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VOYAGER OBSERVATIONS OF LOWER HYBRID NOISE IN THE IO PLASMA TORUS AND ANOMALOUS PLASMA HEATING RATES

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ABSTRACT

A study of *Voyager 1* electric field measurements obtained by the plasma wave instrument in the Io plasma torus has been carried out. A survey of the data has revealed the presence of persistent peaks in electric field spectra in the frequency range 100–600 Hz consistent with their identification as lower hybrid noise for a heavy-ion plasma of sulfur and oxygen. Typical wave intensities are 0.1 mV m^{-1}, and the spectra also show significant Doppler broadening, $\Delta\omega/\omega \sim 1$. A theoretical analysis of lower hybrid wave generation by a bump-on-tail ring distribution of ions is given. The model is appropriate for plasmas with a superthermal pickup ion population present. A general methodology is used to demonstrate that the maximum plasma heating rate possible through anomalous wave-particle heat exchange is less than approximately 10^{-14} ergs cm^{-3} s^{-1}. Although insufficient to meet the power requirement of the EUV–emitting warm torus, the heating rate is large enough to maintain a low-density (0.01%–0.1%) superthermal electron population of keV electrons, which may lead to a small but significant anomalous ionization effect.

Subject headings: planets: Jupiter — planets: satellites — plasmas

I. INTRODUCTION

The Io plasma torus is a subject of considerable interest with regard to its formation, maintenance, and dissolution. With radiation exceeding 10^{12} W at EUV wavelengths, the warm torus represents a significant source of nonthermal radiation, second only to the Jovian aurora (Sandel *et al.* 1979). By comparison, the source strength of the decimetric and decametric radio emissions is 10^9–10^{10} W, whereas power levels of 10^{12} W had been considered appropriate only for the kinetic-energy budget of particles and plasma being ejected from the Jovian system (Kennel and Coroniti 1979). Thus, the Io torus is unique for its large radiative capacity, and the study of it to determine its kinetic properties may reveal how the electron temperature is maintained against strong radiative losses.

The first question to address is the nature of the source for the heavy-ion plasma. Ions are deposited in the torus generally either (*a*) by direct injection in the near vicinity of Io or (*b*) by creation out of a more or less complete torus of neutral atoms. Several key issues have revolved around these two cases, most important of which is the energy source for EUV radiation. If the primary energy source is the thermal energy of newly created "pickup" ions (Broadfoot *et al.* 1979), case *a* allows the possibility of injection of ions with energy much less than the full pickup value (Goertz 1980), while case *b* necessarily involves acceleration to full pickup gyroenergy ~ 500 eV (see Shemansky and Sandel 1982 for a recent discussion of other energy input options).

Direct injection at 50 eV was initially proposed as a major source because *in situ* measurements by the plasma probe gave just this value for the kinetic temperature of the dense plasma (Bagenal and Sullivan 1981). But this proposal has since met with observational difficulties associated with the lack of emissions localized to Io (Shemansky 1980) and theoretical difficulties associated with the low energy per ion injection rate (Barbosa, Coroniti, and Eviatar 1983). Direct injection at full pickup energy (e.g., 500 eV for S II) may not be ruled out, since there is a finite heating time for electrons comparable to the radiation lifetime which would preclude any T_e hot spot near Io, and also the direct observation of an enhanced density of high-temperature ions (340–500 eV) is difficult (Brown 1982). However, the relevance of ion-neutral charge exchange processes (Eviatar, Mekler, and Coroniti 1976; Brown, Pilcher, and Strobel 1983; Brown, Shemansky, and Johnson 1983) has given the distributed-source scenario certain advantages, and we will proceed with case *b* as a working model.

The energy requirements of the EUV luminosity have posed difficulties for finding an adequate energy source and also a feasible mechanism for delivering energy to the electrons. *In situ* measurements gave an ion temperature of 50 eV and an electron temperature of 10–26 eV (Scudder, Sittler, and Bridge 1981). Thorne (1981) concluded that binary Coulomb collisions between ions and electrons at these temperatures could not transfer energy at a sufficiently fast rate. He therefore suggested an alternate energy source of secondary electrons resulting from energetic ring current ion precipitation into the Jovian ionosphere to power the EUV torus via electron-electron Coulomb collisions. Smith, Palmadesso, and Strobel (1981) retained the pickup ions as the primary energy source but asked whether anomalous energy exchange through plasma waves could heat electrons fast enough. Shemansky and Sandel (1982) gave evidence for fast (< 10 hr) time variations of the EUV luminosity much less than the Coulomb ion-electron equilibration time and advocated a local time-dependent source of electron-electron heating.

In view of the possibility that wave-particle interactions might be important for the torus energetics, the authors initiated an investigation of the *Voyager* plasma wave data in search of evidence for any anomalous heat exchange processes at work. Earlier

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investigations of a similar nature had already given evidence for a broad-band electrostatic noise in the middle magnetosphere which included a component at lower hybrid (LH) frequencies (Barbosa *et al.* 1981; Barbosa 1981, 1982). The noise there was attributed to local dissipation processes acting to accelerate ions and electrons in the region where the plasma exhibited a significant departure from corotation. If the energetics of the Io torus required also a strong anomalous dissipation process in order to radiate so intensely, the plasma wave data would provide a definite quantitative measure of the role of anomalous processes.

With the preliminary results of this paper in hand, Barbosa, Coroniti, and Eviatar (1983) reexamined the assumptions underlying the Coulomb collisional energy transfer from pickup ions to electrons. They found that a self-consistent model could be constructed which demonstrated that a population of ions at full pickup energy was a feasible energy source for the EUV torus and that energy was indeed communicated by Coulomb collisions. A source strength of $\dot{N} \approx 2.5 \times 10^{28}$ s^{-1} at 500 eV gave 2×10^{12} W of radiated power, and since all of this ion kinetic energy is lost to the system, the pickup ions are degraded in energy to a temperature predicted to be 53 eV, while the electron temperature is regulated at a self-consistent value computed to be 5.5 eV. Thus, the primary energy requirements of the Io torus seem to be accounted for, and we inquire now into any secondary effects brought about by wave-particle interactions in the torus.[5]

The purpose of this paper is to report the results of a survey of the Io torus for wave emissions which may be important for either anomalous ionization or anomalous heat exchange. The data were obtained by the plasma wave system (PWS) on *Voyager 1*, which measures electric fields over the range 10 Hz to 56.2 kHz (see Scarf and Gurnett 1977 for a detailed description of the instrumentation). Previously, intense plasma wave emissions were found throughout the inner magnetosphere by *Voyager 1* (Scarf, Gurnett, and Kurth 1979). The dominant wave mode was tentatively identified as whistler-mode hiss (Scarf *et al.* 1979) quantitatively consistent with the theoretical predictions of Coroniti (1974) and Barbosa and Coroniti (1976). The source of the hiss was established as inward-diffusing energetic electrons which generate whistler-mode noise through a loss-cone anisotropy of the particle distribution when the electron flux is above the Kennel-Petschek value. Significant electron precipitation into the Jovian atmosphere was inferred to exist (Scarf *et al.* 1979).

A more recent study of emissions in the Io torus revealed the presence of other wave modes, including an electrostatic component which had the signature of strongly Doppler shifted ion acoustic waves (Scarf, Gurnett, and Kurth 1981). On the basis of measurements made by other *Voyager* experiments, in particular the plasma probe (Bagenal and Sullivan 1981) and ultraviolet spectrometer (Broadfoot *et al.* 1981), as well as ground-based measurements in the visible (Brown and Ip 1981), there is now good evidence for other particle sources of plasma wave emissions, most notably the newly created pickup ions which are a major source for plasma in the torus (see Barbosa, Eviatar, and Siscoe 1984 for a firm theoretical basis for the energy and ion injection rates). Thus, we have conducted a survey of the Io plasma torus to search for evidence of plasma waves in the lower hybrid frequency range that may be associated with the pickup ions.

The present study will also have a bearing on the physical processes that created the torus. If a neutral-atom torus is a significant source for ions, the primary mechanisms for ionization are electron impact and charge exchange. Related to this is the possibility that Alfvén's critical velocity hypothesis may have an influence on the formation of the torus (Alfvén 1954, 1960). There has always been, however, a theoretical difficulty in explaining how plasma can effect an anomalous ionization, since the scale lengths for atomic and plasma processes are so disparate.

Recently, however, Galeev (1981) and Galeev and Chabibrachmanov (1983) have described a self-consistent theory for anomalous ionization involving the generation of lower hybrid emissions from a "seed" population of pickup ions. Provided that the ion distribution is sufficiently unstable to growth of LH emissions, the wave energy can be converted to accelerate and maintain a superthermal electron population. Electron-electron heating ensues, as well as an enhanced ionization from superthermal electron impact on neutrals, leading to either an avalanche or a quasi–steady state anomalous ionization phenomenon (Sherman 1972; Raadu 1978; Formisano, Galeev, and Sagdeev 1982) (see Haerendel 1982 for a recent review).

We will take advantage of this elaborate theory which provides a framework for interpreting our plasma wave observations. Indeed, the prediction of Galeev and Chabibrachmanov (1983) that the anomalous process in effect has an efficiency of 2.5% is in very good agreement with our conclusions based on *in situ* measurements and with results obtained by Smith, Palmadesso, and Strobel (1982) (R. A. Smith 1983, private communication). Still, we emphasize the independence of our study of theirs, and we present our results in a manner that does not depend critically on the assumptions or restrictions of any particular theory or model (we are, in fact, continuing along previous lines discussed by Barbosa 1981). However, the proposed source of the waves, the fresh pickup ions, is compatible with previous work, and we will proceed under this assumption.

In § II the results of the plasma wave survey of the Io torus are given. Lower hybrid emissions with an amplitude of 0.1 mV m^{-1} are consistently found throughout the cold and warm tori. In § III we give growth rate calculations for a ring distribution of pickup ions. In § IV we estimate plasma heating rates using the observed amplitude of the LH waves and the growth rates for a weak ring distribution. This leads to an estimated efficiency of $\lesssim 1\%$ for the anomalous heat exchange process to electrons. In § V we infer the properties of the hot electron population (density and temperature) that exists in the warm torus, and the maximum heating rate available from this superthermal electron component is compared with that due to wave-particle interactions. Section VI summarizes our results.

II. PLASMA WAVE SURVEY

The *Voyager 1* spacecraft trajectory is shown in Figure 1 for several hours around periapsis. The lower panel displays the projection of the trajectory onto the Jovigraphic plane with the x-axis pointing toward local noon. The top panel gives the distance

[5] However good the case for Coulomb energy exchange from pickup ions may be, we should caution the reader that conflicting evidence is still apparent (D. E. Shemansky 1984, private communication), and all other possible energy sources for the torus should be investigated thoroughly to evaluate their feasibility and relative importance.

