JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 94, NO. A7, PAGES 8966–8972, JULY 1, 1989

An Experimental Study of Electrostatic Ion Cyclotron Waves in a Two-Ion Component Plasma

D. M. SUSZCYNSKY, N. D'ANGELO, AND R. L. MERLINO

Department of Physics and Astronomy, University of Iowa, Iowa City

Two-ion component electrostatic ion cyclotron (EIC) waves are studied in a single-ended *Q*-machine containing variable concentrations of Cs^+ and K^+ ions. Measurements of the excitation and propagation characteristics of the waves are presented and compared with available theories. The waves are internally excited by drawing an electron current along the magnetic field to an 11-mm exciter disk. Both Cs^+ and K^+ EIC waves can be simultaneously excited over a large range of relative ion concentrations. The EIC wave features are found to depend on the relative ion concentrations. As the light ion (K^+) concentration is increased, the frequency of the heavy ion (Cs^+) mode shifts toward its cyclotron frequency. Likewise, the frequency of the light ion mode approaches the light ion cyclotron frequency as the heavy ion concentration is increased. The critical drift velocity for the excitation of the heavy ion (Cs^+) mode is more strongly dependent on the relative ion concentrations than that of the light ion (K^+) mode. These results are of interest in the context of EIC wave excitation in the ionosphere.

1. INTRODUCTION

Electrostatic ion cyclotron (EIC) waves were discovered in 1961 in laboratory work in a *Q*-machine [*D'Angelo and Motley*, 1962] and later given a theoretical interpretation by *Drummond and Rosenbluth* [1962], who developed a Vlasov theory for current-driven EIC waves in a homogeneous, collisionless, magnetized plasma. *Motley and D'Angelo* [1963] obtained, from fluid theory, a dispersion relation of the simple form

$$\omega^2 = \Omega_{ci}^2 + K_\perp^2 C_s^2 \tag{1}$$

where ω is the angular frequency of the wave, Ω_{ci} is the ion gyrofrequency, C_s is the ion-acoustic speed, and $K_\perp$ is the component of the propagation vector, **K**, normal to the magnetic field. Equation (1) is valid in the long-wavelength regime, $K_\perp \rho_i < 1$, where ρ_i is the ion gyroradius, and is appropriate in the interpretation of the laboratory results.

Since the early 1960s a large amount of laboratory work has been performed on EIC waves [e.g., *Levine and Kuckes*, 1966; *Dakin et al.*, 1976; *Krumm and Alport*, 1984; *Cartier et al.*, 1985; *Hatakeyama et al.*, 1985; *Suszcynsky et al.*, 1986; *Pécseli et al.*, 1988; *Stern*, 1988; *Alport and Van Niekerk*, 1988].

In the more recent years, work on EIC waves has also been motivated by observations of the waves in the high-latitude ionosphere [e.g., *Martelli et al.*, 1977; *Bering*, 1983, 1984; *Bering et al.*, 1975; *Kintner et al.*, 1979; *Fejer et al.*, 1984; *Providakes et al.*, 1985; *Reed*, 1980; *Haldoupis et al.*, 1985].

The Earth's ionosphere, however, contains a mixture of several positive ion species, e.g., H^+, O^+, NO^+, with concentrations varying according to altitude. Thus it has become necessary to understand the excitation of EIC waves in multispecies plasmas by performing laboratory experiments in plasmas with more than one positive ion component. A theory for such a situation, of direct application to the case of the Earth's ionosphere, was presented by *Kindel and Kennel* [1971], using the kinetic theory developed earlier by *Drummond and Rosenbluth* [1962]. More recent theoretical work has been performed by, e.g., *Satyanarayana et al.* [1985] and *Ganguli et al.* [1985].

As far as laboratory work is concerned, there have been a few experiments on EIC waves in multi-ion-species plasmas, in which the waves were externally launched. *Ono et al.* [1980] investigated the parametric excitation of EIC waves in a He^+-Ne^+ plasma, using an external RF oscillator. *Sugai et al.* [1982] launched waves in a He^+-Ne^+ plasma using an electrostatic antenna. They concentrated their investigation on the effect of light minority ions with small concentrations (~1%).

So far, only two experimental studies in two-ion component plasmas have been reported, in which the EIC waves were excited internally by passing a current through the plasma. *Rynn* [1986] discussed his and Lang's work in a K^+/Ba^+ plasma, their main concern being the question of ion heating by the EIC waves. More recently, *Suszcynsky et al.* [1988*a*] have presented a short, preliminary account of their studies in a Cs^+/K^+ plasma, in which the relative concentrations of the two-ion species could be varied over a rather wide range. They also developed a simple, resistive three-fluid model to account for some of the observed wave properties. This investigation has now been expanded and a more detailed and comprehensive account is given here.

The paper is organized as follows. Section 2 contains a short summary of theories of the EIC instability, which are relevant to the present experiments. Section 3 describes the experimental arrangement and, in particular, the technique used to determine relative ion concentrations. Section 4 presents the experimental results on the excitation of the "heavy" and "light" ion modes. Of particular interest is the experimental determination of the critical drifts required to excite either mode, at different relative Cs^+ and K^+ concentrations. Finally, section 5 contains the conclusions.

