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Current-Driven Electrostatic and Electromagnetic Ion Cyclotron Instabilities

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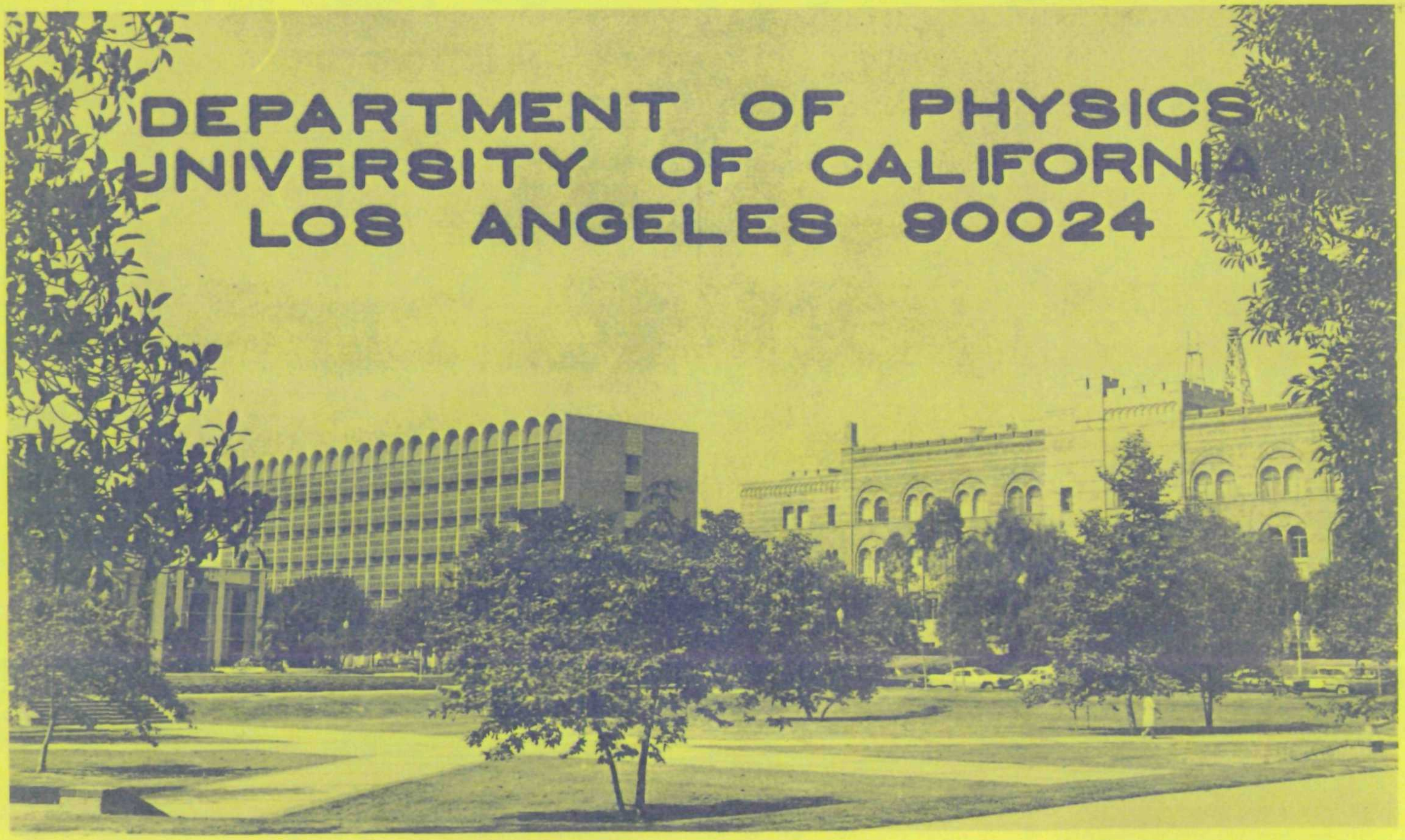

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Current-Driven Electrostatic and Electromagnetic Ion Cyclotron Instabilities