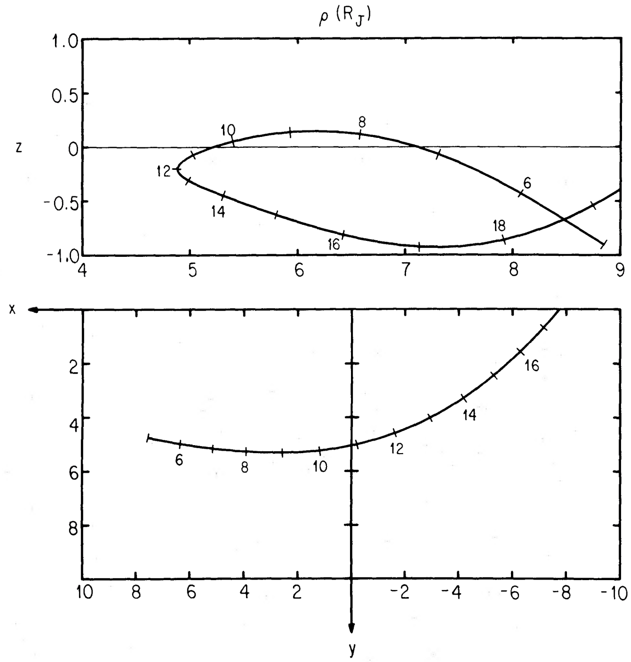

FIG. 1.—The spacecraft trajectory around periapsis is projected into the Jovigraphic equator (*bottom panel*) and into a centrifugal meridian plane (*top panel*). The centrifugal axis points toward 202° λ_{III}(1965), with a tilt angle of 6°4 from the rotational axis.

of the spacecraft above or below the centrifugal equator, with tick marks indicated every hour of spacecraft event time (SCET). The axis of the centrifugal plane points toward 202° λ_{III}(1965) with a tilt angle of 6°4 from the planet's rotational axis and 3°2 from the dipole axis, also oriented toward 202° (Cummings, Dessler, and Hill 1980).

Figure 2 shows for reference a summary plot of the averaged plasma wave observations obtained by the 16 channel spectrum analyzer around closest approach. In each channel the electric field amplitude of the received noise is shown as the envelope of the dark area with a dynamic range of 100 dB below 100 mV m^{-1}. A broad region of intense noise is observed throughout the inner magnetosphere at distances $< 10\ R_J$, consistent with expectations of whistler-mode hiss. The superposed traces correspond to the lower hybrid (LH) resonance frequency for an $A/Z = 1$ and $A/Z = 32$ high-density plasma based on the measured magnetic field strength (Ness *et al.* 1979). Although there is no obvious correspondence with these frequencies in a compressed survey plot of this kind, we will make a detailed examination of the wave spectra over shorter time periods for evidence of emissions in this frequency range. This survey will concentrate on the intervals 0800–1000 UT and 1330–1630 UT, during which times the spacecraft was in the Io plasma torus.

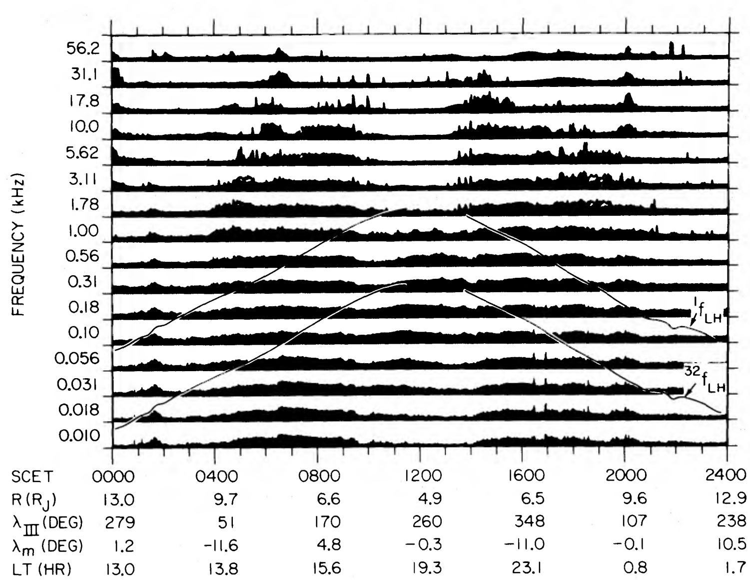

FIG. 2.—A compressed plot of the 16 channel spectrum analyzer data around periapsis, 1979 March 5 (day 64). The two traces are the lower hybrid frequencies (without density correction) for an H^+ and S^+ plasma based on the on-board magnetometer measurements.

There are several difficulties encountered in a study of this sort associated with low frequencies of less than 1 kHz. There is the continuous background of whistler-mode hiss at an intensity level comparable to those of the lower hybrid emissions being sought, as is evident from Figure 2. Spacecraft-generated noises and interference signals from other experiments are also a potential problem in this frequency range. The most problematic aspect, however, is the Doppler smearing of the modes due to the large relative motion of the plasma with respect to the spacecraft. This prohibits a determination of the effective mass composition and charge state of the torus with high accuracy. Our approach will be to look for peaks in the wave spectra obtained by the 16 channel on-board spectrum analyzer (which has low resolution in frequency and time) and to ascertain whether the spectral structure is theoretically compatible with the known properties of the heavy-ion torus.

In Figure 3 we show two frequency-time spectrograms of low-frequency emissions taken at 0859 and 0931 UT. The lower panel illustrates a case when the background noise is weak and the strongest signal is a 400 Hz interference tone associated with the modulation of a grid in the plasma probe. The signal persists throughout the 48 s of the frame, and odd harmonics of it are most apparent from 32 to 42 s. In the upper panel the spectrogram shows the background noise at a higher intensity such that the automatic gain control has reduced the receiver gain and the interference tone is masked by the natural emission.

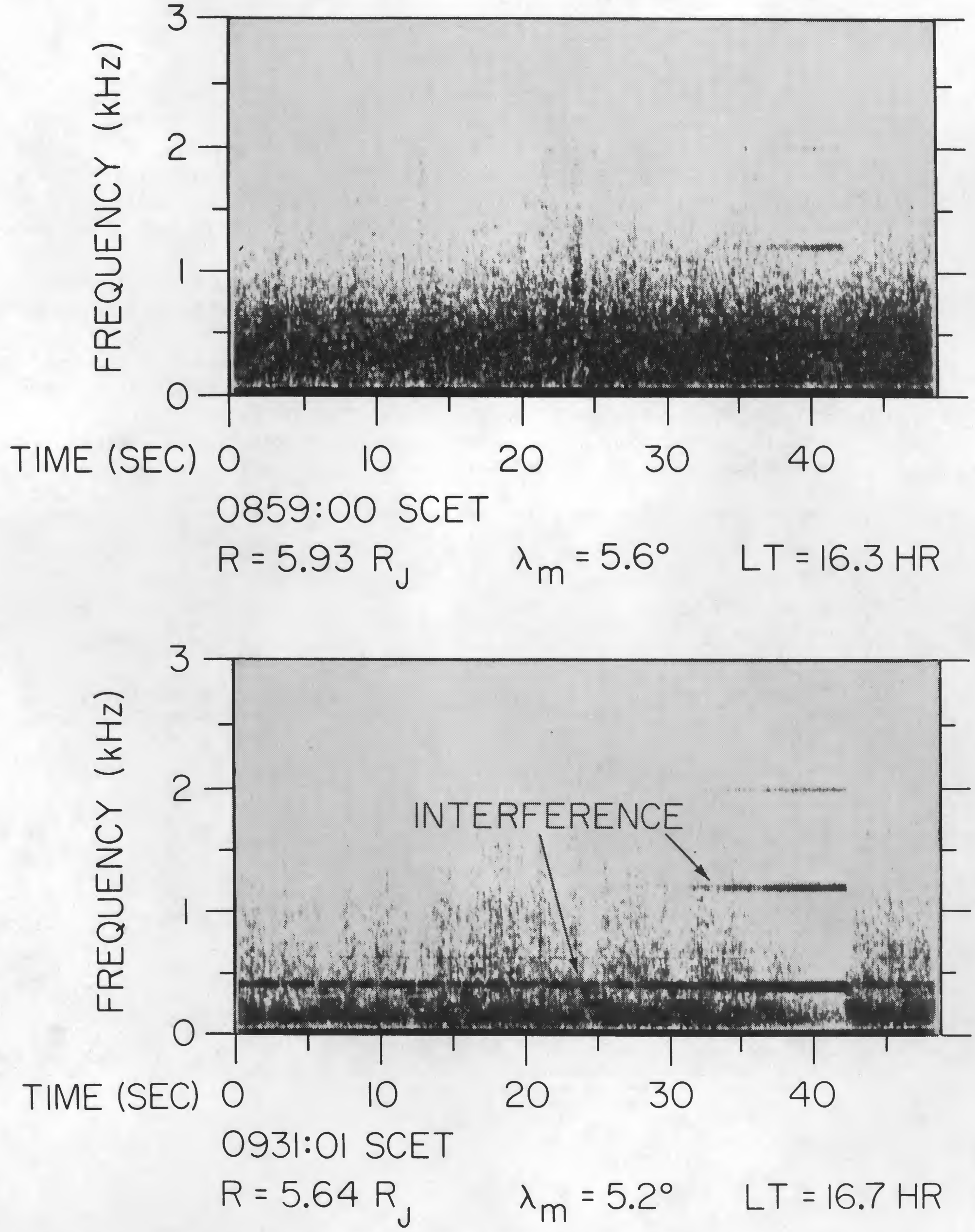

FIG. 3.—Two wide-band spectrograms of low-frequency noise in the Io torus taken on 1979 March 5 (day 64). The lower panel illustrates a case when the plasma noise is relatively weak and an interference tone at 400 Hz and odd harmonics are prominent. The upper panel shows the plasma noise when it is more intense, and the automatic gain control has compensated.

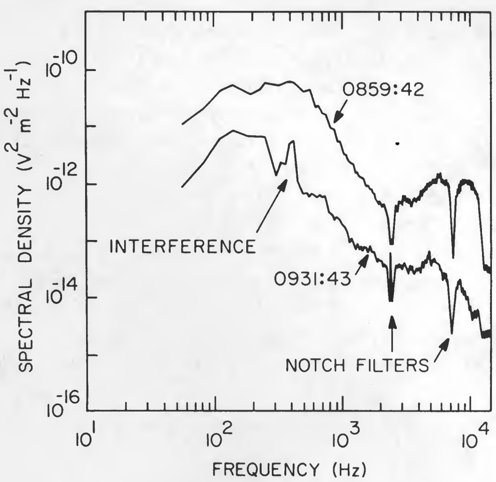

FIG. 4.—Line-scan spectra of the last 6 s of each of the wide-band frames in Fig. 3. The spectra were calibrated using the absolute values from the spectrum analyzer.

