

DETECTION OF JOVIAN WHISTLER MODE CHORUS;  
IMPLICATIONS FOR THE I<sub>o</sub> TORUS AURORA

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**Abstract.** Near the I<sub>o</sub> torus outer boundary ( $L \approx 8$ ), the Voyager 1 plasma wave instrument detected high frequency ( $f$ ) waves near one-half the electron cyclotron frequency  $f_c$ . High resolution waveform measurements demonstrate that these  $f \approx f_c/2$  signals are banded whistler mode chorus at  $f \lesssim f_c/2$  and half-cyclotron frequency emissions with  $f$  slightly above  $f_c/2$ . The high resolution spectral information, and the theory of whistler mode waves, permit us to estimate the density ( $\approx 2.5 \text{ cm}^{-3}$ ), energy (few keV), and omnidirectional energy flux ( $10^2 \text{ ergs/cm}^2\text{-sec}$ ) of the electrons resonant with the chorus. Chorus precipitates about  $6 \text{ ergs/cm}^2\text{-sec}$  of few keV electron energy to the Jovian ionosphere at  $L = 8$ . Electrostatic emissions, probably electron cyclotron half-harmonic modes, have also been detected near the magnetic equator in the I<sub>o</sub> torus region. At  $L = 8$ , the multimode pitch-angle diffusion associated with the detected waves should produce a precipitation flux about a factor two below the  $50 \text{ ergs/cm}^2\text{-sec}$  required to generate the observed auroral emissions; however, the flux could well be larger deeper within the torus.

### Introduction

The Voyager 1 and 2 encounters with Jupiter confirmed that plasma waves are found throughout the Jovian magnetosphere [Scarf *et al.*, 1979a; Gurnett *et al.*, 1979]. Within the I<sub>o</sub> torus region Scarf *et al.* [1979a] tentatively identified a low frequency ( $f < 1 \text{ kHz}$ ) electric field noise band as whistler mode hiss, and suggested that it could pitch-angle scatter energetic electrons. Subsequently, Scarf *et al.* [1979b] and Thorne and Tsurutani [1979] quantitatively demonstrated that the whistler pitch-angle diffusion rates would cause substantial energetic electron precipitation. In addition, Thorne and Tsurutani noticed that an intensity peak at higher frequencies ( $f \approx 10 \text{ kHz}$ ) observed near  $8 R_J$  on the Voyager 1 inbound pass [see Scarf *et al.*, 1979a] might also be whistler mode noise, and Scarf *et al.* [1979b] pointed out that similar high frequency waves, capable of interacting with low energy (1–10 keV) electrons, were detected on the outbound pass.

High resolution waveform data obtained on March 5, 1979 as Voyager 1 crossed the magnetic equator at  $L = 8$  (in the outer region of the I<sub>o</sub> torus) reveal two distinct high-frequency emissions: (a) banded whistler mode chorus with  $f \approx 10 \text{ kHz}$ , and (b) a narrowband mode with a frequency just above one-half the electron cyclotron frequency ( $f_c$ ). Banded whistler chorus and half- $f_c$  emissions are commonly observed together in the terrestrial magnetosphere [Burtis and Helliwell, 1969; Coroniti *et al.*, 1971; Tsurutani and Smith, 1974]. The Voyager 1 16-channel spectrum analyzer continued to detect high frequency noise below  $f_c$  throughout the I<sub>o</sub> torus region; unfortunately, wideband recordings were obtained only for the inbound pass near  $L = 8$ , thus limiting a definitive mode identification to that event. However, the similar character of all the high frequency ( $f < f_c$ ) digital data suggests that whistler chorus and half- $f_c$  emissions occur throughout the torus region.

