

GENERATION OF ORDINARY MODE AURORAL KILOMETRIC RADIATION FROM EXTRAORDINARY MODE WAVES

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Abstract. The ratio of x to o mode radiation produced when an x mode wave strikes a steep density gradient is determined for wave and plasma parameters typical of those observed in the auroral kilometric radiation source region. We find that the waves reflected from or transmitted through the density gradient generally have an o mode component 20 dB or more weaker than the x mode component. This agrees with the ratio of x to o mode intensity observed in auroral kilometric radiation signals near the auroral plasma cavity by both the DE 1 and ISIS 1 spacecraft.

1. Introduction

Observations of auroral kilometric radiation (AKR) indicate that it originates in a region of depleted electron density which forms a plasma cavity in the high-latitude auroral regions and that it is associated with inverted-V electron precipitation events [Gurnett, 1974; Gurnett and Green, 1978; Benson and Calvert, 1979]. One of the most important properties of the radiation is its polarization. The mode of propagation of AKR is usually determined either by direct polarization measurements or by inferring the polarization of the radiation from local plasma resonance and cutoff frequencies, although the latter method may lead to ambiguities in the identification of the mode polarization. It is widely believed that AKR consists predominantly of x mode waves [Gurnett and Green, 1978; Kaiser et al., 1978; Benson and Calvert, 1979; Shawhan and Gurnett, 1982]. However, Oya and Morioka [1983] interpret the dominant AKR radiation detected by the Jikiken (EXOS B) satellite to be in the o mode, and Benson [1984] has also found examples of AKR where the o mode is dominant.

Although both x and o mode waves are known to be present in AKR, there have been few observations of the relative intensities of the two modes. When viewed from several AU by Voyagers 1 and 2, AKR was found to be polarized predominantly (i.e., 80%) in the x mode [Kaiser et al., 1978]. Direct polarization measurements close to the source region of AKR suggest that the o mode component is much weaker than the dominant x mode component. Observations made by DE 1 are consistent with the o mode component down by 17 dB from the x mode component [Shawhan and Gurnett, 1982; Mellott et al., 1984]; observations made by Hawkeye 1 indicate AKR contains o mode signals 20 dB or more weaker than the x mode radiation [Calvert, 1982]. The ISIS 1 observations indicate that the maximum power level of observed o mode is around 30 dB below the most intense x mode component [Benson, 1985]. The ISIS 1 data also show that within the plasma de-

pletion associated with the AKR source region the o mode is usually weaker than the x mode. In general, the o mode is more intense than the x mode only at latitudes outside the plasma cavity. This is consistent with the observations of predominantly o mode AKR made by Oya and Morioka [1983] which were at latitudes on the equatorial side of the AKR source region.

Hence there appear to be two classes of o mode AKR: one class is observed outside the auroral plasma cavity at higher electron densities when the o mode is generally the dominant mode; the other class is observed within the plasma depletion region where there is a predominance of x mode radiation, and the o mode component is much weaker.

In this paper we explore a possible interpretation of the weak o mode seen within the plasma cavity. Specifically, we investigate the suggestion [Melrose et al., 1984] that this o mode is produced by reflection of strong x mode waves from steep density gradients which have been observed both at the edge of the plasma cavity and in density enhancements within the cavity itself [Calvert, 1981a; Benson and Akasofu, 1984]. We assume the x mode waves are produced by cyclotron maser emission [Wu and Lee, 1979]. For the purpose of this investigation we assume that the maser produces only an x mode component. It is possible in principle for the maser to produce some o mode emission and even for this to be the dominant mode of emission under specific conditions [Melrose et al., 1984]. Such generation of the o mode may be relevant to the class of o mode emission observed outside the plasma cavity. However, it seems unlikely that the o mode component within the plasma cavity is generated directly by the maser; we discuss this point further in section 5.

In section 2 we review the theory of reflection of magnetoionic waves from a sharp density change and discuss the conditions under which the strongest secondary o mode is produced from an incident x mode. We calculate the relative intensities of the secondary x and o modes in section 3, and in section 4 we compare the results with x to o mode intensity ratios observed in AKR.