In Figure 4 we display calibrated line-scan spectra taken over the last 6 s of the spectrograms in Figure 3. The calibration procedure used was to superpose the unnormalized wide-band spectra on the low-resolution analyzer data (averaged over the same interval of 6 s) which provide absolute values for the wave spectral density. In the majority of cases the spectra compare very well, and this determines the normalization for the wide-band data.

The 400 Hz tone is easily identifiable at times characterized by low noise levels but is completely masked by the background noise when the spectral density is approximately $10^{-10}\ V^2\ m^{-2}\ Hz^{-1}$. We note also the characteristically broad feature in the spectrum at 0859 UT having a center frequency near 300 Hz and extending to at least 600 Hz. This feature is typical of the emission spectra observed in the wide-band data in the Io plasma torus at frequencies near the LH resonance. It is attributed to a significant Doppler smearing $\Delta f/f \sim 1$ of the wave mode due to plasma corotation, as will be discussed in the next section. Finally, the emissions above the 2.4 kHz notch filter are the ion acoustic waves described by Scarf, Gurnett, and Kurth (1981).

During the period 1030–1050 UT on the inbound leg a series of wide-band spectrograms was obtained in the cold torus that showed clear evidence for narrow-line emission near the LH resonance frequency. Figure 5 gives a good example of one of these

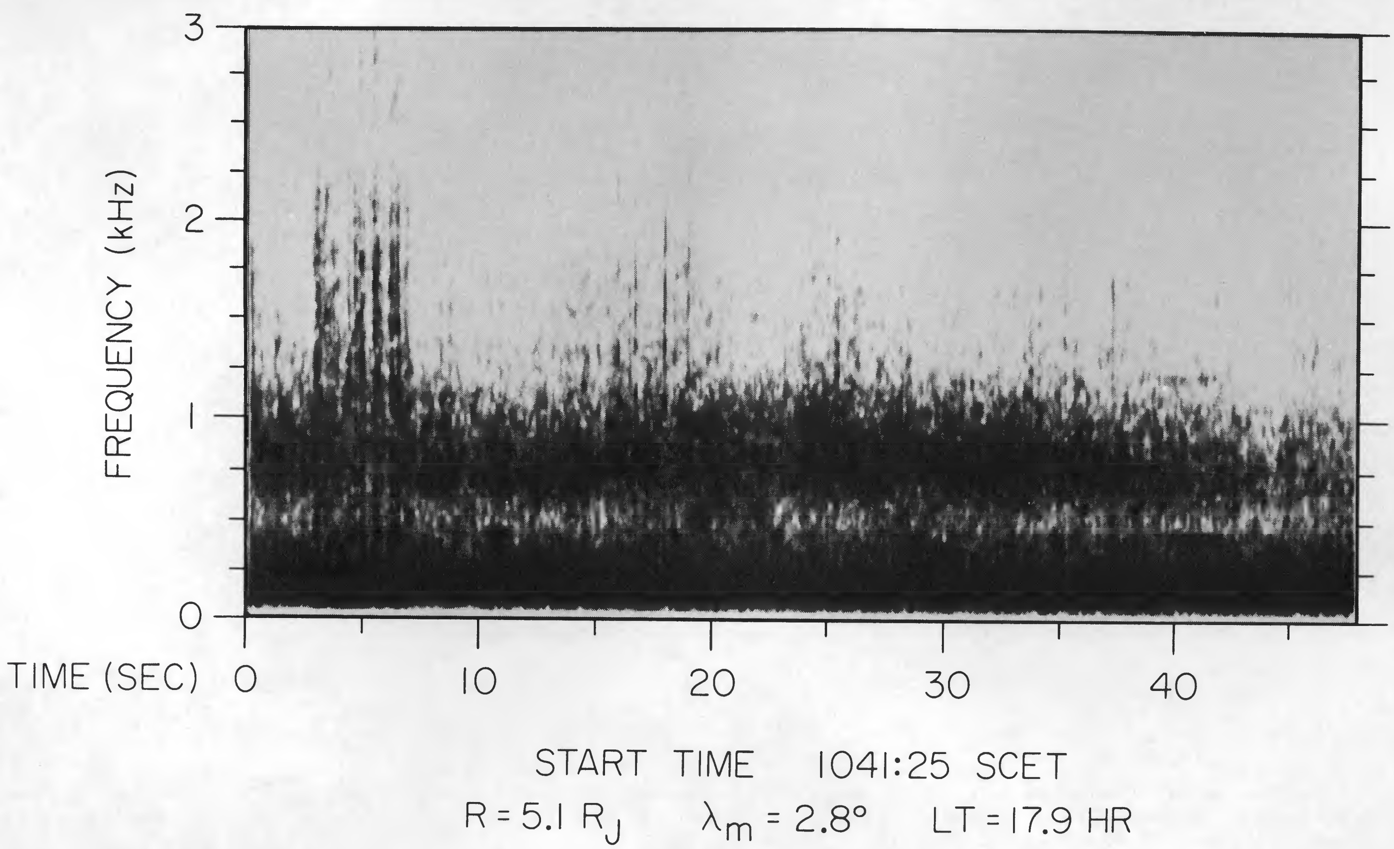

FIG. 5.—A spectrogram taken in the cold torus, 1979 March 5, during which time a well-resolved line emission near the lower hybrid frequency was observed

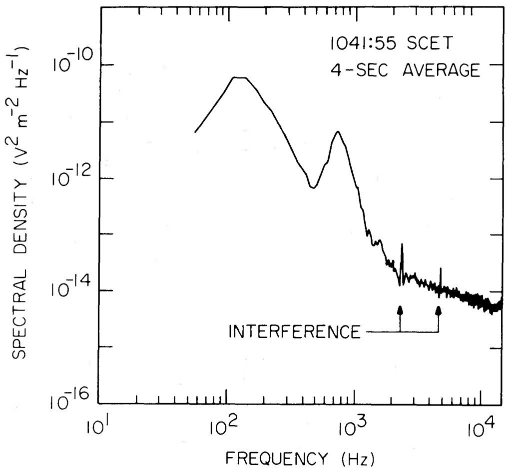

FIG. 6.—Line-scan spectrum of the time interval around 1041:55 UT, 1979 March 5 (day 64). The calibration procedure is similar to that of Fig. 4.

particular measurements. The emission extends over the full 48 s of the frame, with a center frequency of approximately 750 Hz and a bandwidth of 500 Hz. The ratio $\Delta f/f \approx 0.67$, so that this noise is more narrow-banded than that obtained in the warm Io torus and is easily identifiable.

A 4 s line-scan spectrum of the same data was made for 1041:55 UT and is shown in Figure 6. The normalization procedure was similar to that described previously using the calibrated spectrum analyzer data. The line emission stands out clearly, with a peak spectral density of 10^{-11} V^2 m^{-2} Hz^{-1}, more than an order of magnitude above the background level. The electric field strength of the signal at 700 Hz is 90 μV m^{-1}.

In Figure 7 we display calibrated spectrum analyzer data at approximately half-hour intervals throughout the Io torus. The spectra are stacked with time running downward, and the plot gives the square root of the spectral density in V m^{-1} $Hz^{-1/2}$. The labeled axes for the spectra alternate consecutively between the left-hand and the right-hand scales. The dashed curve is the peak value, and the solid curve is the average during 96 s intervals.

There are emissions over the full range of observing frequencies which conform with a background power-law spectrum with

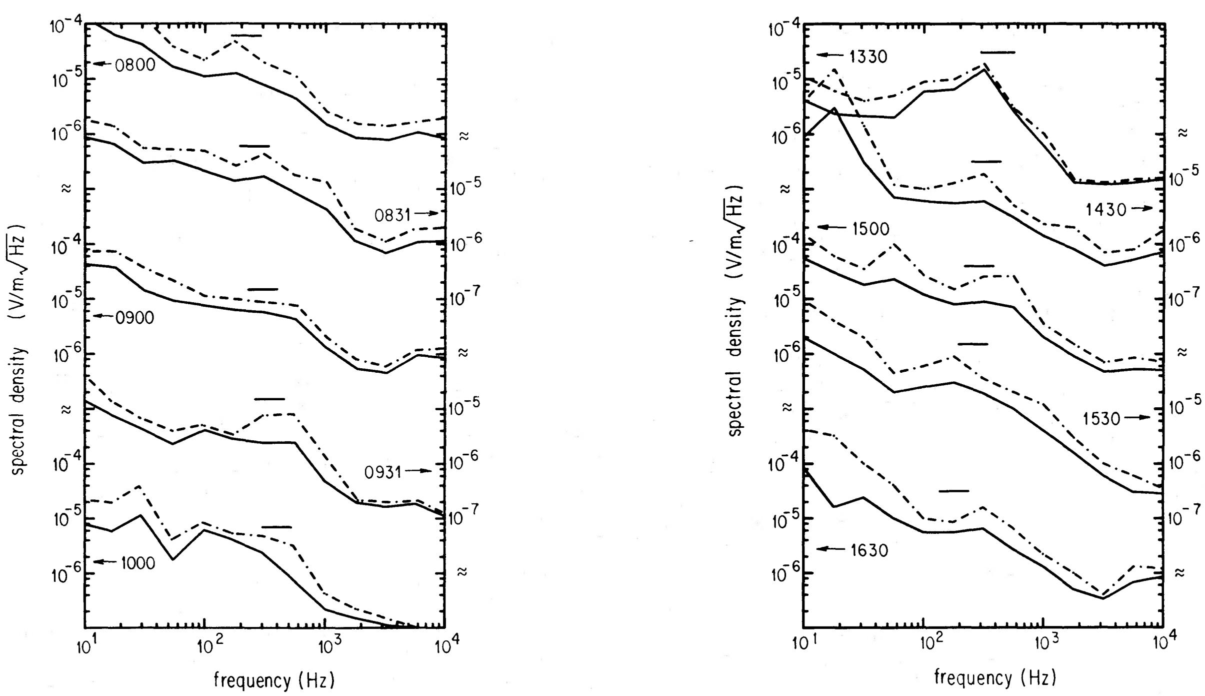

FIG. 7.—Spectra obtained from the spectrum analyzer at roughly half-hour intervals for the inbound (*left-hand panel*) and outbound (*right-hand panel*) legs of the *Voyager 1* encounter. The broken line is the peak value, and the solid line is the average value over a 96 s interval. The vertical axis is the square root of the spectral density in V m^{-1} $Hz^{-1/2}$; note that the scale alternates consecutively from the labels on the left to those on the right. The horizontal solid bar above each spectrum is the predicted lower hybrid frequency for $A/Z = 32$–10.7.

variable slope. However, it is also evident that persistent structure in the spectra is present, with peaks in the range 100–600 Hz for both inbound and outbound legs of the spacecraft trajectory. These emission peaks are generally consistent with their identification as LH modes with frequency given by (Barbosa 1982)

$$f_{\mathrm{LH}}^2 = \frac{R}{1+R} f_{\mathrm{ce}} \sum_i \frac{Z_i n_i}{n_e} f_{\mathrm{ci}} . \tag{1}$$

Here $f_{\mathrm{ci}} = q_i B/2\pi M_i c$ is the ion gyrofrequency, Z_i is the charge state of the ion species with density n_i, $R = f_{\mathrm{pe}}^2/f_{\mathrm{ce}}^2$ is the squared ratio of electron plasma frequency to electron gyrofrequency, and the sum runs over all ion species of the plasma.

