Absence of a magnetic-field signature in plasma-wave observations at Callisto

D. A. Gurnett*, W. S. Kurth*, A Roux† & S. J. Bolton‡

* *Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa 52242, USA*
† *Centre d'Etudes des Environnements Terrestre et Planetaires, Université Versailles Saint Quentin, 10/12 Avenue de l'Europe, 78140 Velizy, France*
‡ *Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, California 91109, USA*

The galilean moons of Jupiter are substantial bodies—three of them are larger than the Earth's Moon, and one is larger than Mercury—yet little has been known about them until very recently. The discovery of a magnetosphere[1] and magnetic field[2] associated with Ganymede was surprising, and raised the possibility that other galilean satellites, particularly Callisto (which is the second largest after Ganymede), also might have an internally generated magnetic field. Here we report observations of plasma waves around Callisto, detected during the recent fly-by of the Galileo spacecraft. The nature of the plasma waves indicates that Callisto, unlike Ganymede, does not have a magnetosphere or an internal magnetic field. The electron density near Callisto, however, is substantially higher than that in Jupiter's magnetosphere at this orbital radius, indicating that Callisto is a significant source of locally generated plasma. This plasma most probably comes from a tenuous atmosphere around Callisto, which may be similar to the hydrogen cloud around Ganymede, as the electron densities are somewhat comparable.

The trajectory for the 4 November Callisto fly-by is shown in Fig. 1. This first close fly-by of Callisto was designed to provide measurements in the wake created by the co-rotating plasma of Jupiter[3], which flows by Callisto at a speed of roughly 200 km s^{-1} (ref. 4). The closest approach occurred at 13:34:30 UT (universal time) at an altitude of 1,129 km and a radial distance of 1.47 R_C (where Callisto's radius, R_C, is 2,403 km). As can be seen, the trajectory passed directly through the geometric wake of Callisto. The time required to cross the wake is about 10 minutes.

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. For a description of the plasma-wave instrument, see ref. 5. As can be seen in the bottom panel of Fig. 2, there are no magnetic wave fields associated with Callisto. The absence of a magnetic response is in sharp contrast to the Ganymede fly-by[1], where strong electromagnetic emissions propagating in a mode known as the whistler mode[6] were observed at frequencies up to about 5 kHz. The absence of whistler-mode emissions at Callisto can be explained in part by magnetometer measurements[7], which show that the magnetic field near Callisto is very weak, $B \lesssim 35$ nT. As the whistler mode cannot propagate at frequencies above the electron cyclotron frequency, $f_c = 28\,B$ Hz, where B is the magnetic field strength in nanoteslas, whistler-mode emissions would not be expected in the vicinity of Callisto at frequencies above about 1 kHz. However, the weak magnetic field does not explain the absence of whistler-mode emissions at frequencies below 1 kHz. At Ganymede, strong whistler-mode emissions were observed down to frequencies as low as a few hundred hertz. The absence of similar low-frequency whistler-mode emissions at Callisto indicates that Callisto's interaction with the jovian magnetosphere is fundamentally different from at Ganymede. Most probably this difference is caused by the absence of an internally generated magnetic field.

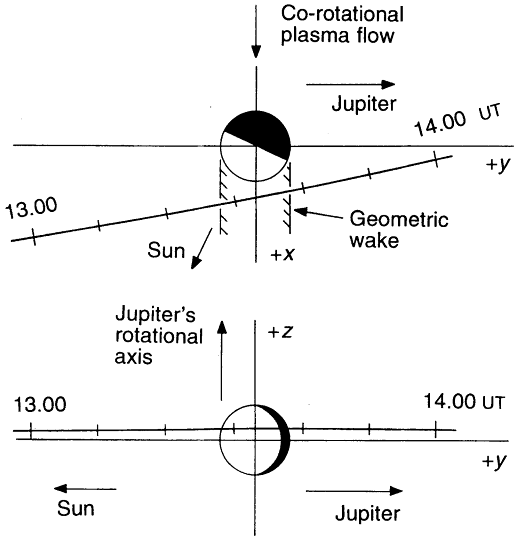

Figure 1 The Galileo trajectory during the 4 November 1996 Callisto fly-by. The Callisto-centred coordinate system has the +*z*-axis aligned parallel to Jupiter's rotational axis and the +*x*-axis parallel to the nominal co-rotational plasma flow induced by Jupiter's rotation. The +*y*-axis completes the right-hand coordinate system.

