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PARTIAL PONDEROMOTIVE FORCES OF ALFVÉN WAVES IN NEAR-EARTH PLASMA

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Abstract. In the study of the ponderomotive action of Alfvén waves on near-Earth plasma, the general formula for ponderomotive forces, known in classical electrodynamics of continuous media, was previously used. The formula does not explicitly take into account the multi-ion composition of the plasma. Under the action of the waves, significant changes were found in macroscopic parameters — plasma density and velocity. Plasma in Earth's magnetosphere contains ions with different charge-to-mass ratios. Besides hydrogen and helium ions, the plasma has an admixture of oxygen ions of ionospheric origin, as well as an admixture of other heavy ions. In this connection, a wide range of problems arise on the ponderomotive separation of ions of various types. To solve these problems, it is proposed to use partial ponderomotive forces and to describe the plasma not by hydrodynamic, but by quasi-hydrodynamic equations. In this paper, we discuss the derivation of partial forces for a traveling monochromatic Alfvén wave, and also suggest a method for deriving more general formulas by expanding the classical formula, known in macroscopic electrodynamic, into the sum of partial forces. The ponderomotive separation of ions is illustrated by the example of the problem for diffusion equilibrium of magnetospheric plasma. We propose a hypothesis that Alfvén waves redistribute plasma along geomagnetic field lines in such a way that the plasma at the magnetic field minima is characterized by an increased content of heavy ions. We suggest that a small admixture of heavy ions exists in the polar wind jet stream. The article is dedicated to the 80th anniversary of the discovery of Alfvén waves.

Keywords: electrodynamics, plasma, Alfvén wave, ponderomotive force, geomagnetic field, ambipolar diffusion, height scale, resonant acceleration, polar wind.

INTRODUCTION

The ponderomotive force is a force quadratic in amplitude and averaged over the oscillation period, which is exerted by an electromagnetic wave on charged particles. Near-Earth plasma features a rich variety of electromagnetic waves, but we are interested in ultralow-frequency (ULF) waves since their amplitude, as a rule, significantly exceeds the amplitudes of waves of other frequency ranges [Guglielmi, 1979].

The word "ponderomotive" comes from the Latin words pondus (weight) and motor (mover). The term "ponderomotive forces" was introduced in the old days when ether was considered in parallel with ordinary "heavy" bodies. In modern terminology, by ponderomotive force is usually meant a nonlinear average force characteristic of an oscillating field.

We have devoted a number of theoretical studies to the problem of ponderomotive forces in near-Earth plasma (see [Guglielmi, Feygin, 2018; Guglielmi, 1992; Feygin at al., 1997, 1998; Nekrasov, Feygin, 2013; Barnett et al., 2022; Espinoza-Troni et al., 2023] and references therein). At the same time, we considered the plasma medium in a hydrodynamic approximation as a whole. In contrast, in this paper we describe plasma quasi-hydrodynamically. This makes it possible to investigate the phenomenon of separation of ions with different charge-to-mass ratios when exposed to ponderomotive forces.

The second difference of this work from the previous ones is closely related to the first and lies in the fact that we use partial ponderomotive forces acting on electrons and ions of various types, and not the total ponderomotive force known in the electrodynamics of continuous media [Landau, Lifshits, 2003a] and acting on the unit volume of plasma medium. Finally, if we previously dealt with the ponderomotive forces of ion-cyclotron waves, now we focus on the ponderomotive forces of Alfvén waves. We should remind that Alfvén and ion-cyclotron waves belong to the same branch of dispersion curves [Ginzburg, 1967]. Thus, the results of this work naturally complement the results we have obtained earlier.

Recall that the existence of Alfvén waves was theoretically proved 80 years ago [Alfvén, 1942] (see also [Alfvén, 1950]). In the second half of the last century, it was established that the concept of Alfvén waves plays a key role in physics of geoelectromagnetic ULF waves [Nishida, 1980].