We have indicated the predicted LH frequency for an $A/Z = 32$–10.7 plasma as a solid bar above each spectrum in Figure 7. The high-density limit $R \gg 1$ of equation (1) was assumed. The spectral features are in accord with the predictions based on a multiply charged heavy-ion plasma. Although there may be some contribution to these spectra from the 400 Hz interference tone, the frequencies of the spectral features are variable, indicating a natural origin. Also, if either the peak or average spectral density exceeds approximately 10^{-10} V^2 m^{-2} Hz^{-1}, the interference contributes negligibly to the power spectrum as discussed previously. Another point to be made is that the LH frequency for an all-proton plasma is generally above 1 kHz for the spectra in Figure 7, and, since there is little or no structure that can systematically be associated with ${}^1f_{\mathrm{LH}}$, we may conclude that the spectra are compatible only with a predominantly heavy-ion plasma.

In fact, the spectra also permit an estimate of the proton concentration to be made. We note the presence of a feature at 31 Hz on the inbound leg at 1000 UT and a very prominent line at 18 Hz on the outbound leg at 1430 UT. Both of these lines lie below the proton cyclotron frequency, which is 40 Hz and 34 Hz, respectively, in each instance. If we identify these lines as the Buchsbaum (H/O) resonance (Barbosa 1982), then the relative proton concentration may be estimated to be roughly 2%–4% for the 1000 UT spectrum and 7%–10% for the 1430 UT spectrum, the range depending on whether the ratio of oxygen density to sulfur is 0 or 2 (see Fig. 2 of Barbosa 1982). Although other interpretations may be possible, the values deduced are qualitatively consistent with what is expected near the equator (1000 UT) and off the equator (1430 UT) from centrifugal confinement of the heavy ions. The values are also quantitatively consistent with those based on the dispersion of discrete whistlers (Gurnett *et al.* 1979; Tokar *et al.* 1982). Thus, because of the relatively large magnetic field of Jupiter, the frequency of this gyroresonance is within our observation window, and we are pleased to report that this is the first detection of the Buchsbaum ion-ion mode occurring under natural conditions in space.

We can now make an estimate of the LH frequency appropriate to the event in Figure 6. At this time the spacecraft was very close to the centrifugal equator. We thus take a mix of 4% H^+, 48% O^+, and 48% S^+. The electron cyclotron frequency was 75.6 kHz, and the electron plasma frequency was 300 kHz (Birmingham *et al.* 1981), so that high-density $R \gg 1$ conditions apply. Thus, the effective mass-to-charge ratio as calculated from equation (1) is $A/Z \approx 11.8$, and the predicted LH frequency is $f_{\mathrm{LH}} \approx 514$ Hz, just below the peak frequency of 700 Hz in Figure 6. This value compares very well with the empirical definition obtained from Earth-based studies: that the LH resonance defines a sharp low-frequency cutoff to a band of hisslike noise (cf. Brice and Smith 1965).

The low-resolution spectra consistently show structure in the LH frequency range for a heavy-ion plasma, but it is very difficult to get a precise measure of the effective mass-to-charge ratio as good as that in the preceding wide-band event. To illustrate this we have plotted in Figure 8 three spectra handpicked for their outstanding features for detailed discussion. The proton cyclotron frequency and proton plasma frequency are indicated by the arrows, and the LH frequency for $A/Z = 32$–10.7 is again denoted by the bar above the spectra.

The first spectrum at 1342 UT shows very clearly the LH resonance at 178 Hz and the Buchsbaum resonance at 31 Hz. This particular case was the best example found in the low-resolution data for the sharp delineation of the spectral line features. It is still representative of those spectra taken in the cold torus and may be compared with 1430 UT, and better yet with 1000 UT, which has close to the same magnetic field strength. The third peak at 10 kHz is the emission identified as auroral hiss by Gurnett, Kurth, and Scarf (1979). The upper hybrid frequency was determined to be 116 kHz from Birmingham *et al.* (1981), and this was used to compute an electron plasma frequency of 87 kHz, since the electron cyclotron frequency was 77 kHz. Equation (1) then predicts ${}^{32}f_{\mathrm{LH}}$ to be 240 Hz, and this compares very well with the observed line-center frequency of 178 Hz in Figure 8.

However, because of the broadness of the feature we cannot use the data to infer accurately the actual A/Z. For example, if for the same parameters we assume that the observed LH frequency is at 100, 178, or 311 Hz, corresponding to the center and edges of the feature, the inverse use of (1) predicts A/Z to be 180, 57, or 18. This sensitivity relates to the dependence on the square of the observed LH frequency, and because of the broadness of the line due to the Doppler effect we cannot give a detailed profile of Io plasma torus composition. We can, however, distinguish between A/Z of the magnitude 1 or 32 on the basis of the LH emission, and the general run of spectra are compatible with a heavy-ion plasma with $A/Z = 10$–32 and definitely not a proton plasma with even as much as 20% H^+. At 1342 UT the proton cyclotron frequency is 42 Hz, and the Buchsbaum (H/O) line at 31 Hz indicates a proton concentration of roughly 2%–4%.

The second spectrum at 1400 UT occurs when the spacecraft is approaching the sharp density gradient to reenter the warm torus at a large centrifugal latitude. It is atypical when compared with those taken in the cold or warm tori. Distinguishing features are a narrow emission at 1.4 times the proton cyclotron frequency (which is likely an electrostatic hydrogen cyclotron mode) and an intense broad emission extending from 1 kHz to 17.8 kHz. This spectrum was taken during the reception of a broad-band spike of noise, which is clearly shown in Figure 1 of Gurnett, Kurth, and Scarf (1979) also. It is likely to be an occurrence of intense auroral hiss, and these observations support the suggestion of Gurnett, Kurth, and Scarf (1979) that there are field-aligned electric currents flowing at the sharp inner edge of the warm torus.

The third spectrum at 1601 UT is representative of those in the warm torus with the general broad feature at 178–311 Hz. The example here is slightly more intense than most of those displayed in Figure 7. There are enough data points in the average curve to

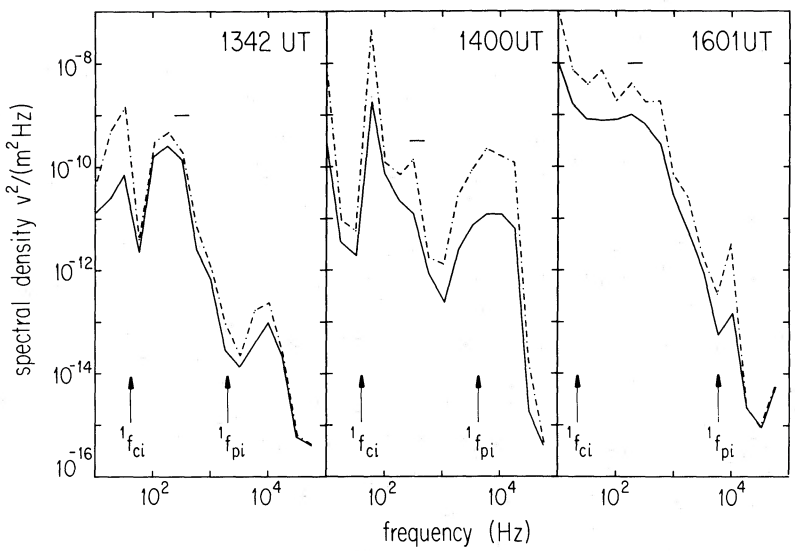

FIG. 8.—Three examples of spectra representative of the cold torus (*left-hand panel*), density gradient transition zone (*middle panel*), and the warm torus (*right-hand panel*). The proton cyclotron frequency ${}^1f_{ci}$ and the proton plasma frequency ${}^1f_{pi}$ are indicated by arrows, and the solid bar over each spectrum is the lower hybrid frequency for $A/Z = 32$–10.7.

demonstrate the upturning of the spectrum at 31.1 Hz away from what would otherwise be a power law with a spectral index of about 2. At 562 Hz the curve begins to fall off rapidly with a slope of 3 until the background hiss level is reached. A small feature at 10 kHz is present here, but in other spectra, especially on the inbound leg at smaller latitudes, the signature of Doppler shifted ion acoustic noise is usually found at these frequencies.

We may summarize the results of the wave survey as follows:

1. A variety of wave emissions is found in the Io plasma torus at frequencies below the electron cyclotron frequency. For $f < 10$ kHz these include, but are not limited to, whistler-mode hiss, ion acoustic waves, auroral hiss, lower hybrid noise, Buchsbaum ion-ion modes, and, tentatively, the electrostatic hydrogen cyclotron mode at $1.4f_{cp}$.

2. The LH noise appears as persistent peaks in 16 channel wave spectra in the frequency range 100–600 Hz, consistent with a multiply charged majority heavy-ion plasma with an effective A/Z of 10–32. The noise has a typical amplitude of 0.1 mV m^{-1}, and the spectral feature is broadened by an amount $\Delta f/f \sim 1$ due to plasma-spacecraft relative motion.

3. The Buchsbaum (H/O) resonance appears regularly in the cold torus, indicating a relative proton concentration of roughly 2%–4% close to the centrifugal equator and 7%–10% away from it.

4. The tentative identification of the electrostatic hydrogen cyclotron (EHC) mode occurring in the region of large density gradient at the inner edge of the warm torus supports the suggestion of Gurnett, Kurth, and Scarf (1979) that field-aligned electric currents are flowing there between the Jovian ionosphere and the warm plasma torus.

III. PLASMA WAVE EMISSION RATE

The EUV radiation from the warm torus requires an electron volume heating rate of $\xi = (2\text{–}4) \times 10^{-13}$ ergs cm^{-3} s^{-1}. We have demonstrated in another paper (Barbosa, Coroniti, and Eviatar 1983) the conditions under which newly created pickup ions can supply this power with Coulomb collisions as the energy transfer mechanism. The presence of the lower hybrid emissions in the torus suggests that a collective plasma wave process is operative also as an anomalous heat exchange mechanism. Knowing the amplitude of the LH emissions (~ 0.1 mV m^{-1}), we may determine the volume rate of plasma heating by computing the growth rate of the LH waves from an unstable pickup-ion distribution. The rate at which low-energy particles are energized must be equal to the rate at which wave energy is generated in a long-term quasi–steady state situation with a constant level of wave intensity. The LH wave then serves as the mediator of the forces which act to equipartition kinetic energy among the plasma species.