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ABSTRACT

Growth rates and parameter dependences are calculated for the current-driven instabilities of electrostatic (with finite-β corrections) and electromagnetic ion cyclotron waves. For $0.25 < T_e/T_i < 2.5$, ion cyclotron waves have large growth rates, while ion acoustic waves are still stable. In fusion devices, where electrostatic waves may be stable, electromagnetic ion cyclotron waves are unstable for $\beta_i > 10^{-3}$. The suggestion is made that ion cyclotron waves may provide an anomalous resistance, with $\nu_{eff} \approx A^{1/2}\Omega_{ci}(T_{e,\parallel}/T_{i,\perp})$.

INTRODUCTION

Ion cyclotron instabilities, driven by magnetic-field-aligned currents and/or electron heat conduction, are of interest to the physics of the solar wind,[1] the ionosphere,[2] Q-machine plasmas,[3-5] and to certain controlled thermonuclear fusion devices such as tokamaks, which have confining electron currents. We report recent salient results concerning four basic extensions of the Drummond-Rosenbluth[6] investigation of the electrostatic ion cyclotron instability: arbitrary T_e/T_i, where T_e/T_i is the electron-to-ion temperature ratio; growth rates well above marginal stability; effects of contaminations by low charge-to-mass ratio ions; finite β_i corrections, where β_i is the ratio of ion particle to magnetic field pressure. Moreover, we report some preliminary results concerning the electromagnetic ion cyclotron current instability,[7,8] and discuss a few implications of saturated ion cyclotron turbulence. The details of this work will be published elsewhere.[9]

ELECTROSTATIC ION CYCLOTRON INSTABILITIES

For purposes of analysis, we have chosen isotropic Maxwellian distributions (albeit with different T_e and T_i) drifting along a uniform-background magnetic field $B_o \hat{e}_z$. Thus, we have neglected the effect of the self-consistent magnetic field created by the current. To facilitate calculation in analytically difficult parameter regimes, a computer program has been developed which solves the dispersion relation for small-amplitude electrostatic waves.[6,7] The general electrostatic dispersion relation is cast into the Gordeyev integral form.[10] Complex roots of the dispersion relation are obtained numerically by a standard algorithm, such as Muller's method.[11] A given wave mode is found either by making a suitably accurate guess or by following known wave modes into the parameter range of interest.

SINGLE ION SPECIES

A marginal stability analysis[2, 6, 8] indicates that when $T_e/T_i = 1$, the wave that is marginally stable to the smallest current has $K_\perp^2 R_i^2 \approx 1$, $\omega \simeq 1.2\,\Omega_{ci}$, and $K_\perp/K_\parallel = 12$, where R_i is the thermal ion Larmor radius, ω is the wave frequency, and $K_\perp/K_\parallel$ is the ratio of wave numbers perpendicular and parallel to B_o. Here, we focus on unstable ion cyclotron waves. The general electrostatic dispersion relation[6, 7] has dependences upon the following parameters: $K_\perp^2 R_i^2$, $K_\perp/K_\parallel$, V_D/a_e [the electron drift relative to ions in units $(2T_e/m_e)^{1/2}$], m/M, T_e/T_i, and the ratio of ion plasma to cyclotron frequency ω_{pi}/Ω_{ci}. We can eliminate some dependences: We consider $\omega_{pi}^2/\Omega_{ci}^2 > 10$, since this implies weak $\omega_{pi}^2/\Omega_{ci}^2$ dependence.[9] We eliminate the dependences upon $K_\perp/K_\parallel$ and $K_\perp^2 R_i^2$ by searching numerically for local maxima in the growth rate. Choosing $M/m = 1836$, corresponding to an H^+ plasma, we plot in Fig. 1 contours of maximum growth rate for the $n = 1$ wave as a function of the two remaining parameters, V_D/a_e and T_e/T_i. For comparison, we also plot the marginal stability contour for the $K_\perp = 0$ ion acoustic wave, corresponding to the magnetic field-free calculations of Fried and Gould[12] and Stringer,[13] and the contour for $\gamma_{max}/\omega_{pi} = 1$, which marks the transition to the nonresonant electron-ion beam instability originally studied by Buneman. The shaded region denotes the portion of the T_e/T_i, V_D/a_e parameter space for which the ion cyclotron wave is unstable but the ion acoustic wave is stable. The ion cyclotron wave is unstable to the smaller current over the range $0.05 < T_e/T_i < 8.5$. Furthermore, it has a significant growth rate $\gamma_{max}/\Omega_i = 0.1$ (while the ion acoustic wave is still stable) over the range $0.25 < T_e/T_i < 2.5$. Thus, the ion cyclotron instability dominates the ion acoustic instability over an interestingly large portion of parameter space. It can be shown that the region of ion cyclotron dominance increases as M_i increases.[2]