2. Review of Magnetoionic Wave Reflection

The theory of reflection of magnetoionic waves from a steep density gradient has been described in a previous paper [Hayes, 1985]. Briefly, we consider a wave travelling in the x-z plane with wave vector $k_{\perp n}$ and frequency ω , which strikes a boundary between two regions of different densities at an angle $\theta_{\perp n}$ to the boundary normal. The boundary normal is taken to be in the z direction, and there is a uniform external magnetic field B . In general, the incident wave produces two transmitted waves and two reflected waves (see Figure 1). The energy transferred from the incident wave into each of the secondary waves may be determined using the boundary conditions on the electric and

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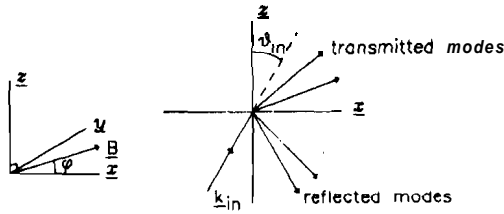


Fig. 1. Boundary between the initial plasma and the final plasma lies in the x - y plane at $z = 0$. For $z < 0$ the plasma frequency is ω_{p1} and for $z > 0$ the plasma frequency is ω_{p2} . The external magnetic field \mathbf{B} is assumed to have components in the x and y directions only, and the incident, transmitted, and reflected wave vectors lie entirely in the x - z plane.

magnetic fields and the dispersion relations of the five waves.

Hayes [1985] considered the case of an incident x mode. The external magnetic field was assumed to lie in the x - y plane. It was found that it is possible to describe changes in the relative strengths of the reflected and transmitted waves in terms of variations in the plasma and wave parameters, where the parameters considered were the incident wave frequency ω and direction of propagation (θ_{in} with respect to the boundary normal), the plasma frequencies ω_{p1} and ω_{p2} on the initial and final sides of the boundary, the gyrofrequency Ω_e related to the external magnetic field strength, and the angle ϕ between the external magnetic field and the x axis. The main conclusions of that paper concerning the reflected and transmitted o modes were as follows.

1. The relative intensity of the transmitted o mode (i.e., with respect to the incident x mode) increases when the transmitted x mode is evanescent. As the plasma and wave parameters vary, the intensity of the transmitted o mode is maximized when (1) the gyrofrequency is small compared to the plasma frequency, (2) when the magnetic field is in the x direction, and (3) when the final plasma frequency ω_{p2} is large compared to the initial plasma frequency ω_{p1} .

2. The relative intensity of the reflected o mode is substantial only at frequencies below the cutoff frequency for the transmitted x mode. The intensity of the reflected o mode increases as the ratio ω_{p2}/ω_{p1} increases, as the ratio ω/Ω_e increases, as the magnetic field moves into the plane of incidence (i.e., along the x axis), and for angles of incidence around 45° .

These results indicate it is unlikely that at frequencies above the x mode cutoff ω_{c2} in the second, denser region the secondary o modes would be strong enough to account for the o mode component observed in AKR. Hence we only consider frequencies $\omega < \omega_{c2}$ where

$$\omega_{c2}/\Omega_e = \frac{1}{2} \{ 1 + (1 + 4\omega_{p2}^2/\Omega_e^2 [1-r^2])^{1/2} \} \quad (1)$$

Here r is Snell's constant, i.e., $r = n \sin \theta$, where n is the refractive index of the transmitted x mode, and θ is the angle between its wave vector and the z axis (i.e., the direction of the density gradient). Also, we do not need to consider frequencies below the cutoff frequency for the incident x mode, ω_{c1} , where

$$\omega_{c1}/\Omega_e = \frac{1}{2} \{ 1 + (1 + 4\omega_{p1}^2/\Omega_e^2)^{1/2} \} \quad (2)$$

Within the frequency range $\omega_{c1} < \omega < \omega_{c2}$ the transmitted waves may be either o mode or, at frequencies below the x mode resonance in the transmission region, they may be z mode waves. When the transmitted z mode propagates it is the dominant secondary mode produced by an incident x mode. However, in this paper we are interested in the o mode component of AKR, so we consider only frequencies above the transmitted x mode resonance ω_{r2} where

$$\omega_{r2}/\Omega_e = (1 + \omega_{p2}^2/\Omega_e^2)^{1/2} \quad (3)$$

Hence the frequency range we consider is given by

$$\text{maximum}(\omega_{c1}, \omega_{r2}) < \omega < \omega_{c2} \quad (4)$$

There are four other independent variables (ω_{p2}/ω_{p1} , ω_{p1}/Ω_e , θ_{in} , and ϕ) still to be considered. Some indication of the values of these parameters for which the strongest o mode component is produced is given in conclusions (1) and (2) above. For example, the o mode is strongest for larger values of ω_{p2}/ω_{p1} and larger values of ω_{p1}/Ω_e . However, we wish to apply the reflection of magnetoionic waves to the generation of AKR, so the four parameters must be chosen to be consistent with observations of the AKR waves and the source region. They must also be applicable to x mode waves generated by cyclotron maser emission. The frequency range already chosen includes frequencies just above the x mode cutoff, which is where the growth rate for x mode waves produced by the cyclotron maser is largest. The values or ranges of values for the four remaining parameters are chosen as follows.