From the measured density and magnetic field, we can estimate that whistler mode chorus resonates with several keV electrons at the magnetic equator. The existence of chorus therefore allows us to infer that significant fluxes of keV electrons are present. Combining the observed chorus frequency spectrum with an analysis of the path-integrated whistler growth rate permits us to infer that the omni-directional  $\sim 1 \text{ keV}$  equatorial energy flux is about  $10^2 \text{ ergs/cm}^2\text{-sec}$ ; the observed amplitudes suggest that chorus may be responsible for about  $6 \text{ ergs/cm}^2\text{-sec}$  in precipitation of 1 keV electrons to the Jovian ionosphere. An electron

precipitation energy flux budget, made for  $L = 8$  by combining the pitch angle scattering effects of hiss, chorus, and  $3 f_c/2$  electrostatic waves, is within a factor two of the  $50 \text{ ergs/cm}^2\text{-sec}$  required to explain the observed Jovian auroral luminosity [Sandel *et al.*, 1979].

### Whistler Chorus and Half- $f_c$ Observations

The bottom panel of Figure 1 shows some of the 16-channel analyzer measurements during the one-hour interval (0545 to 0645) surrounding the period of available wideband data. A strong enhancement in the electric field amplitude at 10 kHz was observed from 0555 to 0635. The strong emission at 31 kHz which began at 0620 was above the electron cyclotron frequency and was electrostatic  $3 f_c/2$  cyclotron harmonic noise [Kurth *et al.*, 1980].

The top panel in Figure 1 shows 48 seconds of wideband frequency-time measurements obtained from 0617:24 to 0618:12. The frequency response of the wideband AGC receiver extends from 50 Hz to 12 kHz, and has a sharp rolloff above 12 kHz; two notch filters, that eliminate spacecraft interference, are at  $f = 2.4$  and  $7.2 \text{ kHz}$ . A single frequency sweep is made every 60 milliseconds. At this time the local plasma density determined by the radio astronomy investigation [Warwick *et al.*, 1979] was  $N_e = 230 \text{ cm}^{-3}$ , giving an electron plasma frequency of  $f_p = 136.5 \text{ kHz}$ ; the magnetic field strength [Ness *et al.*, 1979] was 800 gammas, giving an electron cyclotron frequency of  $f_c = 22.4 \text{ kHz}$ .

Three distinct frequency bands are evident in the  $f$ - $t$  diagram. Below 1 kHz there is a quasi-continuous emission which Scarf *et al.* [1979a,b] identified as low frequency whistler mode hiss. Just below 10 kHz, where  $f \approx 0.3$ – $0.45$  of the electron cyclotron-frequency, there is a band of emissions having short durations and rising frequencies. The banded frequency range, the burst-like nature, and rising frequency structure are all characteristics of whistler mode chorus commonly observed in the earth's outer magnetosphere [Burtis and Helliwell, 1969]. Hence the wideband data identify these Jovian Magnetospheric signals as whistler chorus.

The third narrowband emission in Figure 1 exhibits a sharp low frequency cutoff at 11.2 kHz, which is at half the local electron cyclotron frequency. Although similar half- $f_c$  emissions are often observed in the earth's magnetosphere by both electric and magnetic wave detectors [Coroniti *et al.*, 1971; Tsurutani and Smith, 1974], the theoretical identification of the half- $f_c$  mode is still uncertain. It could be generated by a mixed thermal anisotropy-loss cone instability on the electrostatic Bernstein branch [Young, 1974], or by the interaction of several hundred keV electrons with the electromagnetic ordinary mode [Curtis, 1978].

Figure 2 displays a second 48-second wideband frame and three successive short-time averages of the relative electric field spectral density. The chorus bandwidth is largely confined between 8 and 10 kHz, although several of the chorus bursts extend down to 7–7.5 kHz. The spectral density plots cover the time interval of the first two chorus elements in the  $f$ - $t$  diagram. The first burst (36.4–37.0) has a bandwidth from 8.5 to 9.5 kHz, with a very sharp decrease of about  $10^3$  in spectral density at 8.0 and 10.0 kHz. The peak chorus spectral density, which is comparable to the intensity of the half  $f_c$  emission, is clearly separated from the half  $f_c$  peak by a deep gap (essentially down to the background level of the wideband sensitivity).

