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ELECTROSTATIC INSTABILITY OF RING CURRENT PROTONS BEYOND THE PLASMAPAUSE DURING INJECTION EVENTS

F. V. Coroniti[1], R. W. Fredricks[2],
Roscoe White[1]

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[1]Physics Department, University of California, Los Angeles,
California 90024

[2]Space Sciences Department, TRW Systems Group, Redondo
Beach, California 90278

ELECTROSTATIC INSTABILITY OF RING CURRENT PROTONS BEYOND THE PLASMAPAUSE DURING INJECTION EVENTS

ABSTRACT

The stability of ring current protons with an injection spectrum modeled by an m = 2 mirror distribution function has been examined for typical ring current parameters. It is found that the "high frequency loss cone mode" with $\omega_{ci} < \omega \lesssim \omega_{pi}$ can be excited at wave numbers $k\lambda_{Di} \sim 0.1 - 0.5$, at frequencies $\omega \sim (0.2 - 0.6)\ \omega_{pi}$ and with growth rates up to $\gamma/\omega_{pi} \sim 0.03$. These waves interact with the main body of the proton distribution, and propagate nearly perpendicular $[k_{||}/k \sim (m_e/m_i)^{1/2}]$ to the local magnetic field. Cold particle partial densities tend to reduce the growth rate in such a way that the waves are quenched at or near to the plasmapause boundary. Wave e-folding lengths are comparable to 0.1 R_e, compared to the value of $\sim 4\ R_e$ found for ion cyclotron waves at the same plasma conditions. The electrostatic waves investigated should lead to significant $v_{\perp}$ diffusion, and thus act to fill in the empty loss cone of the initial injection spectrum on time scales of 10^3 to $\sim 10^2$ seconds. Their detailed properties as a precipitator and diffusor mechanism require analysis beyond the scope of the present report.

ELECTROSTATIC INSTABILITY OF RING CURRENT PROTONS BEYOND THE PLASMAPAUSE DURING INJECTION EVENTS

During substorms and magnetic storms ring current protons of 5 to 50 keV energies (Frank, 1967) are injected deep into the magnetosphere, presumably by rapid internal convection from the plasma sheet. Russell and Thorne (1970) found that the innermost penetration of the dusk-midnight asymmetric ring current was about 0.5 R_e inside the plasmapause. Whether convection causes protons to flow to the plasmapause or the plasmapause location is determined by the ring current interaction with cold ionospheric plasma (Vasyliunas, 1972) is unclear. Cornwall, Coroniti, and Thorne (1970; referred herein as CCT) suggested that if the ring current protons penetrated the plasmapause, intense resonant electromagnetic ion cyclotron turbulence would lead to their rapid precipitation loss. CCT also argued that since in the low density ($N \sim 10$ particles/cm^3), high-β ($\beta = 8\pi P/B^2$) region just outside the plasmasphere, ion cyclotron instability for ring current energies requires a large pitch angle anisotropy; the ring current in this region should be stable to electromagnetic cyclotron waves. Cornwall and Shulz (1972) calculated the ion cyclotron growth rate γ_{cyc} for a hot ring current plasma with $\beta = 1$, and anisotropy $A = \frac{T_\perp - T_\parallel}{T_\parallel}$ ($T_\perp, T_\parallel$ are the perpendicular and parallel temperatures for a bi-Maxwellian distribution), and no cold or plasmaspheric plasma. They found the maximum growth rate $\gamma_{cyc}/\Omega_i = 5 \times 10^{-3}$ ($\Omega_{i,e} = eB/m_{i,e}c$, the ion cyclotron frequency). Estimating the wave group speed as the Alfven speed, $c_A = B/\sqrt{4\pi N m_i}$, and for $L = 4$ ring current parameters, the e-folding or growth length along the field line is $\sim c_A/\gamma_{cyc} \sim 4\ R_e$. Hence, the ion cyclotron wave is effectively stable just outside the plasmapause due to convective wave losses, which compensate wave growth.

