A kinetic approach to the Ponderomotive Force

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[1] It has been suggested that Magnetic Holes (MHs) are caused by perpendicular proton energization due to the Ponderomotive Force (PF) associated with phase steepened Alfvén waves. Here we include particle finite Larmor radius (FLR) effects and the effects of ion gyroharmonics in the PF expression. The general expression for the PF is derived by using the hot plasma dielectric tensor from kinetic theory. The fully kinetic expression has a multiple resonance character which is not revealed in the fluid picture. It will be shown that by including such effects, the expression for the PF will be significantly altered, both at the low frequency and high frequency limit. Also, an explicit analytic expression for the PF keeping only the first order FLR terms is given for conceptual purposes for the readers. *INDEX TERMS:* 7827 Space Plasma Physics: Kinetic and MHD theory; 7807 Space Plasma Physics: Charged particle motion and acceleration; 7867 Space Plasma Physics: Wave/particle interactions; 7819 Space Plasma Physics: Experimental and mathematical techniques; 7839 Space Plasma Physics: Nonlinear phenomena. **Citation:** Dasgupta, B., B. T. Tsurutani, and M. S. Janaki, A kinetic approach to the Ponderomotive Force, *Geophys. Res. Lett.*, *30*(21), 2128, doi:10.1029/2003GL017385, 2003.

1. Introduction

[2] Magnetic Holes (MHs) and Magnetic Decreases (MDs) are localized regions in interplanetary space (and the magnetosphere) where the magnetic field intensities locally decrease by up to 90% or greater [*Turner et al.*, 1977; *Winterhalter et al.*, 1994; *Fränz et al.*, 2000; *Tsurutani et al.*, 1999, 2002a, 2002b; *Neugebauer et al.*, 2001]. *Winterhalter et al.* [1994] have shown that the plasma plus magnetic pressure across MHs/MDs is approximately constant.

[3] Figure 1 [from *Tsurutani et al.*, 2002a] is an example of phase-steepened Alfvén waves and MHs/MDs over the north solar pole. Three consecutive cycles of an Alfvén wave can be noted in the figure. The nonlinear, nonsinusoidal waves can be detected in the top of the panel, labelled B_1. The field coordinate system corresponds to the eigenvector directions of the covariance matrix, with B_1, B_2 and B_3 corresponding to the field components along the maximum, intermediate and minimum eigenvector directions, respectively. The three wave cycles are from 0402:00 to 0410:05 UT, 0410:05 to 0424:30 and 0424:30 to 0433:30 UT. A MH was detected at the edge of the first wave, a MD at the end of the second wave cycle and a MH/MD (both) were detected at the end of the third wave cycle. In all cases, the MHs/MDs occurred near the phase-steepened edge of the Alfvén waves, the regions that contains the highest wave frequency components.

[4] It has also been shown that the proton perpendicular temperatures inside MDs are larger than those just outside the MDs [*Fränz et al.*, 2000; *Winterhalter et al.*, 1994; *Tsurutani et al.*, 2002b]. *Tsurutani et al.* [2002b] have suggested that the Ponderomotive Force (PF) associated with the phase steepened Alfvén waves is accelerating the protons primarily in the perpendicular direction (and increasing the kinetic energy component perpendicular to the ambient magnetic field, $W_\perp$). The latter effect is believed to cause the MDs by diamagnetic effects.

[5] The PF is the time-averaged nonlinear force of an electromagnetic wave associated with the wave field gradient. An expression from a single particle picture, and also using the cold plasma theory has been derived by many authors [*Li and Temerin*, 1993; *Shukla and Stenflo*, 2000]. A finite temperature fluid expression is derived by *Lee and Parks*, [1983]. Heating and energization of ions by the PF in the auroral zone and has been discussed by *Pottelette et al.* [1993], *Shukla et al.* [1996], and *Shukla and Stenflo* [2002].

[6] *Guglielmi and Lundin* [2001] have derived an expression for ponderomotive acceleration for the ions by ion cyclotron and Alfvén waves over the polar regions, and suggested that ponderomotive effects play a dominant role in formation of structures in the magnetosphere. *Tsurutani et al.* [2003] have similarly suggested that Alfvén waves play a fundamental role within the magnetosphere for the acceleration of both electrons and ions.

[7] In the solar wind, it is often imperative to use a kinetic expression for the PF. For a typical set of parameters in interplanetary space, $T \sim 10^5$ K, and $B \sim 2.5$ nT, and ρ_{Li}, the proton larmor radius is $\sim 10^7$ cm. For an obliquely propagating Alfvén wave with a perpendicular component of the wave number, $k_\perp$, then $k_\perp \rho_{Li} \sim 1$. Thus for this case (interplanetary) the FLR effects must not be neglected.

