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Estimation of Heavy Ion Densities From Linearly Polarized EMIC Waves at Earth

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Estimation of Heavy Ion Densities from Linearly Polarized EMIC Waves at Earth

Eun-Hwa Kim[1], Jay R. Johnson[1], and Dong-Hun Lee[2]

Linearly polarized EMIC waves are expected to concentrate at the location where their wave frequency satisfies the ion-ion hybrid (IIH) resonance condition as the result of a mode conversion process. In this letter, we evaluate absorption coefficients at the IIH resonance in the Earth geosynchronous orbit for variable concentrations of helium and azimuthal and field-aligned wave numbers in dipole magnetic field. Although wave absorption occurs for a wide range of heavy ion concentration, it only occurs for a limited range of azimuthal and field-aligned wave numbers such that the IIH resonance frequency is close to, but not exactly the same as the crossover frequency. Our results suggest that, at $L = 6.6$, linearly polarized EMIC waves can be generated via mode conversion from the compressional waves near the crossover frequency. Consequently, the heavy ion concentration ratio can be estimated from observations of externally generated EMIC waves that have polarization.

1. Introduction

Electromagnetic ion cyclotron (EMIC) waves are low frequency waves typically in the Pc 1-2 (0.2-5Hz) frequency range that are excited below the proton gyrofrequency and are commonly observed in the plasmasphere and magnetosphere. Polarization of these waves has been generally reported to be left-hand (LH) polarized, however, right-hand (RH) or linear polarizations have also been reported [e.g., *Fraser and McPherron*, 1982; *Anderson et al.*, 1992; *Min et al.*, 2012]. Linearly polarized EMIC waves are interesting because the wave modes should be predominantly LH or RH except the crossover frequency ($\omega_{\rm cr}$) [*Smith and Brice*, 1964] or at oblique propagation near the multi-ion hybrid resonances [e.g., *Lee et al.*, 2008].

Although linear polarization can result from refraction [*Rauch and Roux*, 1982; *Horne and Thorne*, 1993], absorption at high latitudes [*Horne and Thorne*, 1997] would likely limit such polarizations to higher latitudes. *Denton et al.* [1996] suggested that the linear polarization may result from superposition of two waves, but the mechanism requires multiple waves and appropriate differences in phase. Alternatively, *Lee et al.* [2008] suggested that linearly polarized EMIC waves can be generated via mode conversion near the ion-ion hybrid (IIH) resonance location. When the frequency of incoming compressional waves matches the IIH resonance condition in an increasing (or decreasing) heavy ion concentration or inhomogeneous magnetic field strength (B_0), wave energy from incoming compressional waves concentrates and mode converts to EMIC waves. Mode conversion at this resonance has been simulated using a multi-fluid code [*Kim et al.*, 2008; *Kim et al.*, 2013], showing that the resulting EMIC waves are strongly guided by the ambient magnetic field ($\mathbf{B}_0$) and have linear polarization.

The IIH resonance condition is apparent in the wave dispersion relation of compressional waves in the ion cyclotron frequency range,

$$n_\perp^2 \cong \frac{(\epsilon_r - n_\parallel^2)(\epsilon_l - n_\parallel^2)}{(\epsilon_s - n_\parallel^2)}, \tag{1}$$

where subscriptions of $\perp$ and $\parallel$ represent the perpendicular and parallel to $\mathbf{B}_0$ and ϵ_r, ϵ_l, and ϵ_s are the plasma electric tensor components in notation of Stix [*Stix*, 1992]. The dispersion relation exhibits a resonance ($n_\perp \to \infty$) where

$$n_\parallel^2 = \epsilon_s, \tag{2}$$

which is called the IIH resonance because it occurs between the two ion cyclotron frequencies.

Because the IIH resonance frequency ($\omega_{\rm ii}$), where $\epsilon_s(\omega_{\rm ii}) = n_\parallel^2(\omega_{\rm ii})$, depends on B_0 and the ratio of the ion densities, $\eta_{\rm ion} = N_{\rm ion}/N_{\rm e}$, where $N_{\rm e(ion)}$ is an electron (ion) number density, *Kim et al.* [2008] and *Lee et al.* [2008] suggested that $\eta_{\rm ion}$ can be estimated using $\omega_{\rm ii}$ of the observed linearly polarized EMIC waves. However, the dependence of $\omega_{\rm ii}$ on field-aligned wave number ($k_\parallel$) seen in Eq. (2) introduces a free parameter that must be constrained in order for the method to be useful.