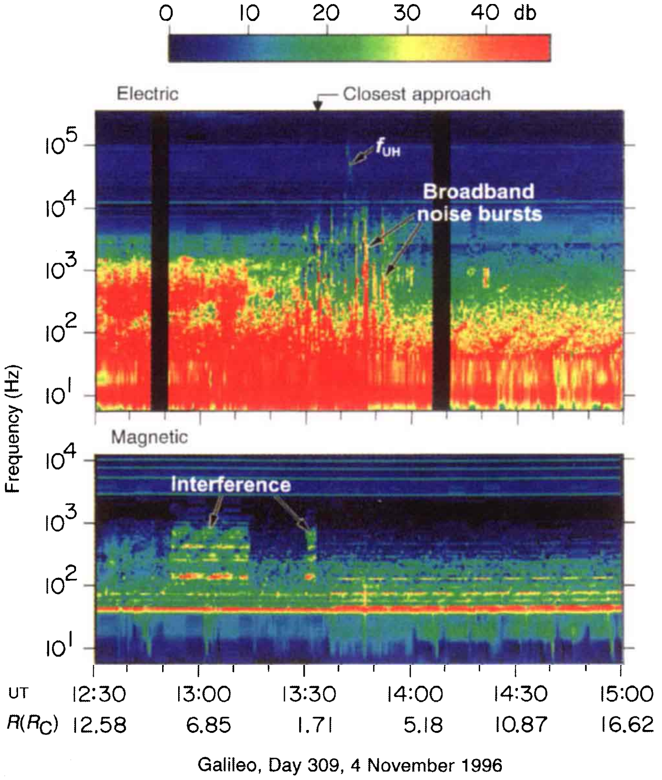

Figure 2 Frequency-time spectrograms of the electric (top panel) and magnetic (bottom panel) field intensities detected by the Galileo plasma wave instrument. The radial distance, R, from the centre of Callisto is given at the bottom of the plot in Callisto radii, R_C. The time of closest approach is indicated by the arrow at the top. Various horizontal lines, particularly in the magnetic field spectrogram, are caused by spacecraft-generated interference. The broadband magnetic field enhancements below about 10^3 Hz from about 12:52 to 13:12 UT, and again from about 13:29 to 13:33 UT, are caused by interference from the Ultraviolet Spectrometer instrument.

Inspection of the electric field spectrogram in Fig. 2 shows a series of noise bursts, from about 13:28 to 13:52 UT, which clearly stand out above the prevailing noise background. These noise bursts extend over a frequency range from about 10^2 to 10^4 Hz and seem to be associated with Callisto. No comparable noise bursts have been observed during other crossings of Callisto's orbit. Comparisons with the magnetic field measurements of ref. 7 clearly show that the bursts of electric field noise are closely correlated with magnetic field rotations. For example, the noise bursts at 13:33, 13:47 and 13:52 UT all correspond to abrupt changes in the B_x and B_y magnetic field components, changes that are indicative of field-aligned currents. Khurana *et al.*[7] have suggested that some of these field rotations (particularly from 13:40 to 13:52 UT) may be related to field-aligned currents flowing along the boundary of Jupiter's plasma sheet. Galileo was just crossing into the plasma sheet at the time of the Callisto fly-by. Data from the forthcoming Galileo fly-bys of Callisto should allow us to identify the origin of these field-aligned currents.

In addition to the bursts of electric field noise, a weak narrow-band emission can be seen in the electric field spectrogram drifting downwards in frequency from about 90 kHz at 13:41:30 UT to about 20 kHz at 13:43:30 UT. This emission intensifies at about 13:42:00 UT, causing a well defined enhancement in the spectrum at about 50 kHz. From similar observations at Jupiter and other planets[8–11], we can identify this emission as an electrostatic oscillation that occurs at the upper hybrid resonance frequency. For a discussion of this resonance, see ref. 6. Upper hybrid emissions provide a very accurate measurement of the local electron density. The upper hybrid resonance frequency is given by $f_{\mathrm{UH}} = (f_{\mathrm{p}}^2 + f_{\mathrm{c}}^2)^{1/2}$, where $f_{\mathrm{p}} = 8{,}980\sqrt{N}\,\mathrm{Hz}$ is the electron plasma frequency[6] and N is the electron density in cm^{-3}. Solving the above equation for the electron density gives $N = (f_{\mathrm{UH}}^2 - f_{\mathrm{c}}^2)/(8{,}980)^2\,\mathrm{cm}^{-3}$. For $f_{\mathrm{c}} = 1\,\mathrm{kHz}$ (that is, $B \approx 35\,\mathrm{nT}$), the corresponding electron densities vary from about $100\,\mathrm{cm}^{-3}$ ($f_{\mathrm{UH}} = 90\,\mathrm{kHz}$) at 13:41:30 UT to about $5\,\mathrm{cm}^{-3}$ ($f_{\mathrm{UH}} = 20\,\mathrm{kHz}$) at 13:43:30 UT. As $f_{\mathrm{c}} \ll f_{\mathrm{UH}}$, the magnetic field plays only a minor role in the calculation of electron density. The electron density associated with the intensification at 13:42:00 UT ($f_{\mathrm{UH}} = 50\,\mathrm{kHz}$) is $31\,\mathrm{cm}^{-3}$.

