JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 106, NO. A11, PAGES 26,225–26,232, NOVEMBER 1, 2001

Electron densities near Io from Galileo plasma wave observations

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

A. Roux
Centre d'Etude des Environnements Terrestre et Planetaires, Université de Versailles Saint Quentin Velizy, France

S. J. Bolton
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

Abstract. This paper presents an overview of electron densities obtained near Io from the Galileo plasma wave instrument during the first four flybys of Io. These flybys were I0, which was a downstream wake pass that occurred on December 7, 1995; I24, which was an upstream pass that occurred on October 11, 1999; I25, which was a south polar pass that occurred on November 26, 1999; and I27, which was an upstream pass that occurred on February 22, 2000. Two methods were used to measure the electron density. The first was based on the frequency of upper hybrid resonance emissions, and the second was based on the low-frequency cutoff of electromagnetic radiation at the electron plasma frequency. For three of the flybys, I0, I25, and I27, large density enhancements were observed near the closest approach to Io. The peak electron densities ranged from 2.1 to 6.8 $\times 10^4$ cm^{-3}. These densities are consistent with previous radio occultation measurements of Io's ionosphere. No density enhancement was observed during the I24 flyby, most likely because the spacecraft trajectory passed too far upstream to penetrate Io's ionosphere. During two of the flybys, I25 and I27, abrupt step-like changes were observed at the outer boundaries of the region of enhanced electron density. Comparisons with magnetic field models and energetic particle measurements show that the abrupt density steps occur as the spacecraft penetrated the boundary of the Io flux tube, with the region of high plasma density on the inside of the flux tube. Most likely the enhanced electron density within the Io flux tube is associated with magnetic field lines that are frozen to Io by the high conductivity of Io's atmosphere, thereby enhancing the escape of plasma along the magnetic field lines that pass through Io's ionosphere.

1. Introduction

For nearly 40 years it has been known that Jupiter's moon Io has a strong controlling influence on decametric radio emissions from Jupiter [*Bigg*, 1964]. To account for this control, *Piddington and Drake* [1968] and *Goldreich and Lynden-Bell* [1969] were the first to suggest that the radio emissions were produced by field-aligned currents associated with an Alfven wave excited by Io as it moved through the magnetosphere of Jupiter. This model was later confirmed by direct in situ magnetic field and plasma measurements with the Voyager 1 spacecraft [*Ness et al.*, 1979; *Belcher et al.*, 1981]. Although the Voyager 1 spacecraft was able to detect the Alfven wave currents generated by Io, it did not fly sufficiently close to determine the exact nature of the interaction that occurs in the vicinity of Io. To explore the nature of this interaction, the Galileo spacecraft, which is in orbit around Jupiter, is in the process of carrying out a series of close flybys of Io. Since the electrical currents generated by the moon must be carried by the plasma, the plasma density in the vicinity of Io is a key parameter. In this paper we discuss the electron densities obtained from the plasma wave instrument during the first four flybys of Io. For a description of the Galileo spacecraft, see *Johnson et al.* [1992], and for a description of the Galileo plasma wave instrument see *Gurnett et al.* [1992].

Paper number 2000JA002509.
0148-0227/01/2000JA002509$09.00

The spacecraft trajectories during the first four flybys of Io are shown in Figure 1. These flybys are labeled I0, I24, I25, and I27. The letter I stands for Io, and the number indicates the orbit number during which the flyby occurred. As can be seen, these four flybys provide good spatial coverage in the immediate vicinity of Io. The I0 flyby, which occurred on December 7, 1995, passed directly through the downstream wake near Io's equatorial plane, with a closest approach altitude of 897 km. The entry into the geometric wake (assumed to be a cylinder tangent to the surface of Io) occurred at 1744:34 UT, and the exit occurred at 1748:39 UT. The time of closest approach was 1745:58 UT. The I24 flyby, which occurred on October 11, 1999, passed diagonally through the upstream region near the equatorial plane, with a closest approach altitude of 611 km. The time of closest approach was 0433:03 UT. The I25 flyby, which occurred on November 26, 1999, passed almost directly over the south pole, with a closest approach altitude of 301 km. The time of closest approach was 0405:21 UT. The I27 flyby,