1. PONDEROMOTIVE FORCES

Consider a charged particle in the field of a traveling monochromatic Alfvén wave. The nonlinear part of the Lorentz force acting on the particle has the form $\frac{e}{c}[\mathbf{vb}]$, where e is the charge of the particle; c is the speed of light; $\mathbf{v}(\mathbf{x},t)$ is the particle velocity; $\mathbf{b}(\mathbf{x},t)$ is the Alfvén wave magnetic field. Ponderomotive redistribution of particles in near-Earth space (magnetosphere) occurs most effectively along geomagnetic field lines $\mathbf{B}(\mathbf{x})$. Accordingly, we focus on the longitudinal component of the $\frac{e}{c}[\mathbf{vb}]_{\parallel}$ nonlinear part of the Lorentz force. We should average this value over the oscillation period to obtain the ponderomotive force longitudinal component

$$F = \frac{e}{c}\left\langle [\mathbf{vb}]_{\parallel} \right\rangle = \frac{e}{2c}\mathrm{Re}\left[\mathbf{v}^{*}\mathbf{b}\right]_{\parallel}. \qquad (1)$$

To get a quadratic approximation for F, we use the linearized equation of motion and calculate $\mathbf{v}$. Finally, through the induction equation we express $\mathbf{b}$ in terms of the amplitude E of Alfvén wave electric field oscillations. Thus we obtain the gradient part of the ponderomotive force longitudinal component

$$F = \frac{mc^2}{4B^2}\partial E^2. \qquad (2)$$

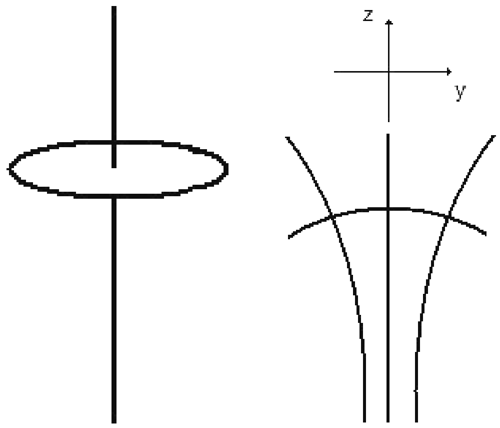
Here m is the particle mass; ∂ is the derivative along a geomagnetic field line.

It remains to add an additional term to the right side of (2)

$$F' = -\frac{mc^2}{2}\left(\frac{E}{B}\right)^2 \partial \ln B, \qquad (3)$$

arising due to the longitudinal inhomogeneity of the geomagnetic field. The additional term is sometimes called the force of diamagnetic ejection of a particle and this is reasonable. Indeed, look at the figure, or more precisely, at its left part. Shown here is the trajectory of a particle rotating around the external magnetic field line. The particle current field averaged over the rotation period is equivalent to the diamagnetic moment field. The moment can be calculated exactly in the homogeneous external magnetic field. If the external field decreases from the bottom up, from qualitative considerations we can assume that the particle will be ejected into the region of a weaker field. A disadvantage of this reasoning is that the condition of dependence $\mathbf{B}(z)$, where z is the coordinate along a homogeneous field line, contradicts the divergence-free condition $\nabla\cdot\mathbf{B}=0$. Correct the disadvantage and represent force (3) as a centrifugal force [Potapov, Guglielmi, 2010].

The quasi-vertical lines in the right part of the figure are lines of the homogeneous magnetic field. The electric field is directed perpendicular to the plane of the figure. At the top of the figure is the orientation of coordinate axes. Constant magnetic and alternating electric fields have components $\mathbf{B}=(0,B_y,B_z)$ and $\mathbf{E}=(E_x,0,0)$, with $B_y=-y\partial B$, $B_z=B(z)$, $E_x=E\exp(-i\omega t)$. Here, $\mathbf{E}\perp\mathbf{B}$, as it should be within the framework of ideal magnetic hydrodynamics [Alfven, 1950], the field nonuniformity $\mathbf{B}$ is also clearly taken into account from the very beginning. We analyze the charge motion in a small neighborhood of the Z-axis such that $|B_y| \ll |B_z|$



Two views on the origin of the ponderomotive force of diamagnetic ejection (see text)

and $|\mathbf{B}|\approx|B_z|$. The field $\mathbf{B}$ is divergence-free $(\nabla\cdot\mathbf{B}=0)$, and we have $B_y=-y\nabla_{\parallel}B$. Here, $B(z)=B_z(z)$, $\nabla_{\parallel}=\partial/\partial z\equiv\partial$. The curve segment in the right part of the figure is the particle electric drift path. The drift curvature radius is equal to $R=-(\nabla_{\parallel}\ln B)^{-1}$. The above formulas allow us to calculate the centrifugal acceleration, which, after multiplied by mass and averaged over time, yields Formula (3).