2. THEORETICAL SUMMARY

Kindel and Kennel [1971] discussed the EIC instability in the context of an ionospheric-magnetospheric plasma, pointing out that this instability has the lowest threshold among

Paper number 89JA00504.
0148-0227/89/89JA-00504$05.00

several current-driven instabilities. Their treatment, however, was appropriate only to situations in which particle collisions could be altogether neglected. This restricted the validity of their analysis to altitudes well above the *F* region density maximum. Excitation of EIC waves at much lower altitudes, where collisions are frequent, was also discussed using a fluid theory [e.g., *D'Angelo*, 1973; *Chaturvedi*, 1976]. In Chaturvedi's approach, the EIC instability appears as a resistive instability in which electron collisions provide the dissipation and prevent the instantaneous rearrangement of the electrons to a Boltzmann distribution in the potential of the wave. Electron collisions thus provide the destabilization of the waves, while collisions of the ions with the neutral gas atoms are stabilizing. Bridging these two extreme treatments of the EIC instability is the one provided by *Satyanarayana et al.* [1985]. They used a kinetic treatment rather than a fluid model, with the addition of a collision term of the BGK type, with a strength that depends on altitude through the collision frequencies of ions and of electrons. This approach has the advantage that the entire altitude range between 100 km and, say, 600 km could be examined. As compared to the fluid model of *Chaturvedi* [1976], it has the advantage of not being restricted to the approximation $K_\perp \rho_i < 1$ and thus applies to cases [e.g., *Fejer et al.*, 1984] in which $K_\perp \rho_i > 1$. In *Satyanarayana et al.* [1985], however, only single-ion EIC waves are treated, assuming that the entire ionosphere between 100 km and 600 km consists, e.g., either of O^+ ions or of NO^+ ions. Although, strictly speaking, their calculations are thus applicable only to plasmas with single ion species, one can still draw some qualitative conclusions from their results, regarding a multispecies plasma. For instance, it is predicted, in agreement with *Kindel and Kennel* [1971], that when H^+, O^+, O_2^+, and NO^+ are present, the EIC waves of the heavier species are more easily destabilized by parallel currents.

In an attempt to provide ourselves with a simple fluid analysis of EIC waves in a plasma consisting of electrons and two positive ion species, we have adapted the approach of *Chaturvedi* [1976] to the circumstances of our laboratory experiments. We use the continuity and momentum equations for the electrons, the light ions (L) and the heavy ions (H). The magnetic field is taken to be uniform, $\mathbf{B} = B\hat{z}$, and the plasma uniform and charge quasi-neutral, $n_e = n_L + n_H$. In a preliminary calculation it was assumed that both ion species were cold, $T_L = T_H = 0$ [see *Suszcynsky et al.*, 1988*a*]. In the present calculations, both ion species are allowed finite temperatures. The electrons have a temperature T_e, the electron inertia is neglected, and we consider electron motion only parallel to **B**. We assume that the electrons have a uniform zero-order drift $v_{eD}\hat{z}$ and include a resistive term $-\nu_e m_e n_e v_{eD}\hat{z}$ in the electron momentum equation, where ν_e is the electron collision frequency. Performing the usual linearization, one arrives at the dispersion relation

$$\frac{K_z^2}{K_z^2 \kappa T_e - i\nu_e m_e(\omega - K_z v_{eD})} = \frac{\alpha_L K_x^2}{m_L(\omega^2 - \Omega_L^2 - K_x^2 v_L^2)} + \frac{\alpha_H K_x^2}{m_H(\omega^2 - \Omega_H^2 - K_x^2 v_H^2)} \qquad (2)$$

where m_e, m_L, m_H are the electron, light ion, and heavy ion masses, Ω_L and Ω_H the light and heavy ion gyrofrequencies, α_L and $\alpha_H = 1 - \alpha_L$ the fractional concentrations of light and heavy ions, K_x the component of the propagation vector perpendicular to the magnetic field and $\omega = \omega_r + i\gamma$ the (complex) wave frequency. Also, $v_L^2 = \kappa T_L/m_L$ and $v_H^2 = \kappa T_H/m_H$.

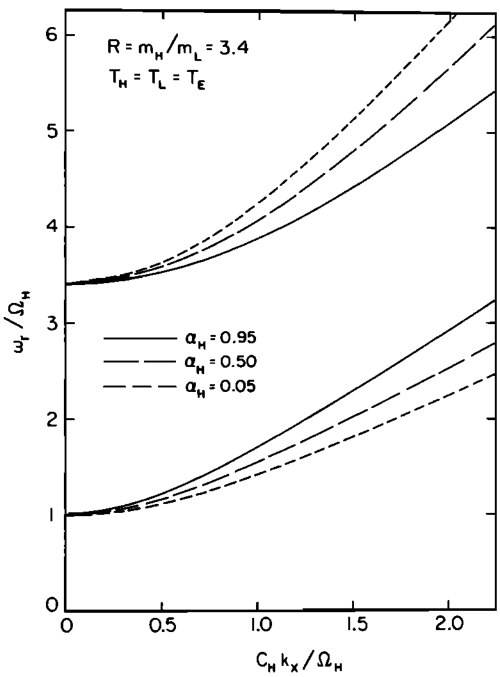

Fig. 1. Dispersion relation for EIC modes in a two-ion component plasma with mass ratio 3.4 for various values of the heavy ion concentration $\alpha_H = 1 - \alpha_L$.

