# TERRESTRIAL F-REGION CYCLOTRON MASER THEORY

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### Abstract

Only recently has a long-term systematic ground-based study of naturally occurring auroral radio emissions between 1-4 MHz been conducted. The reported phenomena involve both broadband, often bursty emissions (MF bursts), and narrow-band emissions (auroral roars) that are interpreted as emissions near the second and third harmonics of the ionospheric electron cyclotron frequency f$_{ce}$. Although experimentally these emissions are becoming better characterized, little work has been done on the theoretical side. Many previous studies are restricted to frequencies below f$_{ce}$, and therefore appear to be inapplicable for these emissions. Recently, however, it has been proposed that a cyclotron harmonic maser might generate 2f$_{ce}$ and 3f$_{ce}$ auroral roar emissions in the lower ionosphere. This paper discusses a detailed maser instability calculation that results in direct generation of waves near harmonics of f$_{ce}$ at F-region altitudes.

## 1 Introduction

Only recently has a long-term systematic ground-based study of naturally occurring auroral radio emissions between $1-4$ MHz been conducted. The reported phenomena involve both broadband, often bursty emissions [*Weatherwax et al.*, 1994; *LaBelle et al.*, 1997], and narrow-band emissions (auroral roars) that are interpreted as emissions near the second and third harmonics of the ionospheric electron cyclotron frequency $f_{ce}$ [*Kellogg and Monson*, 1979, 1984; *Weatherwax et al.*, 1993, 1995; *LaBelle et al.*, 1994, 1995]. Although experimentally these emissions are becoming better characterized, little work has been done on the theoretical side. Many previous studies are restricted to frequencies below $f_{ce}$, and therefore appear to be inapplicable for these emissions. Recently, however, it has been proposed that a cyclotron harmonic maser might generate $2f_{ce}$ and $3f_{ce}$ auroral roar emission in the lower ionosphere. This paper briefly discusses a maser instability calculation that results in direct generation of waves near harmonics of $f_{ce}$ at $F$ region altitudes, and follows the subsequent propagation of these excited waves to the ground.

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## 2 General Formulation

The electron density model of the lower ionospheric auroral zone used in this calculation is based upon the diffuse equilibrium model first given by *Kimura* [1966], and later modified by *Inan and Bell* [1977] and *Horne* [1995] in order to incorporate the effect of plasmapause and lower ionospheric correction. These density models depend only on the altitude $z$, and have no horizontal structure. In reality, horizontal density cavities and/or enhancements are pervasive features of the auroral ionosphere at $F$ region altitudes [*Brinton et al.*, 1978; *Tsunoda*, 1988; *Rodger et al.*, 1992; *Doe et al.*, 1993, 1995]. We have therefore constructed a model for the lower ionospheric electron number density that has both horizontal ($x$) and altitudinal ($z$) dependences,

$$n_e = n_e(x, z). \tag{1}$$

Among the physical quantities, the electron plasma frequency, $f_{pe}$,

$$f_{pe}(x, z) = 8.98 \cdot 10^{-3}\, n_e^{1/2}(x, z) \quad (\mathrm{MHz}), \tag{2}$$

and electron cyclotron frequency, $f_{ce}$,

$$f_{ce}(z) = 2.80\, B(z) \quad (\mathrm{MHz}), \tag{3}$$

are the most important parameters. Here $B(z)$ is the Earth's dipole field strength. In Figure 1, we present three different types of electron density structure: a field-aligned cavity, a field-aligned enhancement, and a combined cavity and enhancement. We parameterize these density structures in terms of

$$f_{pe}(x, z)/f_{ce}(z) \sim n_e^{1/2}(x, z)/B(z). \tag{4}$$

The ratio $f_{pe}/f_{ce}$ also plays a crucial role in the excitation of various wave modes inside the source region. The free energy of the excited waves is assumed to be provided by trapped/loss-cone energetic electrons. On the basis of careful physical consideration, we have constructed a model for the trapped/loss-cone electron distribution function, and have carried out the linear growth rate calculation. (See *Yoon et al.* [1996].) The real frequency is assumed to be determined by the cold, isotropic background electrons (i.e., the magnetoionic theory), and the growth rate is determined by the energetic electrons.

The result of the linear growth rate calculation based upon a model auroral electron distribution function is summarized in Figure 2, which shows the maximum growth rates corresponding to various magnetoionic modes as a function of the ratio $f_{pe}/f_{ce}$. Included in the figure are the maximum growth rates of fundamental O mode (O1), second and third harmonic X mode (X2 and X3), and fundamental and second harmonic Z mode (Z1 and Z2). The fundamental X mode is stable for $f_{pe}/f_{ce} > 0.1$ and therefore is not plotted. For $1 \leq f_{pe}/f_{ce} \leq 1.4$, the dominant mode is X2 (O1 is altogether stable beyond $f_{pe}/f_{ce} > 1$). However, weaker X3 and Z1 modes are also excited. Of course, propagation of the Z mode to the ground is less straightforward than X and O mode, since the Z mode is a trapped mode. For higher ranges of $f_{pe}/f_{ce}$, the dominant mode is Z2, with much weaker X3. From this result, it appears that the Z mode is important and could be the dominant mode for higher values of $f_{pe}/f_{ce}$. Z to O mode conversion and propagation of the resulting waves to the ground is currently being investigated.