The particular advantage that we make use of is the direct measurement of the wave amplitude, thereby sidestepping theoretical issues (often controversial) concerning the saturation level of wave intensity. Thus, quite general conclusions can be drawn regarding the plasma wave heating rates if the time scale for wave generation or absorption can be determined. We will analyze the problem from the viewpoint that the source of the waves is the pickup ions, and computed growth rates for this superthermal ion distribution, subject to certain constraints, will then provide a measure of the heating rate as an upper bound assuming steady state energy balance. The alternative approach would be to estimate the effective wave damping rate by superthermal electrons, but this method is much more model-dependent and tends to give instead a lower bound on the heating rate. However, we still will be able to comment on the energetics of the superthermal electrons on the basis of their Coulomb collisions (see also Smith, Palmadesso, and Strobel 1982).

The ion pickup process creates a monoenergetic energy distribution which looks like a tin can in velocity space (Siscoe 1977), owing to the dipole tilt of the magnetic field with respect to the orbital planes of Io and the neutral atoms. In the absence of collisions or collective processes the pickup distribution would have the characteristics of a sharp delta function in the perpendicular velocity component, which would be very unstable to plasma waves. On the other hand, the requirement that most of the gyroenergy be extracted from the pickup ions to electrons (and ultimately to radiation) during their residence in the torus demands that the pickup distribution function be processed to a "marginally unstable" state as a consequence of the energy redistribution.

These considerations have been dealt with thoroughly by Galeev (1981) and Galeev and Chabibrachmanov (1983) using weak turbulence quasi-linear theory. They find that for conditions appropriate to the Io torus, an initial delta function pickup-ion distribution will relax to the marginally unstable state with only a modest amount of wave energy available for acceleration of electrons. Much of the relaxation process involves acceleration of pickup ions above the injection energy. They estimate that only a 2.5% deficit of ion kinetic energy is channeled into superthermal electrons during the quasi-linear relaxation. We shall find that this estimate of 2.5% (corresponding to an electron energization rate of 5×10^{-15} ergs cm^{-3} s^{-1}) is in reasonable accord with our estimates based on the *in situ* plasma wave measurements.

a) *Particle Model*

In order to make estimates of the energy exchange rate with the above considerations in mind, we will model the pickup-ion distribution as a Dory-Guest-Harris (DGH) function

$$f_{\mathrm{DGH}}(\boldsymbol{v}) = \frac{1}{\pi^{3/2}\Gamma(N+1)a_z a_\perp^2}\left(\frac{v_\perp}{a_\perp}\right)^{2N} e^{-(v_\perp/a_\perp)^2} e^{-(v_z/a_z)^2} , \tag{2}$$

where $a_\perp$ (a_z) is the thermal speed perpendicular (parallel) to the magnetic field and N is a parameter which measures the anisotropy of the distribution as defined by Kennel and Petschek (1966). We take n_1 to be the density of the pickup-ion population in a background field of thermal ions of density n_0.

This function resembles a ring or torus in $\boldsymbol{v}$-space. When $N = 0$, it reduces to a Maxwellian distribution, and when N (the ring anisotropy) is large, the perpendicular energy is concentrated near the maximum

$$v_{\perp\max} = N^{1/2} a_\perp \equiv V . \tag{3}$$

We may take V to be the perpendicular speed of newly created pickup ions, approximately 57 km s^{-1}. The average gyroenergy of expression (2) is

$$\left\langle \frac{1}{2} M v_\perp^2 \right\rangle = \frac{1}{2}(N+1) M a_\perp^2 = \frac{1}{2}\left(1 + \frac{1}{N}\right) M V^2 . \tag{4}$$

This distribution function has many of the features expected for monoenergetic injection of ions corresponding to full pickup. Ion collisions will drive the ions toward a Maxwellian distribution, and quasi-linear wave effects will also act to reduce the anisotropy. Although a self-consistent calculation of the distribution would be useful, the model given in equation (2) with the free parameter N will suffice to make a determination of the wave growth rate and volume emission rate of LH waves in the corotating frame of reference. The reader is referred to Galeev (1981) for a self-consistent quasi-linear analysis of the particle evolution and to Smith, Palmadesso, and Strobel (1982 and manuscript in preparation) for a comprehensive analysis of the particle distribution functions which includes most of the relevant interactions.

b) *Instability Analysis*

The electrostatic LH mode traveling across the magnetic field is well suited to redistribute energy from a distribution like that in equation (2) with most of the energy in the perpendicular gyromotion of the ions. The distribution function can be treated as a superthermal gyrotropic "beam" of ions which can drive LH waves unstable through Landau resonance on the positive slope of the distribution when the rectilinear ion orbit approximation is used (Rosenbluth and Post 1965). Also, in the high-density limit, the LH frequency is the geometric mean of the electron and ion gyrofrequencies, and acceleration of electrons by LH waves is the strongest sink for the wave energy.

We then consider an electrostatic wave with angular frequency $\omega \approx \omega_{\mathrm{LH}}$ traveling in the x-direction with perpendicular wavenumber k_x such that

$$a_c \ll \omega/k_x \lesssim V , \tag{5}$$

where V locates the peak of the pickup distribution (see eq. [3]) and a_c is the background cool-ion thermal speed. We also allow a parallel wavenumber k_z along the magnetic field sufficiently small that resonant damping from the background electrons is negligible. The condition (5) is satisfied when

$$k_x \rho_{\mathrm{ce}} \ll 1 \ll k_x \rho_{\mathrm{ci}} \tag{6}$$

for frequencies near the lower hybrid.

The dispersion relation for LH waves in a multi-ion plasma has been analyzed in detail by Horita and Watanabe (1969) and Barbosa (1982). When first-order ion thermal effects ($T_e \approx 0$; $\omega/k_x a_i \gg 1$) are included, the dielectric constant computed for the background plasma is

$$\epsilon \approx 1 + \frac{\omega_{\mathrm{pe}}^2}{\Omega_e^2}\sin^2\theta - \frac{\omega_{\mathrm{pe}}^2}{\omega^2}\cos^2\theta - \sum_i \frac{\omega_{\mathrm{pi}}^2}{\omega^2}\left(1 + \frac{3k^2 a_i^2}{2\omega^2}\right) , \tag{7}$$

where $\omega_{p\alpha}^2 = 4\pi n_\alpha q_\alpha^2/M_\alpha$, $\Omega_\alpha = q_\alpha B/M_\alpha c$, $\tan\theta = k_x/k_z$, and the sum runs over all background ion species with thermal speed a_i. The above is valid for frequencies $\Omega_i^2 \ll \omega^2 \ll \Omega_e^2$ when the rectilinear ion orbit approximation is justified. The solution of $\epsilon = 0$ is

$$\omega^2 = \left[\omega_{pe}^2 \cos^2\theta + \sum_i \omega_{pi}^2(1 + 3k^2a_i^2/2\omega^2)\right] \Big/ (1 + R\sin^2\theta) , \tag{8}$$

which reduces to equation (1) for $\theta = \pi/2$.

With the addition of the DGH distribution of pickup ions (2), the LH mode can be driven unstable when $N > 0$. The general expression for the dielectric constant when the particles are unmagnetized is

$$\epsilon(B = 0) = 1 + \frac{\omega_p^2}{k^2}\int d\boldsymbol{v}\, \frac{\boldsymbol{k}\cdot(\partial f/\partial \boldsymbol{v})}{\omega - (\boldsymbol{k}\cdot\boldsymbol{v})} , \tag{9}$$

which, for a wave traveling in the x-direction, has an imaginary part

$$\epsilon_i \approx -\frac{\pi\omega_p^2}{k_x^2}\iint dv_y\, dv_z \left.\frac{\partial f}{\partial v_x}\right|_{v_x = v_R} , \tag{10}$$

where $v_R = \omega/k_x$ is the velocity of the ions in Landau resonance with the LH wave.

If we insert expression (2) into equation (10), it may be shown that ϵ_i from the pickup-ion distribution is given by

$$\epsilon_i = \frac{4\omega_{p1}^2}{\Gamma(N+1)\omega^2}\, b^3 e^{-b^2}\int_0^\infty dt\, e^{-t^2}(b^2 + t^2)^N\left(1 - \frac{N}{b^2 + t^2}\right) , \tag{11}$$

where $b = v_R/a_\perp$.

For small growth or damping such that $\gamma/\omega \ll 1$, we may use the expression

$$\gamma = -\frac{\epsilon_i}{\partial\epsilon/\partial\omega} , \tag{12}$$

and we note immediately that for wave growth ($\gamma > 0$) we require $\epsilon_i < 0$. Thus, a necessary condition for growth from inspection of equation (11) is that $b^2 < N$ or, alternatively,

$$\omega/k_x < N^{1/2}a_\perp = V , \tag{13}$$

as already concluded for instability on the positive slope of the beam. From equation (7) we obtain

$$\frac{\partial\epsilon}{\partial\omega} = \frac{2}{\omega}\left(\frac{\omega_{pe}^2}{\omega^2}\cos^2\theta + \sum_i \frac{\omega_{pi}^2}{\omega^2}\right) , \tag{14}$$

and since $\epsilon = 0$ we have

$$\omega\frac{\partial\epsilon}{\partial\omega} = 2\left(1 + \frac{\omega_{pe}^2}{\Omega_e^2}\sin^2\theta\right) . \tag{15}$$

Thus, for $R = \omega_{pe}^2/\Omega_e^2 \gg 1$, the growth rate may be written as

$$\frac{\gamma}{\omega} = -\frac{Z_1 n_1}{n_e}\left\{\frac{Z_1 m_e}{M_1}\frac{\Omega_e^2}{\omega^2}\right\}\frac{2}{\Gamma(N+1)}\, b^3 e^{-b^2}\int_0^\infty dt\, e^{-t^2}(b^2 + t^2)^N\left(1 - \frac{N}{b^2 + t^2}\right) . \tag{16}$$

The factor enclosed by braces is $O(1)$ and is equal to 1 if the mass-to-charge ratio A_1/Z_1 of the pickup ions is equal to that of the background ions. We will take its value as unity; further development of equation (16) is contained in the Appendix.

In Figure 9 we plot numerical values for the expression to the right of the braces in equation (16). The values for $N = 1$ are in agreement with what is expected from equations (A7) and (A9), that is,

$$\left(\frac{\gamma}{\omega}\frac{n_e}{Z_1 n_1}\right)_{\max} = \pi^{1/2} b_0^3 e^{-b_0^2}\left(\frac{1}{2} - b_0^2\right) \approx 0.04 , \tag{17}$$

which occurs at a wave phase velocity of

$$\omega/k_x = (0.52)V . \tag{18}$$

For $N \gg 1$ the characteristic phase velocity would be slightly larger, $\omega/k_x \lesssim V$ as the pickup-ion distribution becomes more sharply peaked.