Equation (2) can be separated into real and imaginary parts, namely,

$$\left(\frac{\Omega_H}{K_x C_H}\right)^2 = \frac{\alpha_L R}{\left(\frac{\omega_r}{\Omega_H}\right)^2 - R^2 - R\left(\frac{\Omega_H}{K_x C_H}\right)^{-2} \frac{T_L}{T_e}} + \frac{1 - \alpha_L}{\left(\frac{\omega_r}{\Omega_H}\right)^2 - 1 - \left(\frac{\Omega_H}{K_x C_H}\right)^{-2} \frac{T_H}{T_e}} \qquad (3)$$

with $R = m_H/m_L$, and

$$\gamma = -\frac{1}{2} G \nu_e \frac{m_e}{m_H} \frac{K_x^2}{K_z^2} \left(1 - \frac{v_{eD}}{\omega_r/K_z}\right) \qquad (4)$$

where

$$G = \frac{\alpha_L R(\omega_r^2 - \Omega_H^2 - K_x^2 v_H^2) + (1 - \alpha_L)(\omega_r^2 - \Omega_L^2 - K_x^2 v_L^2)}{[2\omega_r^2 - \Omega_L^2 - \Omega_H^2 - K_x^2(v_H^2 + v_L^2)] - [R\alpha_L + (1 - \alpha_L)]K_x^2 C_H^2}$$

In the above,

$$C_H^2 = \frac{\kappa T_e}{m_H} \qquad C_L^2 = \frac{\kappa T_e}{m_L}$$

The roots of equation (3) determine which wave modes are possible and are shown in Figure 1 for $R = 3.4$ (the case of Cs^+ and K^+ ions). We have assumed $T_L = T_H = T_e$, as appropriate to our experimental conditions, and vary the heavy ion concentration, α_H, between 0.05 and 0.95. Evidently, two EIC modes are possible, one with $\omega_r \gtrsim \Omega_H$ (the heavy ion mode) and the other with $\omega_r \gtrsim \Omega_L$ (the light ion

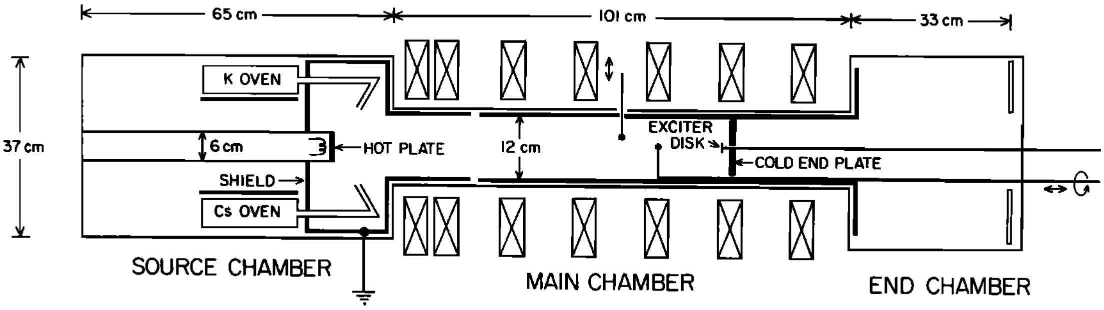

Fig. 2. Schematic diagram of the Q-machine. EIC waves are excited by drawing an electron current to the exciter disk (11 mm diameter). Variable concentrations of Cs^+ and K^+ are produced by independently controlling the neutral flux output of each atomic oven.

mode). As the light ion concentration, $\alpha_L = 1 - \alpha_H$, is increased, the frequency of the heavy ion mode moves closer to its gyrofrequency. In a similar manner, as the heavy ion concentration is increased, the frequency of the light ion mode moves closer to its gyrofrequency. This behavior of the frequency, for both modes, is in line with similar predictions from kinetic theory [*Kindel and Kennel*, 1971]. Both theories give nearly the same ω/Ω_H for small values of $d = C_H K_x/\Omega_H$ but show a different behavior for $d \gtrsim 1$. This discrepancy for large d is, of course, well known for a single-ion plasma.

As far as fluid theory is concerned, a prediction (see equation (4)) that can be made for the growth rate, γ, is that instability should occur ($\gamma > 0$) when $v_{eD} > \omega_r/K_z$, i.e., for waves with a parallel (to **B**) phase velocity less than the electron zero-order drift (see, for example, *Chaturvedi* [1976]). Again, electron collisions are shown to be destabilizing. A more complete analysis would require the inclusion of the (damping) effect of ion-ion collisions.

We close this section with a brief discussion of the critical electron drifts required for excitation of the light and heavy ion modes, as provided by a kinetic theory treatment [e.g., *Kindel and Kennel*, 1971; *Guzdar et al.*, 1987]. Figure 4 of Kindel and Kennel shows how the critical drifts vary, in an H^+-O^+ plasma, as the heavy ion concentration $\alpha_H = n_{O^+}/n_e$ varies from ~0.01 to 1. At low heavy ion concentrations, the light ion mode is more easily destabilized. The contrary is true for heavy ion concentrations in excess of ~15%. The critical drift for the light ion mode has only a very mild increase with increasing concentration of n_{O^+}/n_e, up to values of n_{O^+}/n_e ~0.5–0.6. On the other hand, the critical drift for the heavy ion (O^+) mode decreases rather rapidly with increasing O^+ concentration in the same range of n_{O^+}/n_e. The case examined by *Kindel and Kennel* [1971] corresponds to a heavy ion-light ion mass ratio, R, equal to 16. *Guzdar et al.* [1987] have examined the case of a two-ion species plasma in which the heavy ion is NO^+ and the light ion is O^+, with a mass ratio $R \simeq 1.9$. The behavior of the critical drifts is very similar to that shown by *Kindel and Kennel* [1971] for O^+-H^+, except that "crossover" (equal critical drift for heavy ion and light ion mode) occurs at a larger value of α_H.

3. EXPERIMENTAL SETUP

The experiments were performed in a single-ended Q-machine [e.g., *Motley*, 1975], a schematic diagram of which is shown in Figure 2. A tantalum plate of 6-cm diameter is heated by electron bombardment to a temperature of ~2300°K and thus emits a large number of thermionic electrons. Cs and K neutral atoms are sprayed onto the plate by Cs and K atomic beam ovens, which provide independently variable fluxes of the alkali metals. The Cs and K atoms are surface ionized on the tantalum plate and a plasma column is formed, ~1 m long, which is confined radially by a magnetic field up to ~4 kG. The plasma column is terminated either by a metallic cold endplate, which is electrically floating, or by the front plate of a mass spectrometer (see below). Langmuir probes are used as the main diagnostic tool.