The next two spectral density plots, which are also averages over 10 sweeps of the wideband receiver, show chorus bursts which have con-

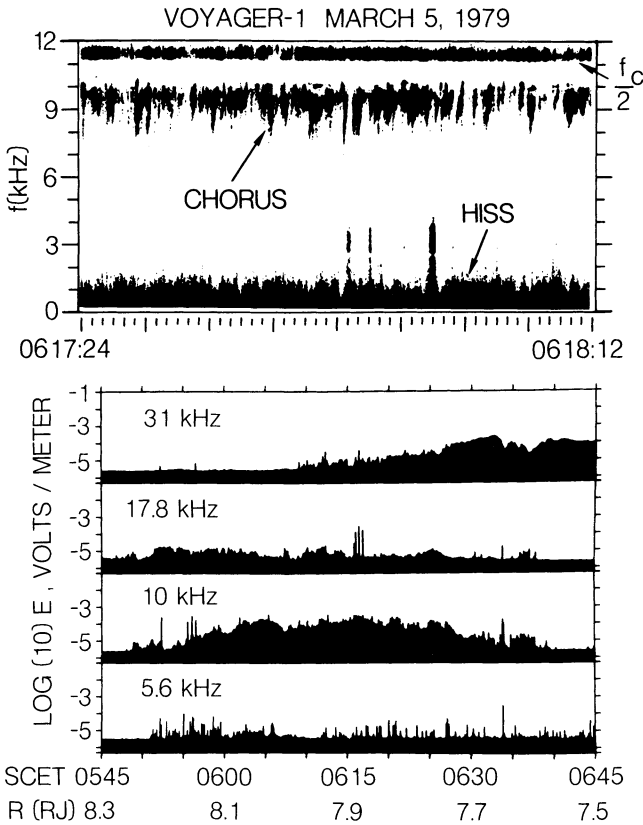


Figure 1. Bottom: Voyager 1 electric field amplitude profiles for four of the sixteen bandpass channels during a one-hour interval centered around 0615 spacecraft event time (SCET) on March 5, 1979. Here the spacecraft crossed the Jovian equator and first entered the outer portion of the Io plasma torus. At 0617 the plasma density was 230 electrons/cm<sup>3</sup> and the magnetic field strength was 800 gammas. Thus the electron cyclotron frequency was 22.4 kHz, and the signals in the 31 kHz channel represent  $3f_c/2$  waves, while the 10 kHz amplitudes are in the spectral range for chorus and  $f_c/2$  emissions. Top: A frequency versus time display of high resolution waveform measurements showing hiss, chorus, and  $f_c/2$  emissions.

siderably broader frequency bandwidth. In the center panel the spectral density of the chorus emission at 5.5 kHz is approximately 10-percent of that at the peak (8.2 kHz). As the chorus burst ends (third panel), the intensity below 7.0 kHz approaches background and the spectral density peak has shifted upwards to 9.5 kHz. In contrast with chorus, the low-frequency hiss spectrum shows little variability.

The top panel of Figure 3 shows the calibrated spectral density of the 4.2-second interval from 0620:44.2 to 0620:48.4, calibrated by using the simultaneous digital spectral data at low frequencies where several digital channels are available. The chorus spectrum peaks between 9.2 and 9.8 kHz with a maximum electric field spectral density of  $10^{-10}$  V<sup>2</sup>/m<sup>2</sup>-Hz. The electric field amplitude ( $E'$ ) in this band is about  $2.6 \times 10^{-4}$  V/M, and the bandwidth of the chorus is quite narrow.