We have so far neglected all damping contributions from the background ions and electrons. The ion contribution from equation (A6) is

$$\frac{\gamma_i}{\omega} \approx -\pi^{1/2}B^3 e^{-B^2} , \tag{19}$$

(where $B = \omega/k_x a_0$ relative to the background ion thermal speed a_0. The effect of including background ion damping, expression

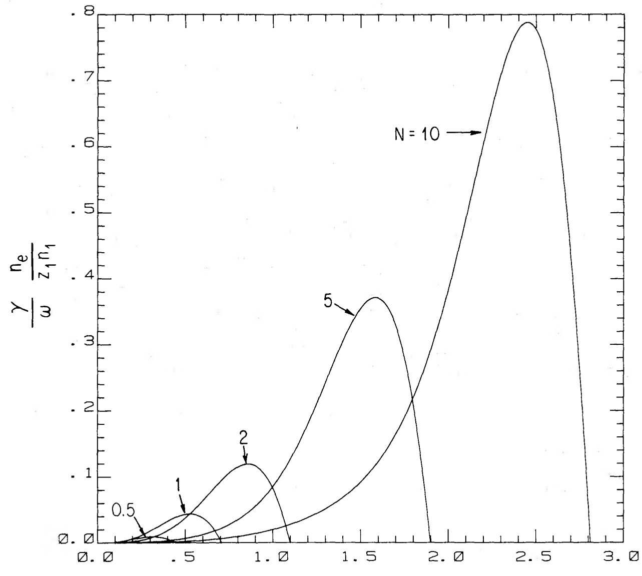

FIG. 9

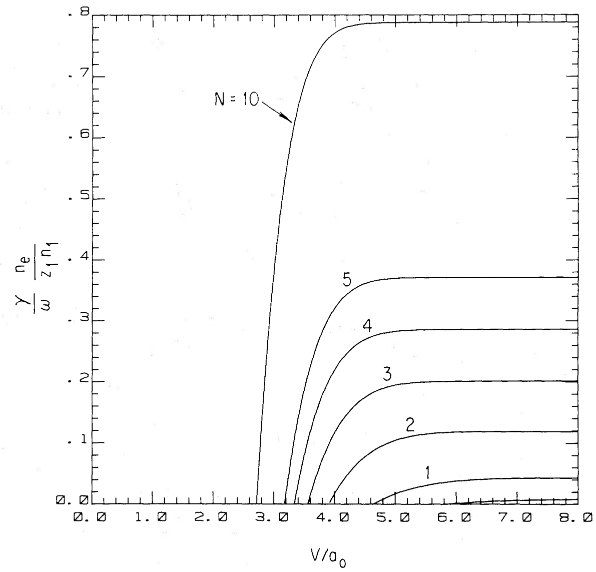

FIG. 10

FIG. 9.—Normalized growth rates for the pickup-ion ring distribution plotted against $b = v_R/a_\perp$ for several values of the ring anisotropy N

FIG. 10.—Normalized maximum growth rate including damping from the background ions

(19), is illustrated in Figure 10. We have set $Z_1 n_1/Z_0 n_0 = 0.2$ and have computed the maximum growth rate $\gamma_{\max}$ (as a function of b) for a given V/a_0. The figure shows $\gamma_{\max}$ suitably normalized versus V/a_0 for various values of N for comparison with Figure 9. Negative values of $\gamma_{\max}$ are not shown, but the zero crossings correspond to marginal stability.

The contribution from damping on electrons arises from finite k_z, since the electrons are magnetized, and is

$$\frac{\gamma_e}{\omega} \approx -\frac{\pi^{1/2}}{2(1+R)}\frac{k_{\mathrm{De}}^2}{k^2}\frac{\omega}{k_z a_e}e^{-(\omega/k_z a_e)^2}, \tag{20}$$

where k_{De} is the electron Debye wavenumber. The above may be expressed as

$$\frac{\gamma_e}{\omega} \approx -\pi^{1/2}\left(\frac{m_e}{M_1}\frac{\Omega_e^2}{\omega^2}\right)(0.52)^2\frac{T_1}{T_e}\frac{\omega}{k_z a_e}e^{-(\omega/k_z a_e)^2}. \tag{21}$$

Thus, the electron damping is significant in comparison with expression (16) unless $\omega/k_z a_e \gg 1$ so that the exponential factor is sufficiently small. If we require, say, $\omega/k_z a_e \gtrsim 5$ and also equation (18), then

$$\frac{k_z}{k_x} \lesssim 4.4 \times 10^{-3}\left(\frac{V}{57\ \mathrm{km\ s^{-1}}}\right)\left(\frac{5\ \mathrm{eV}}{T_e}\right)^{1/2}, \tag{22}$$

which implies that LH waves may be amplified only within 0°25 of strictly perpendicular propagation. For these parameters and a typical lower hybrid frequency $f_{\mathrm{LH}} \sim 300$ Hz, the wavelengths are $\lambda_x \approx 100$ m and $\lambda_z \gtrsim 22$ km. The Doppler shift arising from plasma corotation can be estimated by

$$\Delta\omega/\omega = \boldsymbol{k}\cdot(\boldsymbol{V}_{\mathrm{CR}} - \boldsymbol{V}_{\mathrm{SC}})/\omega \approx V_{\mathrm{CR}}/(0.52V) \sim 1, \tag{23}$$

since in the full pickup process $V \approx V_{\mathrm{CR}}$ and the spacecraft velocity $V_{\mathrm{SC}} \approx 15$ km s$^{-1} \ll V_{\mathrm{CR}}$. This explains the broadness of the spectral line.

The wave-group velocity may be obtained directly from equation (8). The components along and across the magnetic field are

$$V_{gz} = \left\{\omega_{\mathrm{pe}}^2(1+R)\sin^2\theta + \sum_i \omega_{\mathrm{pi}}^2\left[R\sin^2\theta + \frac{3k^2a_i^2}{2\omega^2}(1+2R\sin^2\theta)\right]\right\}\frac{\cos\theta}{\omega k(1+R\sin^2\theta)^2} \tag{24}$$

and

$$V_{g\perp} = -\left\{\omega_{\mathrm{pe}}^2(1+R)\cos^2\theta + \sum_i \omega_{\mathrm{pi}}^2\left[R\cos^2\theta + \frac{3k^2a_i^2}{2\omega^2}(R-1-2R\sin^2\theta)\right]\right\}\frac{\sin\theta}{\omega k(1+R\sin^2\theta)^2}, \tag{25}$$

which in the limit $R \gg 1$ and $\theta \approx \pi/2$ reduce to

$$V_{gz} \approx \frac{\Omega_e^2}{\omega^2}\frac{\omega}{k}\cos\theta \tag{26}$$

and

$$V_{g\perp} \approx \frac{3}{2} \frac{\Omega_e^2}{\omega^2} \frac{\omega}{k} \sum_i \left(\frac{\omega_{\rm pi}}{\omega_{\rm pe}}\right)^2 \left(\frac{ka_i}{\omega}\right)^2 . \tag{27}$$

In the situation of a plasma with a single ion species of mass M, these simplify to $V_{gz} \approx M\omega \cos \theta/mk$ and $V_{g\perp} \approx 3ka^2/2\omega$.

The convective growth rate $k_i = \gamma/V_g$ will have the strongest dependence on the component of the group velocity along the magnetic field, V_{gz}. If we use the simple relation above together with equations (17), (18), and (22), we estimate the scale length for 10 e-foldings to be $L_{10} \lesssim 0.07\ R_J$ in the case of $Z_1 n_1/n_e = 0.2$. This is sufficient to provide the amplification needed. We also note that the propagational change of k_z will transfer energy from a region in $\boldsymbol{k}$-space where growth occurs from the ring distribution, $k_z \approx 0$, to a region where damping on superthermal electrons occurs. Thus, there is a continuity of growth and decay of the waves in the process of the interspecies energy exchange brought about naturally by the inhomogeneity (Barbosa 1982).

IV. VOLUME HEATING RATES

a) Plasma Wave Emission/Absorption Rate

We may now proceed to make an estimate of the volume rate of plasma heating possible from wave-particle interactions. The rate of change of wave energy due to instability in the linear regime is

$$\frac{d}{dt} W = 2\gamma W , \tag{28}$$

where W is the total energy density of the waves and is related to the electric field component by

$$W = \left\langle \frac{E^2}{8\pi} \right\rangle \omega \frac{\partial \epsilon}{\partial \omega} . \tag{29}$$

Taking an amplitude of $E \sim 100\ \mu\text{V m}^{-1}$ and a frequency of $f_{\rm LH} \sim 300$ Hz as representative values for the Io torus (Fig. 7), we find that the fastest volume rate at which wave energy is generated is

$$\dot{W} = 1.8 \times 10^{-13} \text{ ergs cm}^{-3} \text{ s}^{-1} \frac{\gamma}{\omega} \left(\frac{f}{300\ \text{Hz}}\right) \left(\frac{E}{100\ \mu\text{V m}^{-1}}\right)^2 \left(\frac{1+R}{55}\right) . \tag{30}$$

In deriving equation (30) we have used an electron density of $n_e = 2 \times 10^3\ \text{cm}^{-3}$ and a magnetic field value appropriate at 6 R_J so that $f_{\rm pe}/f_{\rm ce} \approx 7.4$.

Several comments are now in order. We first note that the numerical value in equation (30) gives a greatest upper bound to the wave emission rate. The electric field amplitude may rise to 300 μV m^{-1} within short intervals of time, but over the long term it is more typically 100 μV m^{-1}. The important factor which reduces the emission rate is γ/ω. For any sources that we may consider in the Io torus, $\gamma/\omega \ll 1$. If pickup ions are the source, their relative charge density is likely to be $Z_1 n_1/n_e \lesssim 0.2$ (Barbosa, Coroniti, and Eviatar 1983), and if we assume for argument that for a short period of time the anisotropy is as large as 10, then from Figure 9 we would have $\gamma/\omega = 0.16$, giving $\dot{W} \approx 3 \times 10^{-14}$ ergs cm^{-3} s^{-1}. However, this situation would not be permanent, since quasi-linear scattering and Coulomb collisions would act to remove the anisotropy on a time scale shorter than the residence time (Barbosa, Coroniti, and Eviatar 1983). Also, if the pickup ions are indeed responsible for the EUV radiative output, the distribution must be reshaped to give evidence that a significant amount of their gyroenergy has been transferred to plasma waves and/or electrons. Thus, over a long term, an anisotropy $N \lesssim 1$ is more likely to be in effect. If the ion-ion collision time is very short compared with the ion injection time, the anisotropy may be even closer to zero. Thus, we may estimate the possible wave emission rate in the torus due to pickup ions as

$$\dot{W} = (1.5\text{–}30) \times 10^{-15} \text{ ergs cm}^{-3} \text{ s}^{-1} \tag{31}$$

for an anisotropy of $N = 1$–10 and a fractional charge density of 20%. The actual value is likely to be closer to the lower limit of expression (31).