1. The parameter ϕ : one would expect density enhancements within the auroral cavity as well as the cavity walls to be aligned closely with the earth's magnetic field. Using our coordinate system this corresponds to the external magnetic field in the x - y plane (see Figure 1). This was the case considered by Hayes [1985] who found that there was little difference between the intensities of the o modes relative to the incident mode when $\phi = 45^\circ$ and when $\phi = 0^\circ$. Hence we choose the magnetic field angle for which the calculations are simplest, i.e., $\phi = 0^\circ$, where the wave vectors and the external magnetic field lie in the same plane.

2. The parameter θ_{in} : AKR observations indicate that the dominant x mode waves are generated nearly perpendicular to the earth's magnetic field [Calvert, 1981b], and the cyclotron maser theory also predicts a maximum growth rate for the fundamental x mode at angles of 70° or 110° of the wave vector and the magnetic field [Hewitt et al., 1982]. For angles of incidence between 10° and 45° , Hayes [1985] found there is little difference in the relative intensity of the secondary o modes produced by an x mode striking a density discontinuity. In view of the weak θ_{in} dependence of the o mode in the range of angles in which we would expect to find AKR, we choose one representative value $\theta_{in} = 20^\circ$ to be used in all calculations of reflection and transmission coefficients.

3. The parameter ω_{p1}/Ω_e : observations of the auroral plasma cavity indicate that the electron

density, and hence the plasma frequency are extremely low. Typically, ω_{p1}/Ω_e in the AKR source region appears to be 0.1, although values as low as 0.03 have also been observed [Calvert, 1981a]. However, if the x mode propagates away from the source region before encountering a steep density gradient, the value of ω_{p1}/Ω_e where reflection occurs may be larger. A range of values of ω_{p1}/Ω_e between 0.075 and 0.2 is chosen to allow for propagation effects.

4. The parameter ω_{p2}/ω_{p1} : the plasma frequency ω_p is related to the electron number density n_e by

$$\omega_p^2 = 4\pi e^2 n_e / m_e \quad (5)$$

Density changes of a factor of 10 or more have been observed both at the boundary of the plasma cavity and within the cavity itself, and Benson [1985] has also observed density changes within the plasma cavity of a few tens of percent. Hence the relevant range of values of ω_{p2}/ω_{p1} is from 5 (corresponding to large density changes) to values approaching $\omega_{p2}/\omega_{p1} = 1$ (corresponding to the weak density enhancements within the cavity).

Finally, we need to consider how steep the density gradients at the edges of the plasma cavity must be for the approximation of reflection at a density discontinuity to be valid. Hayes [1985] found that the approximation of an infinitely steep density gradient may be made if the distance over which the density varies is of the order of a wavelength. In the case of AKR this corresponds to distances of the order of a kilometer. Density changes of an order of magnitude have been observed at the edges of the auroral plasma cavity. The cavity itself may be quite broad, but both its shape and the scale length of the density enhancement at the edge of the cavity vary considerably between different observations of the AKR source region [Calvert, 1981a; Benson and Akasofu, 1984]. The available data on this density enhancement does not warrant a more detailed model than that of a density discontinuity used in this paper. However, in all discussions of the density gradient, it should be remembered that the scale length of the density gradient may not be small enough for the model of a density discontinuity to be appropriate. Very sharp electron density enhancements ranging in size from several tens of percent to factors of 3 - 10 have also been detected within the auroral plasma cavity [Benson and Calvert, 1979; Benson et al., 1980; Benson, 1985]. However, such thin density enhancements might not always be detected, even when high-resolution measuring techniques are used, and it seems likely that steep density gradients are a common feature of the AKR source region.

3. Relative x and o mode Intensities

The actual quantity measured in an observation of the intensity of an AKR signal is the electric field amplitude squared, i.e., $|\underline{E}|^2$. However, Hayes [1985] chose the component of the Poynting flux normal to the density boundary to describe the energy in a wave. One of the main reasons for choosing this quantity rather than $|\underline{E}|^2$ is that it is more convenient to calculate. For example, for an evanescent wave the normal Poynting flux is zero everywhere, whereas $|\underline{E}|^2$ is zero only at

large distances from the density boundary and is in general nonzero at the boundary. Hence unlike $|\underline{E}|^2$, the normal Poynting flux only needs to be calculated at the boundary. Also, conservation of energy requires that the normal Poynting flux be continuous across the boundary, and this condition is a useful check on the accuracy of numerical calculations. Finally, specific calculations show that the difference between the normal Poynting flux of each secondary wave (relative to the incident wave) and $|\underline{E}|^2$ for each secondary wave (again relative to the incident wave) is not significant, e.g., they could not be distinguished in Figure 2. For these reasons we choose to compare the ratios of normal Poynting fluxes calculated for waves reflected from or transmitted through a steep density gradient with the observed intensity ratios of the different components in AKR signals. Henceforth the normal Poynting flux is represented by S.

