-like plasma with a maximum electron density of about 100 particles cm^{-3} and a scale height of about 1,000 km.

The trajectory for the Ganymede fly-by is shown in Fig. 1. This fly-by was designed to obtain measurements in the wake created by the co-rotating magnetospheric plasma of Jupiter. The closest approach occurred at 06:29:07 UT (universal time, h:min:s, at the spacecraft) at an altitude of 835 km and a radial distance of 1.32 times the radius of Ganymede, $1.32 R_G$ (where $1 R_G = 2{,}634$ km). Spectrograms of the electric and magnetic field intensities obtained from the plasma-wave instrument for a 2.5-hour interval around the time of closest approach are shown in Fig. 2. The intensities are colour coded with red being the most intense and blue being the least intense. A major response is evident for a period of nearly 50 minutes (from 06:14 to 07:02 UT) around the time of closest approach. This response lasts much longer than the time it takes to cross the diameter of Ganymede, which is only about 12 minutes. As no other comparable response has been observed elsewhere in Galileo's orbit, it is clear that these effects are associated with Ganymede.

Because the magnetic field measurements are the simplest to analyse, we start by discussing the magnetic field intensities (Fig. 2*b*). The onset of the magnetic field response associated with Ganymede is somewhat confused by interference from the ultraviolet spectrometer instrument from about 06:13 to 06:18 UT (labelled 'interference' in Fig. 2*b*). A few minutes after this interference ends, at about 06:23 UT, a broad irregular band of noise can be seen starting in the frequency range around a few hundred hertz. This noise is associated with Ganymede. Over the next few minutes, this band of noise becomes more intense and gradually rises in frequency, eventually reaching a peak frequency of about 6 kHz at about 06:29 UT, near closest approach. After closest approach the noise gradually declines in frequency and continues with relatively high intensities for about 30 minutes, to about 06:58 UT. A similar band of noise is also present in the electric field spectrogram (Fig. 2*a*).

As the band of noise described above has both electric and magnetic fields, it clearly consists of electromagnetic waves. In this frequency range, well above the ion cyclotron frequencies and (as we will show) below the electron plasma frequency, the only electromagnetic plasma wave mode that can propagate is the whistler mode[3]. The presence of strong whistler-mode emissions in the vicinity of Ganymede is surprising, as these emissions are normally generated by energetic radiation belt electrons[4]. Although the spacecraft is located in the jovian radiation belt, there is no evidence of comparable whistler-mode emissions either before or after the Ganymede fly-by, so the emissions are clearly associated with Ganymede. Fine structure in the spectrum also shows that the emissions are a mixture of 'chorus' and 'hiss' (these types of whistler-mode emissions are defined in ref. 5). Chorus and hiss are commonly observed in the magnetospheres of the magnetized planets[6].

The presence of whistler-mode emissions has important implications concerning the magnetic field strength in the vicinity of Ganymede. It is known[3] that the whistler mode cannot propagate at frequencies above the electron cyclotron frequency, $f_c = 28B$ Hz, where B is the magnetic field strength in nanotesla. In fact, whistler-mode emissions are seldom observed at frequencies above one-half the electron cyclotron frequency[7]. As the maximum frequency observed near closest approach is approximately 6 kHz, this implies that the electron cyclotron frequency must be at least 12 kHz. From the equation $f_c = 28B$, it follows that the magnetic field strength must be at least 400 nT. This field strength is considerably stronger than the jovian magnetic field at the orbit of Ganymede which is only about 100 nT. We conclude that a relatively strong magnetic field must exist around Ganymede. This result is in agreement with the on-board magnetometer measurements of Kivelson *et al.*[8], which show that Ganymede has an internally generated magnetic field with an equatorial surface field strength of about 750 nT. The electron cyclotron frequency computed from the magnetometer data is shown by the white line labelled f_c in Fig. 2*b*. As can be seen, the maximum frequency of the whistler-mode emissions is approximately one-half the electron cyclotron frequency.