This puts a severe restriction on the model of anomalous heat exchange between pickup ions and electrons since the EUV radiation requires $\xi \approx (2\text{–}4) \times 10^{-13}$ ergs cm^{-3} s^{-1} (Shemansky and Sandel 1982). There is a further problem in the warm torus associated with the fact that the pickup energy for S^+, $E \approx 510$ eV, is not very energetic compared with the background ion temperature of $T_0 \approx 30$ eV (Bagenal and Sullivan 1981). Thus, the peak of the superthermal distribution is situated at $V/a_0 = 4.12$, and if $N = 1$, the speed of resonant ions giving maximal growth (18) is a factor of only 2.14 above the background thermal speed. Thus, damping on the background ions by equation (19) is very likely to inhibit growth for a pickup-ion density of $n_1/n_0 \approx 0.1$ unless the anisotropy is large and appears as a spike rising above the Maxwellian tail of the background ions.

This aspect is made quantitative in Figure 10, which shows that an $N = 1$ anisotropy gives instability above a threshold of $V/a_0 \approx 4.6$. However, we also note that for $N = 2$ instability is present when $V/a_0 \gtrsim 3.9$, and this slightly larger value for the ring anisotropy can produce instability of LH waves for parameters characteristic of the warm torus.

In the cold torus at 5.3 R_J this kinematic problem is not as severe. If we take a pickup energy for S^+ of 385 eV ($V \approx 48$ km s^{-1}) and a background ion temperature of 3.5 eV, then $\omega/k_x a_0 \approx 5.45$. Thus, the background is sufficiently cold that at maximal growth (18) the number of background ions is negligible and anisotropies $N \approx 1$ can drive LH waves unstable. Figure 5*b* gives a clear example of LH waves in the cold torus at 1330 UT.

b) *Other Wave Sources*

Are there any other possible sources for the emissions besides the pickup ions? Lanzerotti *et al.* (1981) report fluxes of energetic ions (0.55–1.05 MeV) which are severely depleted in the torus. If we take a value for the unidirectional flux of ions of $j = 10^7$ ions $(\mathrm{cm^2\ s\ sr\ MeV})^{-1}$, then we can estimate their number density as $n(>E) \approx 4\pi Ej/v$. Thus, assuming that the ions are protons, we have

$$n(>0.55\ \mathrm{MeV}) = 6.7 \times 10^{-2}\ \mathrm{cm^{-3}}$$

and

$$\mathscr{E}(>0.55\ \mathrm{MeV}) = 37\ \mathrm{keV\ cm^{-3}};$$

we can use the same analysis as in the preceding section to conclude that while these energetic ions may also contribute to LH emissions, the small relative density $n(>0.55\ \mathrm{MeV})/n_e$ precludes any large growth rate or significant ion-electron energy transfer via LH waves. We also note that if the characteristic time τ to bring these ions in from the middle/outer magnetosphere (see Siscoe *et al.* 1981) is comparable to the Iogenic plasma confinement time, $\tau \leq \tau_c$, then the volume energy injection rate for a plasma confinement time of 27 days (Barbosa, Coroniti, and Eviatar 1983) is

$$\dot{\mathscr{E}}(>0.55\ \mathrm{MeV}) = 2.5 \times 10^{-14}\ \mathrm{ergs\ cm^{-3}\ s^{-1}}\ . \tag{32}$$

Thus, these ions are not able to meet the energy requirements of the EUV torus (presupposing that the kinetic energy could be delivered to electrons), much less the energy requirements of the UV aurora (Barbosa *et al.* 1981; Barbosa, Coroniti, and Eviatar 1983). If the principal loss mechanism for these energetic ions is ion-neutral charge exchange (Cheng 1980; Ip 1981), then a significant amount of energy is being expended by the system (1.5×10^{11} W) in the final form of very fast (~ 1 MeV) neutrals being ejected.

Finally, we remark that our analysis has been geared toward an ion source for the LH waves to inquire into the role of anomalous heat exchange between superthermal ions and electrons. Alternative interpretations are still possible; for example, the structure in Figure 7 may be due simply to propagation effects on a broad-band whistler-mode spectrum in the vicinity of the lower hybrid resonance (e.g., Thorne and Kennel 1967). Nonetheless, we believe that our analysis of electron energization based on estimating wave growth rates and therefore effective wave damping rates, as summarized in equations (30) and (31), is generally valid. We then turn to the energetics of any superthermal electrons present in the torus with regard to wave-particle interactions.

V. SUPERTHERMAL ELECTRON ENERGIZATION RATES

If a large number of superthermal electrons is present in the Io torus, the energy balance and ionization structure will be affected. Firm evidence for hot (~ 1 keV) electrons was found in the outer portion of the torus (Barbosa and Kurth 1980; Coroniti *et al.* 1980; Scudder, Sittler, and Bridge 1981) and also in the densest part (Birmingham *et al* 1981). But as pointed out by Barbosa and Kurth (1980), the high background electron density implies that at low superthermal energies the time scale for electron-electron scattering can become very short compared with that of other relevant processes, in particular, the radial transport of hot electrons. Scudder, Sittler, and Bridge (1981) have reported on measurements made at the edges of the warm torus, and their results are summarized in Table 1. We note immediately that the short lifetime of keV electrons compared with the time for them to diffuse inward precludes their source being radial transport. There are hot electrons at 5.5 R_J, and if there also are hot electrons in the dense torus ($>10^3$ $\mathrm{cm^{-3}}$), they must have a local source, either the Jovian ionosphere or acceleration by plasma waves.

Several studies attempting to infer the concentration of hot electrons in the dense torus have led to conflicting results. The early work of Strobel and Davis (1980) and Shemansky (1980) was concerned with the ionization balance of the torus and proposed a value of $n_h/n_c \approx 5\%$ and $\lesssim 1\%$, respectively, based on their interpretations of the *Voyager* EUV spectra. However, both these analyses were conducted prior to the final disclosure of results obtained from the *in situ* measurements. A glance at Table 1 indicates that there are insurmountable difficulties in accounting for a density of $n_h \approx 20\ \mathrm{cm^{-3}}$ at 6 R_J given the express radial profile of values. The later study of Brown, Shemansky, and Johnson (1983) concluded that the ground-based upper limit on O III emission implied that $n_h/n_c < 2 \times 10^{-4}$, a value more in harmony with Table 1. Clearly, the issue of the hot electron density is still unsettled, as there are extant proposals that the hot electron population is the main power source for the EUV emitting torus. We shall address these questions, making use of data from independent *Voyager* experiments along with physical arguments regarding the energetics and source of the hot electrons. The general topic of the physical mechanism for superthermal electron acceleration is also discussed and is interesting and important per se to warrant a full elaboration.

Plasma wave data and radio wave data have also shed some light on this subject. The analysis of Birmingham *et al.* (1981), based on the wave measurements of the Planetary Radio Astronomy experiment, indicated that a hot electron component was present

TABLE 1

TWO-COMPONENT ELECTRON MODEL OF THE IO PLASMA TORUS[a]

Parameter	5.5 R_J	7.8 R_J	8.9 R_J
n_h	0.24 $\mathrm{cm^{-3}}$	2.2 $\mathrm{cm^{-3}}$	3.1 $\mathrm{cm^{-3}}$
T_h	0.63 keV	1.2 keV	1.2 keV
n_c	1250 $\mathrm{cm^{-3}}$	157 $\mathrm{cm^{-3}}$	36 $\mathrm{cm^{-3}}$
T_c	5.0 eV	23 eV	26 eV

[a] Scudder, Sittler, and Bridge 1981.

with a hot-to-cold temperature ratio that varied from $T_h/T_c = 200$ at 5.6 R_J to $T_h/T_c = 25$ at 6.5 R_J. While we concur with their conclusions regarding the temperature structure, we differ with them in the overall theoretical interpretation, which has a direct bearing on the present discussion regarding superthermal electrons.

The final conclusion of Birmingham *et al.* (1981) attributed the lack of a single "3/2's" emission and the constant presence of upper hybrid noise in the torus to having $n_c \gg n_h$ everywhere in the torus. According to the theory and predictions of Barbosa and Kurth (1980), we conclude that while $n_c \gg n_h$ is realized throughout the torus, it is not the cause for the absence of 3/2's emission. Instead, the lack of 3/2's emission in the densest part of the torus is due to the extinction of the free energy source by isotropization and deficit of intermediate energy superthermals ($T/T_c = 4$–50) from Coulomb collisions with the background electrons. In a dense plasma when $f_p/f_c \gg 1$, it is these intermediate-energy electrons that kinematically have access to the lower gyroharmonic bands through wave-particle resonance. Rapid Coulomb collisions among these electrons will lead to the absence of the 3/2's emission. On the other hand, higher energy electrons (e.g., $\gtrsim 1$ keV) have access kinematically to the upper hybrid resonance frequency and neighboring harmonic bands. Since collisions among these electrons are much less frequent, they can sustain a loss-cone distribution which is unstable to the upper hybrid frequency. Thus, the situation permits an upper hybrid emission without accompanying lower harmonic bands. Again, $n_c \gg n_h$ does not require that this occur; rather, it is due to the preferential scattering of electrons with frequency-dependent interaction energies. Remove the assumption of Coulomb scattering and 3/2's emission can occur when $n_c \gg n_h$.

A clear demonstration of this interpretation is contained in Figure 2 of Lecacheux (1981). As the spacecraft enters the torus at 0630 UT, both the upper hybrid and low harmonic waves are present in the circumstance $n_c \gg n_h$ (see Fig. 4 of Kurth *et al.* 1980). As the spacecraft penetrates the dense torus, the spectrogram is completely cleaned of low harmonic noise, while the upper hybrid trace persists. Finally, at 1600 UT, when the total electron density is 750 cm^{-3} (Birmingham *et al.* 1981), the low harmonic bands begin to appear again (see Fig. 5 of Kurth *et al.* 1980). Thus, we would conclude instead that on the basis of all plasma wave observations, $n_c \gg n_h$ throughout the torus, and the radial profile of gyroharmonic emissions is strongly influenced by the Coulomb scattering of intermediate energy ($T/T_c = 4$–50) electrons, while the "hot" keV electrons ($T/T_c \gtrsim 100$) are more durable.