Expression (2) needs an additional transformation because of the following reasons. Satellite measurements give local values of E. In order to be able to compare theoretical conclusions with observational data, it is necessary to express the term ∂E^2 through E. To do this, we apply the Umov—Poiting theorem, which in this case has the form $\nabla\cdot\langle\mathbf{S}\rangle=0$, where $\mathbf{S}=\frac{c}{4\pi}[\mathbf{Ed}]$ is the Poiting vector. After simple transformations, we get

$$\partial E^2 = E^2\partial\ln\left(B^2/\rho^{1/2}\right). \qquad (4)$$

When deriving (4), we used the relation $b=\frac{c}{c_{\mathrm{A}}}/E$, that holds for Alfvén waves. Here $c_{\mathrm{A}}=B/\sqrt{4\pi\rho}$ is the Alfvén velocity; ρ is the plasma density.

Combining formulas (2)–(4) yields

$$F = -\frac{mc^2}{8}\left(\frac{E}{B}\right)^2\partial\ln\rho. \qquad (5)$$

The occurrence of the ponderomotive force of a traveling monochromatic Alfvén wave is seen to depend on the irregularity of plasma density distribution along geomagnetic field lines, but does not explicitly depend on the geomagnetic field nonuniformity.

The question arises for what purpose we use ponderomotive forces instead of the simpler Lorentz force (see, e.g., the monograph [Landau, Lifshitz, 2003b], which contains a number of classical problems solved using the fundamental Lorentz force). This is explained by the fact that the dynamics of charge motion driven by the Lorentz force often turns out to be very complex and not always physically clear. The rather cumbersome formulas for ponderomotive forces significantly simplify the dynamics and expand the range of problems that admit a solution and are of geophysical interest.

2. DIFFUSION EQUILIBRIUM

For simplicity, we consider the magnetospheric plasma isothermal and neglect collisions between particles. We describe the balance of forces acting along geomagnetic field lines, using a system of quasi-hydrodynamic equations

$$\partial p_{\mathrm{e}} = m_{\mathrm{e}} N g_{\|} - eNE_{\|} + f_{\mathrm{e}}, \tag{6}$$

$$\partial p_i = m_i N_i g_{\|} + eN_i E_{\|} + f_i. \tag{7}$$

Here, p_{e} and p_i are partial pressures of electrons and ions; the i index indicates ion species, all ions are considered singly charged and positive; m_{e} and m_i are electron and ion masses; N is the electron density; N_i is the ion density; $g_{\|}$ is the projection of gravity acceleration on the tangent to the geomagnetic field line; e is the elementary electric charge; $E_{\|}$ is the ambipolar electric field; $f_{\mathrm{e}} = NF_{\mathrm{e}}$ and $f_i = N_i F_i$ are the partial ponderomotive forces acting respectively on electrons and ions in a unit volume of plasma. Add the equations of state $p_{\mathrm{e}} = NT$ and $p_i = N_i T$, where T is the plasma temperature, to (6), (7). Combining (6) and (7) in view of the equations of state and the quasineutrality condition $N = \sum N_i$, find an ambipolar electric field

$$E_{\|} = -\frac{m_+}{2e} G, \tag{8}$$

where $G = g_{\|} + a$, a is the ponderomotive acceleration

$$a = -\frac{b^2}{32\pi\rho} \partial \ln \rho. \tag{9}$$

Substituting (8) in (7) yields a system of equations describing the spatial distribution of ions

$$T \partial \ln N_i = \left(m_i - \frac{m_+}{2} \right) G. \tag{10}$$

Here $m_+ = \rho / N$ is the mean ionic mass.

Above the maximum of the ionospheric F2 layer, the plasma density ρ decreases with distance from Earth. Accordingly, the ponderomotive acceleration a is upward. Ponderomotive reduction of gravity acceleration occurs which leads to interesting consequences.