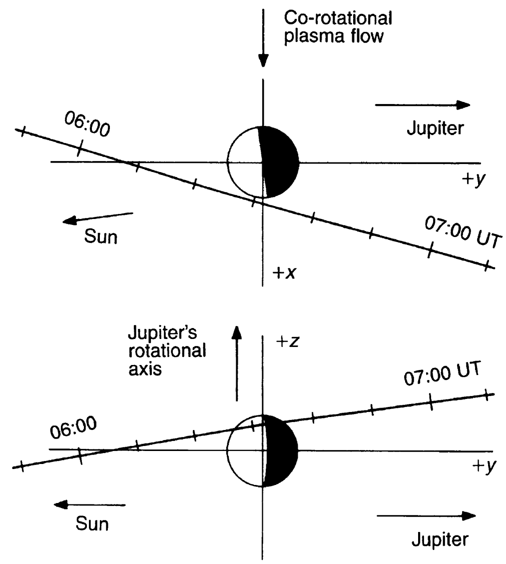

FIG. 1 The trajectory of Galileo during the first Ganymede fly-by. The Ganymede-centred coordinate system has the $+z$ axis aligned parallel to Jupiter's rotational axis and the $+x$ axis parallel to the nominal co-rotational plasma flow induced by Jupiter's rotation. The top diagram shows the view looking towards the $+z$ axis, and the bottom diagram shows the view looking towards the $+x$ axis.

We now consider the electric field spectrum. On the inbound pass, a series of broadband electric field noise bursts can be seen in Fig. 2*a*, from about 06:14 to 06:20 UT, and again on the outbound pass, from about 06:58 to 07:02 UT. These broadband noise bursts effectively define the outer limits of the plasma wave response associated with Ganymede. The noise bursts are most intense at low frequencies, but extend with measurable intensities to frequencies as high as 10^5 Hz. No comparable response can be seen in the magnetic field, so the noise is electrostatic. Broadband electrostatic noise bursts of this type are commonly observed in planetary magnetospheres, and typically occur at boundaries, such as the bow shock[9] and magnetopause[10]. Comparisons with the magnetometer data of Kivelson *et al.*[8] show that the innermost noise burst at 06:19 UT on the inbound pass, and a similar noise burst at 07:00 UT on the outbound pass, coincide with abrupt magnetic field rotations that they identify as magnetopause crossings. Whether some of the remaining noise bursts could be associated with a bow shock remains to be investigated.

Immediately after the inbound magnetopause crossing, a narrowband emission can be seen in the electric field spectrogram starting at a frequency of about 20 kHz at 06:20 UT, rising to a frequency of about 60 kHz at 06:30 UT, and then declining to about 16 kHz at 06:40 UT. Narrowband emissions of this type are a common feature of planetary magnetospheres[11–14], and are caused by electrostatic waves at the upper hybrid resonance frequency, $f_{\rm UH}$. Upper hybrid emissions can be used to provide very accurate measurements of the local electron density. The upper hybrid frequency is given by $f_{\rm UH} = (f_{\rm p}^2 + f_{\rm c}^2)^{1/2}$, where $f_{\rm p} = 8{,}980\sqrt{N}$ Hz is the electron plasma frequency and N is the electron number density in $\rm cm^{-3}$ (ref. 3). From these equations, one can show that the electron density is given by $N = (f_{\rm UH}^2 - f_{\rm c}^2)/(8{,}980)^2\ \rm cm^{-3}$. Because $f_{\rm UH} \gg f_{\rm c}$, the cyclotron frequency contribution can be ignored. The electron density computed using this technique is shown in Fig. 3*b*. As can be seen, the electron density profile has a parabolic shape that is nearly symmetric around closest approach, starting at about $5\ \rm cm^{-3}$ at 06:20 UT, rising to about $45\ \rm cm^{-3}$ at 06:30 UT, and declining to about $4\ \rm cm^{-3}$ at 06:40 UT. A corresponding radial profile is shown in Fig. 3*a*. The close similarity between the inbound and outbound radial profiles shows that Ganymede is surrounded by a dense plasma envelope with a scale height of about 1,000 km. If the observed height dependence is extrapolated downwards, the electron density near the surface is estimated to be about $100\ \rm cm^{-3}$. Such large electron densities imply a substantial plasma source near Ganymede, probably caused by ionization of a neutral gas. At present, the only gaseous molecule known to exist at Ganymede is ozone, which is trapped in the surface ice[15]. These results strongly imply the existence of a substantial atmosphere around Ganymede.

