GEOPHYSICAL RESEARCH LETTERS, VOL. 27, NO. 13, PAGES 1867-1870, JULY 1, 2000

Plasma densities in the vicinity of Callisto from Galileo plasma wave observations

D. A. Gurnett, A. M. Persoon, W. S. Kurth
Dept. of Physics and Astronomy, University of Iowa, Iowa City

A. Roux
CETP/UVSQ, Velizy, France

S. J. Bolton
Jet Propulsion Laboratory, Pasadena, California

Abstract. The Galileo spacecraft has made seven close flybys of Jupiter's moon Callisto. During the closest of these (C22), which approached to within 535 km of the surface, the plasma wave instrument detected a very clear upper hybrid emission as the spacecraft passed near the moon. The peak electron density indicated by the upper hybrid resonance emission was 400 cm^{-3}, almost one-thousand times the electron density in the magnetosphere of Jupiter at the orbit of Callisto. These observations indicate that Callisto is probably surrounded by a dense ionospheric-like plasma.

Introduction

The Galileo spacecraft, which is in orbit around Jupiter, is in the process of carrying out a series of flybys of Jupiter's four large moons, Io, Europa, Ganymede, and Callisto. In this paper we report measurements of the plasma density in the vicinity of Callisto using data from the Galileo plasma wave instrument. For a description of the Galileo plasma wave instrument, see Gurnett et al. [1992]. One of the primary objectives of the Galileo plasma wave investigation is to obtain very accurate measurements of the local plasma density by measuring one or more of the characteristic frequencies of the plasma. As of this time, we have processed plasma wave data for seven flybys: C3, C9, C10, C20, C21, C22 and C23, where C stands for Callisto and the number is the orbit number on which the flyby occurred. The plasma wave observations obtained during the first Callisto flyby, C3, have already been reported by Gurnett et al. [1997]. During the C3 flyby a narrowband upper hybrid emission was observed as the spacecraft flew through the wake region downstream of Callisto. Upper hybrid emissions are important because the frequency of the emission can be used to compute the electron density. The peak electron density reported during the C3 pass was about 100 cm^{-3}. These observations provided the first hint of high plasma densities in the vicinity of Callisto. Unfortunately, the duration of the upper hybrid emission was very short (only about 2 minutes), so it was not possible to obtain a complete plasma density profile. Of the remaining Callisto flybys, only two, C10 and C22, produced plasma wave emissions that were suitable for determining the electron density.

The trajectories of the Galileo spacecraft during the C10 and C22 flybys are shown in Figure 1. The C10 flyby occurred on September 17, 1997, and the C22 flyby occurred on August 14, 1999. The coordinate system used in Figure 1 is a Callisto-centered coordinate system with the +z axis aligned parallel to Jupiter's rotational axis and the +x axis aligned parallel to the nominal plasma flow induced by the rotation of Jupiter's magnetosphere. The +y axis completes the right-hand coordinate system. As can be seen, on both flybys the spacecraft passed almost directly through the center of the geometric wake, which is taken to be a cylinder aligned along the +x axis and tangent to the surface of Callisto. On C10 the altitude of closest approach was 535 km and the time of closest approach was 0018:55 UT. On C22 the altitude of closest approach was 2299 km and the time of closest approach was 0830:52 UT.

C10 observations

A frequency-time spectrogram of the electric field intensities obtained from the Galileo plasma wave spectrum analyzer during the C10 flyby is shown in Figure 2. The spectrogram covers a total time span of 1 hour, from 2350 UT on September 16 to 0050 UT on September 17, and the frequency range extends from 5.6 Hz to 400 kHz. The intensities are color coded with red being the most intense and blue being the least intense. A relative intensity scale in dB is shown at the top of the spectrogram. The white line at a frequency of about 10^3 Hz is the electron cyclotron frequency computed from Galileo magnetic field measurements [Kivelson et al., 1999] using the equation $f_{ce} = 28$ B Hz, where B is the magnetic field in nT. As can be seen, a broad region of low-frequency electric field noise occurs on the inbound leg, from about 2355 UT (on September 16) to 0017 UT (on September 17), and a similar, but narrower, region of low-frequency electric field noise occurs on the outbound leg, from about 0030 to 0038 UT (on September 17). The frequency of this noise extends from the lowest frequency measured (5.6 Hz) to about 10 kHz. From similar observations during other Callisto flybys, such as C3, see Gurnett et al. [1997], it is clear that this noise is associated with Callisto.