[8] The purpose of this paper is to derive an explicit expression for the PF including the FLR terms, using a fully kinetic expression for the dielectric tensor of a magnetized plasma. We will show that the analytical expression for the PF will be significantly altered. An explicit expression for the PF containing only the first order FLR terms is also derived.

2. Formal Expression for the PF

[9] A general expression for the PF was obtained by *Guglielmi et al.* [1993].We derive a formal expression for

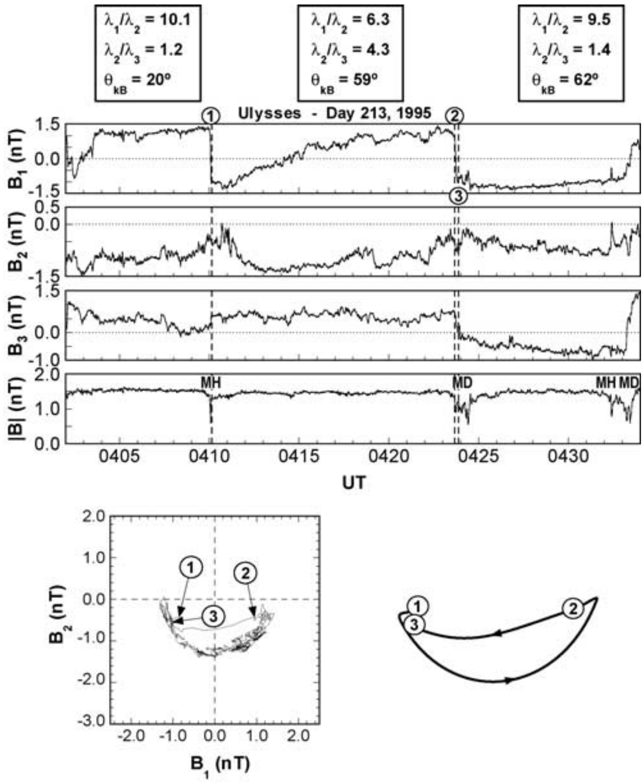

Figure 1. An example of phase steepened Alfvèn waves and MDs/MHs taken over the north solar pole regions by Ulysses [from *Tsurutani et al.*, 2002a], showing that MDs/MHs occurred near the steepened edge of the wave.

the PF following *Myra and D'Ippolito* [2000]. For each species, the continuity and momentum equation are:

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{u}) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(nm\mathbf{u}) + \nabla \cdot \Pi = Zqn\mathbf{E} + \frac{1}{c}\mathbf{J} \times \mathbf{B} \equiv \mathbf{F_L} \tag{2}$$

where, n, $\mathbf{u}$, m, Zq, $\mathbf{J} = Zqn\mathbf{u}$, Π are the number density, flow velocity, mass, charge and current density, and pressure tensor of each species. $\mathbf{F_L}$ is the Lorentz Force. In terms of the particle distribution function, f,

$$n = \int fd^3v, n\mathbf{u} = \int \mathbf{v}fd^3v, \Pi = m\int \mathbf{vv}fd^3v \tag{3}$$

The above set of equations are valid in a fully kinetic picture. In this work, we consider only the Lorentz Force part.

[10] From the continuity equation, we get the linearized expression for the perturbed density, (denoted by n), as:

$$n = -\frac{i}{Zq\omega}\nabla \cdot \mathbf{J} \tag{4}$$

The Lorentz force terms are expressed as:

$$\mathbf{F_L} = -\frac{i}{\omega}(\nabla \cdot \mathbf{J})\mathbf{E} + \frac{i}{\omega}\mathbf{J} \times \nabla \times \mathbf{E} \tag{5}$$

We use the relationship $\mathbf{J} = \sigma \cdot \mathbf{E}$, to eliminate the current density terms (σ is the conductivity tensor). We note the relationship between the dielectric tensor, ε, the susceptibility tensor χ, and the conductivity tensor, σ:

$$\chi = \frac{4\pi i}{\omega}\sigma; \varepsilon = \mathbf{I} + \chi \tag{6}$$

where $\mathbf{I}$ is the unit tensor. The Lorentz force term can be expressed in terms of the dielectric tensor of the plasma. To obtain the formal expression for the PF, we now take the quasilinear time average (to be denoted by the angular bracket, $\langle \ldots \rangle$) of the Lorentz force term:

$$\langle \mathbf{F_L} \rangle \equiv \mathbf{F_{PM}} = \frac{1}{32\pi}\nabla[(\mathbf{E}^* \cdot \chi\mathbf{E}) + \mathbf{E} \cdot \chi\mathbf{E}^*)] \tag{7}$$