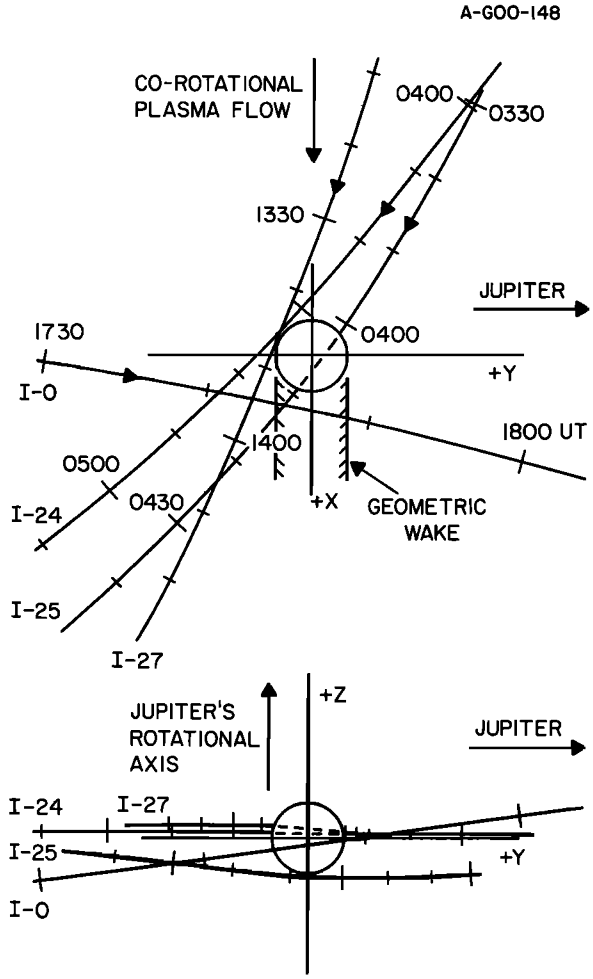

Figure 1. The trajectory of the Galileo spacecraft during the I0, I24, I25, and I27 flybys of Io. The coordinate system is centered on Io and has the $+z$ axis aligned parallel to Jupiter's rotational axis and the $+x$ axis aligned parallel to the nominal corotational plasma flow induced by Jupiter's rotation. The $+y$ axis completes the right-hand coordinate system.

which occurred on February 22, 2000, passed diagonally through the upstream region near the equatorial plane, very similar to the I24 flyby, but with a much lower closest approach altitude, only 198 km. The time of closest approach was 1346:41 UT. For discussion of previous Galileo measurements of magnetic fields, plasmas, and plasma waves in the vicinity of Io, see *Kivelson et al.* [1996], *Frank et al.* [1996], *Williams et al.* [1996], and *Gurnett et al.* [1996].

2. Principles of Measurement

Two methods are used in this paper to measure the electron density. The first, which is the most common, is based on the frequency of a thermally excited electrostatic emission at the upper hybrid resonance frequency. As discussed by *Stix* [1962], the upper hybrid frequency is given by

$$f_{UH} = \sqrt{f_{pe}^2 + f_{ce}^2},$$

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 number density in electrons per cubic centimeter and the electron cyclotron frequency is given by $f_{ce} = 28B$ Hz, where B is the magnetic field strength in nanoteslas. If the electron cyclotron frequency is known, as it usually is from onboard magnetometer measurements, then it is easy to show that the electron density can be computed from the upper hybrid frequency using the equation

$$N_e = (f_{UH}^2 - f_{ce}^2)/(8980)^2\ cm^{-3}. \quad (1)$$

If the electron cyclotron frequency is much less than the upper hybrid frequency, $f_{ce} < f_{UH}$, as is often the case, then the electron density is simply proportional to the square of the upper hybrid resonance frequency. Since the upper hybrid resonance involves a weakly damped normal mode of the plasma, oscillations at the upper hybrid frequency are continually excited by thermal fluctuations. Thermally excited emissions of this type are a common feature of planetary magnetospheres [*Walsh et al.*, 1964; *Mosier et al.*, 1973; *Shaw and Gurnett*, 1975; *Warwick et al.*, 1979] and have been frequently used to determine the electron density in planetary magnetospheres [*Birmingham et al.*, 1981; *Gurnett et al.*, 1981, 1996, 1998]. Upper hybrid waves driven by plasma instabilities are also frequently observed [*Kurth et al.*, 1979, 1980] and have also been used to determine the electron density. Since the wavelengths of the upper hybrid emissions are generally much larger that the dimensions of the spacecraft, this method of measuring the electron density has the advantage that the measurements are completely unaffected by spacecraft charging and sheath effects.

The second method of determining the electron density relies on the well-known propagation cutoff of electromagnetic radiation at the electron plasma frequency [*Stix*, 1962]. When electromagnetic radiation with a broad range of frequencies and wave normal directions is incident on a region of increasing plasma density, a sharp low-frequency cutoff is produced at the electron plasma frequency. The electron density can then be computed using the equation

$$N_e = f_{pe}^2\,/(8980)^2 cm^{-3}, \quad (2)$$

where f_{pe} is the cutoff frequency. Although simple in principle, this technique must be used with care, since similar low-frequency cutoffs can be produced between a distant source and the observer. Also, if the distribution of wave normal directions is not sufficiently broad, no waves may actually reach the propagation cutoff, in which case the observed cutoff only provides an upper limit to the electron density. Despite these limitations, the low-frequency cutoff has been frequently used to determine the electron density in planetary magnetospheres [*Gurnett and Shaw*, 1973; *Gurnett and Frank*, 1974; *Gurnett et al.*, 1981; *Ansher et al.*, 1992].

3. Frequency-Time Spectrograms

Frequency-time spectrograms of the plasma wave electric field intensities obtained during the first four Io flybys are shown in Plates 1 and 2, with I0 and I24 in Plate 1 and I25 and I27 in Plate 2. The point of closest approach is indicated by the arrow labeled CA at the top center of each panel. The intensities are color coded, with red being the most intense and blue being the least intense. An electric field spectral density scale,