An electrostatic instability of ring current protons was first suggested by *Swift* (1968) as a mechanism to produce VLF chorus. He investigated the case of wave growth rates less than the ion gyrofrequency, in which case harmonics of the ion gyrofrequency are excited. This is also a case in which the ion gyrofrequency (or its harmonic being excited) exceeds the lower hybrid resonance frequency. Thus, Swift's calculation is for a plasma regime quite distinct from that which we investigate in the present note.

Recently Frank (private communication) on Injun V detected the direct injection of ring current protons during the expansion phase of a magnetospheric substorm. The pitch angle distribution was strongly peaked at 90° with virtually no proton flux in the loss cone. Hence the ring current injection spectrum contains abundant free energy to drive plasma instabilities. In this note we investigate the stability of a high frequency electrostatic ion loss cone mode for ring current parameters appropriate to the high-beta region outside the plasmapause. We find that waves with frequencies around the ion plasma frequency $\omega_{pi} = \left(\frac{4\pi N e^2}{m_i}\right)^{1/2}$ can have growth rates at least two to three orders of magnitude greater than those of the ion cyclotron wave, for the same ring current distribution.

For the ring current protons we choose a loss-cone distribution (*Dory et al.*, 1965) given by

$$f_{rc}\,(v_\perp, v_\parallel) = \frac{N(1-r)}{\pi^{3/2} a^3 m!} \left(\frac{v_\perp}{a}\right)^{2m} \exp\left[-\frac{v_\perp^2 + v_\parallel^2}{a^2}\right]$$

where N is the total plasma density and r is the ratio of the cold proton density to the total density, N. $f_{rc}\,(v_\perp, v_\parallel)$ has a positive slope $\partial f_{rc}/\partial v_\perp > 0$

between $v_\perp = 0$ and $v_\perp = \sqrt{m\,a^2}$. For this distribution the parallel temperature is $T_\parallel = \frac{m_i a^2}{2}$ and the perpendicular temperature is $T_\perp = (m+1)\,\frac{m_i a^2}{2}$; hence the anisotropy is $A = \frac{T_\perp - T_\parallel}{T_\parallel} = m$. We include an isotropic cold ion component in order to model the possible mixture of cold plasmaspheric and ring current protons which might exist just outside the storm-time plasmapause. For the electrons we take a single isotropic Maxwellian given by

$$f_e(v) = \frac{N}{\pi^{3/2} b^3} \exp\,[-\,v^2/b^2] \;,$$

so that b is the electron thermal speed. We examine the stability of this plasma to high frequency (ω) electrostatic waves near the ion plasma frequency ω_{pi} and wave numbers k near the ion Debye length $\lambda_{Di} \equiv a/\omega_{pi}$, $k\lambda_{Di} \lesssim 1$. In computing the plasma dielectric response, we can approximate the proton trajectories as being essentially straight-line orbits provided that the wave growth rate $\gamma = \mathrm{Im}\,\omega$ satisfies $\gamma > \Omega_i$ (Post and Rosenbluth, 1966). We note that even if the plasma $\beta \gtrsim 1$, for these frequencies and wave numbers the electrostatic approximation is valid since $kc/\omega_{pe} \gg 1$ ($\omega_{pe} = [\frac{4\pi N e^2}{m_e}]^{1/2}$ is the electron plasma frequency).

Choosing A = m = 2 in the ring current distribution function, the dispersion relation can be written as

$$\varepsilon(\omega,k) = 1 + \frac{\omega_{pe}^{\;2}}{\Omega_e^{\;2}}\sin^2\theta - \frac{\omega_{pe}^{\;2}}{k^2 b^2}\, Z'\left(\frac{\omega}{k_\parallel b}\right) - \frac{\omega_{pi}^{\;2}\, r}{\omega^2}$$

$$- \frac{\omega_{pi}^{\;2}(1-r)}{k^2 a^2}\left[Z'\left(\frac{\omega}{ka}\right) + \frac{\sin^2\theta}{2}\, Z'''\left(\frac{\omega}{ka}\right) + \frac{\sin^4\theta}{32}\, Z^{(v)}\left(\frac{\omega}{ka}\right)\right] .$$

