Auroral hiss observed near the Io plasma torus

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A band of whistler-mode noise identified as auroral hiss has been observed on the inner edge of the Io plasma torus. This noise provides evidence for the existence of aurora-like charged particle beams on magnetic field lines through the inner edge of the torus. These beams probably consist of low-energy electrons and may be associated with field-aligned currents linking the plasma torus to the jovian ionosphere.

DURING the Voyager 1 flyby of Jupiter on 5 March 1979 an unusual band of electric field noise was detected by the plasma wave instrument near the Io plasma torus. This band of noise has spectral characteristics very similar to a type of whistler-mode emission called 'auroral hiss'[4] which is commonly observed in the Earth's auroral regions[1-5]. Auroral hiss is believed to be produced by low-energy (10 eV to 1 keV) beams of auroral electrons by a Cerenkov radiation mechanism[6,7]. Because the presence of auroral hiss near the Io torus may indicate the occurrence of charged particle acceleration processes similar to the Earth's auroral zones, we have undertaken a detailed analysis of these noise bands. This article describes the characteristics of the auroral hiss emissions detected at Jupiter, compares these characteristics with similar emissions detected in the Earth's magnetosphere, and comments on the implications regarding the interaction of the plasma torus with the jovian magnetosphere. The plasma wave instrumentation on Voyager 1 and an initial survey of the Voyager 1 plasma wave observations at Jupiter are given elsewhere[8,9].

Observations

The noise bands of interest were observed near the inner edge of the Io plasma torus on both the inbound and outbound portions of the Voyager 1 pass by Jupiter. For a discussion of the plasma torus formed by material escaping from Jupiter's satellite Io see refs 10 and 11. The plasma wave electric field intensities detected near the closest approach to Jupiter are shown in Fig. 1*b*. A sketch of the spacecraft trajectory in relation to the plasma torus is shown in Fig. 1*a* together with the electron plasma frequency, f_p^-, obtained from the planetary radio astronomy experiment[11] and the electron gyrofrequency, f_g^-, obtained from the magnetometer experiment[12].

The emissions identified as auroral hiss are indicated by the cross-hatched areas in Fig. 1*b*. The distinguishing characteristic of these emissions is the systematic change in the emission frequency with spatial position, increasing with increasing time for the event at 09.30 UT, and decreasing with increasing time for the event at 14.00 UT. Because of the limited frequency–time resolution of the intensity measurements in Fig. 1 it is not possible to identify these emissions as auroral hiss on the basis of these data alone. Fortunately, for the event at 09.30 UT, a series of wideband waveform measurements was available, providing much better frequency–time resolution. The wideband waveform mode of operation uses the 115 kbit s^{-1} telemetry system normally used for pictures to transmit a 12 kHz bandwidth of electric field waveforms to the ground. Because the 115 kbit s^{-1} telemetry link must be time shared with the imaging system, the waveform measurements are not obtained continuously. During the period around 09.30 UT, one 48-s burst of waveform data was being obtained every 192 s. No wideband measurements were obtained for the period around 14.00 UT. Three consecutive 48-s spectrograms of the wideband waveform measurements are shown in Fig. 2 for the event at 09.30 UT. These spectrograms show a broadband emission with a very sharp low frequency cutoff which increases linearly with increasing time. The broadband character of the emission and the smoothly varying low frequency cutoff provide an almost unmistakable identification of this emission as a V-shaped auroral hiss event of the type described by Gurnett[2], McEwen and Barrington[3] and others. As will be discussed, the low frequency cutoff is a whistler-mode propagation effect. At the Earth the spatial variation of the cutoff frequency produces a characteristic V shape on a frequency–time spectrogram with the centre of the V located in a region of intense low-energy electron precipitation[4].

The auroral hiss emissions detected by Voyager are unusual in that only one branch of the V-shaped low frequency cutoff is evident. Such unsymmetrical V-shaped auroral hiss events are also occasionally seen in the Earth's auroral zone, usually in association with a large density gradient. A similar relationship is evident for the events detected by Voyager. As Fig. 1 shows both of the auroral hiss events occur near a very large density gradient at the inner edge of the plasma torus. Whether the missing branch of the V is a propagation effect related to the density gradient or is simply obscured by the more intense chorus and hiss emissions[9] inside the plasma torus is not known.