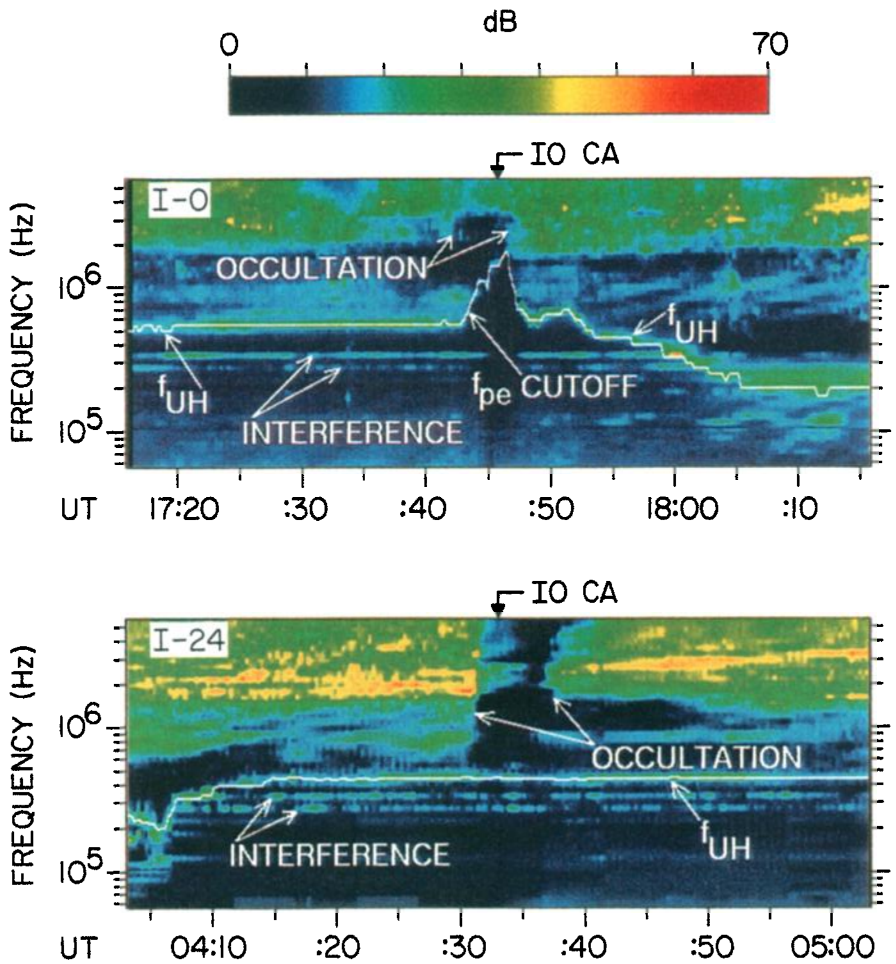

Plate 1. Frequency-time spectrograms of the electric field intensities detected by the Galileo plasma wave instrument during the I0 and I24 flybys of Io. The electron density measurements presented in this paper are based primarily on the frequency of a narrowband electrostatic emission at the upper hybrid resonance frequency. The upper hybrid frequency is indicated by the white line marked f_{UH}.

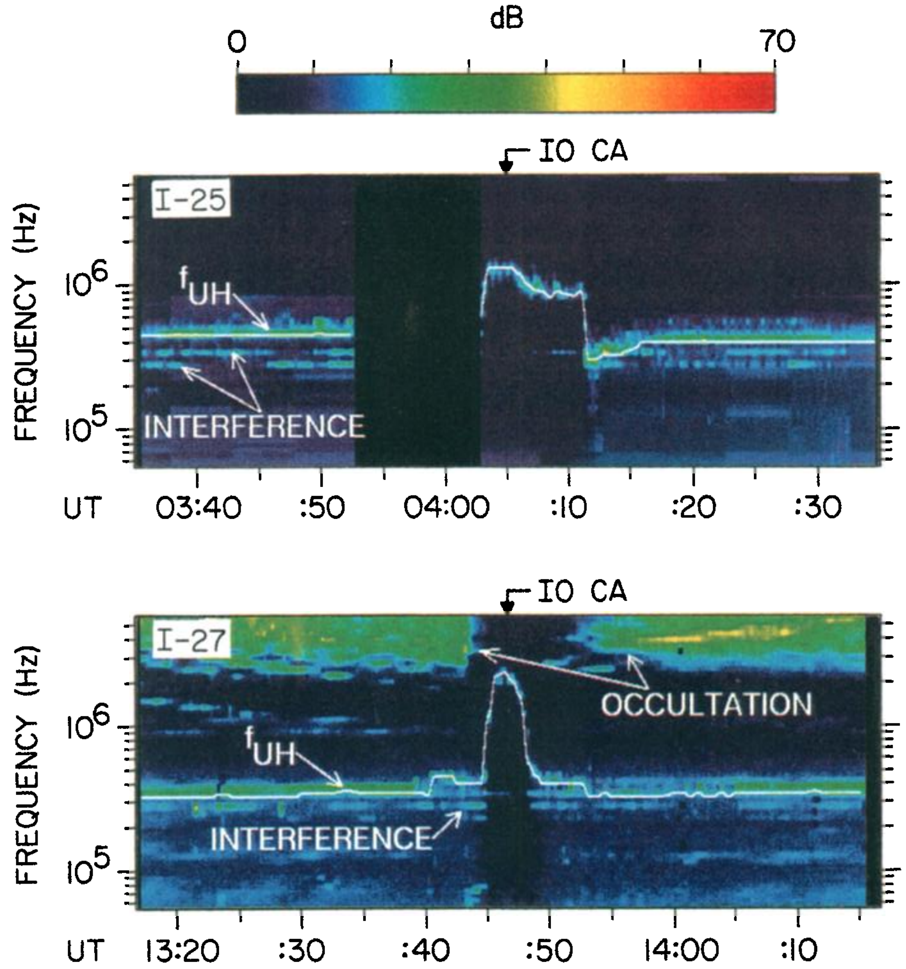

Plate 2. Frequency-time spectrograms of the electric field intensities observed during the I25 and I27 flybys.