Typical plasma parameters are an electron density, $n \approx 10^9$ cm^{-3} to 10^{11} cm^{-3}, electron and ion temperatures (determined by the hot plate temperature) $T_e \approx T_{Cs^+} \approx T_{K^+} \approx 0.2$ eV and a base pressure in the vacuum vessel of ~1×10^{-6} torr. In these conditions the electron and ion mean-free paths for collisions with the neutral gas background are much larger than the machine length. On the other hand, the Coulomb collision mean-free path (e.g., *e-i* collisions) is ~60 cm at a plasma density $n \simeq 1 \times 10^9$ cm^{-3} and ~6 cm at a density of ~1×10^{10} cm^{-3}. Thus a single electron, in general, collides one or several times with ions over the entire length of the plasma column. As is usual in this type of experiment, the EIC waves are excited by drawing an electron current along the axis of the plasma column to an exciter disk of 11-mm diameter. The spectral properties of the EIC waves are analyzed with an HP 3585A spectrum analyzer.

Of special importance in the present experiment was the determination of the Cs^+ and K^+ relative concentrations. In a preliminary set of experiments [*Suszcynsky et al.*, 1988*a*], this was accomplished by raising the temperature of just one oven at a time and attributing any increase in the ion density as measured with a Langmuir probe, to an increase of the partial density of the species emitted by that oven.

A different method, which was used as a check on the technique just described, provided better determinations of the relative Cs^+ and K^+ ion concentrations. This method consisted of using a magnetic mass spectrometer which was designed and built for use in the Q-machine, and is described in detail by *Suszcynsky et al.* [1988*b*]. Cs^+ and K^+ ions are accelerated into the collection region of the spectrometer through a series of three tantalum electrodes, at a 30° angle to the **B** field, and then are selectively collected, depending

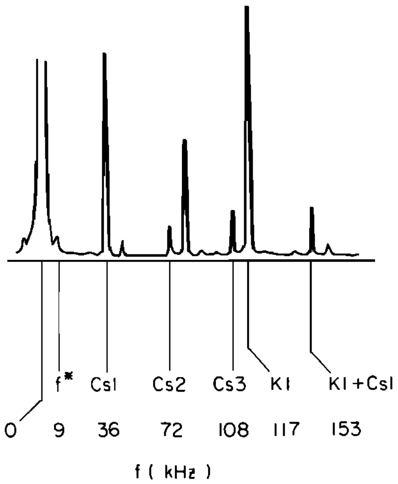

Fig. 3. Typical power spectrum of EIC wave fluctuations for B = 2500 G in a plasma consisting of ~20% cesium and ~80% potassium. The primary EIC modes as well as a few combination modes are identified.

on the size of their gyroradii, by a cylindrical collector. Relative ion concentrations are determined to an estimated accuracy of about 5–10% by measuring the collector current as a function of the accelerating voltage.

4. EXPERIMENTAL RESULTS AND DISCUSSION

As stated in section 3, the EIC instability is excited by drawing an electron current to a metallic disk of 11-mm diameter (thus with a radius several times the gyroradius of the heavy-ion species, but smaller than the plasma column), located on the axis of the plasma column and biased, generally, at a few volts above the plasma potential. The disk is located ~1 cm in front of an electrically floating, cold endplate, ~90 cm from the hot plate. We detect the instability by observing the fluctuations in the current to the exciter disk. Typically, the EIC wave amplitude, $\Delta n/n$, can be as large as 30–40%.

A frequency spectrum of the current fluctuations is shown in Figure 3, with B = 2500 G, $n \simeq 2 \times 10^{10}$ cm^{-3}, and roughly an 80% K$^+$ and 20% Cs$^+$ ion composition. The two largest spectral peaks in Figure 3 correspond to the Cs$^+$ and K$^+$ EIC fundamentals (Cs1 and K1) which are seen, under these conditions, to be simultaneously excited in the plasma. In addition to the Cs$^+$ and K$^+$ fundamentals, we also observe the Cs$^+$ first (Cs2) and second (Cs3) harmonics. The ratio of the observed frequency for the Cs1 and K1 modes is consistent with the inverse ratio of the ion masses, $\Omega_{K+}/\Omega_{Cs+} = M_{Cs+}/M_{K+} = 3.4$. The K$^+$ and Cs$^+$ EIC mode frequencies are ~20% higher than the corresponding gyrofrequencies of f_{K+} = 97.4 kHz and f_{Cs+} = 28.6 kHz, at B = 2500 G, and the waves propagate radially outward from the current channel.

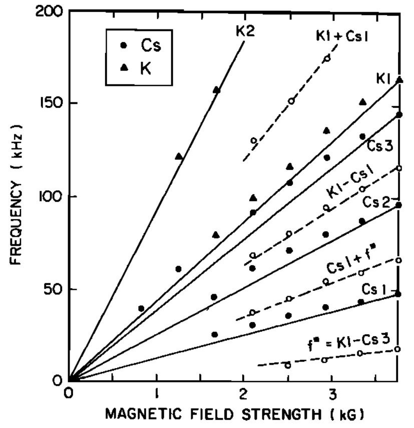

Fig. 4. Frequencies of EIC modes as a function of the magnetic field strength. The solid lines are the Cs$^+$ and K$^+$ EIC harmonics. The dashed lines indicate sum and difference modes.