Paper number 2000GL003751.
0094-8276/00/2000GL003751$05.00

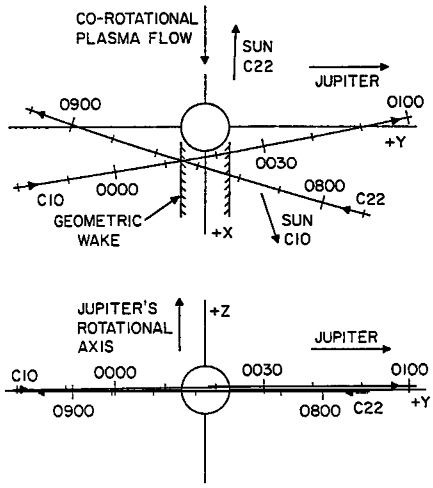

Figure 1. The Galileo trajectory in a Callisto-centered x, y, z coordinate system for the C10 and C22 flybys. The nominal co-rotational plasma flow induced by the rotation of Jupiter's magnetosphere is directed along the +x axis, with Jupiter located to the right, along the +y axis.

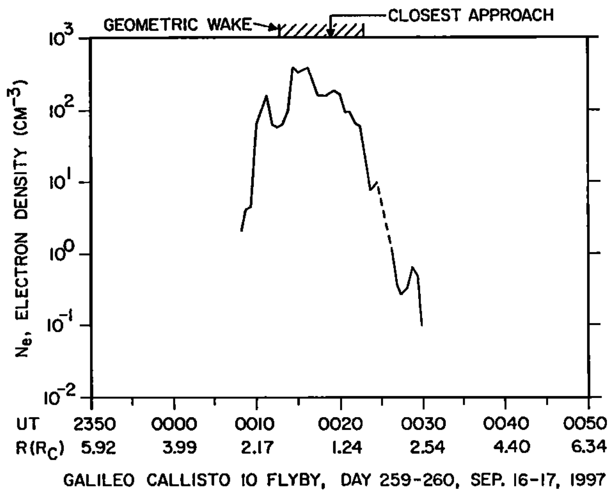

Figure 3. The electron density profile determined from the upper hybrid resonance frequency, f_{UH}, and the electron plasma frequency, f_{pe}, during the C10 flyby.

At frequencies above about 10 kHz, a narrow band of emission can be clearly seen in Figure 2 extending through the region near closest approach. The narrowband emission starts at a frequency of about 15 kHz at 0008 UT, shortly before the entry into the geometric wake, rises to a peak frequency of about 100 kHz from about 0010 to 0023 UT, within the geometric wake, and falls to a frequency of about 10 kHz at 0025 UT, near the exit from the geometric wake. We have considered two possible explanations for this emission. The first possibility is that the emission is caused by narrowband kilometric radiation, which is a Jovian radio emission sometimes abbreviated nKOM, and the second possibility is that the emission is caused by electrostatic waves at the upper hybrid resonance frequency, f_{UH}. Narrowband kilometric radiation has a sharply defined peak at about 100 kHz [Kaiser and Desch, 1980], and is strongly modulated by the rotation of Jupiter, typically with one peak per rotation. We have checked to see if an emission comparable to Figure 2 occurred in synchronism with the Jovian rotation, and none was observed. Therefore, we have concluded that the emission is not nKOM.