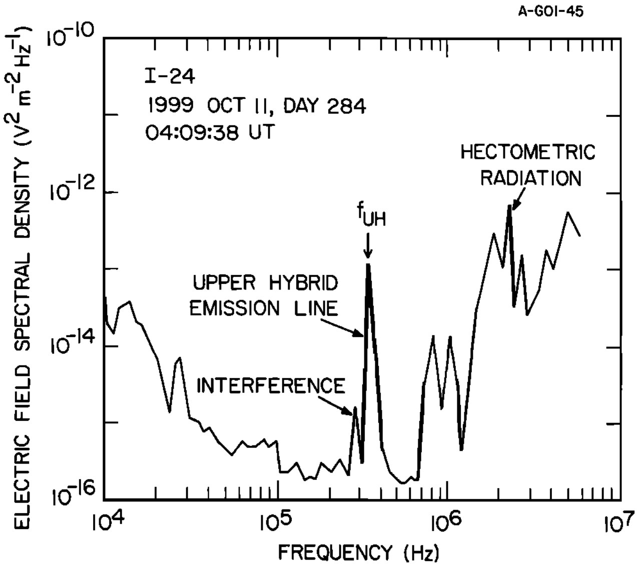

Figure 2. A representative plot of the electric field spectral density as a function of frequency. One such spectrum is obtained every 18.67 s. The upper hybrid frequency f_{UH} is taken to be the peak intensity within the upper hybrid emission line. Note that the peak is shifted slightly toward the lower edge of the emission line.

in decibels above a fixed background level, typically about 10^{-17} V^2 m^{-2} Hz^{-1}, is given at the top of each illustration. Normally the upper hybrid line consists of a smooth continuous emission with a bandwidth ranging from a few percent to sometimes as much as 10 percent. The electric field strength is typically about 10–100 μV m^{-1}, which corresponds to peak spectral densities of about 10^{-14} to 10^{-12} V^2 m^{-2} Hz^{-1}. A white line marked f_{UH} has been drawn on each spectrogram at the frequency that we have identified as the upper hybrid resonance frequency. The upper hybrid frequency is determined by plotting the electric field spectral density as a function of frequency and manually determining the frequency of peak intensity. An example of such a spectrum is shown in Figure 2. In some cases the emission line is somewhat asymmetrical, with the peak located near the lower edge of the emission line. The upper hybrid emission in Figure 2 shows an example of this effect. Other examples illustrating a more pronounced shift toward the lower edge of the emission line can be seen after about 1805 UT during the I0 flyby (see Plate 1), and in the early part of the I27 flyby (see Plate 2), before about 1340 UT.

When identifying the upper hybrid frequency, care must be taken to distinguish the upper hybrid emission from a series of spacecraft-generated interference lines that occur in the same general frequency range. Examples of these interference lines can be seen in all four flybys and are labeled "interference." Usually it is easy to distinguish the interference lines from the upper hybrid emission since the interference lines are at constant frequencies, whereas the upper hybrid frequency varies with time. Another characteristic that helps distinguish the upper hybrid emission from spacecraft-generated interference is amplitude variations, which are smooth and continuous for the upper hybrid emission and highly irregular for the interference lines (usually a distinctive dot-dash pattern). Also, for reasons that are not completely understood, the spacecraft-generated interference disappears as soon as the upper hybrid frequency drops below the frequency of the interference line. This effect is apparently a plasma effect that decreases the coupling of the interference source to the antenna whenever the upper hybrid frequency exceeds the wave frequency. Examples of this effect can be seen in Plate 1 from about 1757 to 1805 UT during the I0 flyby and from 0406 to 0415 UT during the I24 flyby.

During the I0 flyby, which is shown in the top panel of Plate 1, a narrowband emission can be seen at a frequency of about 5.5×10^5 Hz that extends from the beginning of the spectrogram to within a few minutes of closest approach. This band of emission has been previously identified as the upper hybrid line by *Gurnett et al.* [1996]. As the spacecraft approaches Io, the emission is seen to broaden upward in frequency. The upward broadening, which extends up to about 1.5×10^6 Hz is believed to be due to a weak band of radio emission just above the upper hybrid resonance frequency. In the region of somewhat broader bandwidth, the lower edge of the band, which is the most intense, is taken to be the upper hybrid resonance frequency. This frequency is indicated by the white line labeled f_{UH}. At about 1743 UT the low-frequency cutoff of the band suddenly starts to increase and ramps up to about 1×10^6 Hz at 1744 UT. This low-frequency cutoff is interpreted as the propagation cutoff of electromagnetic radiation at the local electron plasma frequency and is labeled "f_{pe} cutoff" in the spectrogram. Since the electron cyclotron frequency in this region is only about 4.7×10^4 Hz, [see *Kivelson et al.*, 1996], the upper hybrid resonance frequency and the electron plasma frequency are essentially the same (i.e., $f_{pe} \approx f_{UH}$). Therefore the low-frequency cutoff labeled f_{pe} cutoff is indicated by the white line labeled f_{UH}, even though the cutoff is actually at f_{pe}. In the region from about 1744:13 to 1746:43 UT, a series of monochromatic bursts occur that generally increase in frequency, up to a peak of about 1.8×10^6 Hz at 1746:43 UT. These bursts are believed to be upper hybrid emissions, most likely stimulated by a plasma instability rather than by thermal excitation. After the peak at 1746:43 UT, no emissions are observed until 1747:02 UT, at which point a narrow band of emission abruptly starts at a frequency of about 1.2×10^6 Hz. This abrupt onset is again interpreted as being due to the local propagation cutoff of electromagnetic radiation at the electron plasma frequency, so the white line labeled f_{UH} has been drawn downward through this point, again assuming that $f_{pe} \approx f_{UH}$. About 1 min later, at about 1747:39 UT, the upper hybrid emission again reappears at about 7.0×10^5 Hz, gradually decreasing in frequency to about 2.0×10^5 Hz at 1817 UT near the end of the spectrogram. The electron density profile computed from the upper hybrid frequency during this flyby using (1) is shown in the top panel of Figure 3. As discussed by *Gurnett et al.* [1996], the gradual decrease in the electron density from about 1750 to 1805 UT is due to the inbound passage through the inner edge of the Io plasma torus. The peak electron density near Io, at 1746:43 UT, is 4.08×10^4 cm^{-3}.