CYCLOTRON INSTABILITIES IN MULTI-ION PLASMAS

We now turn briefly to the operation of the electrostatic ion cyclotron instability in ion mixtures. Besides the above-listed parameters, there is now an additional dependence on N_i/N_e, the relative ion composition. Only the marginal stability ($\gamma_{max}/\Omega_{ci} = 0$) contour is considered here because of the added dimensionality in parameter space. We may ask the following questions: First, in a mixture, the ion harmonic of which ion is unstable to the smallest current? Second, how do critical electron drifts respond to changes in ion composition? Third, at what point does the plasma switch ion instabilities as the ion composition is varied? fourth, and last, how do these effects vary with T_e/T_i? Figure 2 shows the results of an analytic calculation[2] of the electron drift V_c for marginal stability in a mixture of H^+ and O^+ (a case of ionospheric interest) as a function of T_e/T_i and fractional O^+ concentration, N_{o+}/N_e. It is convenient to represent our results in N_{o+}/N_e,

V_D/a_c space with T_e/T_i as a parameter. Solid and dashed lines denote the marginal stability curves for the instabilities near the first O^+ and H^+ cyclotron harmonics, respectively. The appropriate temperature ratio T_e/T_i is indicated at the intersections of the H^+ and O^+ curves. For simplicity, the H^+ and O^+ temperatures were taken equal. Figure 2 indicates that the heavy-ion harmonic is unstable to the smaller current for surprisingly small heavy-ion contaminations, of the order of 10%.

ELECTROMAGNETIC ION CYCLOTRON WAVES

A computer program which solves the full electromagnetic wave dispersion relation for spatially homogeneous, drifting electron and ion Maxwellian distributions in a uniform magnetic field has also been developed. In addition to the single ion parameters listed above, the dispersion relation now depends upon β_i. For large-enough β_i, it has been shown by Stix[7] that electromagnetic ion cyclotron waves (which have electrostatic corrections at oblique propagation) have a parallel phase velocity sufficiently slow that they can be destabilized by small electron drifts. Details of our investigation of this instability will be considered elsewhere.[9]

Figure 3 shows some of our preliminary results. For M/m = 1836 and $T_e/T_i = 1$, we plot contours of constant maximum growth rate in a β_i, V_D/a_e parameter space.

For purposes of comparison, we have also plotted the marginal stability contour, $\gamma_{max}/\Omega_i = 0$, for the "electrostatic" ion cyclotron wave. This mode is electrostatically polarized for β_i small, and develops small electromagnetic components as β_i increases. These finite β_i corrections are stabilizing. However, ion cyclotron waves of one sort or another continue to be unstable as β_i increases, because of the lower threshold of this new electromagnetic instability for $\beta_i > 10^{-3}$. It is probably this mode which is most important in the solar wind, since $\beta_i > 10^{-2}$, even near the sun.

For $\gamma_{max}/\Omega_i = 10^{-2}$, the real frequency is typically $0.75\Omega_i$, and $K_\perp R_i \approx 1.0 - 1.5$, $K_\parallel R_i < .1$ for maximum growth. As the drift velocity is decreased to the point where $\gamma_{max}/\Omega_i < 10^{-3}$, $K_\perp R_i$ for maximum growth drops rapidly below 1.0 and $K_\parallel R_i$ increases somewhat above 0.1. Drifts then tend toward Stix's estimate.