In the simplest case, the masses of all ions are the same, $m_+ = m_{\mathrm{i}}$ and (10) takes the form

$$\left(c_{\mathrm{s}}^2 - \frac{\alpha}{\sqrt{\rho}} \right) \partial\rho = g_{\|} \rho. \tag{11}$$

Here, $c_{\mathrm{s}} = \left(2T / n_i \right)^2$, $\alpha = \frac{b_0^2}{32\pi} \sqrt{\rho_0}$, b_0, ρ_0 are values at a point on a given field line, for example, at a satellite measurement point. At high latitudes, the geomagnetic field lines are almost vertical, and Equation (11) can be rewritten as

$$\frac{1}{\rho} \left(c_{\mathrm{s}}^2 - \frac{\alpha}{\sqrt{\rho}} \right) \frac{d\rho}{dr} = -\frac{\kappa M}{r^2} \tag{12}$$

and integrated as

$$\frac{r_0}{r} = 1 + \beta \left\{ \ln\left(\frac{\rho\ r}{\rho_0} \right) + \gamma \left[1 - \left(\frac{\rho_0}{\rho\ r} \right)^{1/2} \right] \right\}. \tag{13}$$

Here, M is Earth's mass; κ is the gravitation constant; r is the distance from the center of Earth; r_0 is the above point;

$$\beta = \frac{c_{\mathrm{s}}^2 r_0}{\kappa M}, \quad \gamma = \frac{b_0^2 r_0}{32\pi N_0 T}.$$

The parameter γ characterizes the efficiency of ponderomotive redistribution of plasma density. In passing from $\gamma \ll 1$ to $\gamma \gg 1$, the exponential density decrease at $r \sim r_0$ is replaced by a power-law one. If $\beta \ll 1$, at a distance, say, twice r_0, a strong modification of the density occurs already at

$$\gamma > \exp\left(-\frac{1}{2\beta} \right). \tag{14}$$

In general, to study the spatial redistribution of ions, it is necessary to solve system of quasi-linear equations (10). There is a wide variety of statements of the problem. Let us limit ourselves to a qualitative analysis of the case when plasma contains a mixture of ions of only two species — light (i=1) and heavy (i=2). It can be shown that N_2 decreases with distance from Earth, and N_1 has one maximum. Combine the point r_0 with the maximum density of light ions. Then it follows from (10) that the local height scale for heavy ions increases under the action of the Alfvén wave by a factor of $\gamma' + 1$, and

$$\frac{\gamma'}{\gamma} = \frac{2m_2}{m_1} \left(\frac{m_2 - 2m_1}{m_2 - m_1} \right)^2. \tag{15}$$

For example, for a mixture of H^+ and O^+ ions, γ' is almost 30 times larger than γ. In this sense, we can say that the presence of ions in plasma with different charge-to-mass ratios improves the efficiency of the ponderomotive force of Alfvén waves.

3. DISCUSSION

We have derived formulas for partial forces f_{e}, f_i from the heuristic considerations outlined in Section 1. Is it possible to derive the same formulas by the regular method? Let us discuss this question since it is important in two aspects. First, the canonical derivation will confirm the correctness of our formulas. Second, as we will see, it will be possible to go beyond the ideal magnetic hydrodynamics when analyzing the problem of ponderomotive ion separation.

Proceed from the general expression for the longitudinal component of the total ponderomotive force acting on a unit volume of magnetospheric plasma,

$$f_\Sigma = \frac{1}{16\pi}\left[\left(\varepsilon_{\alpha\beta} - \delta_{\alpha\beta}\right)\partial E_\alpha^* E_\beta + E_\alpha^* E_\beta \frac{\partial \varepsilon_{\alpha\beta}}{\partial \mathbf{B}} \partial \mathbf{B}\right]. \quad (16)$$

Here, $\varepsilon_{\alpha\beta}$ is the plasma permittivity tensor; $\delta_{\alpha\beta}$ is the Kronecker symbol [Landau, Lifshitz, 2003a]. Apply the well-known formula of phenomenological electrodynamics

$$\varepsilon_{\alpha\beta} = \delta_{\alpha\beta} + \frac{4\pi i}{\omega}\sigma_{\alpha\beta} \quad (17)$$

and express f_Σ through the electrical conductivity tensor $\sigma_{\alpha\delta}$ [Lifshits, Pitaevsky, 1979]. In view of the additivity of current, the $\sigma_{\alpha\delta}$ tensor is the sum of partial conductivities of plasma due to charged particles of all species: $\sigma_{\alpha\beta} = \sum_p \sigma_{\alpha\beta}^p$. Here, $\sigma_{\alpha\beta}^p$ is the contribution of p particles to the conductivity tensor. Substitute the sum $\sum_p \sigma_{\alpha\beta}^p$ in the right part of Formula (16) and get a decomposition of f_Σ into the sum of partial forces. After that, it remains to use the well-known expressions for partial conductivities, for example, in the cold plasma approximation [Guglielmi, 1979], to apply polarization relations for the Alfvén wave electric field components E_α, and to neglect all terms of the form of ω/Ω_i as compared to 1. As a result, we obtain the formulas for partial forces applied in Section 2.