$k_\parallel (k_\perp)$ is the parallel (perpendicular) component of the wave propagation vector

$\underline{k}$, $\sin\theta = k_\perp/k$. $Z(s)$ is the plasma dispersion function of complex argument (Fried and Conte, 1961), and prime denotes differentiation with respect to s. The dispersion relation was solved for the real (ω), and imaginary (γ) part of the complex wave frequency with the parameters $\omega_{pe}{}^2/\Omega_e{}^2 = 3$, $\cos\theta = \left(\frac{me}{mi}\right)^{1/2}$, variable r, and $\frac{m_i a^2}{m_e b^2} = 25$, which might correspond to 25 keV ring current protons and 1 keV electrons. Thus the waves are propagating and have electric field polarizations almost perpendicular to the magnetic field. Figure 1 is a plot of ω/ω_{pi} vs $k\lambda_{Di}$ and γ/ω_{pi} vs ω/ω_{pi} for r = 0, 0.5, and 0.9. The maximum growth rate occurs for r = 0 at $\omega/\omega_{pi} \sim 0.4$ and $\frac{\gamma_{max}}{\omega_{pi}} = 0.03$. The frequency range for unstable growth is $0.2 \leq \omega/\omega_{pi} \leq 0.5$. For r = 0.05, the maximum growth rate is reduced by about a factor of 2, and for r = 0.9 the waves are virtually stable. Hence the electrostatic ion loss cone waves should be predominantly unstable in the low density region outside the plasmapause and should be stable in the cold, high density plasmasphere.

For r = 0 and other parameters fixed, changing the propagation angle to $\cos\theta = \frac{1}{2}\left(\frac{me}{mi}\right)^{1/2}$ yielded $\gamma_{max}/\omega_{pi} = 0.03$ at $\omega/\omega_{pi} = 0.3$; for $\cos\theta = \frac{1}{4}\left(\frac{me}{mi}\right)^{1/2}$, $\gamma_{max}/\omega_{pi} = 0.02$ at $\omega/\omega_{pi} = 0.2$. Hence γ_{max} is relatively insensitive to propagation angle. If the ratio $m_i a^2/m_e b^2$ is lowered from 25 to 16 with other parameters fixed, $\gamma_{max}/\omega_{pi} = 0.026$ at $\omega/\omega_{pi} = 0.5$, indicating that the instability should occur for reasonable range of ring current energies. Finally reducing $\omega_{pe}{}^2/\Omega_e{}^2$ to unity, with other parameters fixed, yielded $\gamma_{max}/\omega_{pi} = 0.037$ at $\omega/\omega_{pi} = 0.53$. Hence the region of maximum wave growth might occur off the equatorial plane where lower $\omega_{pe}{}^2/\Omega_e{}^2$ would be expected if N/B is roughly constant along the field line.

Whether or not instability is achieved in a finite dimensional system depends on the path integrated growth across the system, or in the magnetosphere parallel to the lines of force. The total number of wave amplitude exponentiations can be estimated as $\ell\gamma/v_{g_\parallel}$, where ℓ is the effective length along the magnetic field over which instability occurs and $v_{g_\parallel}$ is the parallel wave group speed. Since $k_\parallel/k_\perp \ll 1$, we can estimate $v_{g_\parallel}$ to lowest order in $k_\parallel/k_\perp$ from the dispersion relation as

$$v_{g\parallel} = - \frac{\partial\varepsilon/\partial k_\parallel}{\partial\varepsilon/\partial\omega} \approx \frac{\frac{\omega_{pe}^{2}}{k^2b^2} Z''\left(\frac{\omega}{k_\parallel b}\right) \frac{\omega}{k_\parallel{}^2 b}}{\frac{\omega_{pe}^{2}}{k^2b^2} Z''\left(\frac{\omega}{k_\parallel b}\right) \frac{1}{k_\parallel b}} = \frac{\omega}{k_\parallel} = \frac{\omega}{\omega_{pi} \cdot k\lambda_{D_{+i}}} \cdot \frac{k_\perp}{k_\parallel}\ a.$$