Before closing the discussion of the electromagnetic current instability, let us note that a drifting electron Maxwellian certainly is not the self-consistent equilibrium distribution in a finite β_i current-carrying plasma. However, the Maxwellian should reasonably well describe the electron growth. Furthermore, any stabilizing effect of the inhomogeneous magnetic field, created by the direct current, might be unimportant because of the small wave group velocity. Kan has indicated to us that if the inhomogeneous magnetic field determines a pressure gradient, a drift mode might also be easily destabilized for $\beta_i > 10^{-2}$.

NONLINEAR CONSIDERATIONS

One-dimensional quasilinear electron plateau formation can saturate the electrostatic ion cyclotron instability at $e\phi/T_e \lesssim 10^{-2}$, ϕ being the wave potential integrated over the unstable spectrum.[6,14] Dum and Dupree,[4] however, have shown that if electron plateau formation is inhibited, $e\phi/T_e \sim 1/2$. This large saturation level agrees with Q machine results,[3-5,15] where end effects may prevent plateau formation. We have observed[16] that large $e\phi/T_e$ permits ion cyclotron waves to interact with a significant portion of the electron distribution, at an effective electron-ion frequency $\nu_{eff} \simeq A\Omega_{ci}(T_{e,\parallel}/T_{i,\perp})$, where A is the atomic number, and $\perp$ and $\parallel$ refer to B_o. For large $e\phi/T_e$, anomalous resistance due directly to wave-electron scattering may occur, or turbulence may hold back the bulk of the electron distribution while high-energy electrons carry current demanded above cyclotron threshold. In the latter case, anomalous resistance ultimately may be derived from two-stream instabilities generated by the electron tail. Significant spatial plasma diffusion and perpendicular ion heating may also occur.

The conclusions described above could be important for tokamak controlled-fusion devices. Experiments in the Princeton Model ST may be operating in regimes where the electrostatic ion cyclotron wave is likely to be unstable, but where the acoustic wave may or may not be unstable.[17-19] It has been suggested that larger β_i (higher density) may eliminate electrostatic current instabilities by reducing the electron drift needed to produce the confining magnetic field. However, we must still contend with the electromagnetic ion cyclotron instability. Bers, Manheimer, and Coppi have already suggested that ion cyclotron waves may account for the anomalous perpendicular ion heating observed in the Soviet TM-3 Tokamak.[20]