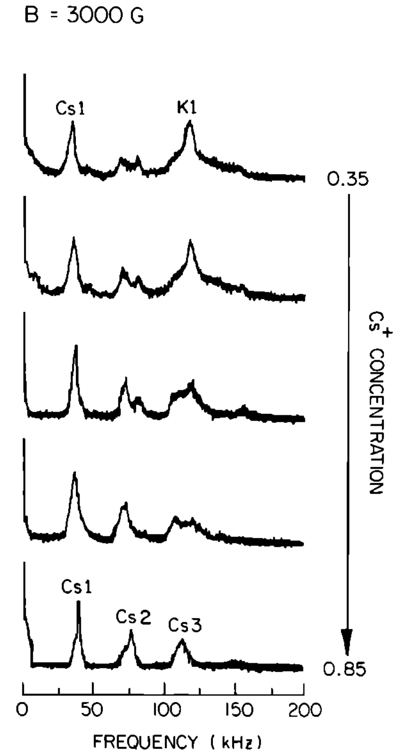

Fig. 5. Evolution of the frequency spectrum as a function of cesium ion concentrations for B = 3000 G. The primary EIC modes are identified.

For a more definitive identification of the EIC modes, we obtained a frequency spectrum at various values of the magnetic field and observed that these modes have frequencies proportional to the magnetic field strength (Figure 4). In addition to the Cs$^+$ and K$^+$ EIC modes, we also observed a low-frequency peak (marked as f^* in Figure 3), corresponding to the difference between the frequencies of K1 and Cs3. Additional modes also appear at frequencies corresponding to K1 − Cs2 = Cs1 + f^*, K1 − Cs1 = Cs2 + f^*, etc. It must be noted that these "combination" peaks were observed only at densities not much larger than ~10^{10} cm^{-3}. If the density was increased by about a factor 10, even though the relative ion concentrations were similar to those of Figures 3 and 4, the "combination" peaks were not observed. We have not been able to identify the nature of these peaks, since phase measurements outside the current channel proved very difficult. We do know, however, that they are present not only in the exciter disk current but also in the signals from Langmuir probes located in the plasma column (or, at least, within the current filament) tens of centimeters away from the disk.

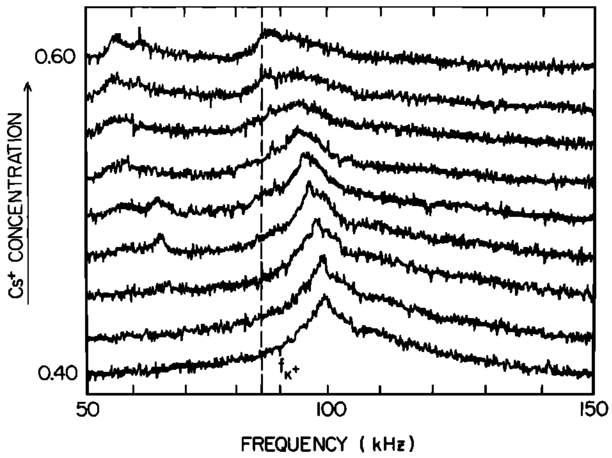

Fig. 6. As the cesium concentration is increased, the potassium fundamental frequency shifts toward f_{K^+} (B = 2200 G).

As seen in Figure 3, Cs^+ and K^+ EIC waves can be simultaneously excited when the two ion concentrations are both appreciable. Questions arise as to the behavior of the individual modes as the concentrations are varied. For example, we typically observe that as Cs^+ ions are introduced into an initially pure K^+ plasma, there is a relatively large range of Cs^+ concentrations for which both K^+ and Cs^+ modes are observed. As the Cs^+ concentration is further increased, a point is reached when the K^+ modes disappear. A similar behavior is observed starting from a pure Cs^+ plasma, although the Cs^+ waves are observed at a lower minor ion concentration than the K^+ waves. An example of this concentration dependence can be seen in Figure 5, which shows a series of five wave spectra, obtained with a magnetic field of 3000 G, as the Cs^+ concentration is varied over the range ~35% to ~85%. Evidently, as the Cs^+ concentration is increased, the Cs^+ EIC modes become more dominant until, at a Cs^+ concentration of ~85%, no K^+ EIC mode is observed.

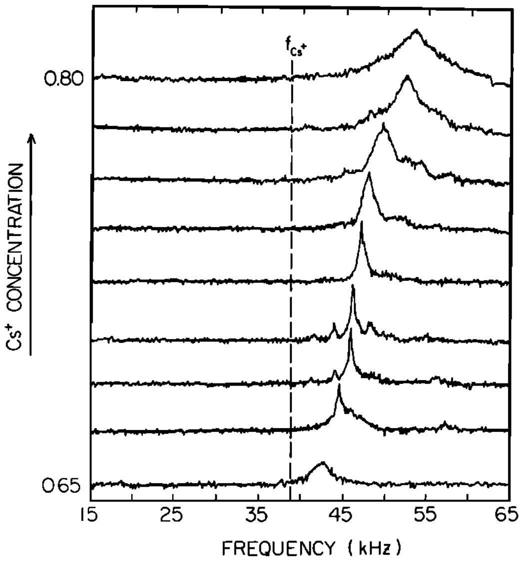

Fig. 7. As the cesium concentration is increased, the cesium fundamental frequency shifts away from f_{Cs^+} (B = 3360 G).