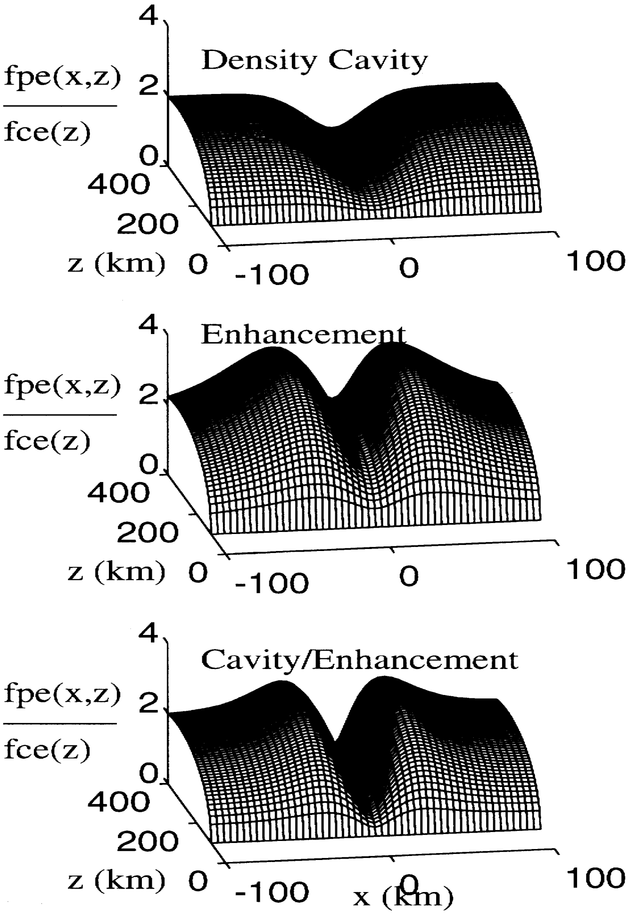

*Figure 1: Models of lower ionospheric density in the auroral zones, expressed in terms of* $f_{pe}(x,z)/f_{ce}(z) \sim n_e^{1/2}(x,z)/B(z)$*. Three types of possible density structure are considered: a density cavity, an enhancement, and a combined cavity and enhancement.*

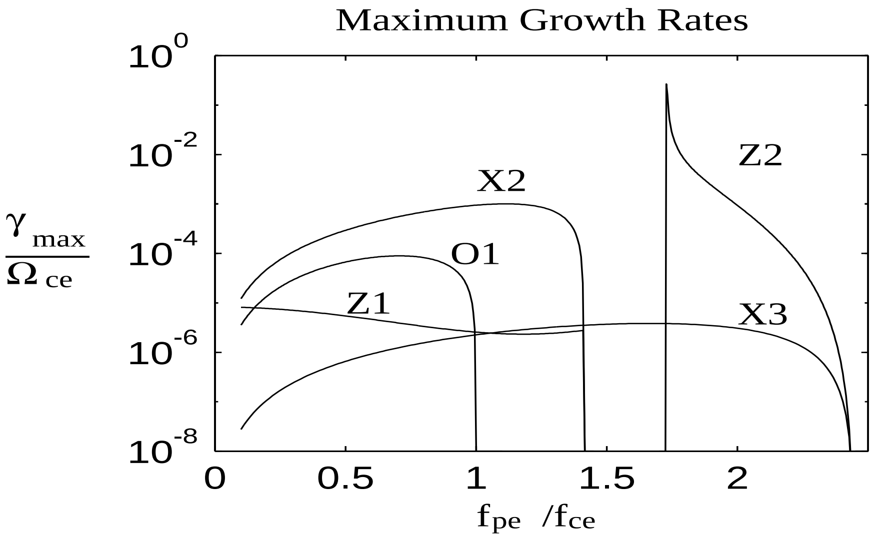

*Figure 2: Maximum growth rates of various magnetoionic modes as a function of* $f_{pe}/f_{ce}$*.*