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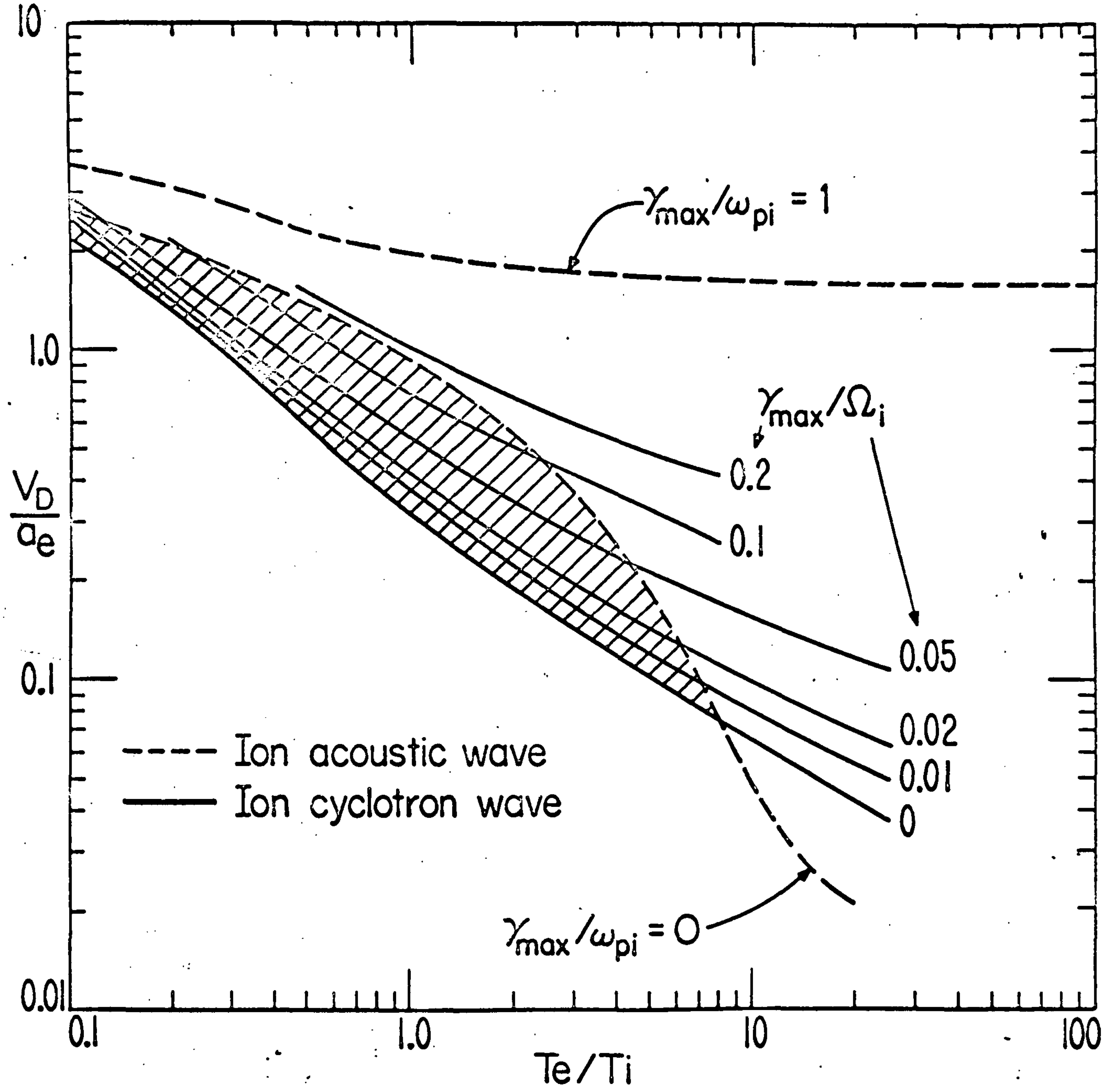
FIGURE CAPTIONS

Fig. 1. Contours of maximum growth for the $n = 1$ H^+ cyclotron wave (solid) and the H^+ acoustic wave (dashed). The shaded region denotes where the cyclotron wave is unstable but the acoustic wave stable.

Fig. 2. Critical drift versus fractional O^+ concentration for $T_e/T_i = 1, 3, 5, 10$. The solid (dashed) lines denotes the $n = 1$, $O^+(H^+)$ critical drift. The transition from O^+ to H^+ waves shifts from $N(O^+)/N_e = 0.15$, at $T_e/T_i = 1$, to $N(O^+)/N_e = 0.06$, at $T_e/T_i = 10$.

Fig. 3. "Electrostatic" and electromagnetic ion cyclotron maximum growth rate contours for $M/m = 1836$ and $T_e/T_i = 1$. The electrostatic mode has $\mathrm{Re}(\omega/\Omega_i) > 1$, whereas $\mathrm{Re}(\omega/\Omega_i) < 1$ for the electromagnetic mode. The dashed extension occurs because of the difficulty of distinguishing the electrostatic from the electromagnetic modes. Above $\beta_i \sim 10^{-3}$, the electromagnetic mode is unstable to the smaller current.