Analysis

For auroral hiss at the Earth it is generally believed[7,13] that the V-shaped low-frequency cutoff is a spatial propagation effect which occurs for short wavelength waves near the resonance cone. As will be shown the beamwidth of whistler-mode radiation near the resonance cone is frequency dependent, with the highest frequencies having the largest beamwidth. As the spacecraft approaches the source the highest frequencies are detected first, because these ray paths can propagate at the largest angle to the magnetic field. Progressively lower frequencies are detected as the spacecraft comes closer to the source.

The spatial dependence of the cutoff frequency is best analysed using the index of refraction construction shown in Fig. 3*b*. The ray path at a given wave normal direction is perpendicular to the index of refraction surface at that wave normal angle[14]. Figure 3*b* shows that the angle between the limiting ray path direction and the magnetic field, $\psi_{\max}$, is given by $\psi_{\max} = \pi/2 - \theta_{\mathrm{Res}}$, where θ_{Res} is the resonance cone angle. Using Stix's notation[14], the angle $\psi_{\max}$ is given by:

$$\cot^2 \psi_{\max} = \tan^2 \theta_{\mathrm{Res}} = -\left(\frac{P}{S}\right) \tag{1}$$

All waves near the resonance cone will have ray path directions less than this limiting angle. For the conditions applicable to the Voyager 1 observations, $f_g^- \ll f_p$, and $f_g^+ \ll f \ll f_g^-$, the terms S and P can be approximated by

$$P = -\left(\frac{f_p}{f}\right)^2 \quad \text{and} \quad S = \left(\frac{f_p}{f_g}\right)^2 \left[1 - \frac{f_{\mathrm{LHR}}^2}{f^2}\right] \tag{2}$$

where $f_{\mathrm{LHR}} = (f_g^- f_g^+)^{1/2}$ is the lower-hybrid resonance frequency.

