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1. Introduction

[1] The authors of a recent paper [*Jones and Su*, 2008] have used two-fluid plasma theory [e.g., *Streltsov et al.*, 1998] to predict the parallel electric field strength of a shear Alfvén wave traveling through the Jovian magnetosphere from the vicinity of Io to the Jovian ionosphere.

[2] Two-fluid analyses give adequate predictions for the parallel electric field strength $E_\parallel$ in plasma regimes where the electron thermal speed $v_{Te} = (2k_BT_e/m_e)^{1/2}$ is much larger, or much smaller, than the Alfvén speed $v_A = B_0(\mu_0\rho)^{-1/2}$. When $v_{Te} \ll v_A$, shear Alfvén waves can have finite $E_\parallel$ when their perpendicular scale lengths are comparable to the electron skin depth $\lambda_e = c/\omega_{pe}$, whereupon the waves are called inertial Alfvén waves. Conversely, when $v_{Te} \gg v_A$, shear Alfvén waves can have $E_\parallel$ when their perpendicular scales are comparable to λ_e (v_{Te}/v_A), and are often known as kinetic Alfvén waves. Analytic studies using full kinetic theory (either with linear approximations [*Lysak*, 1998] or using a fully nonlinear simulation [*Watt and Rankin*, 2008]) have also shown that parallel electric fields are also supported where $v_{Te} \sim v_A$, if the perpendicular scale length is comparable to the kinetic scale length.

[3] If we consider a magnetic fluxtube connecting Io (at $5.9R_J$ radial distance) with the high-latitude ionosphere at roughly 65^o latitude, then the lower portion of this fluxtube has $v_{Te} < v_A$ and is in the inertial regime, whereas plasma in the vicinity of Io is more likely to have $v_{Te} \sim v_A$ due to the decreasing magnetic field strength and increasing ion number density in the Io torus.

[4] Two-fluid analyses are inadequate in this plasma environment. By portraying the kinetic and inertial corrections to the Alfvén wave dispersion as "competing" effects, the underlying physics of Alfvén waves with finite perpendicular scale lengths becomes obfuscated. In this paper, we show the correct equation for the dispersive factor given in equation (3) of *Jones and Su* [2008], and we present an alternate explanation for the small ratio of parallel to perpendicular electric fields predicted in the vicinity of Io.

2. Kinetic Theory

[5] The full derivation of the kinetic dispersion relation for infinite plasma waves in a uniform plasma is given by *Lysak and Lotko* [1996], along with a discussion of the necessary assumptions and approximations required. We will focus on the plasma parameters given by *Jones and Su* [2008] for the vicinity of Io (i.e., for $6.0R_J < s < 7.9R_J$, where s is the spatial parameter along the magnetic field). In this region, $v_A \ll c$, and so the dispersion relation given by equation (5) of *Lysak and Lotko* [1996] is valid. The ratio of parallel to perpendicular electric fields is given by [*Lysak*, 1998, equation (3)]

$$\frac{E_\parallel}{E_\perp} = \frac{n_\parallel^2 - \frac{c^2}{v_A^2}\frac{1-\Gamma_0(\mu_i)}{\mu_i}}{n_\parallel n_\perp}, \tag{1}$$

where $n_\parallel = ck_\parallel/\omega$, $n_\perp = ck_\perp/\omega$, and $k_\parallel$, $k_\perp$, and ω are the parallel and perpendicular wave numbers and the angular frequency of the shear Alfvén wave, respectively. Here, $\mu_i = k_\perp^2\rho_i^2$, $\rho_i = k_BT_i/(m_i\,\Omega_i^2)$, and Γ_0 (μ_i) is the modified Bessel function $\Gamma_0 = e^{-\mu_i}I_0(\mu_i)$.

[6] The dispersive factor of *Jones and Su* [2008] gives the ratio between the parallel electric field and the wave scalar potential:

$$\Psi = \frac{E_\parallel}{ik_\parallel\phi}. \tag{2}$$

Since $E_\perp = -ik_\perp\phi$, we have

$$\Psi = -\frac{k_\perp}{k_\parallel}\frac{E_\parallel}{E_\perp}, \tag{3}$$

and so the electric field ratio given in equation (2) can be used to obtain Ψ using kinetic theory, for comparison with the predictions given by two-fluid theory.

[7] In this paper, Ψ is calculated using the same plasma model and perpendicular scale lengths as in the baseline model of *Jones and Su* [2008]. These values are used in the

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kinetic dispersion relation [*Lysak and Lotko*, 1996] to find the complex frequency ω as a function of $k_{\parallel}$ at equally spaced points along the magnetic field. As in the work of *Jones and Su* [2008], we assume that the results from an idealized, uniform linear dispersion relation are valid locally, and so we ignore the plasma inhomogeneities along the field line. One (ω, $k_{\parallel}$) pair is selected from the solutions of the dispersion relation at each spatial point, and then used in equation (2) to calculate $E_{\parallel}/E_{\perp}$, before equation (4) is used to evaluate Ψ. Note that we have investigated a wide range of values of $k_{\parallel}$, and Ψ is insensitive to the selection of a particular (ω, $k_{\parallel}$) pair.