Upper hybrid resonance emissions are a common feature of planetary magnetospheres [Mosier et al., 1973; Warwick et al., 1979; Kurth et al., 1980], and typically have bandwidths ranging from one to several percent. The spectrum of the narrowband emission in Figure 2 is typical of upper hybrid emissions that have been observed at Io [Gurnett et al., 1996a], Europa [Gurnett

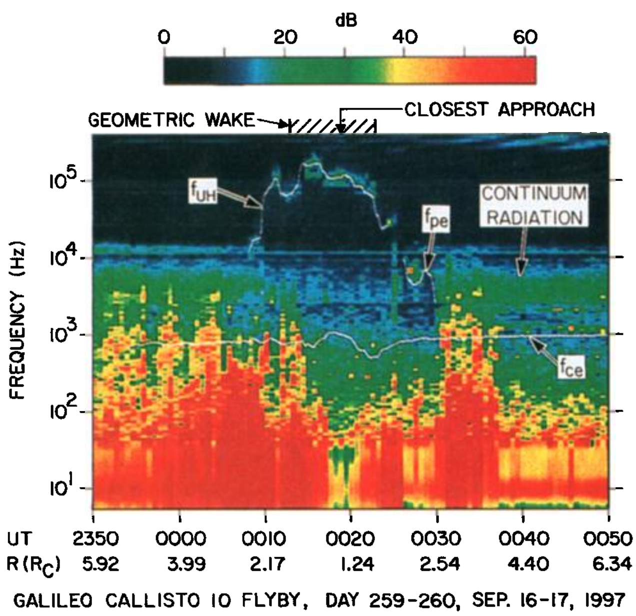

Figure 2. A frequency-time spectrogram of the electric field intensities detected by the Galileo plasma wave instrument during the C10 flyby. The radial distance to the center of Callisto, R, is given at the bottom of the spectrogram in Callisto radii, R_C, which is taken to be 2403 km.

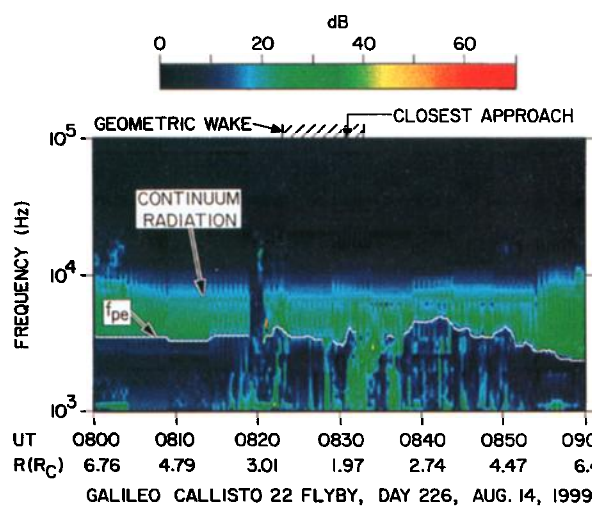

Figure 4. A frequency-time spectrogram of the electric field intensities detected by the Galileo plasma wave instrument during the C22 flyby. The white line indicates the low-frequency cutoff of the band of trapped continuum radiation, which is believed to be at or very near the electron plasma frequency, f_{pe}.

et al., 1998], and Ganymede [Gurnett et al., 1996b]. Therefore, we have concluded that the emission is at the upper hybrid resonance frequency. Upper hybrid emissions are important because they provide a method of making very accurate and reliable measurements of the electron density. The upper hybrid resonance frequency is given by $f_{UH} = (f_{pe}^2 + f_{ce}^2)^{1/2}$, where f_{pe} is the electron plasma frequency and f_{ce} is the electron cyclotron frequency. The electron plasma frequency is given by $f_{pe} = 8980\sqrt{N_e}$ Hz, where N_e is the electron density in cm^{-3}. When the cyclotron frequency is known, as it is from the Galileo magnetometer measurements, the electron density can be determined directly from the upper hybrid resonance frequency. Specifically, the electron density is given by $N_e = (f_{UH}^2 - f_{ce}^2)/(8,980)^2 cm^{-3}$. If the upper hybrid frequency is much greater than the electron cyclotron frequency ($f_{UH} \gg f_{ce}$), as it is in this case, then the electron density is directly proportional to the square of the upper hybrid resonance frequency. Since the wavelengths of upper hybrid waves are almost always much larger than the characteristic dimensions of the spacecraft, this method of measuring the electron density has the advantage that the electron density is almost completely unaffected by spacecraft charging and sheath effects.