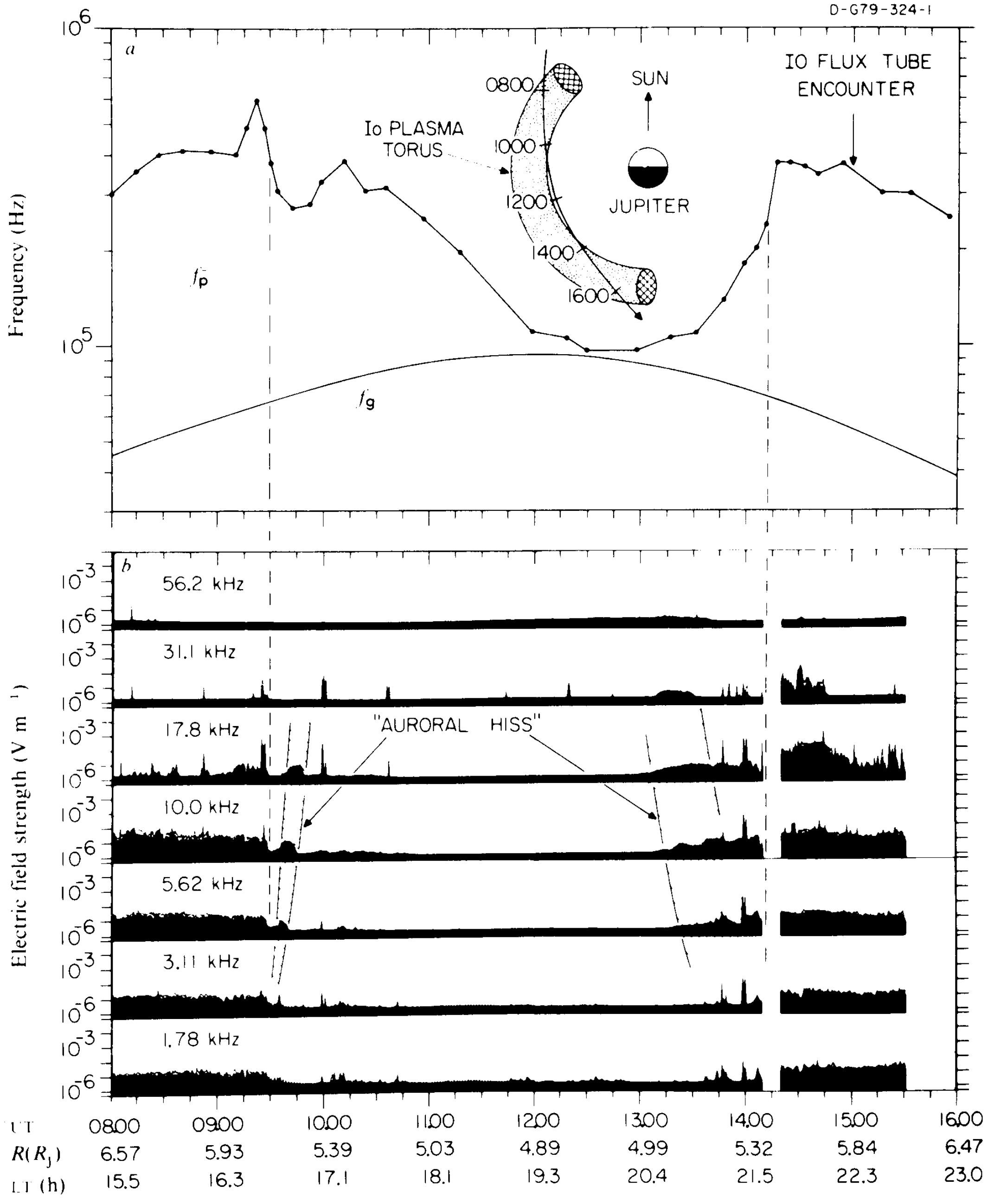

Fig. 1 The plasma wave electric field measurements for the Voyager 1 pass through the Io plasma torus. The emissions identified as whistler-mode auroral hiss are identified by the cross-hatched areas. In both cases the auroral hiss emissions were observed near an abrupt gradient in the plasma density (see the vertical dashed line) near the inner edge of the torus.

Combining these terms gives the following equation for the limiting ray path angle as a function of frequency,

$$\tan^2 \psi_{\max} = \frac{f^2 - f_{\mathrm{LHR}}^2}{(f_g^-)^2} \tag{3}$$

Equation (3) shows that the limiting ray path angle increases monotonically with increasing frequency for $f^2 \gg f_{\mathrm{LHR}}^2$, and goes to zero at $f = f_{\mathrm{LHR}}$. If we now consider an idealised point source emitting all frequencies the resulting radiation will illuminate a conical region along the magnetic field with a beamwidth which increases with increasing frequency and goes to zero at f_{LHR}. This frequency-dependent beamwidth is illustrated in Fig. 3*a*. A spacecraft passing through the illumination region first detects the highest frequency, f_2, then progressively lower frequencies, f_1, until the lowest frequency f_{LHR} occurs when the spacecraft is on the magnetic field line through the source. The frequency-dependent beamwidth explains the V-shaped spatial variation of the low frequency cutoff.

For the Voyager auroral hiss observations, as for the terrestrial auroral hiss, it seems more appropriate to consider a line source extending azimuthally along the torus rather than a point source. This configuration is supported by the fact that somewhat similar symmetrical auroral hiss emissions were observed on both the inbound and outbound crossings at substantially different local times. Ignoring the curvature of the magnetic field lines, the ray path problem can be reduced to a simplified two-dimensional geometry by introducing a coordinate x, which is the perpendicular distance from the spacecraft to the magnetic field line through the source, and a distance h, which is the height of the spacecraft above the source (see Fig. 3). Simple trigonometry shows that for the limiting ray path $x/h = \tan \psi_{\max}$. Substituting into equation (3) and simplifying gives the following equation for the cutoff frequency as a function of x,

$$f^2 = f_{\mathrm{LHR}}^2 + \left(\frac{x}{h}\right)^2 (f_g^-)^2 \tag{4}$$

This equation is a hyperbola. Even when the magnetic field curvature is considered, equation (4) is still valid to second order provided x is measured perpendicular from the magnetic field through the source.

To obtain the approximate location of the source, equation (4) has been adjusted to fit the measured cutoff frequencies. The cutoff frequencies, which can be measured with very good accuracy (~ 100 Hz), are shown by dots in Fig. 3*c* along with the best fit hyperbola representing the propagation cutoff. Only three free parameters occur in equation (4), the lower-hybrid