The second panel in Figure 3 shows the calculated index of refraction for parallel propagating whistlers. If we assume that the chorus propagates primarily along the magnetic field, the wave magnetic field amplitude in the band 9.2 to 9.8 kHz is  $B' = nE'/c \approx 10$  milligammas. The parallel whistler index of refraction may not be appropriate for the half- $f_c$  emission.

The third panel of Figure 3 shows the minimum parallel electron energy for first-order cyclotron resonant interactions with whistlers [Kennel and Petschek, 1966]. In the chorus frequency band, the minimum resonant energy is about 3 keV; the characteristic energy,  $B^2/8\pi N_0$ , is 7 keV. Since few keV electrons have not been discussed in reports from the Pioneer 10 and 11 or Voyager particle experiments, the detection of whistler mode chorus provides the first evidence that the inner

Jovian magnetosphere contains a population of keV energy electrons.

The index of refraction for parallel whistler propagation can be used with the measured electric field spectral density to compute the equivalent wave magnetic field intensity as a function of frequency. We can then calculate the time scale for local pitch-angle scattering, defined simply as the inverse of the pitch-angle diffusion coefficient  $T_S = D_{\alpha\alpha}^{-1}$ . In the bottom panel of Figure 3,  $T_S$  is plotted against frequency. At 0.1 kHz the digital spectral measurements were used to compute  $T_S$ , but at higher frequencies we used the calibrated wideband spectral density. In the chorus frequency band (9–10 kHz) the local scattering time is  $3\text{--}5 \times 10^3$  seconds. At  $L = 7.8$  the minimum precipitation lifetime ( $T_M$ ) for a 3-keV electron is  $T_M = 1.4 \times 10^4$  sec. Since the chorus is quasi-continuous on the time scale of an electron bounce ( $\sim 10$  seconds), we can estimate the precipitation lifetime at  $T_L \sim 10 T_S$ , assuming that the whistler interaction region extends  $\pm 1 R_J$  from the magnetic equator. Hence we find  $T_M/T_L \sim 1/3$ , so that the chorus intensity is within a factor 3 of maintaining the keV electrons on strong diffusion [Kennel, 1969].

The scattering time increases rapidly for electron energies above about 10 keV, but then decreases sharply for electrons in the energy range 0.12 to 1.0 MeV, where hiss dominates the wave-particle interaction. At these higher energies the minimum lifetime is of order  $1.7 \times 10^3$  sec. With a precipitation lifetime of  $T_L \sim 10^4$  (1 MeV) to  $2 \times 10^5$  (0.12 MeV) seconds we find  $T_M/T_L \sim 0.2$  (1 MeV) to 0.01 (0.12 MeV) so that the whistler mode hiss can produce substantial energetic electron precipitation [Scarfi et al., 1979b; Thorne and Tsurutani, 1979].

#### Discussion

Although the detection of high frequency whistler chorus implies the presence of keV electrons in the inner Jovian magnetosphere, their significance for the overall energetics of the Io torus region depends on their number and energy densities. To estimate these parameters, we make the plausible assumption that the chorus emissions are unstably