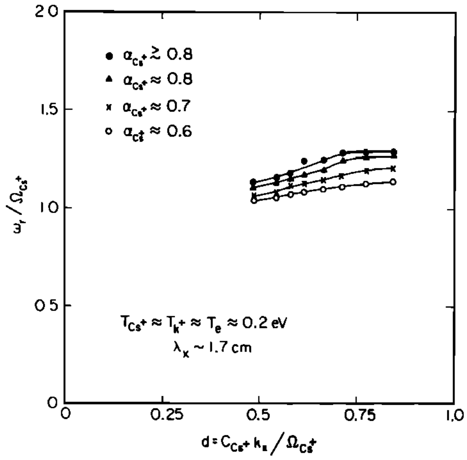

Fig. 8. Experimental determination of heavy ion mode dispersion relation for several values of the heavy ion concentration. The parameter d was controlled by varying the magnetic field strength.

As remarked upon in section 2, one of the predictions of both the kinetic theory and the fluid theory of EIC waves is that, as the light ion concentration is increased, the frequency of the heavy ion mode moves closer to the heavy ion gyrofrequency. Similarly, as the heavy ion concentration is increased, the frequency of the light ion mode moves closer to the light ion gyrofrequency. This prediction was tested by observing, in two separate experiments, the frequency vari-

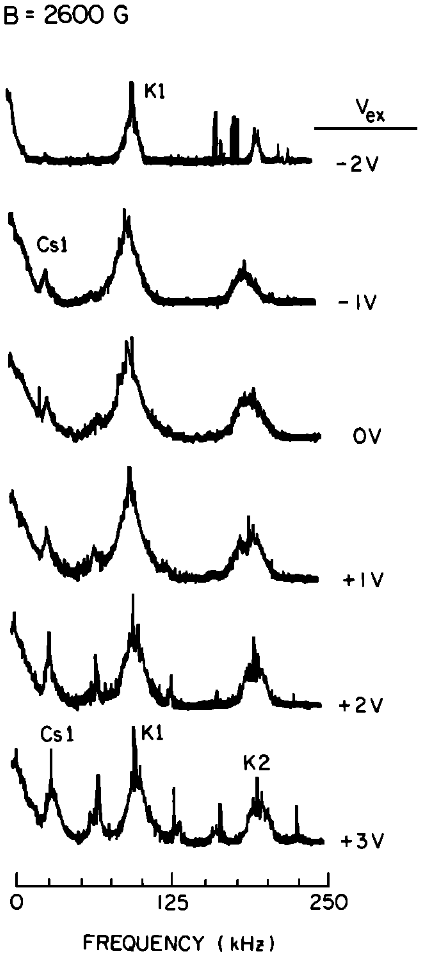

Fig. 9. Evolution of the frequency spectrum as a function of exciter bias for B = 2600 G. The primary EIC modes are identified.

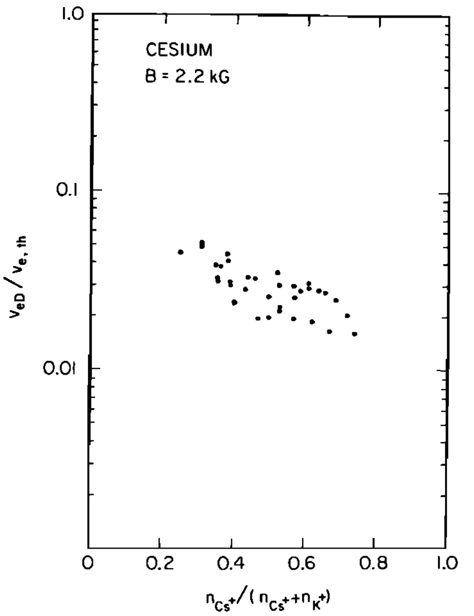

Fig. 10. The critical drift velocity, $v_{eD}/v_{e,th}$, for excitation of the cesium fundamental as a function of cesium ion concentration.

ation of K1 (Figure 6) and Cs1 (Figure 7), as the cesium concentration was varied in the range 0.40–0.60 and in the range 0.65–0.80, respectively. Note that, as the Cs^+ concentration increases, the frequency of the potassium fundamental (K1) decreases, while that of the cesium fundamental (Cs1) increases. This behavior is in agreement with the predictions of section 2.

A partial test of the dispersion relation for the EIC modes (Figure 1) was accomplished as shown in Figure 8. Here the ratio ω_r/Ω_{Cs^+} is plotted vs. the quantity $d = C_{Cs^+}K_x/\Omega_{Cs^+}$, for four different concentrations of the Cs^+ ions. The parameter d was controlled by varying the magnetic field strength. The component K_x of the wave vector, obtained from wave phase measurements, corresponded to a perpendicular wavelength of ~1.7 cm. One observes in Figure 8 both the expected increase in wave frequency with increasing d, and, for any fixed d, a frequency increase with increasing Cs^+ ion concentration.

Finally, the question of the critical electron drifts for excitation of the Cs^+ and K^+ EIC modes was addressed (see section 2). The drift velocity of the electrons along the magnetic field was varied by adjusting the bias on the exciter disk. Figure 9 shows the evolution of the wave spectrum, at a magnetic field of 2600 gauss, as the exciter bias was varied between −2 V and +3 V (the space potential is, typically, ~−2 V). In this case the Cs^+ concentration was ~30%.

Figure 10 and Figure 11 show the variation of the critical drift for excitation of the Cs^+ EIC mode and of the K^+ mode, respectively, as a function of the Cs^+ ion concentration. In both cases the magnetic field was 2200 G. The critical drifts have been normalized to the electron thermal speed, $v_{e,th}$. The determination of the critical drift velocity for each mode consisted of measuring the current collected by the exciter disk at a bias where the mode in question just begins to appear in the frequency spectrum of the exciter current oscillations. This current can then be related to the critical drift velocity with a knowledge of the plasma density and exciter area. As the Cs^+ ion concentration increases from ~20% to ~80%, the Cs^+ critical drift decreases by about a factor 3, while the K^+ critical drift shows at best only a very mild increase. The uncertainty in the measurements is indicated by the scatter of the data points in Figures 10 and 11. Due to this rather large scatter it is difficult to determine precisely the "crossover" point, namely, the Cs^+ ion concentration at which the two critical drifts are equal. "Crossover" appears to take place when the Cs^+ ion concentration is about 0.4 to 0.5.