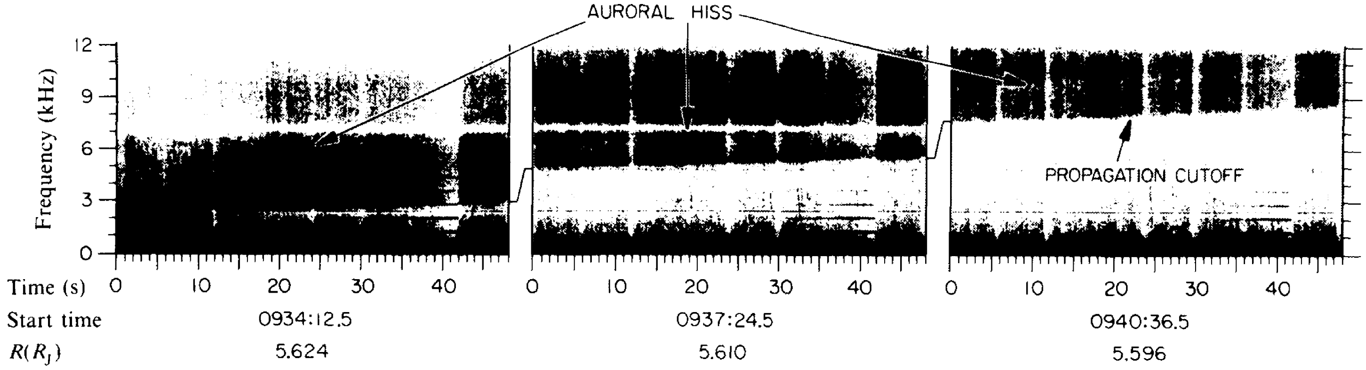

Fig. 2 A sequence of wideband spectrograms for the event near 09.30 UT in Fig. 1. The broadband character of the emission and the sharp low frequency propagation cutoff increasing linearly with time provide a clear identification of this emission as auroral hiss.

resonance frequency, the location of the magnetic field line through the source, and the height h of the spacecraft above the source. In principle, the lower-hybrid resonance frequency can be determined from the plasma parameters and need not be considered a free parameter. However, the lower-hybrid resonance frequency depends on the ion composition which varies considerably. As the ion composition is not well known along the ray path, f_{LHR} is considered an unknown parameter. The best fit parameters indicate that the magnetic field line through the source was crossed at 09.32 UT, that the distance h to the source was 0.65 R_J, and that the lower-hybrid resonance frequency was 1.56 kHz. At the time of the closest approach to the source, Voyager was 0.51 R_J north of the magnetic equator. Two possible source positions must be considered, either northward along the magnetic field line towards Jupiter, or southward along the magnetic field towards the magnetic equator. The northward position would place the source approximately $0.65\ R_J + 0.51\ R_J = 1.16\ R_J$ north of the equator on the $L \simeq 5.6$ field line. The southward position would place the source approximately $0.65\ R_J - 0.51\ R_J = 0.14\ R_J$ south of the magnetic equator. These two source positions are illustrated in Fig. 4*a* and *b*. Since the plasma wave instrument does not have any capability for determining the direction of propagation, it is not possible to distinguish experimentally these two source locations.

Although the north–south ambiguity cannot be resolved, certain indirect arguments can be made favouring each of the two source positions shown in Fig. 4. The equatorward source is favoured by the fact that this location, only 0.14 R_J south of the magnetic equator, coincides with an obvious symmetry point where a source could reasonably be expected. The best fit lower-hybrid resonance frequency is not, however, in good agreement with the lower-hybrid resonance frequency expected in this region. Since the inner region of the Io torus is thought to