10
1.0
0.1
0.01
$\frac{V_D}{a_e}$
0.1
1.0
10
100
Te/Ti
$\gamma_{max}/\omega_{pi} = 1$
γ_{max}/Ω_i
0.2
0.1
0.05
0.02
0.01
0
$\gamma_{max}/\omega_{pi} = 0$
Ion acoustic wave
Ion cyclotron wave

Fig 1

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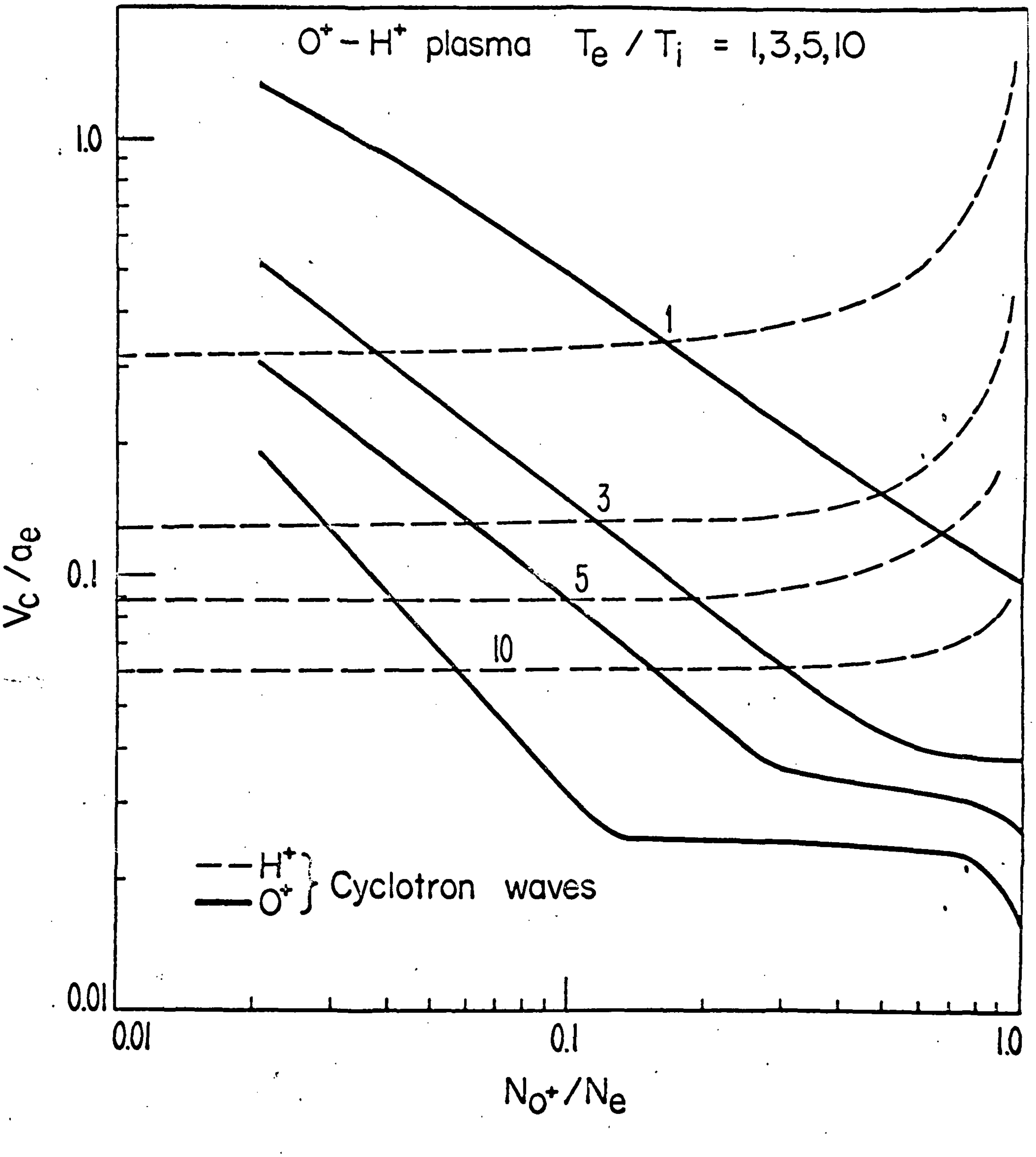
$O^+ - H^+$ plasma T_e / T_i = 1,3,5,10
1.0
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Cyclotron waves
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