3. Results and Discussion

[8] Figure 1a shows the predictions of $|\Psi|$ from the two-fluid analysis given by *Jones and Su* [2008] (solid line) and the kinetic analysis discussed in this paper (diamonds). We compare $|\Psi|$, since equation (4) returns a complex quantity, especially where $v_{Te} >\sim v_A$ (Figure 1b gives the ratio v_{Te}/v_A for the same model region). The two-fluid analysis predicts that the parallel electric field will disappear at $s \sim 7.2$, but the full kinetic analysis reveals that $E_{\parallel}$ is nonzero over the entire Io plasma torus ($6.0 < s < 7.9$). The vital difference between the two approaches is that the kinetic treatment retains the full complex relationship between $E_{\parallel}$ and $E_{\perp}$. The complex nature of $E_{\parallel}/E_{\perp}$ is important because the phase difference between $E_{\parallel}$ and $E_{\perp}$ changes as the ratio v_{Te}/v_A is increased, with the imaginary part becoming comparable to the real part [see *Watt and Rankin*, 2008].

[9] The kinetic and inertial corrections to the Alfvén wave dispersion do not "cancel," but must be treated carefully using a full kinetic analysis which retains the imaginary part of $E_{\parallel}/E_{\perp}$.

[10] The explanation for the small values of $|\Psi|$, and hence the small predicted values of $E_{\parallel}$, in the Io torus lies in

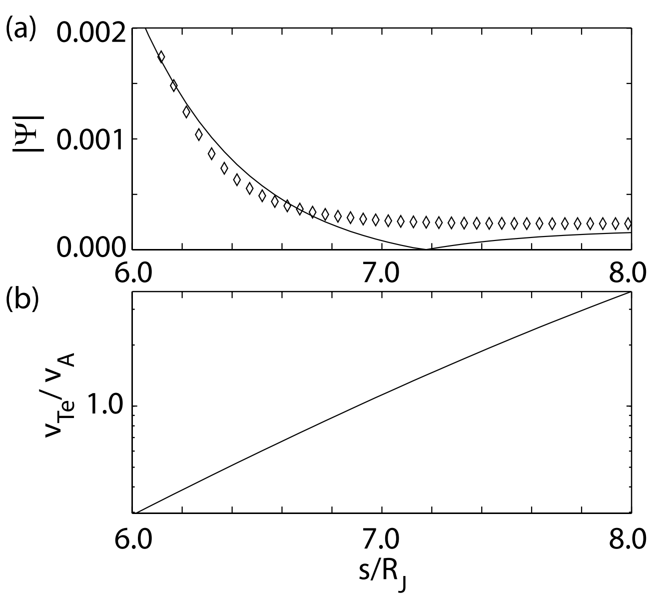

Figure 1. (a) Predictions of $|\Psi|$ using two-fluid theory (solid line) and kinetic theory (diamonds) for the Io torus region. (b) Modeled v_{Te}/v_A for the same plasma region.

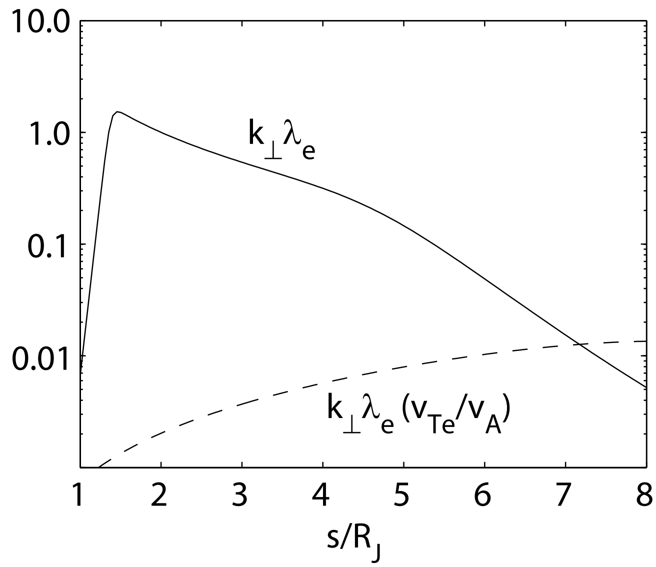

Figure 2. The modeled perpendicular wavelength of shear Alfvén waves over the entire Io-Jupiter fluxtube compared to the inertial scale length λ_e (solid line) and the kinetic scale length $\lambda_e v_{Te}/v_A$ (dashed line).

the selection of $k_{\perp}$ in the model of *Jones and Su* [2008]. Figure 2 shows the variation of $k_{\perp}\lambda_e$ and $k_{\perp}\lambda_e v_{Te}/v_A$ throughout the model domain ($1.0 < s < 7.9$). For $6.0 < s < 7.9$, both quantities are much smaller than one, indicating that the modeled perpendicular scale length of the Alfvén wave is too large to support any significant $E_{\parallel}$ in the vicinity of Io.

[11] If we were to repeat this analysis with larger values of $k_{\perp}$, then the full kinetic treatment would yield larger values of Ψ, and hence $E_{\parallel}$, throughout the region near Io, whereas the two-fluid analysis would erroneously produce $\Psi = 0$ at some point close to Io [see *Jones and Su*, 2008, Figure 5]. Only observations of waves near Io can indicate realistic perpendicular scale sizes, but once researchers have this information, it is clear that the full kinetic treatment should be used to predict the size of the parallel electric fields due to shear Alfvén waves in this region.

4. Conclusions

[12] 1. For plasma with $v_{Te} \sim v_A$, a full kinetic analysis should be used to obtain more accurate predictions of parallel electric field strength due to shear Alfvén waves.

[13] 2. For the model used by *Jones and Su* [2008], the predicted parallel electric field strength is small in the vicinity of Io not because the inertial and kinetic effects of the shear Alfvén waves are "in competition," but because the modeled perpendicular scale length is large compared to characteristic length scales in the plasma.

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