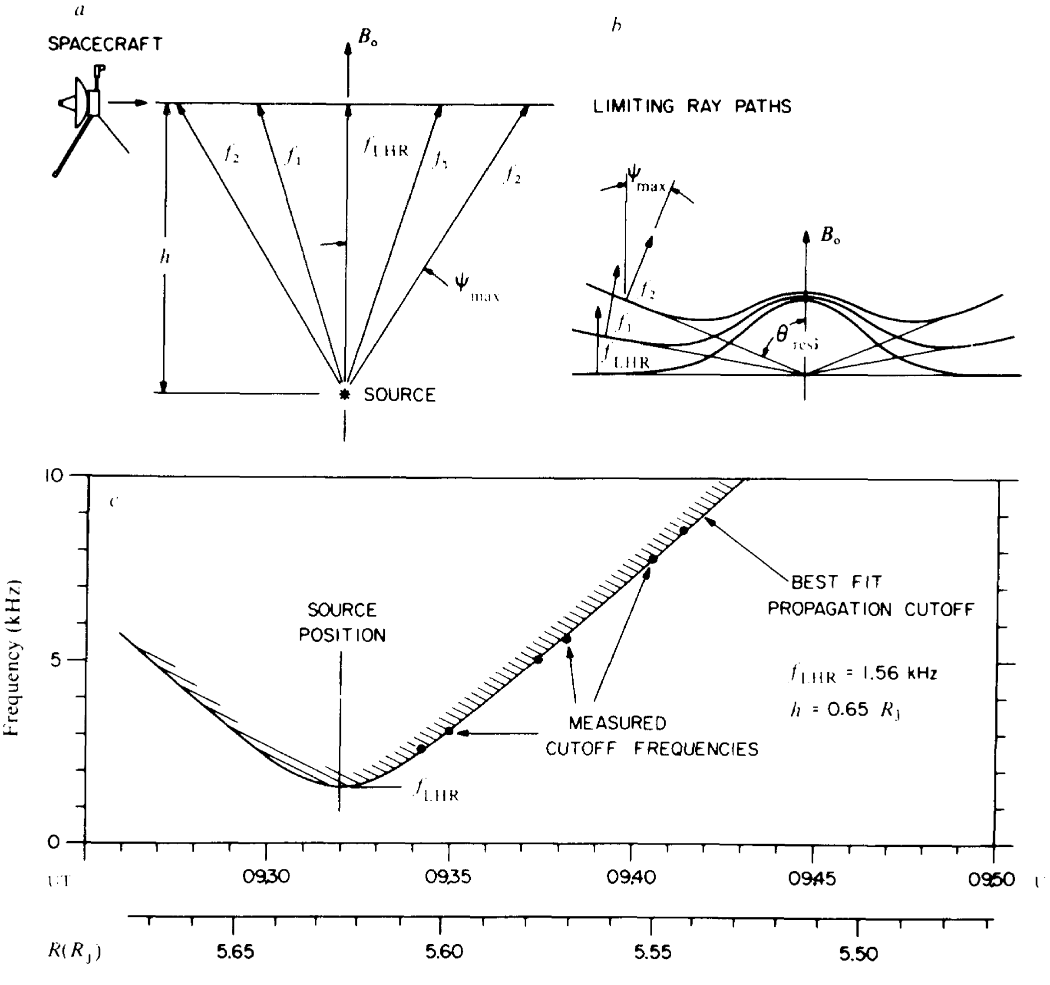

Fig. 3 *a* And *b* show that the beamwidth of whistler-mode emissions near the resonance cone increases with increasing frequency. A spacecraft approaching a point source, therefore, detects the highest frequencies first, forming a V-shaped low frequency cutoff. *c*, The best fit propagation cutoff for the auroral hiss emission near 09.30 UT. Only one branch of the V-shaped cutoff was observed.