An interesting conclusion about the ponderomotive redistribution of ions can be drawn if we take into account the terms of the order of ω/Ω_i, but at the same time retain the condition $\omega<\Omega_{\min}$, where $\Omega_{\min} = \dfrac{eB}{m_{\max} c}$ is the gyrofrequency of the heaviest ions. The conclusion concerns the chemical composition of plasma in geomagnetic field minima. Let us discuss the problem in more detail.

It has been shown [Guglielmi, Feygin, 2018] that taking into account the terms ω/Ω_i in the expression for the ponderomotive force leads to the conclusion that there are maxima of the plasma density ρ in minima of the geomagnetic field B. In the central regions of the magnetosphere, the minima are located in the plane of the geomagnetic equator. On the periphery of the dayside magnetosphere, two minima are symmetrical at a distance from the equator plane. In the calculations, plasma was described hydrodynamically, i.e. without regard to its multi-ion composition. The quasi-hydrodynamic description allows us to make the following important clarification. Since the effect of ponderomotive sweeping of plasma to the field minima is stronger the closer is the value of ω/Ω_i to 1, an increased content of heavy ions should be observed in maxima of the plasma density ρ. Generally speaking, this prediction allows for experimental verification by satellite mass spectrometric measurements.

If the condition $\omega<\Omega_{\min}$ is violated, sharp changes will occur in the structure of Alfvén waves. Along the propagation path, the refractive index zero and pole will appear, with an opacity band between them. Assume that the concentration of heavy ions is so small that the presence of the opacity band can be neglected. The Alfvén wave will cross the band with almost no distortions. At the same time, heavy ions in the vicinity of the resonance $\omega=\Omega_{\min}$ will experience an abnormally high upward acceleration. However, detailed analysis of the ponderomotive resonance acceleration of heavy ions in the Alfvén wave field calls for a separate study.

Concluding the discussion, we would like to touch upon the question about the quasi-hydrodynamic description of multi-ion plasma stream. It is known that there is an anabatic flow over the polar cap, called the polar wind (see, e.g., [Banks, Holzer, 1968; Chugunin et al., 2018]). At a sufficiently large distance from Earth, the polar wind consists mainly of hydrogen ions with a small admixture of heavy ions, such as oxygen ions. In the hydrodynamic approximation, plasma acceleration driven by Alfvén waves is shown to increase upstream [Guglielmi, Feygin, 2018]. The quasi-hydrodynamic description makes it possible to make an important clarification. Namely, at $\omega\sim\Omega_{o+}$ there is a significant correction to the partial force acting on heavy ions. As a result, fast jet streams of heavy ions can occur in the polar wind flow.

CONCLUSION

We have put forward the idea about partial ponderomotive forces of electromagnetic ULF waves in plasma. Formulas for partial forces make it possible to turn from a hydrodynamic description of the effect of waves on plasma to the quasi-hydrodynamic one. This significantly expands the range of problems for the redistribution of multi-ion magnetospheric plasma along geomagnetic field lines under the influence of ULF waves of natural origin. Within the framework of the traveling monochromatic Alfvén wave model, gradient and centrifugal forces, proportional to ∂E^2 and $E^2\partial B$ respectively, act in collisionless plasma. Already in this simplest model, the theory can be predictive. However, in terms of non-monochromaticity, the range of interesting problems expands due to the appearance of the Abraham force [Ginzburg, 2020], proportional to $\partial E^2/\partial t$. The Abraham force can also be decomposed into partial forces by the method discussed above. Taking into account the collision frequency ν between particles in the ionosphere opens up additional possibilities due to the ponderomotive force proportional to νE^2. Note that, for an obvious reason, in macroscopic electrodynamics [Landau, Lifshitz, 2003b] a force of this kind is ignored in the general expression for ponderomotive force, hence the question about decomposition into partial forces does not arise.

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