These preliminaries then lead us to investigate the possibility for a local source of hot electrons. In order to gauge the effectiveness of wave-particle interactions, we can compute the lifetime of the superthermals against Coulomb scattering, which is most likely the fastest loss mechanism. Although the electron distribution at high energies is non-Maxwellian, we will assume a characteristic temperature $T_h \gg T_c$ and density $n_h \ll n_c \approx n_e$ for the hot component relative to the background electrons. In this case the volume heating rate of the background electrons by the superthermals is (Barbosa, Coroniti, and Eviatar 1983)

$$\dot{\mathscr{E}}_c \approx \frac{4(2\pi)^{1/2} e^4 n_e^2 \ln \Lambda}{(mT_h)^{1/2}} X_h \,, \tag{33}$$

where $X_h = n_h/n_e$, and the above is evaluated as

$$\dot{\mathscr{E}}_c \approx 5 \times 10^{-15} \text{ ergs cm}^{-3} \text{ s}^{-1} \left(\frac{n_e}{2 \times 10^3 \text{ cm}^{-3}}\right)^2 \left(\frac{1 \text{ keV}}{T_h}\right)^{1/2} \left(\frac{X_h}{10^{-4}}\right) . \tag{34}$$

We have adopted a temperature for the hot electrons corresponding to the value measured by Scudder, Sittler, and Bridge (1981) at 7.8 R_J. The Coulomb energy degradation time for these electrons is (Barbosa, Coroniti, and Eviatar 1983)

$$\tau = 10^5 \text{ s} \left(\frac{2 \times 10^3 \text{ cm}^{-3}}{n_e}\right) \left(\frac{T_h}{1 \text{ keV}}\right)^{3/2} , \tag{35}$$

and we note that a smaller (e.g., 100 eV) hot electron temperature would imply a lifetime of only 0.9 hr. Thus, a hot electron temperature $T_h \gtrsim 1$ keV is likely to be the case in the dense torus also.

The more uncertain quantity is the relative concentration. If $X_h = 1\%$, the hot electrons can power the EUV torus. For this situation, however, the mean electron energy with a 5 eV background would be $\langle T \rangle \approx 15$ eV, and such a high temperature would probably be detectable in the EUV data. The present evidence is not favorable for this case (Shemansky and Sandel 1982). If $X_h = 0.1\%$, then $\langle T \rangle \approx 6$ eV, which is, on the other hand, not entirely ruled out. We then estimate the volume heating rate from superthermal electrons as $\dot{\mathscr{E}}_c = (5\text{–}50) \times 10^{-15}$ ergs cm^{-3} s^{-1}, with a preference for the smaller value (see also Brown, Shemansky, and Johnson 1983).

If we now compare this result with our estimate based on the LH emissions (eq. [31]), we find that the waves, at least energetically, can maintain a small-density population of keV superthermal electrons through wave-particle interactions. The details of this interaction would have to be worked out, but we believe that this study has given some support to the hypothesis of anomalous heating and ionization at a significant level, albeit secondary to classical Coulomb interactions (Barbosa, Coroniti, and Eviatar 1983).

VI. SUMMARY AND CONCLUDING REMARKS

We have conducted a survey of the Io plasma torus for evidence of electrostatic emission near the lower hybrid frequency. Persistent structure in electric field spectra throughout the cold and warm tori has been found, with frequencies consistent with identification as LH emissions in a high-density, heavy-ion plasma with an effective mass-to-charge ratio $A/Z = 32$–10. This result is compatible with those of previous studies (*in situ* and remote) which indicated a cold torus composed primarily of S^+ and a warm outer torus consisting of multiply charged sulfur and oxygen ions. The data also give possible evidence for the Buchsbaum ion-ion (hydrogen-to-oxygen) resonance with a relative proton concentration of between 2% and 10% depending on the latitude of the spacecraft relative to the heavy-ion plasma located at the centrifugal equator.

A theoretical instability analysis of LH wave generation by a Dory-Guest-Harris ring distribution of superthermal ions was carried out. The purpose was to investigate the conditions under which newly created pickup ions could amplify LH waves, giving rise to an anomalous heat exchange with the background plasma. It was found that because of the relatively small ratio of the pickup gyrospeed to background ion thermal speed in the warm torus, the instability required moderately large anisotropy ($N \gtrsim 2$) of the pickup-ion distribution in order to work. This suggested that ion-electron anomalous heat exchange was effective only for sharply peaked pickup distributions and only for a limited interval of time. In the cold torus, the gyrospeed ratio is larger, and the instability was possible for smaller anisotropy ($N \approx 1$), thus permitting a good proportion of kinetic energy to be extracted from the pickup ions.

We may thus conclude that a plasma wave amplification process is occurring in the cold torus which produces the observed LH emissions over a fairly wide range of parameters. In the warm torus, the required anisotropy is larger and the instability is more sensitive to the higher background ion temperature. Although instability is more difficult to obtain, it can still occur for moderate values of the anisotropy. This result suggests either of two possibilities for the cause of the warm torus LH emissions: that a more refined and self-consistent kinetic model of the ion distribution function will lead manifestly to an instability, or that spontaneous generation of the waves is occurring in the presence of a marginally stable but nonthermal ion distribution. If pickup ions are present, an enhanced level of plasma wave activity is inevitable owing to the two-component nature of the total ion distribution. The fact that we observe LH waves in the warm torus gives support to our theoretical hypothesis that the pickup ions are present.[6]

We have also investigated by a general methodology the energetics of the torus to address whether the LH emissions are a significant factor for powering the EUV radiation. It was concluded that only a modest volume heating rate, $(1.5\text{–}30) \times 10^{-15}$ ergs $\text{cm}^{-3}\ \text{s}^{-1}$, was possible through wave-particle interactions via the LH mode. This ruled out anomalous heat exchange as the dominant mechanism for energy communicated to plasma electrons. However, the heating rate was still of sufficient magnitude to maintain a superthermal population of ~ 1 keV electrons with a relative concentration of $10^{-4}\text{–}10^{-3}$. At these densities the hot electrons can supply $(5\text{–}50) \times 10^{-15}$ ergs $\text{cm}^{-3}\ \text{s}^{-1}$ to the background electrons, and although electron-electron heating cannot power the EUV torus, the latter possibility leaves open the question of the energy source for the hot electrons. Anomalous electron acceleration and ionization phenomena are viable options for the torus dynamics.

In this regard, the *Voyager* plasma wave measurements have provided the first evidence for an anomalous ionization effect in a naturally occurring space environment. The summary of experiments reported by Haerendel (1982) refers to active experiments conducted by rocket at ionospheric heights where explosive charges are ignited (without accompanying diagnostic measurements of plasma waves or particles). Our investigation has dealt with passive *in situ* observations of an extraterrestrial system which is similar in many respects to astrophysical gaseous nebulae. Although the anomalous ionization effect in the Io torus is not as dramatic as one might have imagined, nevertheless, the characteristic observational signatures are present and the heating efficiency (~ 1%) compares well with theoretical predictions. In the long term, Coulomb collisions suffice to produce the requisite interactions between particles. In the short term, where intense particle injections occur and sharp features in the distribution are produced, collective wave-particle interactions can then predominate in the manner described herein. Our paper has thus given observational support to the theoretical scenario of anomalous ionization phenomena.

This paper has also provided a detailed account of the plasma physics underlying the pickup-ion instability appropriate to the Io torus. Other mechanisms (see discussion by Haerendel 1982) specify excessively large growth rates ($\gamma \sim \Omega_{\text{LH}}$) and also encounter various conceptual difficulties. We have analyzed an instability that is driven by the gyromotion of the newly created pickup ions (ring anisotropy). The advantageous use of the Rosenbluth-Post rectilinear ion orbit approximation (RIOA) has allowed an instability of LH waves to occur which avoids electron Landau damping, a notoriously difficult obstacle for theoretical attempts at generating ion waves without requiring extravagant particle drift motions. We intend to make considerable use of this theoretical device in future work.

The acceleration of electrons forming a low-density tail has not been treated in detail, but is an important part of the overall process. A superthermal electron component can provide an efficient ionizing capability without imposing a burden on the energetics of the system. The import of this for astrophysics is clear. In quasi-static systems the assumption of thermal equilibrium permits definite and accurate predictions of the ionization balance to be made for the interpretation of plasma emission spectra (e.g., Jordan 1969). However, in many circumstances the system is dynamically evolving rapidly, so that nonequilibrium reaction rates are required to interpret astrophysical data properly (Shapiro and Moore 1977). Multicomponent electron populations and non-Maxwellian distributions are the general rule when anomalous plasma wave activity and concomitant particle acceleration occur in flarelike situations.

Our study of the plasma wave properties of the Io plasma torus has contributed to a deeper understanding of the plasma physical processes involved in relation to conventional atomic collision and radiation phenomena. Further theoretical and observational work in this area is needed.

R. A. Smith has kindly pointed out to us work (Smith, Palmadesso, and Strobel 1982) presented at the Ottawa COSPAR meeting, and we thank him for constructive comments on the manuscript. Most of the results here were presented publicly in 1982 December (Barbosa *et al.* 1982). The manuscript has a report date of 1983 February 4 (Barbosa *et al.* 1983). Stewart Moses at TRW is acknowledged for his discovery of the line emission shown in Figure 5.

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[6] We have been informed that there is still apparent controversy at the time of this writing over the existence of the pickup ions and their importance for powering the EUV torus. We contend that the totality of observations, both *in situ* and remote, has given strong support for their presence and functional role (see Barbosa, Eviatar, and Siscoe 1984 for further implications).

APPENDIX

Several properties of expression (11) are listed here. If we define

$$I_N = \int_0^\infty dt\, e^{-t^2/a^2}(b^2 + t^2)^N \,, \tag{A1}$$

we may derive a recursion relation

$$I_{N+1} = [b^2 + a^2(N + \tfrac{1}{2})]I_N - Nb^2a^2I_{N-1} \,. \tag{A2}$$

For $a = 1$ equation (11) takes the form

$$\epsilon_i(N) = \frac{4\omega_{p1}^2}{\Gamma(N+1)\omega^2}\, b^3 e^{-b^2}(I_N - NI_{N-1}) \,, \tag{A3}$$

and thus

$$\epsilon_i(N+1) = \frac{4\omega_{p1}^2}{\Gamma(N+2)\omega^2}\, b^3 e^{-b^2}\left[\left(b^2 - \frac{1}{2}\right)I_N - Nb^2 I_{N-1}\right] . \tag{A4}$$

For integers $N = 0, 1$ we have easily

$$I_0 = \frac{(\pi)^{1/2}}{2} \,, \qquad I_1 = \frac{(\pi)^{1/2}}{2}\left(b^2 + \frac{1}{2}\right) , \tag{A5}$$

from which higher order I_N may be obtained.

In summary, the imaginary part of the dielectric constant for the lowest three orders $N = 0, 1, 2$ are given as

$$\epsilon_i(N = 0) = 2(\pi)^{1/2}\,\frac{\omega_{p1}^2}{\omega^2}\, b^3 e^{-b^2} \,, \tag{A6}$$

$$\epsilon_i(N = 1) = 2(\pi)^{1/2}\,\frac{\omega_{p1}^2}{\omega^2}\, b^3 e^{-b^2}\left(b^2 - \frac{1}{2}\right) , \tag{A7}$$

and

$$\epsilon_i(N = 2) = (\pi)^{1/2}\,\frac{\omega_{p1}^2}{\omega^2}\, b^3 e^{-b^2}\left(b^4 - b^2 - \frac{1}{4}\right) . \tag{A8}$$

Finally, we note that equation (A7) gives instability for $b^2 < \frac{1}{2}$, and the maximum growth occurs at a value

$$b_0 = [\tfrac{1}{2}(3 - \sqrt{6})]^{1/2} \approx 0.52 \,. \tag{A9}$$

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