For $k_\parallel \to 0$, $\omega_{\rm ii}$ reduces to the Buchsbaum resonance frequency ($\omega_{\rm bb}$)

$$\omega_{\rm bb}^2 = \omega_{\rm c1}\omega_{\rm c2}\frac{\omega_{\rm c2}\eta_1 + \omega_{\rm c1}\eta_2}{\omega_{\rm c1}\eta_1 + \omega_{\rm c2}\eta_2}, \tag{3}$$

where $\epsilon_s(\omega_{\rm bb}) = 0$ and $\omega_{\rm c}$ is an ion cyclotron frequency. *Lee et al.* [2008] showed the IIH resonance is close to the Buchsbaum resonance when the field-aligned wavelength of incoming waves is larger than $1{\rm R_E}$ ($\lambda_\parallel = 2\pi/k_\parallel \geq 1{\rm R_E}$) at Earth's geosynchronous orbit and thus suggested that $\eta_{\rm ion}$ can be estimated using $\omega_{\rm bb}$ as well as $\omega_{\rm ii}$.

In contrast, *Othmer et al.* [1999] and *Kazakov and Fülöp* [2013] proposed that compressional wave absorption at the IIH resonance should preferentially occur close to the crossover frequency, $\omega_{\rm ii} \approx \omega_{\rm cr}$ and $k_\parallel \approx k_\parallel(\omega_{\rm ii} \approx \omega_{\rm cr})$, where

$$\omega_{\rm cr}^2 = \omega_{\rm c1}^2\eta_2 + \omega_{\rm c2}^2\eta_1, \tag{4}$$

which would also make it possible to estimate $\eta_{\rm ion}$ from the observed wave frequency.

However, the analysis of *Kazakov and Fülöp* [2013] is not generally applicable to mode conversion near the crossover frequency, because it simplifies wave dispersion by only including a cutoff and resonance (CR) pair in space in order to estimate the value of $k_\parallel$ where the maximum absorption occurs. Instead, *Kim and Johnson* [2014] note that

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the analysis of *Kazakov and Fülöp* [2013] cannot be applied because near the crossover frequency wave propagation is governed by a cutoff-resonance-cutoff (CRC) triplet configuration and the maximum absorption does not generally occur at $\omega \approx \omega_{\rm cr}$ [e.g., *Karney et al.*, 1979; *Ram et al.*, 1996; *Kim et al.*, 2011; *Kim and Johnson*, 2014].

Although the analysis of *Kazakov and Fülöp* [2013] is not generally appropriate, they introduced the concept that a sharply peaked dependence of mode conversion (absorption) on $k_\parallel$ makes it possible to estimate heavy ion concentration. Following this line of reasoning, in this paper we evaluate the general dependence of mode conversion on $k_\parallel$. Previously, *Lee et al.* [2008] and *Kim et al.* [2011] had provided estimates of absorption at the IIH resonance for a given $k_\parallel$, but they did not provide the general dependence of absorption in $k_\parallel$, so we first generalize this work. If the mode conversion is strongly peaked, then $\eta_{\rm ion}$ can be estimated from $\omega_{\rm ii}(k_\parallel^{\rm max})$, where maximum absorption occurs at $k_\parallel = k_\parallel^{\rm max}$.

In this letter, we examine how efficiently compressional waves are absorbed at the IIH resonances as they propagate into the inner magnetosphere of Earth. To address this problem, we consider a simplified 1D model that captures the essential features of the IIH resonance [*Kim et al.*, 2011]. Assuming radial propagation across field lines, we seek to understand how wave absorption depends on the concentration of $\rm He^+$ ($\eta_{\rm He}$), azimuthal (k_y) and field-aligned ($k_\parallel$) wavenumbers of the incoming compressional wave. To isolate the dependence on $\eta_{\rm He}$, k_y, and $k_\parallel$, we consider wave absorption to occur at a particular field line ($L = 6.6$) so that magnetic field and density gradients are kept fixed. We also discuss how linearly polarized EMIC waves at the IIH resonance can be used to estimate the heavy ion densities at the Earth.