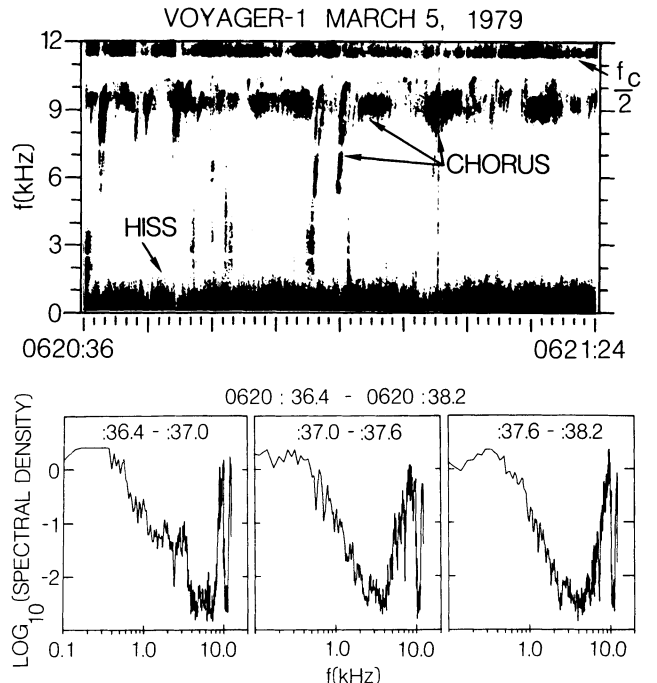


Figure 2. The top panel contains another frequency versus time display showing unstructured hiss, structured chorus, a half-cyclotron frequency gap, and an  $f_c/2$  emission. The bottom panel contains successive 0.6-second spectral density averages made up from the high resolution waveform link which provides one 50-Hz to 12-kHz spectral sweep every 60 milliseconds. These 0.6-second averages have been normalized so that the plots provide relative spectral shapes and not absolute amplitudes.

generated by a bi-Maxwellian [ $A = (T_{\perp} - T_{\parallel})/T_{\parallel} > 0$ ] electron distribution. The spatial amplification increment ( $K_i$ ) is then

$$\frac{K_i c}{\omega_p} = \frac{\sqrt{\pi} N_R}{2 N_0 \sqrt{A_c}} \left| \frac{V_R}{a_{\parallel}} \right| \exp \left( -\frac{V_R^2}{a_{\parallel}^2} \right) (A - A_c) \quad (1)$$

where  $A_c = \bar{f}/(1 - \bar{f})$ ,  $\bar{f} = f/f_c$ ,  $|V_R|/c = (1 - \bar{f})/n\bar{f}$ ,  $\omega_p = 2\pi f_p$ ;  $N_R$  is the number density of the hot unstable electrons with parallel thermal speed  $a_{\parallel} = (2T_{\parallel}/m)^{1/2}$ . Instability requires  $K_i > 0$ , or  $(A - A_c) > 0$ .

The chorus emissions generally showed a sharp spectral density decrease above 10 kHz, and were never detected above 10.5 kHz (Figures 1 and 2). Hence a reasonable choice for the frequency at which  $A = A_c$  is about 10.6 kHz, which implies that the anisotropy is roughly  $A \approx 0.9$ . In order for  $K_i$  to maximize in the frequency range of peak chorus spectral density (9.0 to 10.0 kHz), numerical calculations indicate that  $T_{\parallel}$  must be about  $0.15 B^2/8\pi N_0$  or  $T_{\parallel} \approx 1$  keV. For higher  $T_{\parallel}$ , the maximum of  $K_i$  falls below the chorus band, whereas for lower  $T_{\parallel}$  the unstable bandwidth is too narrow. For  $A \sim 1$ ,  $T_{\perp} \approx 2T_{\parallel} \approx 2$  keV.

The cold plasma density in the Jovian torus decreases away from the magnetic equator with a scale height of roughly  $1 R_J$  [Broadfoot et al., 1979]. If we neglect the change in field strength with distance,  $S$ , away from the equator ( $S = 0$ ), since  $N$  changes more rapidly than  $B$ , the resonant velocity varies as  $V_R(S)/V_R(0) = [N_0/N(S)]^{1/2}$ ; hence  $V_R$  increases rapidly away from the equator, greatly reducing the spatial growth rate. If we model  $N(S)$  as a Gaussian with a width of  $1 R_J$ ,  $K_i(S)$  can be integrated to find a total amplification of approximately  $0.3 K_i(0) R_J$  where  $K_i(0)$  is the equatorial value.

