Galileo plasma wave observations near Europa

D. A. Gurnett,[1] W. S. Kurth,[1] A. Roux,[2] S. J. Bolton,[3]
E. A. Thomsen,[1] and J. B. Groene, [1]

Abstract. In this paper we present results from the Galileo plasma wave instrument during the first two flybys of Europa, which occurred on December 19, 1996, and February 20, 1997. Strong whistler-mode noise was observed in the vicinity of Europa during both flybys. Emission at the upper hybrid resonance frequency, f_{UH}, and a propagation cutoff at the local electron plasma frequency, f_{pe}, provided measurements of the local electron number density. The electron density measurements show a region of highly disturbed plasma in the vicinity of Europa with density enhancements ranging from about 30 to 100 cm^{-3} above the ambient Jovian magnetospheric background, which in both cases was about 80 cm^{-3}.

1. Introduction

The Galileo spacecraft, which was placed in orbit around Jupiter on December 8, 1995, is carrying out a series of close flybys of the four Galilean satellites [*Johnson et al.,* 1992]. Since the Galilean satellites are immersed in the rapidly rotating magnetosphere of Jupiter, the interaction of these satellites with the Jovian magnetospheric plasma has been of considerable interest. In this paper we discuss plasma wave observations obtained during the first two close flybys of Europa, which occurred on December 19, 1996, and February 20, 1997. The spacecraft trajectories during these flybys are shown in Figure 1. A Europa-centered coordinate system is used with the +z axis aligned parallel to Jupiter's rotational axis and the +x axis aligned parallel to the nominal co-rotational plasma flow induced by Jupiter's rotation. The +y axis completes the right-hand coordinate system. The flyby on December 19, 1996, is labeled E4, which is the designation for the Europa flyby that occurred on orbit 4. The flyby on February 20, 1997, occurred on orbit 6 and is labeled E6. As can be seen, the two flyby geometries are quite different. The E4 flyby passed through the wake immediately downstream of Europa, and the E6 flyby passed through the region immediately upstream of Europa. The E4 closest approach to Europa occurred at 06:52:58 Universal Time (UT) at a radial distance of 1.44 R_E (the radius of Europa is taken to be 1 R_E = 1565 km), and the E6 closest approach occurred at 17:06:10 UT at a radial distance of 1.37 R_E.

[1]Dept. of Physics and Astronomy, University of Iowa.
[2]CETP/UVSQ, Velizy, France.
[3]Jet Propulsion Laboratory, Pasadena.

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2. Observations

Spectrograms of the electric and magnetic fields obtained from the Galileo plasma wave instrument during the E4 and E6 flybys are shown in Figures 2 and 3. For a description of the Galileo plasma wave instrument, see *Gurnett et al.,* [1992]. The top panel shows the electric field intensities and the bottom panel shows the magnetic field intensities. The intensities are color coded with red being the most intense and blue being the least intense. An intensity scale in dB is shown at the top of each plot. As can be seen, major responses are evident in both the electric and magnetic field spectrograms around the times of closest approach.

Although the electric and magnetic field responses have some close similarities, they do differ considerably in certain details, particularly with respect to the spectrum. Since the magnetic field spectrum is the simplest, we start with a discussion of the magnetic field. On both flybys the Europa-related magnetic field response extends over a very broad frequency range, from about ten Hz to as much as ten kHz. The peak magnetic field intensity on the E4 flyby occurred at about 06:50

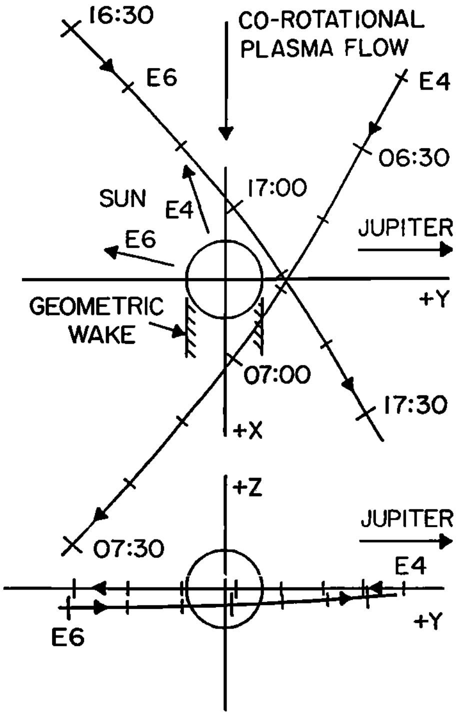

Figure 1. The Galileo trajectories during the E4 and E6 flybys of Europa. The E4 flyby passed through the wake region downstream of Europa with a closest approach altitude of 692 km. The E6 flyby passed through the region upstream of Europa with a closest approach altitude of 586 km.