2. Model Description

As an approximation to radial wave propagation across magnetic flux surfaces, we consider a cold plasma slab model. The slab model is a local approximation where x, y, and z correspond to radial, azimuthal, and field-aligned coordinates. Wave propagation in the cold, fluid model can be described by Maxwell's equations combined with fluid equations for ions and electrons. Using the form of perturbations a simple set of wave equations can be obtained by ignoring electron inertial effects and background gradients related to diamagnetic drift and density compressions [*Kim et al.*, 2011],

$$\frac{c}{\omega}\frac{\partial \mathbf{Y}}{\partial x} = \mathbf{MY}, \qquad (5)$$

where

$$\mathbf{Y} = \begin{pmatrix} E_y \\ \dfrac{c}{\omega}\dfrac{\partial E_y}{\partial x} - i n_y E_x \end{pmatrix}, \qquad (6)$$

and

$$\mathbf{M} = \begin{pmatrix} \dfrac{n_y \epsilon_d}{n_z^2 - \epsilon_s} & 1 + \dfrac{n_y^2}{n_z^2 - \epsilon_s} \\ \dfrac{(n_z^2 - \epsilon_r)(n_z^2 - \epsilon_l)}{n_z^2 - \epsilon_s} & -\dfrac{n_y \epsilon_d}{n_z^2 - \epsilon_s} \end{pmatrix}, \qquad (7)$$

where n_y is refractive index in an azimuthal direction and $\epsilon_d = (\epsilon_r - \epsilon_l)/2$. Eqs. (5)-(7) have been solved with a finite difference approach with nonuniform mesh [e.g., *Johnson et al.*, 1995; *Johnson and Cheng*, 1999; *Kim et al.*, 2011].

We solve the equations in terms of the normalized spatial variable, $L \equiv x/\rm R_E$, and the inner and outer boundaries such that $6.1 \le L \le 7.1$ and assume the resonances occur near Earth's geosynchronous orbit at $L = 6.6$. We adopt an electron-hydrogen-helium plasma in our model with a constant $\eta_{\rm He}$ in x. The B_0 and total density ($N_{\rm e}$) at the magnetic equator are assumed to be [*Lee and Lysak*, 1989]

$$B_0 = \frac{B_s}{L^3}, \qquad (8)$$

$$N_{\rm e} = N_{\rm mp}\frac{L_{\rm mp}^3}{L^3}, \qquad (9)$$

where $B_s = 3.1 \times 10^{-5}$ T is magnetic field strength at the Earth's surface, $N_{\rm mp} = 10\rm cm^{-3}$ is the total density of the magnetopause at $L_{\rm mp} = 10$. Incoming waves are launched at the lower magnetic field region (i.e., outer magnetosphere) and the wave solution is decomposed into WKB solutions to determine reflection, transmission, and absorption coefficients at the boundaries. Figure 1 shows the computational domain and the assumed magnetic field and density profiles.

3. Dispersion Relation

The refractive index perpendicular to $\mathbf{B}_0$ ($k_\perp$) of incoming compressional waves along L are calculated as a function of $k_\parallel$ for $\eta_{\rm He} = 10\%$ and 90% as shown in Figure 2 where the resonance occurs at $L = 6.6$. Here, wavenumbers are normalized to $k_{\rm cr} = k_\parallel(\omega_{\rm ii} = \omega_{\rm cr})$, $K_{\perp(\parallel)} = k_{\perp(\parallel)}/k_{\rm cr}$, and K_y is assumed to be 0.

In Figure 2, blank areas represent wave stop gaps where $K_\perp^2 < 0$. The boundaries of the wave stop gap are the resonance at $L = 6.6$ and cutoffs where $K_\perp^2 = 0$. At the inner boundary at $L = 6.1$, we define $K_{\rm CRC}$ where $K_\perp = 0$ and the compressional waves have a CRC triplet in x for $K_\parallel > K_{\rm CRC}$ and CR pair for $K_\parallel < K_{\rm CRC}$.