We are interested in the ratio of the o mode components (both reflected S_{or} and transmitted S_{ot}) to the reflected x mode component (S_{xr}). The transmitted x mode is assumed to be evanescent and hence $S_{xt} = 0$. It is convenient to define the ratio

$$R_{xo} = \frac{|S_{xr}|}{\{|S_{or}| + |S_{ot}|\}} \quad (6)$$

In the parameter regions chosen in section 2, the intensity of the reflected o mode is approximately equal to the intensity of the transmitted o mode.

In order to determine under what conditions o modes around 30 dB weaker than the x mode are produced (i.e. $R_{xo} = 1000$), we must take into account the variation of five independent parameters:

$$\omega/\Omega_e, \omega_{p2}/\omega_{p1}, \omega_{p1}/\Omega_e, \theta_{in}, \phi$$

The strength of the secondary o modes depends primarily on the wave, plasma, and gyrofrequencies, and we concentrate on the variation due to these parameters.

Our results are presented in the form of three-dimensional contour plots of the quantity R_{xo} , where variation with ω_{p2}/ω_{p1} is shown along the horizontal axis, the vertical axis corresponds to ω/Ω_e , and the remaining axis corresponds to ω_{p1}/Ω_e . Figure 2 shows the results for an incident angle of 20° , i.e., an angle of 70° between the incident wave vector and the magnetic field which is perpendicular to the density gradient. The surface in Figure 2a is a contour corresponding to $R_{xo} = 100$ or an o mode power level 20 dB below the x mode level. Figure 2b shows the surface where the o mode is 30 dB weaker than the x mode, and Figure 2c corresponds to the contour for a power ratio of 40 dB between the x and o modes.

The contours in Figure 2 indicate that not only is it possible to generate a parasitic o mode from an incident x mode in conditions similar to those in the AKR source region, but also that generation of an o mode 20-40 dB weaker than the x mode is fairly widespread in the parameter regions considered. Several trends may be noted in Figure 2. The parasitic o mode is stronger for (1) larger density changes (i.e., larger values of the ratio ω_{p2}/ω_{p1}); (2) higher frequencies ω/Ω_e ; and (3) larger values of ω_{p1}/Ω_e . The contours occupy the upper and right-hand sections of the

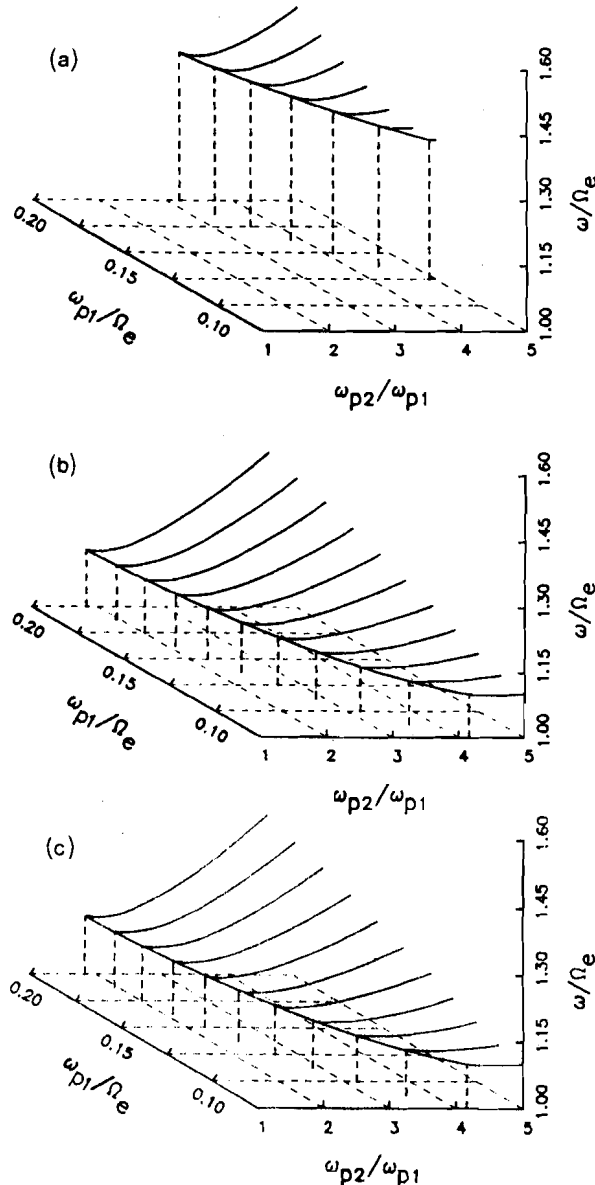


Fig. 2. Contour surfaces illustrate the variation of the ratio of x to o mode energy with the wave, plasma, and gyrofrequencies. For all points $(\omega_{p2}/\omega_{p1}, \omega_{p1}/\Omega_e, \omega/\Omega_e)$ lying on the surface in Figure 2a we have $R_{xo} = 10^2$; for all points on the surface in Figure 2b, $R_{xo} = 10^3$, and for all points on the surface in Figure 2c, $R_{xo} = 10^4$.