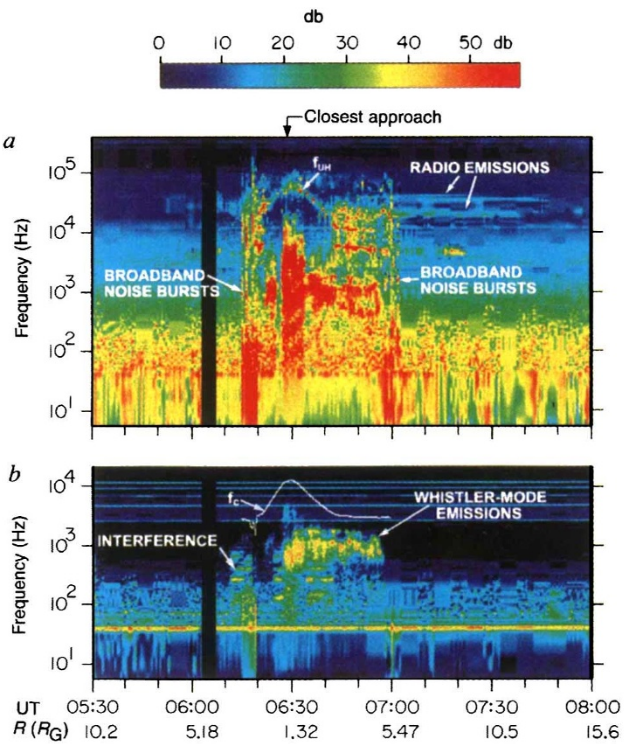

FIG. 2 Frequency–time spectrograms of the electric (*a*) and magnetic (*b*) field intensities detected by the Galileo plasma wave instrument during the 27 June 1996 Ganymede fly-by. The radial distance from the centre of Ganymede, R, is given in Ganymede radii, $R_{\rm G}$. The time of closest approach is indicated at the top. The electron cyclotron frequency, $f_{\rm c}$, shown by the white line in *b*, was computed from the magnetometer data of Kivelson *et al.*[8]. Various horizontal lines, particularly in the magnetic field spectrogram, are caused by spacecraft-generated interference. The colour scale shows the intensity in decibels.

During the interval from about 06:40 to 07:00 UT, a series of narrowband emissions can be seen from about 5 to 20 kHz. Emissions of this type are commonly observed in planetary magnetospheres and are called electrostatic electron cyclotron waves[16–18]. Electrostatic electron cyclotron waves occur near harmonics of the electron cyclotron frequency and are generated by highly anisotropic electron velocity distributions of the type often found in planetary radiation belts. Careful inspection of the electric field spectrogram also clearly shows a weak band of radio emissions propagating outward from the region where the upper hybrid waves are observed (labelled 'radio emission' in Fig. 2). These radio emissions are believed to be produced by a process called mode conversion, wherein the electrostatic energy associated with the upper hybrid waves is converted to escaping electromagnetic radiation. Radio emissions produced by such a mode conversion process are a common feature of planetary magnetospheres[19–22].

We now discuss in more detail the mechanisms by which the waves observed near Ganymede are generated. The whistler-mode emissions are of particular interest. According to Kennel and Petschek[4], the essential feature required to produce whistler-mode emissions is the presence of energetic electrons with a loss-cone anisotropy. A loss-cone anisotropy is produced when particles moving within a cone of directions along the magnetic field (the loss cone) strike the planet and are lost from the system. Such loss-cone distributions are normally associated with radiation belt particles trapped on 'closed' magnetic field lines that link opposite magnetic poles of the same body. However, according to the magnetic field model of Kivelson *et al.*[8], Galileo was on 'open' magnetic field lines during the entire fly-by, that is, field lines that link the magnetic field of Ganymede to the magnetic field of Jupiter. This unique situation arises because Ganymede is located within the magnetosphere of Jupiter. Therefore, it does not appear that the whistler-mode emissions are produced by electrons trapped in a radiation belt at Ganymede. Absorption by Ganymede probably simply imposes a loss cone on the pre-existing energetic jovian electron population, thereby leading to the growth of whistler-mode waves. A rough estimate can be made of the electron energies responsible for the whistler-mode emissions. Kennel and Petschek[4] show that the parallel energy of electrons in cyclotron resonance with a whistler-mode wave of frequency $\omega = 2\pi f$ is given by

$$W_{\parallel} = \frac{B^2}{8\pi N}\frac{\omega_{\rm c}}{\omega}\left(1 - \frac{\omega}{\omega_{\rm c}}\right)^3$$

where $\omega_{\rm c} = 2\pi f_{\rm c}$. Using parameters representative of the region near closest approach ($B \approx 500$ nT and $N \approx 45\ \rm cm^{-3}$), one can show that $B^2/(8\pi N)$ is about 14 keV. For a wave frequency of 1 kHz, the resonant energy is then about 150 keV. Intense fluxes of electrons with energies in this range are known to be present in Jupiter's magnetosphere[23–25]. The enhanced electron densities in