There is a particular value of $K_\parallel \approx 1$, where the resonance and two cutoffs almost match each other, which generally does not allow separation of the CRC triplet. When the IIH resonance occurs with $K_{\rm CRC} < K_\parallel < 1$, the LH (RH) cutoff is on the low (high) magnetic field side of the IIH resonance, while if the resonance occurs with $K_\parallel > 1$, the RH (LH) cutoff is on the low (high) field side of the resonance. For $K_\parallel > K_{\rm CRC}$, absorption at the IIH resonance can occur both as the wave leaks through the resonance as well as when the wave reflects off the inner cutoff and propagates back into the resonance, thus the wave absorption can be as large as 100% [e.g., *Kim et al.*, 2011], which is a characteristic of CRC conditions [*Karney et al.*, 1979; *Ram et al.*, 1996; *Lin et al.*, 2010].

In Figure 2b, we show $K_{\rm no}$ where $K_\perp \to 0$ at the outer boundary. For $K_\parallel > K_{\rm no}$, no wave can propagate into the calculation spatial domain thus no absorption occurs. $K_{\rm no}$ becomes close to $K_\parallel = 1$ when $\eta_{\rm He}$ increases.

Using plasma conditions at $L = 6.6$ ($B_0 = 108$nT and $N_{\rm e} = 34.7\rm cm^{-3}$), we calculate the IIH resonance frequency, $\Omega_{\rm ii} = \omega_{\rm ii}/\omega_{{\rm ci}(L=6.6)}$, where $\omega_{{\rm ci}(L=6.6)}$ is proton cyclotron frequency at $L = 6.6$, as a function of $\eta_{\rm He}$ and $K_\parallel$ in Figure 3a. This figure clearly shows that $\Omega_{\rm ii}$ increases when $\eta_{\rm He}$ and/or $K_\parallel$ increase. The value of $\Omega_{\rm ii}$ has a significant dependence on $K_\parallel$ ranging from $\Omega_{\rm ii} \approx \Omega_{\rm bb}$ for $K_\parallel \to 0$ to $\Omega_{\rm ii} \approx \Omega_{\rm cr}$ as $K_\parallel \to 1$, as discussed in Section 1.

Because of $\Omega_{\rm ii} = \Omega_{\rm ii}(\eta_{\rm He}, K_\parallel)$, $K_\parallel$ can also be expressed as $K_\parallel(\Omega_{\rm ii}, \eta_{\rm He})$ as shown in Figure 3b. $\Omega_{\rm ii}$ monochromatically increases with $\eta_{\rm He}$ and can be easily used to estimate $\eta_{\rm He}$ from Figure 3b, if strong wave absorption occurs. For example, when the linearly polarized EMIC waves are observed with $\Omega_{\rm obs} \approx \Omega_{\rm ii} = 0.61$ and if the maximum absorption is calculated at $K_\parallel^{\rm max} = 0.7$, $\eta_{\rm He}$ can be estimated as $\eta_{\rm He} \approx 45\%$. If the observed waves are identified to be $\omega_{\rm bb}$, $\eta_{\rm ion}$ can be used to estimate the maximum $\eta_{\rm ion}(\Omega_{\rm bb})$. In Section 4, we calculate the wave absorption coefficient ($\mathcal{A}$) as a function of $K_\parallel$ and $\eta_{\rm He}$ and then $\mathcal{A}(K_\parallel, \eta_{\rm He})$. These results are then converted into $\mathcal{A}(\Omega_{\rm ii}, \eta_{\rm He})$ similar to Figure 3.