$\omega_{p2}/\omega_{p1} - \omega_{p1}/\Omega_e$ plane and curve upwards in the upper right-hand corner. There is a sharp cutoff on the lower and left-hand sides of the contours. The projection of this cutoff onto the $\omega_{p2}/\omega_{p1} - \omega_{p1}/\Omega_e$ plane (indicated by the heavy dashed lines) shows that for smaller values of ω_{p1}/Ω_e , larger values of ω_{p2}/ω_{p1} are required to produce o mode 20–40 dB weaker than the x mode. The contour surfaces in Figures 2a and 2b continue to the right-hand edge of the $\omega_{p2}/\omega_{p1} - \omega_{p1}/\Omega_e$ plane, but the surface in Figure 2c ends before it reaches that edge. This is a result of the fact that we investigate a limited range of frequencies (the upper and lower bounds on the wave frequency are given by (4)). If we were to relax the con-

straints on the frequency, then the contour in Figure 2c would continue further to the right.

The conditions for which an o mode 20 dB weaker than an x mode (Figure 2a) is produced by reflection off a steep density gradient may be summarized as follows. For the parameter ranges $0.075 < \omega_{p1}/\Omega_e < 0.2$, $1 < \omega_{p2}/\omega_{p1} < 5$, and $1 < \omega/\Omega_e < 1.6$. (1) the density difference between the two plasma regions must correspond to a density ratio of 10 or more, with larger density ratios required for production of the o mode when the ratio ω_{p1}/Ω_e is smaller; (2) the ratio ω_{p1}/Ω_e must be larger than 0.12 if the density change where the parasitic o mode is generated is not to exceed a factor of 25; and (3) secondary o mode 20 dB weaker than the x mode is produced for waves with a frequency of $\omega = 1.3\Omega_e$ traveling in a region where the ratios ω_{p1}/Ω_e and ω_{p2}/ω_{p1} correspond to values at the left-hand edge of the contour (i.e. $\omega_2/\Omega_e = 0.67$); for large density ratios, the frequency of the waves involved in the o mode production is larger than $1.3\Omega_e$.

The conditions for generation of o mode 30 dB weaker than the x mode (Figure 2b) are as follows.

1. The density ratio between the two plasmas **must** be 3 or more, and again larger density ratios are required to produce the o mode when the incident mode is in a region with small ω_{p1}/Ω_e .

2. An o mode 30 dB weaker than the x mode is produced at all plasma frequencies in the range $0.075 < \omega_{p1}/\Omega_e < 0.2$ and for density ratios < 25 . For example, when $\omega_{p1}/\Omega_e = 0.1$ secondary o mode is produced for a density ratio of 10 or more.

3. The frequency of the incident wave which produces the parasitic o mode is $\omega = 1.1\Omega_e$ for small values of ω_{p1}/Ω_e . For larger ω_{p1}/Ω_e , the frequency ranges from $\omega = 1.1\Omega_e$ with small density changes to $\omega = 1.3\Omega_e$ for larger density changes.

Finally, o mode 40 dB weaker than the x mode (Figure 2c) is produced when (1) the density ratio is 1.7 or more. At all values of ω_{p1}/Ω_e between 0.075 and 0.2 small density changes produce the parasitic o mode. For example, when $\omega_{p1}/\Omega_e = 0.075$, which is the value which needs the largest density change to produce the o mode, a density ratio of ~ 6 is sufficient. O mode 40 dB weaker than the x mode occurs when (2) the generation of the o mode occurs at all plasma frequencies studied. Lastly, it occurs when (3) the frequency of the incident wave which produces the o mode is generally $1.06\Omega_e$, although the wave may have a frequency as high as $\omega = 1.12\Omega_e$ when ω_{p1}/Ω_e is large.

4. Application to AKR

In order to determine whether the parasitic o mode generated by reflection of an x mode wave can account for the o mode AKR component observed in the auroral plasma cavity, we compare the results of the last section with experimental observations of the AKR source region.

Consider the conditions under which x mode reflection produces an o mode component around 20 dB weaker than the x mode component.