The observed behavior of the critical drifts is as expected on the basis of the theory summarized in section 2. The observed "crossover" point also seems to be in line with expectations for a mass ratio $R = 3.4$.

5. CONCLUSIONS

We have presented an experimental study of EIC waves in a two-ion-species plasma. The plasma, consisting of electrons, Cs^+ and K^+ ions was produced in a Q-machine with independent Cs and K atomic beam ovens, so that the relative ion concentrations could be varied over a rather wide range. A fluid theory of EIC waves for such a plasma has also been presented to guide in the interpretation of the experimental results.

A concise summary of the experimental findings is as follows:

1. Both Cs^+ and K^+ EIC waves are present over a large range of relative ion concentrations (however, the Cs^+ waves are typically observed at lower minor ion concentrations than the K^+ waves).
2. The frequency of the heavy ion mode shifts towards the heavy ion cyclotron frequency as the light ion concentration is increased. Likewise, the frequency of the light ion mode approaches the light ion cyclotron frequency as the heavy ion concentration is increased.
3. The critical drift velocity for excitation of each EIC mode depends on the relative ion concentrations, although the dependence for the heavy ion mode appears to be much more pronounced than for the light ion mode (see Figures 10 and 11).

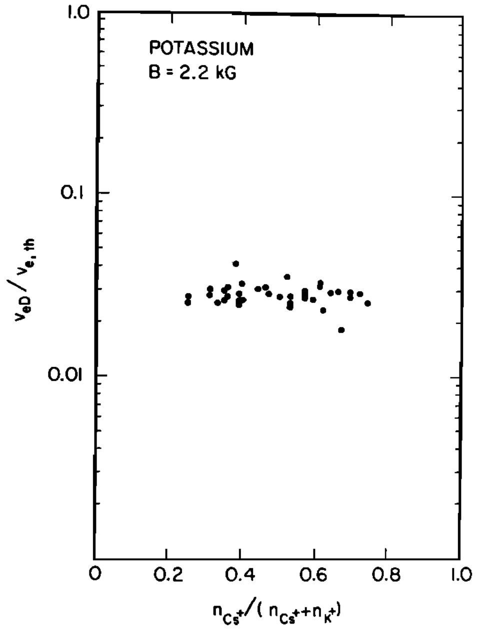

Fig. 11. The critical drift velocity, $v_{eD}/v_{e,th}$, for excitation of the potassium fundamental as a function of cesium ion concentration.

4. For low total plasma densities ($n \lesssim 2 \times 10^{10}$ cm^{-3}), combination modes with frequencies given by sums and differences of various Cs^+ and K^+ EIC wave harmonics have been observed. It has proved difficult to establish the nature of these combination modes, since phase measurements outside the current channel were either impossible or unreliable. At the same time, it was found that the combination modes were present, not only in the spectra of current fluctuations on the exciter disk, but also in the signals from Langmuir probes located in the main body of the plasma as well. However, it is not clear whether these modes are true plasma effects or are generated by, e.g., nonlinear sheath characteristics of the exciter.

The present study shows general agreement with theoretical predictions on EIC waves in multi-ion plasmas. Thus the relevant theories may now be applied with more confidence to actual ionospheric situations. In particular, point 3 above, concerning the critical drifts, may be useful as a diagnostic tool for determining the strength of field-aligned currents in those cases in which only one ion EIC mode is detected, although the plasma contains several species of ions.

Acknowledgments. We wish to thank Al Scheller for his technical assistance. This work was supported by the ONR and NASA.

The Editor thanks H. L. Pecseli and I. Roth for their assistance in evaluating this paper.

REFERENCES

Alport, M. J., and E. G. van Niekerk, Phase measurements of the ion cyclotron instability, in *Proceedings of the Workshop on the Current-Driven Electrostatic Ion-Cyclotron Instability*, edited by R. Schrittwieser, World, Singapore, 1988.

Bering, E. A., Apparent electrostatic ion cyclotron waves in the diffuse aurora, *Geophys. Res. Lett.*, *10*, 647, 1983.

Bering, E. A., The plasma wave environment of an auroral arc: Electrostatic ion cyclotron waves in the diffuse aurora, *J. Geophys. Res.*, *89*, 1635, 1984.

Bering, E. A., M. C. Kelley, and F. S. Mozer, Observations of an intense field aligned thermal ion flow and associated intense narrow-band electric field oscillations, *J. Geophys. Res.*, *80*, 4612, 1975.

Cartier, S. L., N. D'Angelo, and R. L. Merlino, Electrostatic ion-cyclotron waves in a nonuniform magnetic field, *Phys. Fluids*, *28*, 3066, 1985.

Chaturvedi, P. K., Collisional ion cyclotron waves in the auroral ionosphere, *J. Geophys. Res.*, *81*, 6169, 1976.

Dakin, D. R., T. Tajima, G. Benford, and N. Rynn, Ion heating by the electrostatic ion cyclotron instability: Theory and experiment, *J. Plasma Phys.*, *15*, 175, 1976.

D'Angelo, N., Type III spectra of the radar aurora, *J. Geophys. Res.*, *78*, 3987, 1973.