4. Wave Absorption at the IIH resonance

In Figure 4, we calculate the absorption coefficient ($\mathcal{A}$) of the compressional waves as a function of $K_\parallel$ and $\eta_{\rm He}$ for $K_y = 0 - 0.3$. For all K_y cases, the maximum value of $\mathcal{A}$ ($\mathcal{A}^{\rm max}$) can be as large as 100% where $K_\parallel > K_{\rm CRC}$. In this region, the waves encounter a CRC triplet and thus $\mathcal{A}$ oscillates in both $K_\parallel$ and $\eta_{\rm He}$ due to the interference effect between incoming and reflected compressional waves. For $K_\parallel < K_{\rm CRC}$, $\mathcal{A}^{\rm max}$ is near 25% which is Budden limit of the CR pair. In Figure 4a, for $K_\parallel = 1$ at $\Omega_{\rm ii} = \Omega_{\rm cr}$, no absorption occurs, which is consistent with previous calculations [*Klimushkin et al.*, 2006; *Kim et al.*, 2011].

We define the minimum ($K^\dagger$) and maximum (K^*) $K_\parallel$, and the width of the $K_\parallel$ absorption window ($\Delta K_\parallel = K^* - K^\dagger$) where the absorption occurs. When $\eta_{\rm He}$ increases, $\Delta K_\parallel$ becomes narrower for $\eta_{\rm He} \le 0.53$ and wider for $\eta_{\rm He} \ge 0.53$ in Figure 4a. As an example, $\mathcal{A}$ is large in the range $0.9 \le K_\parallel \le 1.04$ ($\Delta K_\parallel \approx 0.11$) for $\eta_{\rm He} = 0.14$, in the range $0.938 \le K_\parallel \le 0.998$ ($\Delta K_\parallel \approx 0.05$) for $\eta_{\rm He} = 0.53$, and in the range $0.84 \le K_\parallel \le 0.998$ ($\Delta K_\parallel \approx 0.158$) for $\eta_{\rm He} = 0.93$, respectively.

Figure 4 also shows that the absorption occurs less effectively when incoming waves propagate with higher K_y. When K_y increases, $K_{\rm CRC}$ and $K^\dagger$ decrease and $\Delta K_\parallel$ becomes slightly narrower. For smaller $\eta_{\rm He}$, absorption decreases as K_y increases, thus for $K_y = 0.3$, almost no absorption occurs for $0.1 \le \eta_{\rm He} \le 0.5$. $K^\dagger$ exhibits little dependence on K_y for $\eta_{\rm He} > 0.5$ ranging from ~ 0.997 to ~ 0.97.

We focus on the range of $K_\parallel$ where the absorption at the IIH resonance is maximized. Thus, we choose $\mathcal{A}^{\rm max}$ among $\mathcal{A}$ for $K_y = 0 - 0.3$ and plot it as a function of $K_\parallel$ and $\eta_{\rm He}$ in Figure 5a. In this figure, the edge of ΔK is clearly visible as a function of $\eta_{\rm He}$. For $\eta_{\rm He} \sim 1$ or 0, the absorption occurs in the relatively wide range of $K_\parallel$, however, for moderate $\eta_{\rm He}$, most absorption occurs for $0.92 \le K_\parallel \le 1$. This range of $K_\parallel$ is much higher and narrower than the range seen at Mercury where maximum efficiency occurs broadly for $K_\parallel = 0.5 - 0.8$ [*Kim et al.*, 2011; *Kim and Johnson*, 2014].

We convert $\mathcal{A}^{\rm max}(K_\parallel, \eta_{\rm He})$ to find $\mathcal{A}^{\rm max}(\Omega_{\rm ii}, \eta_{\rm He})$ as shown in Figure 5b in order to show frequency range where strong absorption occurs. The figure clearly shows that most absorption occurs near $\Omega_{\rm cr}$, where $K_\parallel \approx 1$, but not exactly at $\Omega_{\rm cr}$. Here, the upper and lower edges of the absorption are $\Omega^\dagger(K_\parallel = K^\dagger)$ and $\Omega_{\rm cr}$, respectively. The absorption only occurs in a very narrow region of $\Delta\Omega$ for a single $\eta_{\rm He}$ and the maximum $\Delta\Omega$ is only 2.7%. Similarly, $\Delta\eta_{\rm He} = \eta_{\rm cr} - \eta^\dagger$ for a single Ω is less than 2.5%, where $\eta_{\rm cr} = \eta_{\rm He}(K_\parallel = 1)$ and $\eta^\dagger = \eta_{\rm He}(K_\parallel = K^\dagger)$. Therefore, Figure 5 suggests that the linearly polarized EMIC waves can be generated at $\Omega \sim \Omega_{\rm cr}$ via mode conversion from the incoming compressional waves at $L = 6.6$, and the heavy ion concentration ratio can be estimated using such EMIC waves. For instance, if waves with $\Omega = 0.6$ are detected at $L = 6.6$, then the heavy ion density can be estimated to be around 25%.