In Figure 3 the electric field spectral density falls from a peak of  $10^{-10} \text{ V}^2/\text{m}^2 \text{ Hz}$  near 9.5 kHz to  $5 \times 10^{-12} \text{ V}^2/\text{m}^2 \text{ Hz}$  at 8.5 kHz. If we assume that all frequency components of the chorus element were linearly amplified over the same path length ( $\approx 0.3 R_J$ ), the factor 20 difference in spectral density between 9.5 and 8.5 kHz then implies that

$$0.3 K_i(9.5) R_J \left( 1 - \frac{K_i(8.5)}{K_i(9.5)} \right) = \frac{\ln(20)}{2} \approx 1.5 \quad (2)$$

Computing the ratio of spatial growth rates from (1), we find that the number of amplitude e-foldings is approximately  $0.3 K_i(9.5) R_J = 8.5$ .

The remaining unknown in (1) is the fractional density of resonant electrons. Combining the above estimates for  $A$ ,  $T_{\parallel}$ , and net spatial amplification, we can substitute into (1) to find  $N_R/N_0 \approx 1.1 \times 10^{-2}$ ; for a cold plasma density of  $N_0 = 230 \text{ cm}^{-3}$ , the density of keV electrons is thus  $N_R \sim 2.5 \text{ cm}^{-3}$ . For  $A \sim 1$  the total omnidirectional trapped flux of keV electrons is approximately  $J_T = 2/\sqrt{\pi} N_R a_{\parallel} (T_{\perp}/T_{\parallel}) \sim 10^{10}/\text{cm}^2\text{-sec}$ , and the total energy flux of the keV electrons is approximately  $H_e \approx (6/\sqrt{\pi}) N_R a_{\parallel} T_{\perp} (T_{\perp}/T_{\parallel}) \approx 10^2 \text{ ergs/cm}^2\text{-sec}$ . The above keV flux estimate greatly exceeds that made by Tsurutani and Thorne [1979] who extrapolated the observed  $>100$  keV electron energy spectrum to 1 keV.

Since whistler waves only interact with electrons whose energies exceed a certain minimum value,  $E_{\min} (\approx 3/2 T_{\parallel})$ , for our present estimates, whistler mode pitch angle diffusion can deliver only a fraction of the trapped energy flux to the Jovian ionosphere. An upper limit to the precipitation energy flux,  $H_p \approx J_p T_{\parallel}$ , due to interactions with the observed chorus emissions, is obtained using the relation  $J_p/J_T \approx T_M/T_L \approx 1/3$ ; on this basis  $H_p \approx 6 \text{ ergs/cm}^2\text{-sec}$ . Energetic electron scattering with whistler hiss also contributes significantly to the electron precipitation energy flux. Krimigis, et al. [1979] measured a trapped energy flux of electrons ( $>100$  keV) of about  $100 \text{ ergs/cm}^2\text{-sec}$ . With our previous estimate,  $T_M/T_L \sim 10^{-1}$ , about  $10 \text{ ergs/cm}^2\text{-sec}$  would be delivered to the Jovian ionosphere by  $>100$  keV electrons [Thorne and Tsurutani, 1979]. Chorus and hiss interactions together could therefore account for  $10\text{-}16 \text{ ergs/cm}^2\text{-sec}$  at  $L \approx 8$  in the Io torus.

Our chorus measurements suggest that the total trapped energy flux of few keV electrons is about  $100 \text{ ergs/cm}^2\text{-sec}$ . Waves that scatter  $\sim 10^2\text{-}10^3$  eV electrons with energies less than  $E_{\min}$  could therefore tap a large electron energy reservoir for precipitation. At earth, it is thought that electrostatic waves with  $f > f_c$  maintain the few keV hot electron distribution on strong pitch-angle diffusion in the diffuse aurora [Kennel, et al., 1970; Lyons, 1974; Meng, et al., 1979]. The waves at  $3/2 f_c$  observed simultaneously with the chorus and hiss measurements