D'Angelo, N., and R. W. Motley, Electrostatic oscillations near the ion cyclotron frequency, *Phys. Fluids*, *5*, 663, 1962.

Drummond, W. E., and M. N. Rosenbluth, Anomalous diffusion arising from microinstabilities in a plasma, *Phys. Fluids*, *5*, 1507, 1962.

Fejer, B. G., R. W. Reed, D. T. Farley, W. E. Schwartz, and M. C. Kelley, Ion cyclotron waves as a possible source of resonant auroral radar echoes, *J. Geophys. Res.*, *89*, 187, 1984.

Ganguli, G., Y. C. Lee, and R. Hatakeyama, Electrostatic ion-cyclotron instability caused by a nonuniform electric field perpendicular to the external magnetic field, *Phys. Fluids*, *28*, 761, 1985.

Guzdar, P. N., P. K. Chaturvedi, and S. L. Ossakow, Current-driven ion cyclotron instability in two ion component plasmas, paper presented at 29th Annual Meeting, Am. Phys. Soc. Div. of Plasma Phys., San Diego, Calif., Nov. 1987.

Haldoupis, C., P. Prikryl, G. J. Sofko, and J. A. Koehler, Evidence for 50-MHz bistatic observations of electrostatic ion cyclotron waves in the auroral plasma, *J. Geophys. Res.*, *90*, 10,983, 1985.

Hatakeyama, R., F. Muto, and N. Sato, Measurements of potential-driven electrostatic ion cyclotron oscillations in a plasma, *Jpn. J. Appl. Phys.*, *24*, L285, 1985.

Kindel, J. M., and C. F. Kennel, Topside current instabilities, *J. Geophys. Res.*, *76*, 3055, 1971.

Kintner, P. M., M. C. Kelley, R. D. Sharp, A. G. Ghielmetti, M. Temerin, C. Cattell, P. F. Mizera, and J. F. Fennell, Simultaneous observations of energetic (keV) upstreaming and electrostatic hydrogen cyclotron waves, *J. Geophys. Res.*, *84*, 7201, 1979.

Krumm, P. H., and M. J. Alport, The role of the electron-collecting disc in the excitation of the electrostatic ion-cyclotron waves, *Plasma Phys. Control Fusion*, *26*, 1007, 1984.

Levine, A. M., and A. F. Kuckes, Excitation of electrostatic ion cyclotron oscillations, *Phys. Fluids*, *9*, 2263, 1966.

Martelli, G., P. N. Collins, M. Giles, and P. J. Christiansen, Optical detection of electrostatic ion cyclotron waves in the auroral plasma, *Planet. Space Sci.*, *25*, 643, 1977.

Motley, R. W., *Q-Machines*, Academic, San Diego, Calif., 1975.

Motley, R. W., and N. D'Angelo, Excitation of electrostatic plasma oscillations near the ion cyclotron frequency, *Phys. Fluids*, *6*, 296, 1963.

Ono, M., M. Porkolab, and R. P. H. Chang, Parametric decay into ion cyclotron waves and drift waves in multi-ion species plasma, *Phys. Fluids*, *23*, 1656, 1980.

Pécseli, H. L., J. J. Rasmussen, and R. Schrittwieser, The influence of collisions on the current-driven electrostatic ion-cyclotron instability, in *Proceedings of the Workshop on the Current-Driven Electrostatic Ion-Cyclotron Instability*, edited by R. Schrittwieser, World, Singapore, 1988.

Providakes, J., D. T. Farley, W. E. Schwartz, and D. Riggin, Plasma irregularities associated with a morning discrete auroral arc: Radar interferometer observations and theory, *J. Geophys. Res.*, *90*, 7513, 1985.

Reed, R. W., Spectra from 50 MHz auroral radar echoes, Ph.D. thesis, Cornell Univ., Ithaca, N.Y., 1980.

Rynn, N., Laboratory simulation of magnetospheric plasma phenomena using laser induced fluorescence as a diagnostic, in *Ion Acceleration in the Ionosphere*, *Geophys. Monogr. Ser.*, vol. 38, AGU, Washington, D. C., 1986.

Satyanarayana, P., P. K. Chaturvedi, M. J. Keskinen, J. D. Huba, and S. L. Ossakow, Theory of the current-driven ion cyclotron instability in the bottomside ionosphere, *J. Geophys. Res.*, *90*, 12,209, 1985.

Stern, R. A., Ionic response in current-driven electrostatic ion cyclotron instabilities, in *Proceedings of the Workshop on the Current-Driven Electrostatic Ion-Cyclotron Instability*, edited by R. Schrittwieser, World, Singapore, 1988.

Sugai, H., H. Kojima, and T. Okuda, Experimental observation of electrostatic ion cyclotron waves modified by minority ions, *Phys. Lett.*, *92A*, 392, 1982.

Suszcynsky, D. M., S. L. Cartier, R. L. Merlino, and N. D'Angelo, A laboratory study of collisional electrostatic ion cyclotron waves, *J. Geophys. Res.*, *91*, 13,729, 1986.

Suszcynsky, D. M., R. L. Merlino, and N. D'Angelo, Electrostatic ion-cyclotron waves in a two-ion component plasma, *IEEE Trans. Plasma Sci.*, *PS-16*, 396, 1988*a*.

Suszcynsky, D. M., N. D'Angelo, and R. L. Merlino, Mass spectrometer for measurements of relative ion concentrations in plasmas, *Rev. Sci. Instrum.*, *59*, 1376, 1988*b*.

N. D'Angelo, R. L. Merlino, and D. M. Suszcynsky, Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242.

(Received December 20, 1988;
revised February 7, 1989;
accepted March 8, 1989.)