1. Density changes of at least a factor of 10 (typically the density ratio **must** be around 20) are required. Density changes of this size are usually not found within the plasma cavity [Benson, 1985] but suitable density changes are observed at the edges of the auroral cavity.

2. The frequency of the incident x mode waves must be in the range $1.3 < \omega/\Omega_e < 1.6$. This range is outside the range $1.02 < \omega/\Omega_e < 1.1$ for which the cyclotron maser leads to nearly the maximum growth rate for the x mode [Hewitt et al., 1982]. This range is also above the range of ω/Ω_e observed close to the AKR source region [Benson and Calvert, 1979].

3. The ratio of plasma frequency to gyrofrequency must be $\omega_{p1}/\Omega_e > 0.12$. This is larger than the value of 0.1 usually observed in the plasma cavity.

We conclude that generation of an o mode no weaker than 20 dB below the x mode by reflection of an initial x mode can only occur in regions where both ω_{p1}/Ω_e and ω/Ω_e are slightly larger than values typical of the AKR source region. We interpret this as indicating that the reflection occurs at higher altitudes than the generation of the initial x mode, i.e., the maser generated x mode is refracted upwards and propagates some distance before striking a steep density gradient at the edge of the plasma cavity and producing reflected x and o modes. O mode AKR 17 dB weaker than the x mode AKR component was observed by the DE 1 spacecraft at altitudes higher than the AKR source region [Mellott et al., 1984]. The altitude of DE 1 was probably also higher than the regions where we expect reflection of an x mode to produce an o mode component around 20 dB weaker than the x mode. Hence reflection of an initial x mode into x and o mode components which then propagate to higher altitudes is a possible explanation for the DE 1 observations.

Generation of a weaker o mode component (between 20 and 30 dB weaker than the x mode) can occur for a wider range of density ratios and for lower values of ω_{p1}/Ω_e and ω/Ω_e than is required for generation of stronger o modes, i.e., o modes less than 20 dB weaker than the x mode. The density changes required can be as small as a factor of 3. Hence this weaker o mode may be produced by relatively large density enhancements within the auroral cavity as well as at the larger density changes at the edge of the cavity. The frequency of the x mode required to produce this weaker level of o mode is around $\omega/\Omega_e = 1.1$. This is the value observed in the AKR source region and it is also the value required by the theory for cyclotron maser generated x mode. The values of ω_{p1}/Ω_e required in this case are in the range $0.075 < \omega_{p1}/\Omega_e < 0.2$. These values are consistent with observations of ω_{p1}/Ω_e near the AKR source.

We conclude that physical conditions for an initial x mode to generate an o mode component between 20 and 30 dB weaker than the x mode are commonly satisfied in the AKR source region. One would expect to see a widespread background of o mode waves generated by reflection of x mode waves off density gradients. This provides a natural explanation for the observations of Benson [1985], who found o mode at least 30 dB weaker than the x mode distributed throughout the auroral cavity.

Very weak o mode (between 30 and 40 dB below the x mode level) is generated by reflection of x mode waves at all values of ω_{p1}/Ω_e between 0.075 and 0.2 for an incident wave with frequency between $1.06\Omega_e$ and $1.12\Omega_e$. Density changes of several tens of percent (density ratios as low as 1.7) are sufficient to produce the o mode. Thus one would expect generation of very weak o mode

whenever x mode AKR strikes a steep density gradient within the plasma cavity.

These results are for initial x mode waves with frequencies such that when they strike a steep density gradient they produce reflected x and o modes and a transmitted o mode, with the reflected x mode being the strongest secondary mode. It is also possible for an x mode striking a density gradient to generate predominantly transmitted x or z modes rather than a reflected x mode. The regime where the transmitted x mode is dominant corresponds to incident waves with higher frequencies than the waves discussed in the previous sections. In general, these frequencies are outside the range of frequencies typical of AKR signals for any given plasma or gyrofrequencies. Transmitted z modes are generated either below the incident x mode cutoff frequency (in which case they cannot come from maser-generated x mode waves) or in a narrow range of frequencies just above the incident x mode cutoff. This range of frequencies becomes larger as the size of the density change increases, but for density changes or an order of magnitude or less the frequency range is generally small. For these reasons the generation of predominantly transmitted x or z modes is less likely to occur in the AKR source region than the generation of a reflected x mode. Thus when an x mode wave generated within the plasma cavity by the cyclotron maser mechanism encounters a steep density gradient, the result is most likely to be reflected x and o modes and a transmitted o mode, with the o modes 20 dB or more weaker than the x mode.