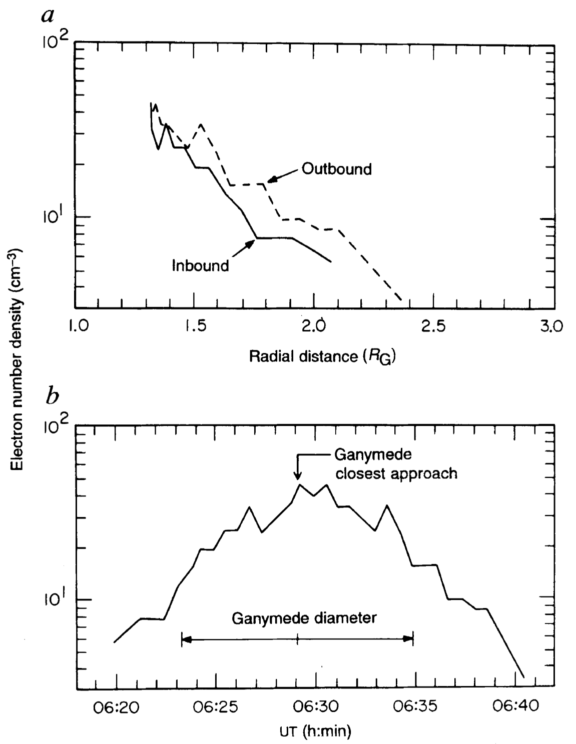

FIG. 3 The lower panel shows the electron density (N) determined from upper hybrid emissions in the vicinity of Ganymede. The upper panel shows the electron number density as a function of radial distance (R). Note the close similarity of the inbound and outbound profiles, which indicates that Ganymede is surrounded by an ionosphere-like plasma envelope extending several thousand kilometres above the surface.

the vicinity of Ganymede probably play an important role in the generation of these emissions by bringing the resonance energy down into a range where there are high electron intensities.

The electrostatic upper hybrid waves and electron cyclotron waves are closely related and constitute a general class known as electron cyclotron harmonic (ECH) waves. ECH waves are also driven by an anisotropy in the electron velocity distribution, similar to the whistler-mode. However, the electron energies involved[18], 10–100 eV, are usually much lower, and the origin of the anisotropy is quite different. Whereas absorption by a planetary body usually causes the anisotropy required to drive whistler-mode emissions, other factors usually cause the anisotropy required to produce electron cyclotron waves. For example, when electrons are convected into a region of strong magnetic field, the perpendicular energy is increased relative to the parallel energy ($W_\perp > W_\parallel$), thereby producing the necessary anisotropy. The electron plasma frequency to cyclotron frequency ratio, f_p/f_c, also plays a crucial role[17]. This ratio varies considerably during the fly-by, which may explain why the whistler-mode waves and the electron cyclotron waves occur in different regions. Electron precipitation into Ganymede's atmosphere due to pitch-angle scattering by whistler-mode or ECH waves could cause observable optical emissions, possibly accounting for the auroral emissions recently observed near Ganymede by the Hubble Space Telescope[26]. □

Received 30 September; accepted 5 November 1996.

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ACKNOWLEDGEMENTS. We thank the Galileo project team at the Jet Propulsion Laboratory for their efforts in obtaining these data, and M. Kivelson for providing the magnetometer data. We also thank L. Granroth and J. Groene for their assistance in the data processing at The University of Iowa. This work was supported by NASA through the Jet Propulsion Laboratory, and by the Centre National d'Etudes Spatiales (France).

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Discovery of Ganymede's magnetic field by the Galileo spacecraft

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THE Galileo spacecraft has now passed close to Jupiter's largest moon—Ganymede—on two occasions, the first at an altitude of 838 km, and the second at an altitude of just 264 km. Here we report the discovery during these encounters of an internal magnetic field associated with Ganymede (the only other solid bodies in the Solar System known to have magnetic fields are Mercury, Earth and probably Io[1]). The data are consistent with a Ganymede-centred magnetic dipole tilted by $\sim 10°$ relative to the spin axis, and an equatorial surface-field strength of ~ 750 nT. The magnetic field is strong enough to carve out a magnetosphere with clearly defined boundaries within Jupiter's magnetosphere. Although the observations require an internal field, they do not indicate its source. But the existence of an internal magnetic field should in itself help constrain models of Ganymede's interior.

On Galileo's first inbound pass following orbital insertion, the magnetometer[2] measurements followed reasonably closely the predictions from a recent model of the magnetic field of Jupiter's magnetosphere[3] that we refer to as the KK96 model. (This model consists of the O6 model[4] of Jupiter's internal field plus the field of a warped and hinged current sheet parametrized to fit the magnetic field measured on the Pioneer 10 outbound pass near the dawn meridian.) The field increased in magnitude with approach to Jupiter and varied in orientation at Jupiter's rotation period. Data from 00:00 UT (universal time; h:min) to 12:00 UT on