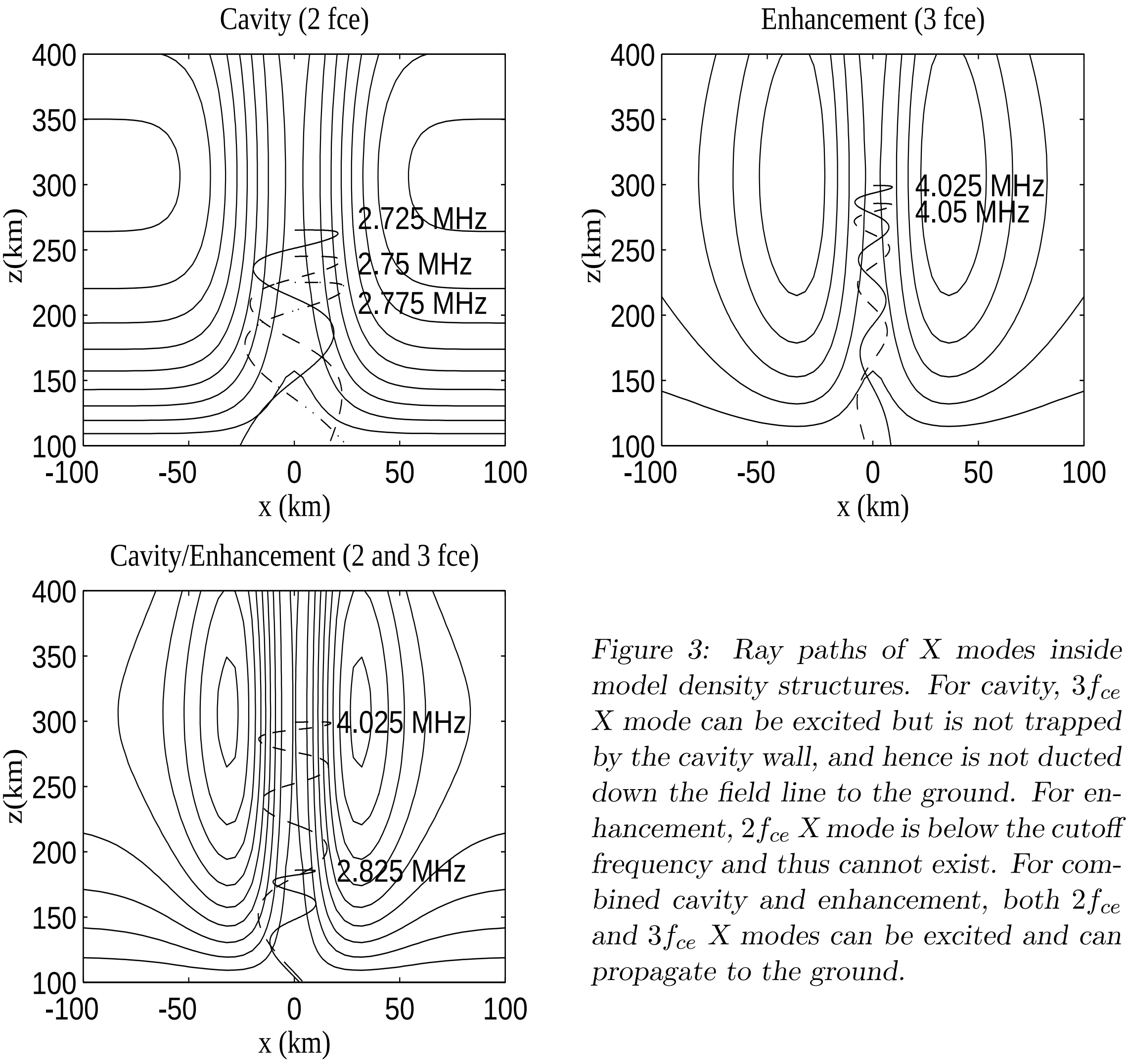

*Figure 3: Ray paths of X modes inside model density structures. For cavity, $3f_{ce}$ X mode can be excited but is not trapped by the cavity wall, and hence is not ducted down the field line to the ground. For enhancement, $2f_{ce}$ X mode is below the cutoff frequency and thus cannot exist. For combined cavity and enhancement, both $2f_{ce}$ and $3f_{ce}$ X modes can be excited and can propagate to the ground.*

For the moment, however, we concentrate on the propagation characteristics of the free-space modes, X2 and X3; i.e., we interpret the $2f_{ce}$ and $3f_{ce}$ emissions as X2 and X3, respectively. We have developed a ray tracing code to calculate the ray paths of both X2 and X3 modes using the density model of Equ. (1) and dipole magnetic field. The results are summarized in Figure 3. For density cavity model, both $2f_{ce}$ and $3f_{ce}$ waves can be excited according to linear growth rate calculation (Figure 2). However, $3f_{ce}$ waves are not trapped because of their high wave frequency and thus, cannot be ducted toward the ground. On the other hand, $2f_{ce}$ waves are trapped by density cavity wall and are ducted down field lines to the ground. Shown in the figure are three rays with frequencies $f = 2.725$, 2.75 and 2.775 MHz. For the given density enhancement, $2f_{ce}$ waves are below the cutoff frequency and thus cannot exist. In this case, only $3f_{ce}$ waves are excited, and these waves bounce off the enhanced density on either side of the source and propagate to the ground. The $3f_{ce}$ waves shown in the figure correspond to 4.025 MHz and 4.05 MHz. Finally, when both cavity and enhancement coexist, both $2f_{ce}$ (in this case 2.825 MHz) and $3f_{ce}$ (4.025 MHz) waves can be excited simultaneously, as shown in the figure.

The maser instability calculation presented in this paper indicates that direct generation of X, O, and Z mode waves near harmonics of $f_{ce}$ at $F$ region altitudes is indeed feasible within the structured plasma of the ionosphere. Such a mechanism is similar to the one proposed to explain auroral kilometric radiation at much higher altitudes [*Wu and Lee,* 1979]. Our calculations also suggest that these excited waves can propagate to ground-based facilities directly or via indirect processes.

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