In addition to the upper hybrid line, a broadband emission can be seen extending across the top of the I0 spectrogram in the frequency range from about 2.2 to 5.6×10^6 Hz. This noise is hectometric radiation [*Warwick et al.*, 1979], which is an intense Jovian radio emission generated at high latitudes along the auroral field lines [*Ladreiter and Leblanc*, 1991]. An abrupt bite-out can be seen in the hectometric radiation spectrum near closest approach at frequencies from about 2.2 to 3.0×10^6 Hz. This bite-out is a radio occultation effect that occurs as Io passes between the source and the spacecraft. Radio occul-

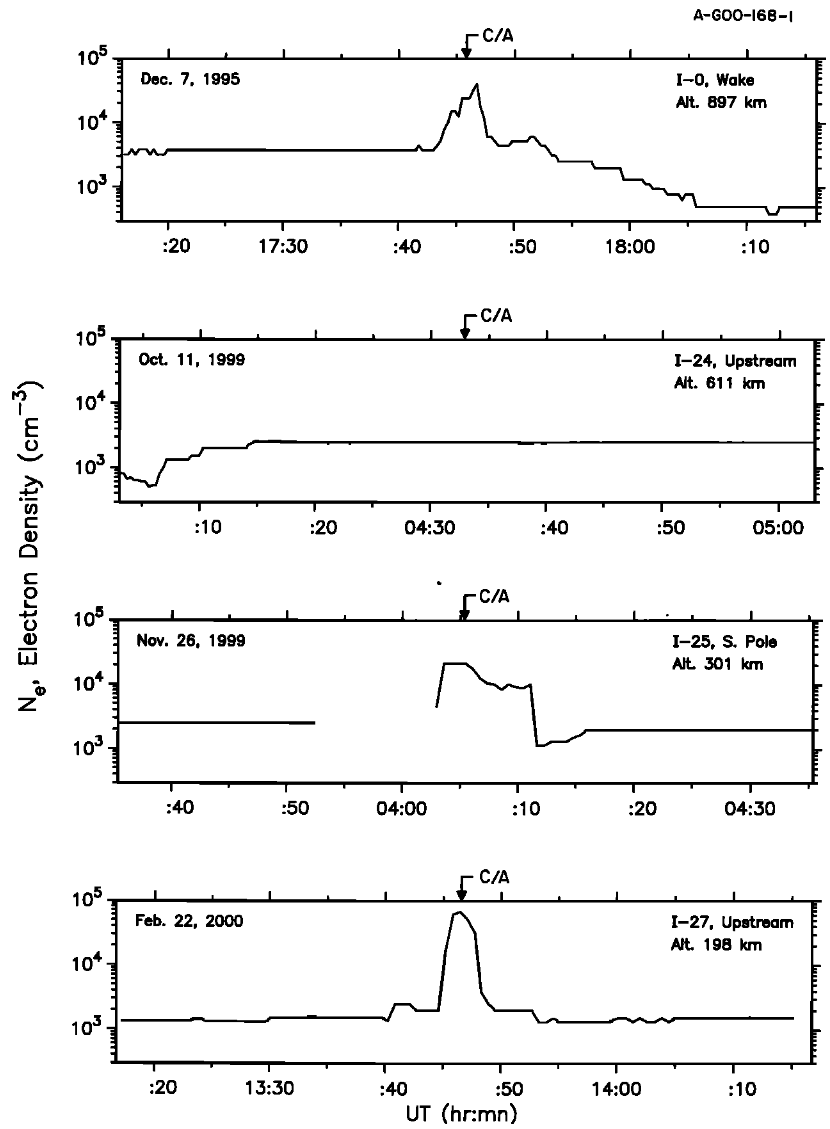

Figure 3. The electron density profiles obtained from the upper hybrid resonance frequencies in Plates 1 and 2. Large electron density enhancements were observed near Io on three of the four flybys. Most striking is the nearly rectangular electron density profile observed over the southern polar region during the I25 flyby. The step-like boundaries of this region of enhanced plasma density correspond well with boundaries of the magnetic flux tube through Io, based on the O_6 model of Jupiter's magnetic field [*Connerney*, 1992].

tation bite-outs of this type can be caused by two effects: blockage by the ionosphere and blockage by the solid object. Blockage by the ionosphere occurs at frequencies below the maximum electron plasma frequency along the ray path, and blockage by the solid object occurs at all frequencies. In this case, the existence of a low-frequency cutoff indicates that the occultation is due primarily to blockage by the ionosphere (i.e., the ray paths pass through the ionosphere but not the solid body of Io). Since the remote low-frequency cutoff implies that only frequencies above the maximum plasma frequency along the ray path can reach the spacecraft, the plasma frequency in the ionosphere of Io must be at least 3.0×10^6 Hz, which corresponds to an electron density of 1.1×10^5 cm^{-3}. For further discussion of this occultation and its implications regarding the plasma density near Io, see *Louarn et al.* [1997].