For the maximally unstable mode with $\omega/\omega_{pi} = 0.4$, $k\lambda_{Di} = 0.5$, and $k/k_\parallel = \left(\frac{m_e}{m_i}\right)^{1/2}$, we find $v_{g_\parallel} \approx 30$ a. Imposing the condition that the wave amplitude exponentiate at least 10 times to be considered unstable and taking $a \approx 2 \times 10^8$ cm/sec and $\gamma \sim (0.01\text{-}0.03)\ \omega_{pi}$ gives $\ell \approx 10\ v_{g_\parallel}/\gamma \approx 2$ to $2/3\ R_e$ for the length of the growth region. Hence the electrostatic loss cone waves are unstable even though the wave energy is rapidly convected along the lines of force.

Since the unstable free energy derives from the positive slope in the ring current proton perpendicular velocity distribution, the nonlinear turbulent relaxation will be predominantly a diffusion toward lower $v_\perp$ for $0 \leq v_\perp \leq (m_i a^2)^{1/2}$, i.e., toward the atmospheric loss cone (Galeev, 1966). We have not solved the nonlinear diffusion problem to determine the turbulent electric field energy density and the time evolution of the distribution function so that only a crude estimate of the wave amplitude can be made. Two dimensional numerical simulations of electrostatic ion waves indicate that, as a rough rule-of-thumb, wave saturation occurs when the wave-particle trapping frequency $(ekE'/m_i)^{1/2}$, based on the rms electric field E', becomes comparable with the linear growth rate (*Forslund and Shonk*, 1970; *Davidson et al.*, 1970). Using this criteria as an estimate $(ekE'/m_i)^{1/2} \approx \gamma$, for $\gamma/\omega_{pi} \approx 0.01 - 0.03$, we find $E' \sim 10 - 10^2$ mV/meter.

To estimate the diffusion time for a proton to reach the loss cone, we construct a phenomenological diffusion coefficient for perpendicular velocities $D = \frac{(\Delta v_\perp)^2}{2\Delta t}$, where $\Delta v_\perp \sim \frac{eE'}{m_i} \Delta t$ is the scattering step in $v_\perp$ and Δt is the wave-particle correlation time. Assuming $\Delta t \sim \gamma^{-1}$, we find $D \sim \frac{\omega_{pi} a^2}{2k^2\lambda^2_{Di}} (\gamma/\omega_{pi})^3$. For $\gamma/\omega_{pi} \approx 0.01 - 0.03$, the time for a proton to diffuse the characteristic velocity a is 3×10^3 to 10^2 seconds. If the 10^2 second (higher E') time scale occurs, then a rapid relaxation of the ring current anisotropy and significant proton precipitation should result. For the longer time scale (lower E'), however, the injected protons could drift out of the unstable region (e.g., their drift orbits might cross the plasmapause) before significant perpendicular diffusion occurred. In this case, the electrostatic turbulence would only partially reduce the anisotropy, and little precipitation would result. Thus whether or not the electrostatic ion loss cone turbulence outside the plasmapause substantially reduces the ring current proton fluxes via precipitation is very much an open question.

In conclusion, the injection of highly anisotropic ring current protons will destabilize the electrostatic ion loss cone mode in the zero or small cold ion plasma density regions outside the plasmapause. Since the electromagnetic ion cyclotron wave is virtually stable in this region, electrostatic waves will dominate any turbulent relaxation of the proton anisotropy and any proton precipitation. Several important questions, however, remain unanswered. Further instability investigations are needed to determine the threshold ring current density, energy, and anisotropy for instability. This information is necessary to determine at what L-value the injected protons first become unstable. The nonlinear turbulence theory must be investigated to establish the wave saturation level, the time scale for diffusive relaxation of the anisotropy, and the extent to which electrostatic waves contribute to precipitation losses.