[11] Using the symmetry/antisymmetry of the off-diagonal terms of the susceptibility tensor, one can simplify the terms in the bracket to:

$$2Re\chi_{xx}|E_x|^2 + 2Re\chi_{yy}|E_y|^2 + 2Re\chi_{zz}|E_z|^2 + 2\chi_{xz}|E_x||E_z| \tag{8}$$

3. Calculation of the Full FLR Terms of the Dielectric Tensor Elements

[12] For an isotropic Maxwellian plasma, consisting of electrons and ions, we start with the full kinetic expressions for the dielectric tensor elements, ε_{xx}, ε_{yy}, ϵ_{zz} and ε_{xz}. These are:

$$\varepsilon_{xx} = 1 + \sum_j \frac{\omega_{pj}^2}{\omega k_\parallel v_{tj}} \sum_{n=1}^{n=\infty} \frac{n^2\Gamma_n(\lambda_j)}{\lambda}\left[Z(\zeta_{nj}) + Z(\zeta_{-nj})\right] \tag{9}$$

$$\begin{aligned}\varepsilon_{yy} = 1 &+ \sum_j \frac{\omega_{pj}^2}{\omega k_\parallel v_{tj}} \sum_{n=1}^{n=\infty} \frac{n^2\Gamma_n(\lambda_j)}{\lambda}\left[Z(\zeta_{nj}) + Z(\zeta_{-nj})\right] \\ &- 2\sum_j \frac{\omega_{pj}^2}{\omega k_\parallel v_{tj}}\left[\lambda_j\Gamma_0'(\lambda_j)Z(\zeta_{0j})\right. \\ &+ \left.\sum_{n=1}^{n=\infty}\lambda_j\Gamma_n'(\lambda_j)\left\{Z(\zeta_{nj}) + Z(\zeta_{-nj})\right\}\right]\end{aligned} \tag{10}$$

$$\begin{aligned}\varepsilon_{zz} = 1 &- \sum_j \frac{\omega_{pj}^2}{\omega k_\parallel v_{tj}}\left[\Gamma_0\zeta_{0j}Z'(\zeta_{0j}) + \sum_{n=1}^{n=\infty}\Gamma_n\left\{\zeta_{nj}Z'(\zeta_{nj})\right.\right. \\ &+ \left.\left.\zeta_{-nj}Z'(\zeta_{-nj})\right\}\right]\end{aligned} \tag{11}$$

$$\varepsilon_{xz} = \sum_j \frac{k_\perp\omega_{pj}^2}{2k_\parallel\omega\omega_{cj}\lambda_j}\sum_{n=1}^{n=\infty} n\Gamma_n(\lambda_j)\left[Z'(\zeta_{nj}) - Z'(\zeta_{nj})\right] \tag{12}$$

where $\lambda_j = \frac{1}{2}k_\perp^2\rho_{Lj}^2$, ρ_{Lj} = Larmor radius of the j-th species, $\Gamma_n(\lambda_j) = e^{-\lambda_j}I_n(\lambda_j)$, $I_n(\lambda_j)$ = the modified Bessel Function of order n, $k_\parallel$, $k_\perp \rightarrow$ parallel, perpendicular wave number, ω_{cj} = gyrofrequency of the j-th species, ω_{pj} = plasma frequency of

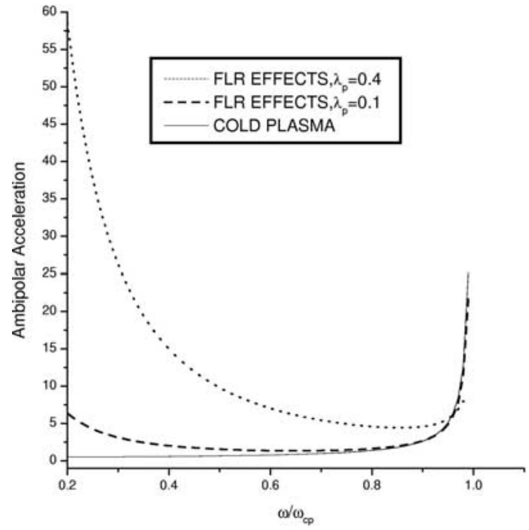

Figure 2. Plot of proton acceleration (ambipolar) in dimensionless unit due to the PF against the normalized wave frequency. The lower curve (solid line) shows the acceleration obtained from a cold plasma model (ion Larmor radius is set equal to zero). The upper curves incorporate the finite ion Larmor radius (FLR) effects for two values of λ_p. This shows that FLR effects can enhance the acceleration of a particle both at $\omega \to 0$ and $\omega \to \omega_{ci}$.