The C10 electron density profile

The broad peak in the upper hybrid resonance frequency evident in Figure 2 clearly shows that the spacecraft passed through a dense plasma near and immediately downstream of Callisto. To determine the electron density profile, we traced the upper hybrid resonance frequency from the spectrogram, and then converted these measurements to electron densities. The upper hybrid resonance frequency obtained using this procedure is shown by the white line labeled f_{UH} in Figure 2. As can be seen, the bandwidth of the emission line varies considerably, from a minimum of about 6 percent, which is the channel-to-channel spacing, to sometimes as much as 30 percent, which corresponds to a spacing of five channels. Because of the line broadening there is a question of where to place the upper hybrid resonance frequency. The broadening is most likely a hot plasma effect in which the upper hybrid resonance emission splits into several closely spaced bands near the upper hybrid frequency. The frequency spacing between the bands is typically the electron cyclotron frequency [Ashour-Abdalla and Kennel, 1978], which in this case is about 10^3 Hz. When significant line broadening occurs our procedure is to assign the upper hybrid frequency to the channel with the highest intensity, which is usually near the center of the band.

After about 0026 UT it is no longer possible to clearly identify the upper hybrid emission line. However, starting at about this same time a well-defined low-frequency cutoff can be seen for approximately 4 minutes in the band of radio emission from 3 to 8 kHz on the right-hand side of the spectrogram. This type of radio emission is a common feature of planetary magnetospheres and is called continuum radiation [Gurnett and Shaw, 1973]. Continuum radiation is known to consist of free-space electromagnetic radiation that is trapped in the low density cavity of the magnetosphere. Since free-space electromagnetic radiation cannot propagate at frequencies less than the electron plasma frequency, continuum radiation often has a sharp low-frequency cutoff at the local electron plasma frequency. This cutoff can be used to provide measurements of the electron density [Scarf et al., 1979; Gurnett et al., 1981]. In principle, the low-frequency limit of the continuum radiation only provides an upper limit to the local electron plasma frequency, since the radiation may not be accessible to the point where the wave frequency is equal to the plasma frequency. However, since the continuum radiation is almost certainly incident with a broad range of wave normals on a region with a steep density gradient, in this case there is good reason to believe that the propagation cutoff is at the local electron plasma frequency. The sharp cutoff typically provides a good indication that the cutoff is at the local plasma frequency. Note that the band of continuum radiation is completely excluded from the region of high plasma density from about 0008 to 0026 UT, as one would expect, since the upper hybrid resonance frequency, hence electron plasma frequency, is much greater than the frequency of the continuum radiation. Based on these arguments, we will assume that the low-frequency cutoff from 0026 to 0030 UT is at the local electron plasma frequency. The electron density can then be computed using $N_e = (f_{pe}/8980)^2 cm^{-3}$, where f_{pe} is the low-frequency cutoff of the continuum band in Hz.