During the I24 flyby, which is shown in the bottom panel of Plate 1, the upper hybrid emission line can be easily identified and is indicated by the white line labeled f_{UH}. Near the beginning of the spectrogram the upper hybrid frequency gradually increases from about 2.5×10^5 Hz at 0403 UT to about 4.5×10^5 Hz at 0415 UT and then remains essentially constant at 4.5×10^5 Hz to the end of the spectrogram. The gradual increase from 0403 to 0415 UT is due to the passage through the inner edge of the Io plasma torus, similar to the I0 flyby, but this time on an outbound pass. No significant variations in the upper hybrid frequency are evident in the region near closest approach. The constancy of the upper hybrid frequency (hence the electron density) in the region near closest approach is surprising, given the large increase that was observed near closest approach during the I0 flyby. We have considered the possibility that an interference line might have been misidentified as the upper hybrid emission line, which would account for the constant frequency. However, the continuous character of the emission, and the gradual upward frequency

Table 1. Io Flyby Parameters

	Closest Approach				
Flyby	Location	Altitude, km	Local Time, hours	Solar Zenith Angle, deg	Maximum Electron Density, cm^{-3}
I0	downstream	897	17.1	76.1	4.08×10^4
I24	upstream	611	7.8	63.1	0.27×10^4
I25	south pole	301	19.3	97.4	2.14×10^4
I27	upstream	198	7.4	68.5	6.80×10^4

variation near the beginning of the spectrogram, convince us that the emission line has been properly identified. The electron density profile computed from the upper hybrid frequency during this flyby using (1) is shown in the second panel from the top in Figure 3. Most likely, the absence of a significant density perturbation near Io is due to the fact that the trajectory passed well upstream of Io, where the density would be expected to be nearly uniform. As can be seen in Plate 1, a clearly defined occultation effect is again observed in the Jovian hectometric radiation spectrum near closest approach. The bite-out in the spectrum in this case extends above the highest frequency measured (5.6×10^6 Hz). Since there is no evidence of a low-frequency cutoff in the occultation spectrum, it appears that the occultation was caused primarily by the solid body of Io rather than by the ionosphere.

During the I25 flyby, which is shown in the top panel of Plate 2, the upper hybrid emission line can again be easily identified and is indicated by the white line labeled f_{UH} starting near the beginning of the spectrogram at about 4.5×10^5 Hz. Unfortunately, a data gap occurs just before closest approach, from 0352:23 to 0402:58 UT. Immediately after the data gap, the first frequency spectrum gives an upper hybrid frequency of 6.12×10^5 Hz. The upper hybrid frequency then abruptly steps up to 1.3×10^6 Hz at 0403:36 UT, decreases slowly over a period of several minutes to about 9.07×10^6 Hz at 0411:03 UT, and then abruptly steps down to a frequency of 3.05×10^5 Hz at 0411:41 UT. After the abrupt downward step, the upper hybrid frequency gradually increases over a period of several minutes, asymptotically approaching a frequency of 4.0×10^5 Hz, which is very close to the frequency that existed at the beginning of the spectrogram. The electron density profile computed from the upper hybrid frequency during this flyby using (1) is shown in the third panel of Figure 3. The peak electron density near Io, which remains essentially constant from 0403:36 to 0405:28 UT, is about 2.14×10^4 cm^{-3}. As can be seen in Plate 2, no Jovian hectometric radiation was present during this flyby, so no occultation effect could be observed.

During the I27 flyby, which is shown in the bottom panel of Plate 2, the upper hybrid emission line can again be easily identified and is indicated by the white line labeled f_{UH} starting near the beginning of the spectrogram at a frequency of about 3.3×10^5 Hz. The upper hybrid frequency remains essentially constant at 3.3 to 3.6×10^5 Hz until 1345:12 UT, at which point the frequency rapidly increases to a peak of about 2.3×10^5 Hz at 1346:27 UT, decreases back down to 4.5×10^5 Hz at 1348:57 UT, and then remains essentially constant at a level of about 3.3 to 3.5×10^5 Hz to the end of the spectrogram. The electron density profile computed from the upper hybrid frequency during this flyby using (1) is shown in the bottom panel of Figure 3. The peak electron density near Io, at 1346:27 UT, is about 6.80×10^4 cm^{-3}. As can be seen in the spectrogram, a clearly defined occultation effect is again observed in the Jovian hectometric radiation spectrum near closest approach. The bite-out again extends above the highest frequency measured (5.6×10^6 Hz). Since there is no evidence of a low-frequency cutoff in the spectrum, the occultation appears to be caused primarily by the solid body of Io rather than by the ionosphere.

4. Discussion

In this paper we have presented measurements of electron densities near Io from Galileo plasma wave observations during the first four flybys of Io. For three of the flybys, I0, I25, and I27, large density enhancements were observed near Io; but during the I24 flyby, no density enhancement was observed that could be attributed to Io. The maximum electron densities measured during each of the four flybys are summarized in Table 1, along with the type of flyby, the altitude at closest approach, the local time at closest approach, and the solar zenith angle at closest approach. Since Io is known from radio occultation measurements to have an ionosphere [*Kliore et al.*, 1974, 1975; *Hinson et al.*, 1998], the question naturally arises whether the density enhancements observed are due to Io's ionosphere. For a gravitationally bound ionosphere the electron density is expected to have approximate spherical symmetry and to decrease exponentially with increasing height, with a scale height given by H = kT/mg. The radio occultation measurements of *Kliore et al.* [1974] show that the dayside ionosphere extends to an altitude of at least 700 km and has a peak electron density of about 6×10^4 cm^{-3} at an altitude of about 100 km. The scale height is about 220 km. On the nightside of Io, *Kliore et al.* [1975] show that the ionosphere is confined much closer to Io and has a peak electron density of about 9×10^3 cm^{-3} at an altitude of about 50 km, with a scale height of about 60 km. As can be seen from Table 1, the maximum electron densities reported here are quantitatively similar to those given by Kliore et al. and therefore are almost certainly of ionospheric origin. However, the electron densities do not show the systematic dependence on radial distance and solar zenith angle that would be expected for a simple static ionosphere. For example, note the pronounced asymmetry between the I24 upstream flyby and the I0 downstream wake flyby. Both of these flybys occurred at similar solar zenith angles, 63.1° and 76.1°, and at altitudes that are not significantly different, 611 and 897 km. However, the peak electron densities are drastically different, 0.25×10^4 cm^{-3} in the upstream region versus 4.08×10^4 cm^{-3} in the downstream wake region. Also, the upstream I27 flyby, which had a solar zenith angle similar to I24 but passed much closer to Io, had a peak electron density of 6.8×10^4 cm^{-3}, much greater than the I24 flyby and comparable to the much more distant I0 flyby. These asymmetries imply that the ionospheric plasma density is being strongly influenced by the magnetospheric plasma flow around Io. Similar effects were observed in the Galileo radio occultation measurements reported by *Hinson et al.* [1998].