the j-th species, and v_{tj} = thermal velocity of the j-th species. $Z(\zeta)$, the plasma dispersion function is:

$$Z(\zeta_{nj}) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} \frac{e^{-u^2}}{u - \zeta_{nj}} du, \zeta_{nj} = \frac{\omega - n\omega_{cj}}{k_{\|} v_{tj}},$$

and $Z'(\zeta)$ is the derivative of $Z(\zeta)$ with respect to its argument. A fully kinetic expression for the PF containing FLR terms of all orders is obtained by substituting the expressions for the dielectric tensor elements given in (9)–(12), in the right hand side of equation (8).

4. Expression of PF With First Order FLR Effects

[13] To extract the first order corrections in λ_j, we use the expansion for $\Gamma_n(\lambda_j) = e^{-\lambda j} I_n(\lambda_j)$ for n = 0, 1, 2 in powers of λ_j. Further, we consider only the real part of the plasma dispersion function and use asymptotic expansion, $Z(\zeta_{nj}) \to -1/\zeta_{nj}$, $Z'(\zeta_{nj}) \to 1/\zeta_{nj}^2$. One gets the following expressions for the elements of the dielectric tensors containing terms up to first order in λ_j:

$$\varepsilon_{xx} = S - \sum_j \lambda_j \left[\frac{\omega_{pj}^2}{\omega_{cj}^2 - \omega^2} - \frac{\omega_{pj}^2}{4\omega_{cj}^2 - \omega^2} \right] \tag{13}$$

$$\varepsilon_{yy} = S - \sum_j \lambda_j \left[2\frac{\omega_{pj}^2}{\omega^2} + 3\frac{\omega_{pj}^2}{\omega_{cj}^2 - \omega^2} - \frac{\omega_{pj}^2}{4\omega_{cj}^2 - \omega^2} \right] \tag{14}$$

$$\varepsilon_{zz} = P + \sum_j \lambda_j \left(\frac{\omega_{pj}^2}{\omega^2} + \frac{\omega_{pj}^2}{\omega_{cj}^2 - \omega^2} \right) \tag{15}$$

where S and P are the corresponding expressions for a cold plasma. The cross term ε_{xz} is given by:

$$\varepsilon_{xz} = -\sum_j \frac{\omega_{pj}^2 k_\perp k_\| v_j^2}{\left(\omega^2 - \omega_{cj}^2\right)^2} = -\sum_j \frac{2k_\|}{k_\perp} \frac{\lambda_j \omega_{pj}^2 \omega_{cj}^2}{\left(\omega^2 - \omega_{cj}^2\right)^2} \tag{16}$$

[14] Using equations 13–16, we get the the expression for the PF with first-order correction terms in λ_j, (finite Larmor radius effect) for an isotropic Maxwellian plasma.

[15] Since $\omega_{pj}^2 = 4\pi q_j{}^2 n_{0j}/m_j$, one gets the expression for $\mathbf{F}_{PMj}$, the Ponderomotive Force on a single particle of j-th species can be written as (dividing by n_{0j}, without the summation):

$$\begin{aligned} \mathbf{F}_{PMj} = \frac{q_j^2}{4m_j} \nabla \Bigg[& \frac{1}{\omega_{cj}^2 - \omega^2} |E_\perp|^2 - \frac{1}{\omega^2} |E_z|^2 \\ & + \lambda_j \Bigg\{ \left(\frac{1}{4\omega_{cj}^2 - \omega^2} - \frac{1}{\omega_{cj}^2 - \omega^2} \right) |E_\perp|^2 \\ & - \left(\frac{1}{\omega^2} + \frac{1}{\omega_{cj}^2 - \omega^2} \right) |E_z|^2 \\ & + 2\left(\frac{1}{\omega^2} + \frac{1}{\omega_{cj}^2 - \omega^2} \right) \left[|E_z|^2 - |E_y|^2 \right] \\ & - \frac{k_\|}{k_\perp} \frac{4\omega_{cj}^2}{\left(\omega_{cj}^2 - \omega^2\right)^2} |E_x||E_z| \Bigg\} \Bigg] \end{aligned} \tag{17}$$

[16] From the above expression, it is easy to see that for $\lambda_j = 0$ the expression for the PF reduces to:

$$\mathbf{F}_{PMj} = \frac{q_j^2}{4m_j} \nabla \left[\frac{1}{\omega_{cj}^2 - \omega^2} |E_\perp|^2 - \frac{1}{\omega^2} |E_z|^2 \right] \tag{18}$$

which is the result for a cold plasma.