Finally, we comment on observations of o mode without an associated x mode component. For example, Benson [1985], found weak o mode but almost no x mode in regions with $\omega_{p1}/\Omega_e \approx 1$ outside the plasma cavity. Now when x and o mode waves are reflected from a density gradient in the plasma cavity they are initially at similar angles but they may subsequently be refracted in different directions as they propagate upwards. Hashimoto [1984] studied a model for the refraction of x and o mode waves in the AKR source region. He concluded that refraction can account for the observed distribution of predominantly o mode waves at lower latitudes and x mode waves at higher latitudes if the x and o modes are generated in the same region with similar angles of propagation but with the x mode stronger than the o mode. Another possible source for the o mode observed in regions with higher plasma density is the transmitted o mode produced by an initial x mode. This propagates into regions of increasing ω/Ω_e outside the plasma cavity and would be observed without any accompanying x mode. Both these mechanisms could produce an o mode component without an accompanying x mode component in localized regions outside the auroral cavity.

5. Alternative Mechanism for o Mode Generation

The only alternative theory for the generation of the o mode component in AKR is that it is generated directly by the cyclotron maser. It is possible for the o mode to be the dominant growing mode of the maser under special conditions, e.g., $\omega_{p1}/\Omega_e > 0.2$. However, in most of the auroral plasma cavity ω_{p1}/Ω_e is typically < 0.2 . For $\omega_{p1}/\Omega_e \ll 0.2$, the o mode can grow due to the same

source of free energy as the x mode or due to a separate source of free energy [Melrose et al., 1984; Omid and Wu, 1985; Winglee, 1985]. Very specific conditions are required to account for a weak o mode component in terms of a separate source of free energy: (1) the feature in the electron **distribution** which causes the o mode to grow must not cause a faster growth of the x mode, (2) the free energy available must be about 10^{-3} of that available for growth of the x mode in order to produce an o mode component 30 dB weaker than the x mode (assuming that the growth of both saturates), and (3) the growth of the o mode must be fast enough to reach saturation in the time available. Although separate **growth** of the o mode is **possible** [Omid and Wu, 1985; Winglee, 1985], we believe the conditions for it to be effective **are much** more restrictive than has been assumed. Weak growth of the o mode due to the same source of free energy as the x mode seems more plausible. In this section we argue that a theory based on growth of both modes due to the same source of free energy cannot account for the observations.

Let the cyclotron maser cause both o mode and x mode waves to grow with growth rates γ_o and γ_x , respectively. Let T_o and T_x be the brightness temperatures, and let \bar{T} be a temperature related to the energy of the particles ($\bar{T} \approx \text{few keV} \approx \text{few} \times 10^7$ K here). For either mode the transfer equation is then

$$dT_M/dt = \gamma_M(\bar{T} + T_M) \quad (7)$$

where $M = o$ or x . The relevant solution of (7) if $T_M = 0$ at $t = 0$ is

$$T_M = \bar{T}\{\exp(\gamma_M t) - 1\} \quad (8)$$

Spontaneous emission initially causes T_M to increase linearly with time until T_M reaches \bar{T} . Thereafter the spontaneous emission is amplified and grows exponentially.

Suppose the faster growing mode, in this case the x mode, saturates at $T_x = T_{\max}$ after a time $t = t_{\max}$. At this time all the free energy is exhausted and the slower growing mode also stops growing. The relative intensity of the two modes at $t = t_{\max}$ is determined by

$$(T_o)_{\max}/T_{\max} = \{\exp(\gamma_o t_{\max}) - 1\}/\{\exp(\gamma_x t_{\max}) - 1\} \quad (9)$$

Given an **estimate** of the brightness temperature T_{\max} for x mode AKR we may estimate $\gamma_x t_{\max}$ from (8)

$$\gamma_x t_{\max} \approx \ln(T_{\max}/\bar{T}) \quad (10)$$

Hence if we also know the relative growth rates γ_x and γ_o we may estimate the relative intensity (9) of the two modes.

As an example, let us assume $T_{\max} = 10^{17}$ K, $\bar{T} = 10^7$ K, and $\gamma_o = \gamma_x/10$. Then (10) implies that $\gamma_x t_{\max} \approx 23$ and (9) implies $(T_o)_{\max} \approx 10^8$ K, i.e., an o mode level 90 dB below the x mode. For $\gamma_o = \gamma_x/3$, the o mode level is increased only to 70 dB below the x mode.

We **conclude** that the o mode component produced directly by the maser should be very **much** below

the level of the x mode and such a source for the o mode component cannot account for the observed level. Note, however, that this conclusion is based on the assumption that the o mode and the x mode grow due to the same source of free energy. As was mentioned above, this is not necessarily the case and o mode **AKR may** grow due to a different source of free energy from the x **mode**.

6. Conclusion

The important conclusions from this investigation are as follows.