5. Discussion

In this letter, we examine the compressional wave absorption at the IIH resonance at the Earth's geosynchronous orbit for arbitrary heavy ion density ratio, azimuthal and field-aligned wavenumbers when plasma contains inhomogeneous ambient magnetic field and total density. We show the absorption occurs over a wide range of heavy ion density concentration, while it occurs in the limited range of azimuthal ($K_y \le 0.3$) and field aligned wave numbers ($0.9 \le K_\parallel \le 1.0$). In these regions of $K_\parallel$, the wave frequency is close to the crossover frequency ($\Omega_{\rm ii} \approx \Omega_{\rm cr}$). Therefore, the observed linearly polarized EMIC waves can be treated as waves converted from the compressional waves at the IIH resonance at $\Omega_{\rm ii} \approx \Omega_{\rm cr}$, and thus the heavy ion concentration ratio can be estimated using $\Omega_{\rm cr}$. Interestingly, this result was predicted by *Kazakov and Fülöp* [2013], although their approach does not provide an accurate estimate of wave absorption.

Moreover, because the wave absorption is very sensitive to plasma conditions, such as density scale length, heavy ion density ratio, and magnetic field gradient it is not generally the case that maximum absorption occurs near $K_\parallel = 1$, and the result presented only applies near Earth's geosynchronous orbit. Indeed, at Mercury, the range of $K_\parallel$ with

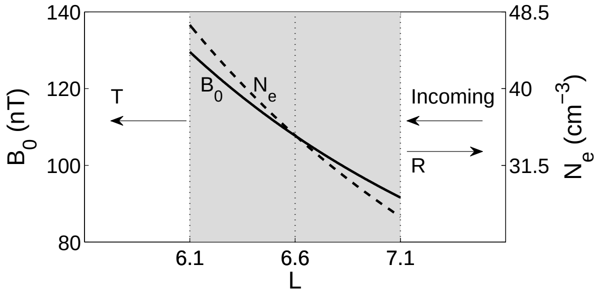

Figure 1. The ambient magnetic field (B_0) and electron density ($N_{\rm e}$) in x. Here, dotted lines and the resonance location at $L = 6.6$ and spatial calculation boundaries at $L = 6.1$ and 7.1, respectively. $\mathcal{R}$ and $\mathcal{T}$ are reflection and transmission coefficients, respectively.

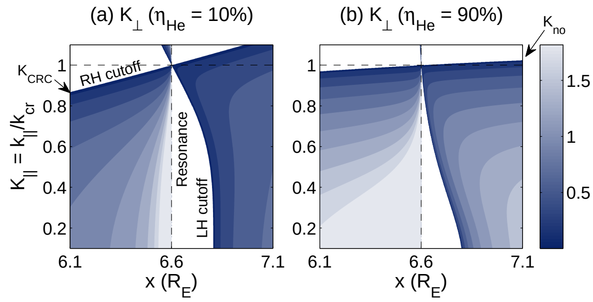

Figure 2. The refractive index $K_\perp = k_\perp/k_{\rm cr}$ of incoming compressional waves with $\omega = \omega_{\rm ii}(L = 6.6)$ as a function of $K_\parallel = k_\parallel/k_{\rm cr}$ for (a) $\eta_{\rm He} = 10\%$ and (b) 90%, respectively. Here, $K_{\rm CRC}$ and $K^{\rm no}$ are where $K_\perp \to 0$ at $L = 6.1$ and 7.1, respectively.