[17] In order to see the effect of the FLR terms, we make some simplifying assumptions, to compare with previous results [*Tsurutani et al.*, 2002b].We assume that $E_y \sim 0$ (linearly polarized), and almost perpendicular propagation, where $k_\|/k_\perp \ll 1$. Then the expression for PF given by equation (18) becomes:

$$\begin{aligned} \mathbf{F}_{PMj} = \frac{q_j^2}{4m_j} \nabla \Bigg[& \frac{1}{\omega_{cj}^2 - \omega^2} |E_\perp|^2 - \frac{1}{\omega^2} |E_z|^2 \\ & + \lambda_j \Bigg\{ \left(\frac{1}{4\omega_{cj}^2 - \omega^2} - \frac{1}{\omega_{cj}^2 - \omega^2} \right) |E_\perp|^2 \\ & + \left(\frac{1}{\omega^2} + \frac{1}{\omega_{cj}^2 - \omega^2} \right) |E_z|^2 \Bigg\} \Bigg] \end{aligned} \tag{19}$$

[18] Figure 2 shows the acceleration of a particle (proton) evaluated from the full expression for the PF given in equation (8) by summing up the complete series containing the Bessel functions of all orders (and thus retaining the FLR effects of all orders). Values of λ_j = 0.1, and 0.4 are illustrated for protons, together with the corresponding expression for a cold plasma, (λ_j = 0). To obtain the numerical value for the PF, we have used the expression

for the polarization, $E_{\|}/E_{\perp}$ for the kinetic Alfvén wave (KAW), as given by *Stasiewicz et al.* [2000] in the low frequency limit. The most important and significant difference between our expression for the PF with the usual cold plasma expression is that the PF is enhanced both at $\omega \rightarrow 0$ and at $\omega \rightarrow n\omega_{ci}$. This enhancement of the PF at $\omega \rightarrow 0$ is not found in cold plasma. This is due to the fact that for KAWs, the dispersion relation shows that $E_{\|} \neq 0$ when $\lambda_j \neq 0$.

5. How Does the PF Accelerate Charged Particles?

[19] A force applied in a direction perpendicular to the ambient magnetic field (such as the PF) causes initial acceleration and energization of the charged particle. The kinetic energy of the particle relative to its original rest frame varies during its gyro-orbit. The amount of kinetic energy gain depends on where in the particle orbit the energy is measured (as a simple example for a cometary oxygen pickup ion, the the particle energy gain varies from zero to 51 keV over its orbit, *Tsurutani*, 1991). Thus, one has to view PF acceleration/energization as being of a stochastic nature.

[20] We note that there are other mechanisms to accelerate energetic particles by low frequency electromagnetic waves. *Janaki and Dasgupta* [1992] and *Chen et al.* [2001] have demonstrated that large amplitude waves at frequencies much below the cyclotron frequency can break the first adiabatic invariant. Also the high frequency components at the phase-steepened edges of the Alfvén wave could lead to resonant stochasticity [*Liberman and Lichtenburg*, 1983]. At this time we do not know the spectrum oe waves. High resolution Cluster data would be appropriate for such analysis.

6. Conclusion

[21] We have presented an explicit and fully kinetic analytical expression for the Lorentz part of the Ponderomotive force, $\mathbf{F}_{PMj}$, correct for all orders of $k_{\perp}\rho_L$. It is easily seen that the expression for $\mathbf{F}_{PMj}$ in the limit $\rho_L \rightarrow 0$ reduces to the usual cold plasma form.

[22] The expression for the PF contains the FLR effects of all order. The complete expression for the PF shows that higher order FLR contributions to the PF are associated with the higher order Bessel functions terms with resonance terms at higher gyroharmonics. The most important and significant difference between our expression for the PF associated with KAW, is that the PF is enhanced both at $\omega \rightarrow 0$ and at $\omega \rightarrow n\omega_{ci}$. As mentioned earlier, this is due to the specific nature of the polarization properties of the wave electric field associated with KAW ($E_{\|}$ vanishes when $\rho_L \rightarrow 0$). Thus PF can play an important role in accelerating particles by the parallel electric field even at low frequencies because of the FLR effects. Also, for the cases when λ is not so small, effects of PF can be significantly enhanced, not only for $\omega \rightarrow \omega_{ci}$, but also for $\omega \rightarrow n\omega_{ci}$. The multiple resonance character PF is not revealed in the fluid picture. Moreover, as shown in equation (20), even the first order expression for PF shows a resonance character at $\omega \rightarrow 2\omega_{ci}$.

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