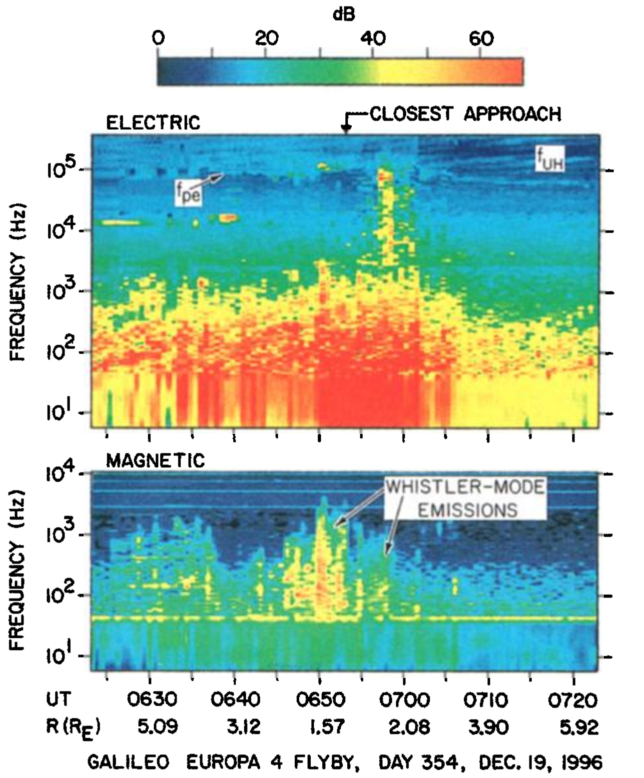

Figure 2. Spectrograms showing the electric and magnetic field intensities detected by the Galileo plasma wave instrument during the E4 flyby. The strong magnetic field response near closest approach (bottom panel) is believed to be due to whistler-mode emissions. The narrowband emissions labeled f_{UH} (top panel) are upper hybrid waves, and the low-frequency cutoff labeled f_{pe} is the propagation cutoff of free-space electromagnetic waves at the local electron plasma frequency.

UT, shortly before closest approach. The broadband root-mean-square (rms) magnetic field strength at this point, integrated over a frequency range from 10 Hz to 10 kHz, was B_{rms} = 0.36 nT. Since the onset and termination of the magnetic field noise is gradual, the boundaries of the region of enhanced magnetic noise is difficult to accurately determine, but is roughly 06:45 to 07:00 UT. These times span a region slightly more than twice the diameter of Europa, and correspond very well with the region where the Galileo magnetometer detected large magnetic field perturbations [*Kivelson et al.*, 1997]. The magnetic field detected by the magnetometer near Europa was about B = 450 nT, which corresponds to an electron cyclotron frequency (f_{ce} = 28 B Hz) of about 12.6 kHz, and a proton cyclotron frequency of about 7 Hz. Thus, the magnetic field noise is between the proton cyclotron frequency and the electron cyclotron frequency. The only electromagnetic plasma wave mode that can propagate in this frequency range is the whistler mode [*Stix*, 1962].

On the E6 flyby the peak magnetic field intensity occurred at about 17:03 UT, again slightly before closest approach. The broadband rms magnetic field strength, integrated from 10 Hz to 10 kHz, was B_{rms} = 0.75 nT, significantly stronger than for the E4 flyby. A discernable magnetic response can be seen extending from about 16:55 to 17:15 UT, again corresponding to a region slightly more than twice the diameter of Europa. Although no data were available from the magnetometer during the E6 flyby [personal communication, M. Kivelson, 1997], since the radial distance from Jupiter is almost the same, one would expect the electron cyclotron frequency near Europa to be comparable to the E4 flyby (i.e., $f_{ce} \simeq 12$ kHz), which again indicates that the noise is propagating in the whistler mode.

