INSTABILITY NEAR PROTON–CYCLOTRON HARMONICS DUE TO ANTI-LOSS CONE PROTON DISTRIBUTIONS

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Abstract. Waves with frequencies near the harmonics of the proton–cyclotron frequency, and propagating almost transverse to the ambient magnetic field, can become unstable by hot protons having an anti-loss cone (ALC) distribution function. The maximum growth rates increase with an increase in anti-loss cone index, ratio of the temperatures of trapped to missing protons, and with a decrease in $\beta_H$ ($\beta_H$ being the ratio of transverse thermal pressure of protons to magnetic field pressure). The growth rates are typically in the range 0.01–1.0 $f_\rho$, where $f_\rho$ is the proton–cyclotron frequency. This instability may be relevant to the observations of EHC waves on auroral field lines (Kintner, 1979), ULF waves in the day-side magnetosphere (Perraut et al., 1978) and the low-frequency part of the electric field spectrum (from 5 Hz to 20 Hz) in the region upstream of the bow-shock (Gurnett et al., 1979).

1. Introduction

Anti-loss cone (ALC) plasmas are characterized by a deficit of particles with $v_\parallel \simeq 0$. Berk and Galeev (1967) reported that plasmas confined in toroidal magnetic fields can develop anti-loss cone distributions. The existence of ALC particle distributions in the magnetosphere was theoretically predicted by Roederer (1967). The observations of West et al. (1973) indicate that electrons can have an ALC distribution beyond plasma-pause in the magnetosphere. Instabilities associated with an ALC distribution of electrons have been studied by several authors (Kennel et al., 1970; Nambu and Watanabe, 1975; Buti, 1976a–d; Bhatia and Lakhina, 1978; Lakhina, 1977). The energetic protons streaming along the magnetic field line with maxima near 0° or 180° pitch angle have distributions which are well described by anti-loss cone type distributions. Such streaming protons have been observed in the day-side magnetosphere (Borg et al., 1978), polar cusp (Gurnett and Frank, 1978) and in the solar wind on magnetic field lines which connect to the Earth’s bow-shock (Gosling et al., 1978). Wu et al. (1978) have investigated the effect of hot streaming ALC ions on the Alfvén, magnetosonic and ion-cyclotron waves, with frequencies below ion-cyclotron frequency, in the presence of high-density cold plasma. They have shown that ALC protons can make these waves unstable via anomalous cyclotron resonance.

In this paper we have investigated the instability, near the harmonics of the proton–cyclotron frequency, excited by hot ALC protons. We have considered waves propagating almost transverse to the ambient magnetic field. The growth rates and the range

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of excited frequencies increase with the increase of anti-loss cone index. The growth rates lie in the range 0.01–1.0 $\Omega_p$ ($\Omega_p$ being the proton–cyclotron frequency).

In Section 2 the dispersion relation is derived and frequency and growth rates are obtained. In Section 3 some possible applications are discussed.

2. Dispersion Relation

Let us consider a uniform collisionless plasma containing a constant magnetic field $B_0$ along the z-axis. The plasma consists of three components: hot streaming protons having an anti-loss cone distribution with number density $N_H$, cold proton with number density $N_C$ and Maxwellian electrons with density $N_e = N_H + N_C$ and temperature $T_e$. The distribution function of hot protons is given (cf. Kennel et al., 1970; Buti, 1976a) by

$$f_H = \pi^{-3/2}N_H\alpha_\perp(\alpha_t^{-1/2} - \alpha_m^{-1/2})^{-1} e^{-\nu_\perp^2\alpha_\perp}e^{-\nu_m^2\alpha_m},$$

where $\alpha_\perp = (m_p/2\pi T_\perp)$, $\alpha_t = (m_p/2\pi T_t)$ and $\alpha_m = (m_p/2\pi T_m)$. $T_t$ and $T_m$ denote the temperatures of trapped and missing protons, and $T_\perp$ is the transverse temperature of protons. The parameter $\rho$ ($0 \leq \rho \leq 1$) controls the strength of the anti-loss cone. We consider the waves to be propagating nearly transverse to the magnetic field and having frequencies near the harmonics of proton–cyclotron frequencies such that $\omega \sim n\Omega_p \ll \Omega_e$ ($\Omega_p$ and $\Omega_e$ being the cyclotron frequencies of protons and electrons, respectively). The response of electrons to the perturbation field is treated as electromagnetic and that of protons as electrostatic. Under these assumptions the dispersion relation can be obtained by solving the linearized Vlasov equation and Maxwell's equations, which can be written as

$$1 + \epsilon_e + \epsilon_c + \epsilon_H = 0,$$

where

$$\epsilon_e = G - F\omega^2_{pe}/\omega^2,$$ (2)

$$\epsilon_c = -\frac{\omega^2_{pc}}{\omega^2},$$ for $n > 1,$ (3)

$$\epsilon_H = \frac{2\omega^2_{ph}(\alpha_\perp^{-1/2} - \alpha_m^{-1/2})}{k^2} \left[ \sum_{n=-\infty}^{\infty} \frac{2\omega^2_{ph}I_n(h_H)e^{-\lambda_H}}{k^2} \times \right.$$ (4)

$$\left\{ \alpha_\perp n\Omega_p[Z(\mu_{\perp p}) - \rho Z(\mu_{m\perp})] + (\omega - n\Omega_p) \times \right.$$ (5)

$$\left\{ \alpha_m Z(\mu_{\perp m}) - \rho \alpha_m Z(\mu_{m\perp}) \right\} \right],$$

$$G = \frac{\omega^2_{pe}}{\Omega^2_e} \left[ \frac{1 - I_0(\lambda_e)e^{-\lambda_e}}{\lambda_e} \right] + \frac{\omega^2_{pe}}{c^2k^2} \left\{ I_0(\lambda_e) - I_1(\lambda_e) \right\} \left( 1 + \frac{I_0(\lambda_e) - I_1(\lambda_e)}{I_0(\lambda_e)} e^{-\lambda_e} \right) \right],$$

$$F = \frac{k^2_{\perp}}{k^2} \frac{I_0(\lambda_e)e^{-\lambda_e}}{1 + (\omega^2_{pe}/c^2k^2)I_0(\lambda_e)e^{-\lambda_e}},$$ (6)

where $\omega_{pe} = (4\pi N_e e^2/m_p)^{1/2}$ and $\Omega_e = (|e|B_0/m_e c)$ are the plasma and cyclotron fre-