Further evidence of the effect of the magnetospheric interaction on the ionospheric plasma distribution is given by the abrupt density discontinuities observed during the I25 and I27 flybys. Both of these flybys have very abrupt step-like density discontinuities at the boundaries of the region of enhanced electron density. Such density discontinuities are not consistent with the exponential radial density distribution that one would expect for a static diffusive equilibrium ionosphere. Such step-like discontinuities are reminiscent of an ionopause-like boundary, such as is observed at Venus and Mars [*Brace et al.*, 1983; *Luhmann*, 1991]. However, these discontinuities cannot be due to an ionopause, since the Galileo magnetometer data show that the magnetic field is essentially continuous across the discontinuity (M. Kivelson, personal communication, 2000). At an ionopause the exterior magnetic field is excluded from the ionosphere side of the boundary. The rectangular electron density profile observed during the I25 flyby over the southern polar region provides an important clue to the origin of these step-like changes. As can be seen by comparing Figures 1 and 3, the step-like discontinuities are nearly coincident with the inbound and outbound edge of the Moon as viewed from along the z axis. Since the Jovian magnetic field is to a first approximation parallel to the z axis, the discontinuities must occur very close to the inbound and outbound crossings of the magnetic flux tube through Io. Unfortunately, because of a spacecraft anomaly, no onboard magnetic field data are available during this flyby. Therefore it is not possible to make a detailed comparison with the actual magnetic field geometry. However, since the trajectory passes very close to Io, comparisons can be made using a simple model for the magnetic field. If we assume that the Io flux tube is a cylinder tangent to Io with the axis of the cylinder parallel to the magnetic field given by the O_6 model of Jupiter's magnetic field [*Connerney*, 1992; *Khurana*, 1997], the predicted entry and exit times of the Io flux tube are 0400:01 and 0408:00 UT. Taking into account the expected Alfven wave angle, which would slightly delay the entry and exit from the Io flux tube, these predicted entry and exit times are in good agreement with the step-like changes in the electron density, which are at 0402:58 and 0411:03 UT (see Figure 3). Small differences of this type could also easily arise from asymmetries in the atmosphere of Io. The identification of the step-like changes in the electron density with the boundaries of the Io flux tube is further supported by comparisons of the electron density profiles with energetic particle (EPD) data obtained during the I27 flyby [*Mauk et al.*, this issue]. During the I27 flyby the EPD data show a very pronounced depletion in the energetic (15 keV to 10.5 MeV) electron intensities from 1345 to 13:49 UT [see *Mauk et al.*, this issue, Figure 4]. The depletion in the energetic electron intensity corresponds almost exactly with the region of enhanced electron density observed by the plasma wave investigation from 1345:12 to 1348:19 UT (see Figure 2). Since the deep depletion in the energetic electron flux provides conclusive evidence that magnetic field lines are passing through or very near Io, it is clear that the step-like discontinuities at the boundaries of the region of enhanced electron density correspond closely with crossings of the Io flux tube. Most likely, the regions of enhanced electron densities observed on I25 and I27 are closely related to the shielding of plasma in the Io flux tube from the surrounding plasma flow as the magnetic field lines in the flux tube contact and are frozen into the dense, highly conducting upper atmosphere of Io. The much lower flow velocity in the region of frozen field lines would then provide more time for plasma to diffuse upward out of the ionosphere, thereby enhancing the electron density along the Io flux tube. It is also possible that impact ionization from energetic electrons may contribute to the enhanced electron densities observed within the Io flux tube.

Acknowledgments. The authors thank Joseph Groene for his assistance in preparing the illustrations used in this paper. The research at the University of Iowa was supported by NASA through contract 958779 from the Jet Propulsion Laboratory.

Janet G. Luhmann thanks Richard M. Thorne and another referee for their assistance in evaluating this paper.

References

Ansher, J. A., W. S. Kurth, D. A. Gurnett, and C. K. Goertz, High-resolution measurements of density structures in the Jovian plasma sheet, *Geophys. Res. Lett., 19*, 2281–2284, 1992.

Belcher, J., C. K. Goertz, J. D. Sullivan, and M. H. Acuna, Plasma observations of the Alfven wave generated by Io, *J. Geophys. Res., 86*, 8508–8512, 1981.

Bigg, E. L., Influence of the satellite Io on Jupiter's decametric radiation, *Nature, 203*, 1008–1009, 1964.

Birmingham, T. J., J. K. Alexander, M. D. Desch, R. F. Hubbard, and B. M. Pedersen, Observations of electron gyroharmonic waves and the structure of the Io torus, *J. Geophys. Res., 86*, 8497–8507, 1981.