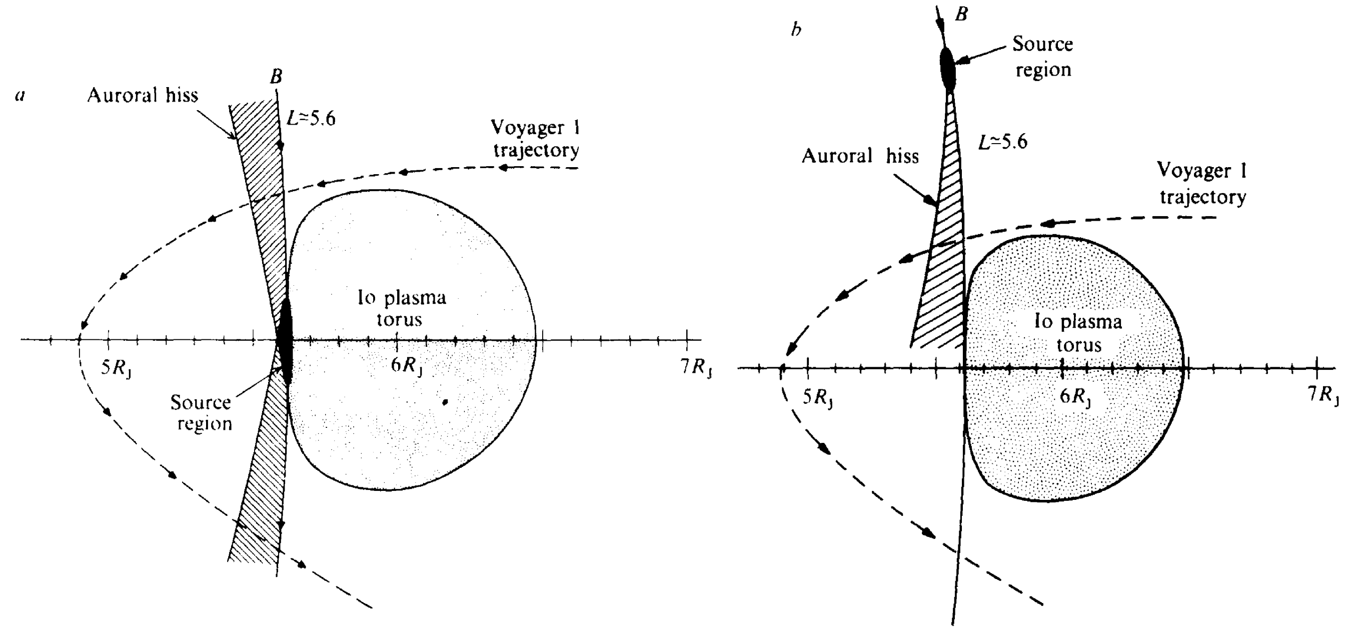

Fig. 4 The two possible source positions obtained from the best fit analysis in Fig. 3. *a*, The equatorward source position. *b*, The northward source position which has a very close analogy to auroral hiss emissions at the Earth, with the Io plasma torus playing a role comparable to the ionosphere at the Earth. The auroral hiss emissions strongly suggest the occurrence of low-energy electron beams and field line currents associated with the large density gradient near the inner edge of the plasma torus.

be dominated by heavy ions[10,15], the lower-hybrid resonance frequency is expected to be of the order of 300–500 Hz inside the torus. The best fit lower-hybrid resonance frequency, 1.56 kHz, seems to be more consistent with a plasma in which protons are the dominant ion species. As protons are expected to be a more important constituent outside the torus, this fact would tend to favour a source well away from the equator, such as in Fig. 4*b*. Note, however, that the lower-hybrid resonance frequency has the largest uncertainty of all the free parameters in equation (4). This difficulty occurs mainly because no wide-band data is available around the time, 09.32 UT, when the cutoff frequency is near the apex of the hyperbola. The uncertainty in f_{LHR}, together with the absence of suitable information on the ion composition away from the torus, makes it very difficult to distinguish between the models in Fig. 4 on the basis of the lower-hybrid cutoff frequency.

Discussion

These observations of auroral hiss provide strong evidence of auroral-like charged particle beams originating from within, or near, the Io torus. As the intensity and spectral characteristics of the auroral hiss detected at Jupiter are very similar to the auroral hiss observed at the Earth, it is expected that the radiation should be generated by comparable particle intensities, namely electrons with energies from about 10 eV to 1 keV and fluxes in the range 10^8 to 10^{10} electrons cm^{-2}. The existence of comparable low-energy electron precipitation from the torus is already implied by the UV spectrometer observations of aurora at the foot of the magnetic field lines through the torus. The fact that the auroral hiss is observed over a very small spatial region with very sharply defined cutoff frequencies implies that the electron beam generating the radiation must be very narrow, not extending over a range of L-values more than about 0.02. The source position of the auroral hiss shows that the electron beam occurs on an L-shell which coincides almost exactly with the abrupt decrease in plasma density at the inner edge of the plasma torus. Again in analogy with the terrestrial auroral zone, it seems likely that the auroral hiss and associated electron beams would be associated with a thin sheet of current which flows along the magnetic field lines linking the inner edge of the plasma torus with the polar ionosphere of Jupiter. At present we are unable to determine the direction of the current in this sheet, as this depends on the direction of propagation of the auroral hiss. For the model in Fig. 4*a*, the auroral hiss and the electrons producing this hiss would be moving away from the equatorial plane, which implies a current directed along the magnetic field lines from Jupiter towards the Io torus. For the model in Fig. 4*b*, the directions would be reserved.

At the present early stage of data analysis, no specific evidence is available, other than the auroral hiss observations, to confirm or disprove the existence of low energy electron beams and field-aligned currents at the inner edge of the Io plasma torus, although such investigations are under way (N. Ness and H. Bridge, personal communication). The likelihood of such field-aligned currents and particle precipitation effects is, however, considered quite high, as several processes can give rise to field-aligned currents at abrupt gradients in the plasma density. Given that a field-aligned current of sufficient magnitude exists, the acceleration of particles to large energies could proceed via the development of parallel electric fields, as in the Earth's auroral zones. Observations of auroral hiss at the Earth have in fact been suggested as being directly related to regions of parallel electric fields and auroral particle acceleration[16].

Research at The University of Iowa was supported by NASA through contract 954013 with the Jet Propulsion Laboratory and through grant NGL-16-001-043 with NASA Headquarters. Research at TRW was supported by NASA through contract 954012 with the Jet Propulsion Laboratory.

Received 16 July; accepted 31 July 1979.

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Printed in Great Britain by Macmillan Production Ltd., Basingstoke, Hampshire