Simple inspection of the electric field spectrograms in Figures 2 and 3 shows that the electric field response consists of three components: (1) a broadband low-frequency component that extends from a few Hz to about ten kHz, (2) a broadband high-frequency component that extends from a few Hz to about one hundred kHz, and (3) a narrowband emission at about 100 kHz. On the E6 flyby the low-frequency electric field component appears to be closely correlated with the low-frequency magnetic field noise, which is consistent with the interpretation that this noise is caused by electromagnetic whistler-mode waves. The peak electric field intensity occurred at 17:08 UT, shortly after closest approach. The broadband rms electric field strength at this point, integrated from 10 Hz to 10 kHz was E_{rms} = 5.1 mV/m. On the E4 flyby, the correlation between the low-frequency electric and magnetic field components is not as good as on the E6 flyby. The low-frequency electric field noise, which extends from about 06:50 to 07:20 UT, extends over a broader region

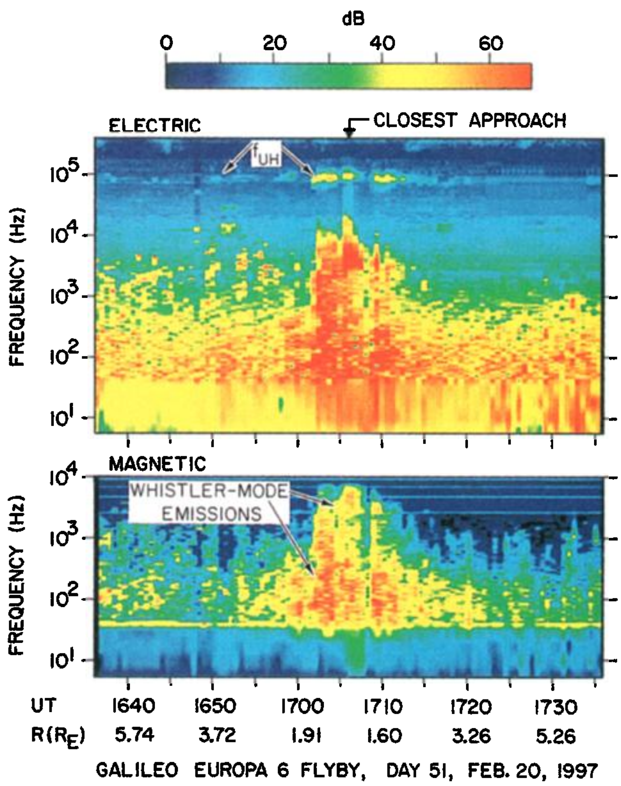

Figure 3. Spectrograms showing the electric and magnetic field intensities detected during the E6 flyby. The strong low-frequency electric and magnetic field noise near closest approach is believed to be due to whistler-mode waves similar to those observed during the E4 flyby (see Figure 2). Upper hybrid resonance emissions at f_{UH} can be seen nearly continuously through the entire flyby.

and occurs later than the low-frequency magnetic field noise, which extends from about 06:45 to 07:00 UT. The poor correlation is most likely due to the presence of a electrostatic noise that partially obscures the electric field of the whistler-mode waves, which were not as intense as on the E6 flyby. After closest approach, at about the time the spacecraft is passing through the wake, a strong broadband high-frequency component can be seen extending up to nearly 100 kHz from about 06:57 to 07:02 UT. This noise is almost certainly electrostatic, since it extends well above the electron cyclotron frequency, and no comparable response can be seen in the magnetic field data. The narrowband emission at about 100 kHz is a common feature of planetary magnetospheres [*Walsh et al.*, 1964; *Mosier et al.*, 1973; *Warwick et al.*, 1979; *Kurth et al.*, 1980], and is caused by electrostatic waves at the upper hybrid resonance frequency, f_{UH}. The upper hybrid resonance frequency is given by $f_{UH} = (f_{pe}^2 + f_{ce}^2)^{1/2}$, where $f_{pe} = 8,980\sqrt{N_e}$ Hz is the electron plasma frequency (N_e = electron number density in cm^{-3}), and f_{ce} is the electron cyclotron frequency. The upper hybrid emission is particularly clear during the E6 flyby (Figure 3), and has several distinct enhancements near closest approach, from about 17:02 to 17:12 UT. During the E4 flyby (Figure 2), the upper hybrid emission line is more difficult to identify and, with the exception of a brief strong intensification at about 80 kHz from 06:57 to 06:59 UT, can be clearly identified only in the downstream region, after about 07:01 UT. The brief, strong intensification from about 06:57 to 06:59 UT has a peak electric field intensity of about 4 mV/m. In the region before 06:57 UT, from about 06:30 to 06:55 UT, a sharp, low-frequency cutoff can be seen at 80 to 90 kHz. This cutoff is believed to be due to the propagation cutoff of free-space electromagnetic radiation at the local electron plasma frequency (see *Stix* [1962]), and is labeled f_{pe}.