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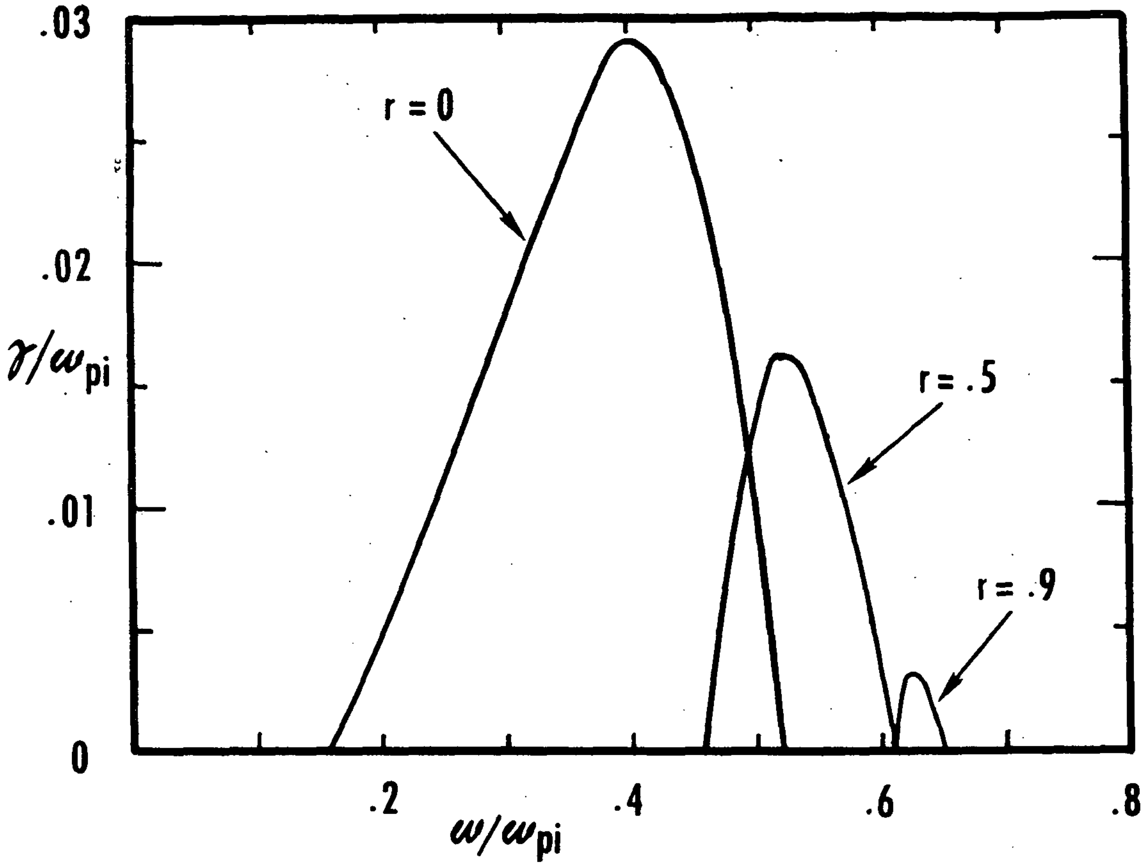
FIGURE CAPTION