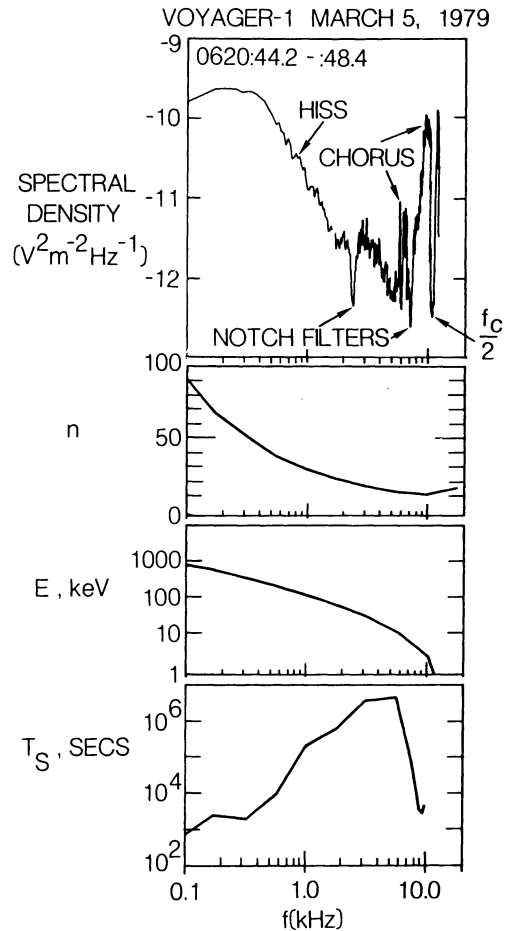


Figure 3. The top panel shows the calibrated electric field spectral density measured during a 4.2-second interval when Voyager 1 was inbound near the magnetic equator at the outer edge of the Io plasma torus ( $7\text{-}8 R_J$ ). The local index of refraction for parallel propagating whistlers is plotted below this, and the next panel down shows the minimum electron parallel kinetic energy for cyclotron resonance. The time scale for local pitch-angle scattering, defined as the inverse of the pitch-angle diffusion coefficient, is plotted in the bottom panel.

shown above, could play a similar role in the Io torus, although we have no quantitative estimate of their effects at present. Thus, the whistler hiss and chorus, together with the  $3/2 f_c$  noise, could account for several tens of  $\text{ergs/cm}^2\text{-sec}$  electron precipitation at  $L = 8$  in the Io torus.

Sandel et al. [1979] estimate that  $50 \text{ ergs/cm}^2\text{-sec}$  of interacting electrons must precipitate into the Jovian ionosphere to account for the average observed auroral luminosity; our estimate (at  $L = 8$ ) of the precipitation energy flux of electrons  $>1$  keV is about a factor two less. However, the precipitation flux could increase towards the center of the Io torus; for example, with  $H_p \propto T^{3/2}$ , a factor two increase in  $T$  could produce a  $50 \text{ ergs/cm}^2\text{-sec}$  precipitation heat flux on strong diffusion. Since the plasma wave instrument 16-channel analyzer detected whistler mode hiss and chorus emissions throughout the Io torus region [Scarf et al., 1979a], and  $3f_c/2$  emissions whenever Voyager 1 crossed the magnetic equator [Kurth et al., 1980], it is reasonable to assume that significant pitch-angle scattering occurs on all the L-shells threading the Io torus. Hence a model of the Jovian aurora similar to that of the terrestrial diffuse aurora remains a viable option.

Finally, Eviatar et al., [1979] noted that keV electrons could exchange energy with cold plasma electrons. For  $N_0 = 230 \text{ cm}^{-3}$  at  $L = 8$ , the energy exchange time is  $\approx 10^6$  sec, but at the peak density of the Io torus,  $N_0 \sim 2 \times 10^3/\text{cm}^3$ , the heating time shortens to about a day. Thus, a significant fraction of the  $H \approx 10^2 \text{ ergs/cm}^2\text{-sec}$  of the keV electrons could be transferred to lower energy electrons whose subsequent precipi-

tation could also contribute to the peak Jovian auroral luminosity.

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