3. Electron Density

Two methods can be used to compute the electron number density from these plasma wave observations. When the radio emission cutoff can be identified, as from 06:30 to 06:55 UT in Figure 2, the electron density can be computed directly from the plasma frequency using $N_e = f_{pe}^2/(8980)^2$ cm^{-3}, where f_{pe} is the cutoff frequency in Hz. In principle, this cutoff only provides an upper limit to the electron density. However, since the cutoff is very sharp we believe a good case can be made that the cutoff is controlled by the local electron density. When the upper hybrid emission can be identified, as it can after about 06:57 UT in Figure 2, and in most regions of Figure 3, the electron density can be computed using $N_e = (f_{UH}^2 - f_{ce}^2)/(8980)^2$ cm^{-3}, where f_{UH} is the upper hybrid emission frequency and f_{ce} is the electron cyclotron frequency, both in Hz. This equation follows directly from the definition of the upper hybrid frequency, $f_{UH}^2 = f_{pe}^2 + f_{ce}^2$. For the E4 flyby, we used magnetic field measurements from the Galileo magnetometer to compute f_{ce}. Since no magnetic field data were available during the E6 flyby, we used the nominal value of B =450 nT, which still gives good accuracy since $f_{ce}^2 \ll f_{UH}^2$.

The electron density profiles obtained using the above procedures are shown in Figure 4. The top panel is for the E4 flyby and the bottom panel is for the E6 flyby.

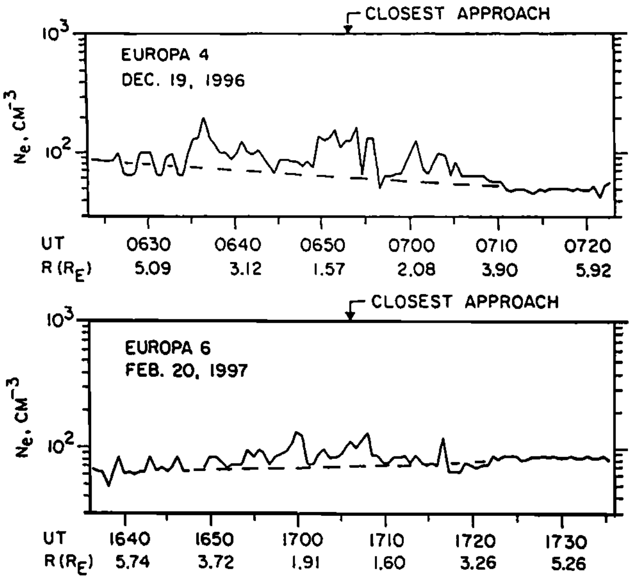

Figure 4. The electron number density, N_e, computed from the upper hybrid resonance frequency, f_{UH}, and the propagation cutoff at the electron plasma frequency, f_{pe}. The dashed line gives our best estimate of the ambient background density of the Jovian magnetospheric plasma.

As can be seen, large disturbances are present in the electron density in the immediate vicinity of Europa. Because of the high Jovian magnetospheric plasma density that exists at the orbit of Europa, approximately 80 electrons cm^{-3}, the density enhancements associated with Europa are difficult to identify. To help identify Europa's contribution to the total electron density, straight dashed lines have been drawn in Figure 4 that are asymptotic to the magnetospheric electron density before and after the Europa flybys (i.e., in the region $R \gtrsim 3\ R_E$). Using these dashed lines as guides, the electron density enhancements associated with Europa are estimated to be about ΔN_e = 50 to 100 electrons cm^{-3} during the E4 flyby, and ΔN_e = 30 to 50 electrons cm^{-3} during the E6 flyby.