1. An x mode component incident on a steep density gradient in or near the auroral plasma cavity produces both o and x mode reflected components and a transmitted o mode component.
2. The observed o mode components in AKR can be explained in terms of this mechanism. In particular, (1) a weak background level (> 30 dB below the x mode level) may be due to the reflections and transmissions at density inhomogeneities within the auroral cavity. Also, (2) stronger o mode components (~ 20 dB below the x mode level) may be generated by reflection from the edges of the cavity at **higher** altitudes than the regions where the cyclotron maser mechanism generates x mode. This result is subject to the approximation of a density discontinuity being applicable to the density gradient at the edge of the plasma cavity. Finally, (3) o mode components observed without an accompanying x mode component may be generated as in (2(1)) and refracted into regions where the x mode **does not** propagate, or they may be generated by transmission of o mode waves at the edge of the plasma cavity.
3. An alternative explanation in which the o mode is generated directly by the **maser** cannot account for the levels of o mode observed except under special conditions. One would expect growth of the o mode by this mechanism to be localized to favorable regions, producing only a locally enhanced o mode component.

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References

- Benson, R. F., Ordinary mode auroral kilometric radiation, with harmonics, observed by **ISIS 1**. Radio Sci., **19**, 543, 1984.
- Benson, R. F., Auroral kilometric radiation: wave modes, harmonics and source region electron density structures, J. Geophys. Res., **90**, 2753, 1985.
- Benson, R. F. and S-I. Akasofu, Auroral kilometric radiation/aurora correlation, Radio Sci., **19**, 527, 1984.
- Benson, R. F., and W. Calvert, **ISIS 1** observations at the source of auroral kilometric radiation. Geophys. Res. Lett., **6**, 479, 1979.
- Benson, R. F., W. Calvert, and D. M. Klumvar. Simultaneous wave and particle observations in the auroral kilometric radiation source region. Geophys. Res. Lett., **7**, 959, 1980.
- Calvert, W., The auroral plasma cavity, Geophys. Res. Lett., **8**, 919, 1981.

- Calvert, W., The signature of auroral kilometric radiation on ISIS 1 ionograms. J. Geophys. Res., **86**, 76, 1981b.
- Calvert, W., A feedback model for the source of auroral kilometric radiation, J. Geophys. Res., **87**, 8199, 1982.
- Gurnett, D. A., The earth as a radio source: terrestrial kilometric radiation, J. Geophys. Res., **79**, 4227, 1974.
- Gurnett, D. A., and J. L. Green, On the polarization and origin of auroral kilometric radiation, J. Geophys. Res., **83**, 689, 1978.
- Hashimoto, K., A reconciliation of propagation modes of auroral kilometric radiation, J. Geophys. Res., **89**, 7459, 1984.
- Hayes, L. M., Reflection of magnetoionic waves from a steep density gradient 1. Incident extraordinary mode, Aust. J. Phys. (in press).
- Hewitt, R. G., D. B. Melrose, and K. G. Rönmark, The loss-cone driven electron-cyclotron maser, Aust. J. Phys., **35**, 447, 1982.
- Kaiser, M. L., J. K. Alexander, A. C. Riddle, J. B. Pearce, and J. W. Warwick, Direct measurements by Voyagers 1 and 2 of the polarization of terrestrial kilometric radiation, Geophys. Res. Lett., **5**, 857, 1978.
- Mellott, M. M., W. Calvert, R. L. Huff, and D. A. Gurnett, DE 1 observations of ordinary mode and extraordinary mode auroral kilometric radiation, Geophys. Res. Lett., **11**, 1188, 1984.
- Melrose, D. B., R. G. Hewitt, and G. A. Dulk, Electron-cyclotron maser emission: relative growth and damping rates for different modes and harmonics, J. Geophys. Res., **89**, 897, 1984.
- Omid, N., and C. S. Wu, The effect of background plasma density on the growth of ordinary and z mode emissions in the auroral zone. J. Geophys. Res., **90**, 6641, 1985.
- Oya, H., and A. Morioka, Observational evidence of z and 1-o mode waves as the origin of auroral kilometric radiation from the Jikiken (EXOS B) satellite, J. Geophys. Res., **88**, 6189, 1983.
- Shawhan, S. D., and D. A. Gurnett, Polarization measurements of auroral kilometric radiation by Dynamics Explorer 1, Geophys. Res. Lett., **9**, 913, 1982.
- Winglee, R. M., Effects of a finite plasma temperature on electron-cyclotron maser emission, Astrophys. J., **291**, 160, 1985.
- Wu, C. S., and L. C. Lee, A theory of terrestrial kilometric radiation. Astrophys. J., **230**, 621, 1979.

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