The electron density profile obtained using the above procedure is shown in Figure 3. As can be seen the electron density profile starts at a value of about 1 cm^{-3} at 0008 UT, a few minutes before entering the geometric wake, rises rapidly to a broad peak of about $4 \times 10^2 cm^{-3}$ near the center of the geometric wake, and then declines rapidly to a value of about 10^{-1} cm^{-3} at 0030 UT, a few minutes after exiting the geometric wake. Typical uncertainties in the electron density range from about ±6% when the upper hybrid line is narrow, to as much as ±30% when the upper hybrid line is broad. Unfortunately, the background electron density in the Jovian magnetosphere (i.e., before 0008 UT and after 0030 UT) cannot be determined, since there is no clearly defined plasma wave resonance or cutoff that would indicate the density. However, from the low-frequency limit of the band of continuum after about 0038 UT, which is at about 2 kHz, we can say that the electron density is probably less than about 5×10^{-2} cm^{-3}.

C22 observations

A spectrogram of the electric field intensities observed during the C22 flyby is shown in Figure 4. During this flyby, a strong band of continuum radiation can be seen from about 3 to 10 kHz. The continuum radiation has a very clearly defined low-frequency cutoff that varies somewhat, but is generally in the range from about 3 to 4 kHz. As described above, the low frequency cutoff of the continuum radiation gives an absolute upper limit to the electron plasma frequency, and is probably at or near the local electron plasma frequency. In the geometric wake region, which is indicated by the crosshatching at the top of the spectrogram, the maximum plasma frequency is 4.1 kHz, which corresponds to a maximum electron density of 0.21 cm^{-3}. There is no evidence of a region of enhanced plasma density comparable to that observed on C10. The only unusual feature is the abrupt dropout of continuum radiation during an approximately one-minute interval from about 0819:30 to

0820:30 UT, shortly before the entry into the geometric wake. This dropout could be caused by an abrupt increase in the plasma frequency (hence electron density) in this region. However, there is no evidence of an upper hybrid emission or any other type of emission in this region that would give the electron density. All we can say is that the electron plasma frequency could be greater than about 10 kHz, which corresponds to an electron density greater than 1 cm^{-3}.

Discussion

The upper hybrid resonance measurements obtained by the plasma wave instrument during the C10 flyby clearly show that the electron densities near Callisto are quite high, much greater than the plasma density in the Jovian magnetosphere at the orbit of Callisto. Clearly Callisto is a significant source of plasma. The peak electron densities observed during the C10 flyby, about 400 cm^{-3}, are comparable to those observed during the G1 and G2 flybys of Ganymede [Gurnett et al., 1996a; Eviatar et al., 2000] and the E4 and E6 flybys of Europa [Gurnett et al.,1998]. However, they are substantially less than the very high electron densities, about 4×10^4 cm^{-3}, observed in the downstream wake of Io [Gurnett et al., 1996b]. Unfortunately, because of the paucity of suitable plasma wave signatures, there is very little that we can say about the spatial and temporal distribution of plasma around Callisto. The observations of high plasma densities in the region immediately downstream of Callisto during the C3 and C10 flybys suggest that a plume of plasma is being swept downstream by an interaction with the magnetospheric plasma. This interpretation would seem reasonable, were it not for the C22 flyby, which showed no evidence at all of enhanced plasma densities in the downstream wake region. The closest approach altitude of C22, which was 2299 km, is considerably higher than the closest approach altitudes of C3 and C10, which were 1135 and 535 km. These observations suggest that the plasma distribution is confined to the near vicinity of the moon, and does not have a plume-like configuration. Such a plasma density distribution would be characteristic of an ionosphere-like plasma distribution, such as has been described by Eviatar et al. [2000] for Ganymede. However, other factors could be responsible for the low plasma density on C22. The closest approaches for C3 and C10, which had the highest plasma densities, were on the sunlight side of the moon (at local times, LT, of 14.5 and 11.6 Hr); whereas the closest approach for C22, which had very low plasma densities, was on the dark side of the moon (LT of 22.9 Hr). This local time dependence could indicate that solar illumination plays a role in controlling the plasma density. Also, since the Jovian magnetosphere is known to have longitudinal asymmetries [Hill et al., 1983], it is possible that the system III longitude and/or the magnetic latitude could play a role in controlling the plasma density.