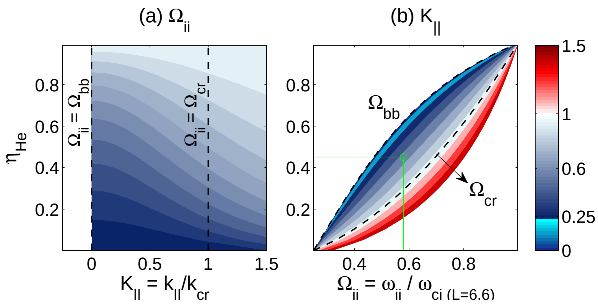

Figure 3. The normalized ion-ion hybrid resonance ($\Omega_{\rm ii}$) to the ion cyclotron frequency ($\omega_{\rm ci}$) at $L = 6.6$ as a function of (a) $K_\parallel$ and $\eta_{\rm He}$ and (b) $\Omega_{\rm ii}$ and $\eta_{\rm He}$. Dashed lines represent where $\Omega_{\rm ii} = \Omega_{\rm bb}$ or $\Omega_{\rm cr}$.

maximum absorption ($0.5 \leq K_{\parallel} \leq 0.8$) is smaller than Earth ($0.9 \leq K_{\parallel} \leq 1$) and thus $\Omega_{\rm cr}$ can not be used to estimate heavy ion density.

In this study, we adopt a constant heavy ion density concentration although wave absorption can also occur when plasma contains inhomogeneous heavy ion concentrations [e.g., *Kim et al.*, 2008; *Lee et al.*, 2008]. We also assume incoming waves propagate from outer magnetosphere, thus incoming waves always encounter the cutoff prior to reaching the IIH resonance. *Lee et al.* [2008] shows the absorption at the IIH resonance is highly effective and the absorption coefficient can increase up to 100% when waves encounter the IIH resonance directly. Moreover, inhomogeneous heavy ion concentration in the radial direction can modify the radial structure of the IIH resonance frequency as well as wave dispersion relation in space [*Kim et al.*, 2011]. Therefore, detailed investigations on the effect of inhomogeneous heavy ion density in dipole magnetic field and comparative studies in different magnetospheres remains as future work.

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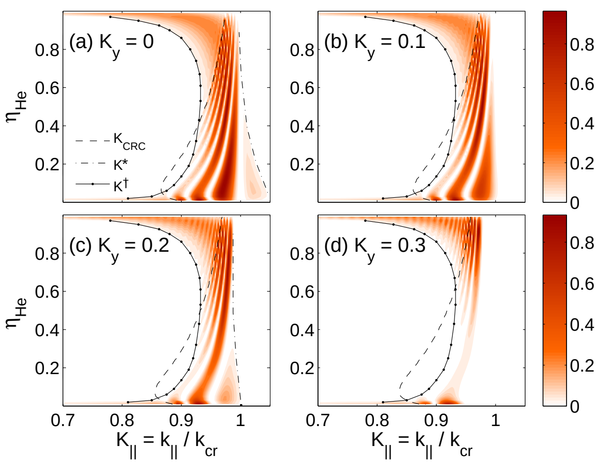

Figure 4. Absorption ($\mathcal{A}$) coefficient at the IIH resonance as a function of $\eta_{\rm He}$ and $K_{\parallel}$ for $K_y = 0 - 0.3$. $K_{\rm CRC}$, K^{*}, and $K^{\dagger}$ are plotted as dashed, dotted-dashed, and solid-dotted lines, respectively.

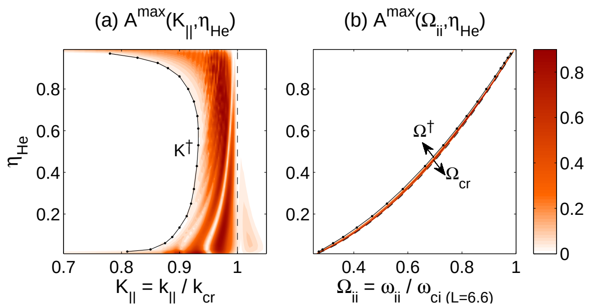

Figure 5. The maximum $\mathcal{A}$ ($\mathcal{A}^{\max}$) of $\mathcal{A}(0 \leq K_y \leq 0.3)$ as a function of (a) $K_\parallel$ and η_{He} and (b) Ω_{ii} and η_{He}.

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