Figure 1. Growth rate versus frequency and frequency versus wave number for the high frequency electrostatic mode driven by an m = 2 proton distribution in the case $T_i/T_e = 25$, $\omega_{pe}{}^2/\Omega_e{}^2 = 3$, $k_\parallel/k = (m_e/m_i)^{1/2}$ for cold-to-total number density ratios r = 0, 0.5, and 0.9. Details in text.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γ/ω_{pi}
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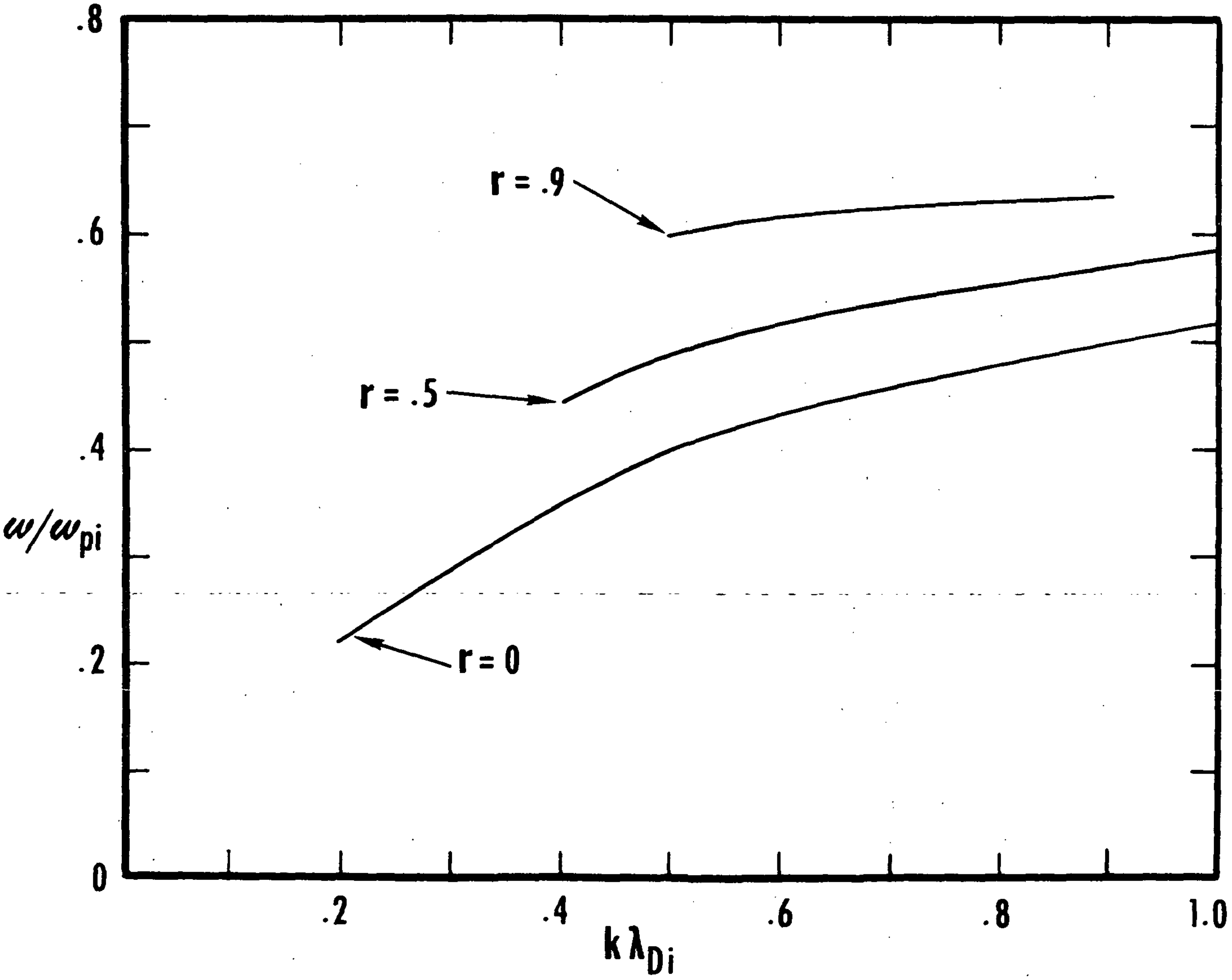
r = .9
.2
.4
.6
.8
ω/ω_{pi}


.8
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r = .9
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r = 0
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$k\lambda_{Di}$

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