Two factors lead us to believe that these plasma densities are associated with Callisto. First, even though upper hybrid emissions are a common features of the jovian magnetosphere, these emissions usually occur in the inner regions of the magnetosphere very close ($\pm 2^\circ$) to the magnetic equator[12]. The Callisto fly-by occurred at a magnetic latitude of -7°, well outside the region where upper hybrid emissions are usually observed. Second, the electron densities, 5–$100\,\mathrm{cm}^{-3}$, are much higher than would be expected in the jovian magnetosphere at Callisto's orbit. For example, from electron density measurements made by Voyagers 1 and 2 (refs 4, 11), the maximum electron density at Callisto's orbit is expected to be less than $1\,\mathrm{cm}^{-3}$. Thus, the plasma detected near Callisto almost certainly originates from Callisto. Because a plasma is usually produced by ionizing a neutral gas, such large plasma densities, up to $100\,\mathrm{cm}^{-3}$, imply that a significant neutral atmosphere must exist around Callisto, possibly similar to the hydrogen exosphere recently discovered around Ganymede[13].

From the above description, it is clear that the plasma-wave signature of Callisto is quite different from that of Ganymede. There is no evidence of the types of plasma waves that are typically associated with a magnetized planet. Instead, the waves observed are more like those found near an unmagnetized object such as the Earth's Moon[14] or a comet[15]. Our results support the measurements of refs 7 and 16, which show that Callisto has little, if any, internally generated magnetic field. ☐

Received 2 January; accepted 18 March 1997.

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Acknowledgements. We thank the Galileo project team at the Jet Propulsion Laboratory for their considerable efforts in obtaining these data. We also thank K. Khurana for providing the magnetic field data before publication, and L. Granroth and J. Groene for their assistance in the data processing at the University of Iowa. This research was supported by NASA through the Jet Propulsion Laboratory, and by the Centre National d'Etudes Spatiales (France).

Correspondence should be addressed to D.A.G. (e-mail: donald-gurnett@uiowa.edu).

Absence of an internal magnetic field at Callisto

K. K. Khurana*, M. G. Kivelson*†, C. T. Russell*†, R. J. Walker* & D. J. Southwood‡

* *Institute of Geophysics and Planetary Physics,* † *Department of Earth and Space Sciences, University of California, Los Angeles, California 90095, USA*
‡ *Department of Physics, Imperial College of Science, Technology, and Medicine, London SW7 2BZ, UK*

Little is known about the internal properties of Callisto—the outermost of Jupiter's four large galilean moons—other than the average density (about $1.8\,\mathrm{g\,cm}^{-3}$). The recent unexpected discovery[1–4] that Ganymede, and perhaps Io, has an internally generated magnetic field, combined with gravity results[5,6] suggesting that both Ganymede and Io are internally differentiated with metallic cores and rocky mantles, has heightened anticipation of the results obtained by the Galileo spacecraft in its recent fly-by of Callisto. Here we report that the spacecraft, passing the moon at a distance of only ~1,100 km from the surface, detected only a small enhancement of the field strength (~7 nT), which may be related to changes in the jovian plasma environment caused by Callisto[7]. Callisto does not have an internally generated magnetic field.

On 4 November 1996, Galileo passed close to Callisto. Low-resolution magnetic-field[8] ($\Delta t = 24\,\mathrm{s}$) and particle data were acquired continuously around the time of closest approach. In addition, 45 minutes of full-resolution magnetic-field ($\Delta t = 0.33\,\mathrm{s}$) and plasma data were tape-recorded on board the spacecraft in the close vicinity of Callisto. These data have now been returned to Earth. Here we summarize the magnetometer observations from this close pass.

The closest approach occurred near 13:34:30 UT at a distance of 1.47 times the radius of Callisto ($1.47\,R_{\mathrm{C}}$; $R_{\mathrm{C}} = 2{,}403\,\mathrm{km}$) at a latitude of 13° with respect to Callisto's equator. The jovian plasma at the radial distance of Callisto moves[9] slower than the co-rotational velocity of $330\,\mathrm{km\,s}^{-1}$ but has a velocity in excess of $200\,\mathrm{km\,s}^{-1}$; it therefore continually overtakes Callisto whose orbital speed is $8.2\,\mathrm{km\,s}^{-1}$. Thus, a wake is formed ahead of Callisto in the downstream plasma. Galileo passed through this wake region at a distance of ~1,100 km from the surface of Callisto.

A five-hour (half jovian day) plot of the merged high- and low-