4. Discussion

We have shown that an enhanced level of plasma wave emissions occurs in the vicinity of Europa. The primary emission consists of electromagnetic noise from a few tens of Hz to about ten kHz, narrowband upper hybrid emissions at about 100 kHz, and broadband electrostatic noise. The frequency range of the low-frequency electromagnetic noise, between the proton cyclotron frequency and the electron cyclotron frequency, strongly suggests that this noise consists of whistler mode emissions. Comparisons of the magnetic-to-electric field ratio with the refractive index of the whistler mode support this interpretation. For example, at 17:04 UT during the E6 flyby, the magnetic and electric field spectral densities at 300 Hz were $B^2/\Delta f = 3 \times 10^{-4}$ nT^2 Hz^{-1} and $E^2/\Delta f = 5 \times 10^{-9}$ V^2 m^{-2} Hz^{-1}, which gives a cB/E ratio of 73. Using representative parameters, $f_{pe} = 10^5$ Hz and $f_{ce} = 1.2 \times 10^4$ Hz, the refractive index of the whistler mode, $n = f_{pe}/(f\ f_{ce})^{1/2}$, is 52, which is very close to the expected cB/E ratio.

Whistler-mode emissions of the type described above are usually driven by energetic electrons with a loss-cone anisotropy [*Kennel and Petschek,* 1966]. Since Europa is unlikely to be the source of such electrons, the emissions are most likely driven by the energetic Jovian electron population. Such electrons have long been known to be a source of whistler-mode radiation in the inner magnetosphere of Jupiter [*Van Allen et al.,* 1975; *Scarf and Sanders,* 1976; *Thorne and Tsurutani,* 1979; *Gurnett et al.,* 1996a, *Bolton et al.,* 1997]. Just why the whistler-mode noise should be enhanced in the immediate vicinity of Europa, and more intense on the E6 flyby than on the E4 flyby, are open questions. If the Jovian magnetic field lines intersect the surface of Europa, the resulting loss cone in the Jovian electron distribution would promote the growth of whistler-mode waves, similar to the generation of whistler-mode noise near Ganymede [*Gurnett et al.,* 1996b]. It is also possible that the enhanced electron density in the vicinity of Europa, or a depressed magnetic field strength (as was observed by the magnetometer on E4), could decrease the cyclotron resonance energy, which would also have the effect of increasing the whistler-mode growth rate (see *Kennel and Petschek* [1966]).

It is clear that other types of waves, such as the upper hybrid emissions and the broadband electrostatic noise, are driven unstable by nonthermal plasma distributions in the vicinity of Europa. The broad band of electric field noise from about 06:57 to 07:02 UT in Figure 2 is worthy of additional comment. Since this noise extends well above the electron cyclotron frequency, it cannot be due to whistler-mode waves. The strong narrowband emission at about 80 kHz near the beginning of this interval, which was earlier interpreted as an upper hybrid emission, suggests that this noise may consist of electrostatic electron cyclotron harmonic (ECH) waves, of the type first studied by *Kennel et al.* [1970], *Ashour-Abdalla et al.* [1975], and others. ECH waves are driven by loss-cone type electron distributions and tend to be strongly enhanced near the upper hybrid resonance frequency [*Rönnmark et al.,* 1978].

Electron number densities obtained from upper hybrid resonance emissions and from the propagation cutoff of Jovian radio emissions clearly show that a region of disturbed plasma exists around Europa. The disturbed plasma extends over a region that has a diameter of about two times the diameter of Europa. Near closest approach the electron densities are enhanced above the ambient Jovian magnetospheric background by about 30 to 100 electrons cm^{-3}. Although our local electron density measurements are not as high as those reported by *Kliore et al.* [1997] from radio occultation measurements, their evidence of densities as high as 10^4 electrons cm^{-3} near the surface strongly suggests that Europa is a significant source of plasma.

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J. B. Groene, D. A. Gurnett, W. S. Kurth, Dept. of Physics and Astronomy, University of Iowa, Iowa City, IA 52242. (e-mail: joseph-groene@uiowa.edu; donald-gurnett@uiowa.edu; william-kurth@uiowa.edu).

A. Roux, CETP/UVSQ, 10/12 Avenue de l'Europe, Velizy, France. (e-mail: alain.roux@cetp.ipsl.fr)

S. Bolton, Jet Propulsion Lab., 4800 Oak Grove Drive, Pasadena, CA 91109. (e-mail: sbolton@gllsvc.jpl.nasa.gov).

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