Brace, L. H., H. A. Taylor Jr., T. I. Gombosi, A. J. Kliore, W. C. Knudsen, and A. F. Nagy, The ionosphere of Venus: Observations and their interpretation, in *Venus*, edited by D. M. Hunten et al.; pp. 779–840, Univ. of Ariz. Press, Tucson, 1983.

Connerney, J. E. P., Doing more with Jupiter's magnetic field, in *Planetary Radio Emissions III*, edited by H. O. Rucker, S. J. Bauer, and M. L. Kaiser, pp. 13-33, Austrian Acad. of Sci., Vienna, 1992.

Frank, L. A., W. R. Paterson, K. L. Ackerson, V. M. Vasyliunas, F. V. Coroniti, and S. J. Bolton, Plasma observations at Io with the Galileo spacecraft, *Science, 274*, 394–395, 1996.

Goldreich, P., and D. Lynden-Bell, Io, a Jovian unipolar inductor, *Astrophys. J., 156*, 59–78, 1969.

Gurnett, D. A., and L. A. Frank, Thermal and suprathermal plasma densities in the outer magnetosphere, *J. Geophys. Res., 79*, 2355–2361, 1974.

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., W. S. Kurth, R. R. Shaw, A. Roux, R. Gendrin, C. F. Kennel, F. L. Scarf, and S. D. Shawhan, 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 plasma torus and near Io, *Science, 274*, 391–392, 1996.

Gurnett, D. A., W. S. Kurth, A. Roux, S. J. Bolton, E. A. Thomsen, and J. B. Green, Galileo plasma wave observations near Europa, *Geophys. Res. Lett., 25*, 237–240, 1998.

Hinson, D. P., A. J. Kliore, F. M. Flasar, J. D. Twicken, P. J. Schinder, and R. G. Herrera, Galileo radio occultation measurements of Io's ionosphere and plasma wake, *J. Geophys. Res., 103*, 29,343–29,357, 1998.

Khurana, K., Euler potential models of Jupiter's magnetospheric field, *J. Geophys. Res., 102*, 11, 295–11, 306, 1997.

Johnson, T. V., C. M. Yeates, and R. Young, The Galileo mission overview, *Space Sci. Rev., 60*, 2–21, 1992.

Kivelson, M. G., K. K. Khurana, R. J. Walker, J. Warnecke, C. T. Russell, J. A. Linker, D. J. Southwood, and C. Polanskey, Io's interaction with the plasma torus: Galileo magnetometer report, *Science, 274*, 396–398, 1996.

Kliore, A. J., D. L. Cain, G. Fjeldbo, B. L. Seidel, and S. I. Rasool, Preliminary results on the atmospheres of Io and Jupiter from the Pioneer 10 S-band occultation experiment, *Science, 183*, 323–324, 1974.

Kliore, A. J., G. Fjeldbo, B. L. Seidel, D. N. Sweetnam, T. T. Sesplaukis, and P. M. Woiceshyn, Atmosphere of Io from Pioneer 10 radio occultation measurements, *Icarus, 24*, 407–410, 1975.

Kurth, W. S., J. D. Craven, L. A. Frank, and D. A. Gurnett, Intense electrostatic waves near the upper hybrid resonance frequency, *J. Geophys. Res., 84*, 4145–4164, 1979.

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.

Ladreiter, H. P., and Y. Leblane, The Jovian hectometric radiation; An overview after the Voyager mission, *Ann. Geophys. 9*, 784–796, 1991.

Louarn, P., S. Perraut, A. Roux, D. Gurnett, W. Kurth, and S. Bolton, The global plasma environment of Io as inferred from the Galileo plasma wave observations, *Geophys. Res. Lett., 24*, 2115–2118, 1997.

Luhmann, J. G., Near-Mars space, *Rev. Geophys., 29*, 121–140, 1991.

Mauk, B. H., D. J. Williams, and A. Eviatar, Understanding Io's space environment interactions: Recent energetic electron measurements from Galileo, *J. Geophys. Res.*, this issue.

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.

Ness, N. F., M. H. Acuna, R. P. Lepping, L. F. Burlaga, K. W. Behannon, and F. M. Neubauer, Magnetic field studies at Jupiter by Voyager 1: Preliminary results, *Science, 204*, 982–987, 1979.

Piddington, J. H., and J. F. Drake, Electrodynamic effect of Jupiter's satellite Io, *Nature, 217*, 935–937, 1968.

Shaw, R. R., and D. A. Gurnett, Electrostatic noise bands associated with the electron gyrofrequency and plasma frequency in the outer magnetosphere, *J. Geophys. Res., 80*, 4259–4271, 1975.

Stix, T. H., *The Theory of Plasma Waves*, p. 12, McGraw-Hill, New York, 1962.

Walsh, D., T. F. Haddock, and H. F. Schulte, Cosmic radio intensities at 1.225 and 2.0 MC measured up to an altitude of 1700 km, *Space Sci. Rev., 4*, 935–959, 1964.

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

Williams, D. J., B. H. Mauk, R. E. McEntire, E. C. Roelof, T. P. Armstrong, B. Wilken, J. G. Roederer, S. M. Krimigis, T. A. Fritz, and L. J. Lanzerotti, Electron beams and ion composition measured at Io and its torus, *Science, 274*, 401–403, 1996.

S. J. Bolton, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109.

D. A. Gurnett, W. S. Kurth, and A. M. Persoon, Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242. (dag@space.physics.uiowa.edu)

A. Roux, Centre d'Etude des Environments Terrestre et Planetaires/ UVSQ, 10-12 Avenue de l'Europe, Velizy, France.

(Received October 9, 2000; revised February 5, 2001; accepted February 6, 2001.)