Acknowledgment. The authors wish to thank M. Kivelson of UCLA for providing the magnetic field data from the Galileo magnetometer. The research at the University of Iowa was supported by NASA through contract 958779 with the Jet Propulsion Laboratory.

References

Ashour-Abdalla, M. and C. F. Kennel, Nonconvective and convective electron cyclotron harmonic instabilities, *J. Geophys. Res.*, 83,1531-1543, 1978.

Eviatar, A., V. Vasyliunas, and D. A. Gurnett, The ionosphere of Ganymede, *Planet. and Space Sci.*, in press, 2000.

Gurnett, D. A., and R. R. Shaw, Electromagnetic radiation trapped in the magnetosphere above the plasma frequency, *J. Geophys. Res., 78,* 8136-8149, 1973.

Gurnett, D. A., F. L. Scarf, W. S. Kurth, R. R. Shaw, and R. L. Poynter, Determination of Jupiter's electron density profile from plasma wave observations, *J. Geophys. Res., 86,* 8199-8212, 1981.

Gurnett, D. A., et al., The Galileo plasma wave investigation, *Space Sci. Rev., 60,* 341-355, 1992.

Gurnett, D. A., W. S. Kurth, A. Roux, S. J. Bolton, and C. F. Kennel, Galileo plasma wave observations in the Io torus and near Io, *Science, 274,* 391-392, 1996a.

Gurnett, D. A., W. S. Kurth, A. Roux, S. J. Bolton, and C. F. Kennel, Evidence for a magnetosphere at Ganymede from plasma waves observations by the Galileo spacecraft, *Nature, 384,* 535-537, 1996b.

Gurnett, D. A., W. S. Kurth, A. Roux, and S. J. Bolton, Absence of a magnetic-field signature in plasma wave observations at Callisto, *Nature, 387,* 261-262, 1997.

Gurnett, D. A., et al., Galileo plasma wave observations near Europa, *Geophys. Res. Lett., 25,* 237-240, 1998.

Hill, T. W., A. J. Dessler, and C. K. Goertz, Magnetospheric models, in *Physics of the Jovian Magnetosphere,* edited by A. J. Dessler, pp. 353-394, Cambridge Univ. Press, Cambridge, 1983.

Kaiser, M. L., and M. D. Desch, Narrow-band Jovian kilometric radiation: A new radio component, *J. Geophys. Res., 7,* 389-392, 1980.

Kivelson, M. G., K. K. Khurana, J. D. Means, C. T. Russell, and R. C. Snare, The Galileo magnetic field investigation, *Space Sci. Rev., 60,* 357-383, 1992.

Kivelson, M. G., et al., Europa and Callisto: Induced or intrinsic fields in a periodically varying plasma environment, *J. Geophys. Res., 104,* 4609-4625, 1999.

Kurth, W. S., D. D. Barbosa, D. A. Gurnett, and F. L. Scarf, Electrostatic waves in the Jovian magnetosphere, *Geophys. Res. Lett., 7,* 57-60, 1980.

Mosier, S. R., M. L. Kaiser, and L. W. Brown, Observations of noise bands associated with the upper hybrid resonance by the IMP 6 radio astronomy experiment, *J. Geophys. Res., 78,* 1673-1677, 1973.

Scarf, F. L., D. A. Gurnett, and W. S. Kurth, Jupiter plasma wave observations: An initial Voyager 1 overview, *Science, 204,* 991-995, 1979.

Warwick, J, W., et al., Voyager 1 planetary radio astronomy observations near Jupiter, *Science, 204,* 995-998, 1979.

S. Bolton, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109.

D. Gurnett, W. Kurth, and A. Persoon, Dept. of Physics and Astronomy, University of Iowa, Iowa City, IA 52242. (e-mail: donald-gurnett@uiowa.edu)

A. Roux, CETP/UVSQ, 10/12 Avenue de l'Europe, 78140 Velizy, France.

(Received January 31, 2000; revised April 9, 2000; accepted April 13, 2000.)