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PONDEROMOTIVE REDISTRIBUTION OF HEAVY IONS ALONG A MAGNETIC FIELD LINE

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Abstract. We set up the problem of ponderomotive separation and acceleration of ions with different charge-to-mass ratios under the influence of Alfvén waves, which constantly exist in the magnetosphere in the form of geomagnetic pulsations. Formulas for partial ponderomotive forces acting on light and heavy (metallic) ions are derived. In the quasi-hydrodynamic approximation, a system of equations is obtained which describes the distribution of ions along magnetic field lines in Earth's magnetosphere. The Clarke number, which characterizes plasma metallicity, is found to be maximum at a minimum magnetic field on the field line along which the Alfvén wave propagates. This leads to the accumulation of heavy ions at the top of the field line at the point of its intersection with the magnetic equator. The theoretical conclusions agree with satellite measurements of the distribution of heavy ions along field lines in Earth's magnetosphere.

Keywords: partial ponderomotive forces, Alfvén waves, heavy ions, Clarke number, ambipolar diffusion, geomagnetic field.

INTRODUCTION

In a linear approximation, propagation of a monochromatic electromagnetic wave in plasma is accompanied by the harmonic motion of electrons and ions. If we use a quadratic approximation in wave amplitude and average over the oscillation period, it turns out that a ponderomotive force **f** acts on a unit volume of plasma. Assume that the plasma is in the external magnetic field **B**, as is the case for Earth's magnetosphere, and decompose the force **f** into longitudinal and transverse components with respect to **B**. The general phenomenological expression for **f** is given in the fundamental monograph [Landau, Lifshitz, 2003]. We focus on the longitudinal component

$$f_\parallel = \frac{1}{16\pi}\left[\left(\varepsilon_{ik}-\delta_{ik}\right)\nabla_\parallel E_i^* E_k + E_i^* E_k \frac{\partial\varepsilon_{ik}}{\partial\mathbf{B}}\partial\mathbf{B}\right], \qquad (1)$$

since under its influence plasma accelerates along geomagnetic field lines, whereas the transverse component leads only to plasma drift at a constant speed. Here, $\varepsilon_{ik}(\omega)$ is the plasma permittivity tensor [Ginzburg, 1967]; **E** is the amplitude of electric field oscillations; the asterisk marks complex conjugation; δ_{ik} is the Kronecker symbol; ω is the wave frequency. The plasma permittivity tensor has the form [Lifshitz, Pitaevsky, 1979]

$$\varepsilon_{ik} = \varepsilon_\perp\delta_{ik} + \left(\varepsilon_\parallel - \varepsilon_\perp\right)\tau_i\tau_k + ig\delta_{ikm}\tau_m, \qquad (2)$$

$$\varepsilon_\perp = 1 - \sum\omega_0^2\Big/\left(\omega^2-\Omega^2\right),$$

$$\varepsilon_\parallel = 1 - \sum\omega_0^2/\omega^2, \qquad (3)$$

$$g = -\sum\Omega\omega_0^2\Big/\left[\omega\left(\omega^2-\Omega^2\right)\right].$$

Here δ_{ikm} is the Levi-Civita symbol; $\boldsymbol{\tau}=\mathbf{B}/B$ is a unit vector tangent to the external magnetic field line; the summation in (3) is performed for particles of all types (electrons, ions); $\omega_0 = \left(4\pi e^2 N/m\right)^{1/2}$ is the plasma frequency; $\Omega = eB/mc$ is the cyclotron frequency; e, m, and N are the charge, mass, and concentration of particles of a given type; c is the speed of light.

In Earth's magnetosphere, the most powerful wave activity occurs in the magnetohydrodynamic (MHD) range. We limit ourselves to the analysis of the ponderomotive force of Alfvén waves [Alfvén, 1952], which are represented in the magnetosphere by various geomagnetic pulsations [Guglielmi, 1979; Nishida, 1980; Guglielmi, Potapov, 2021]. It has been shown [Potapov et al., 2002; Potapov, Guglielmi, 2010; Guglielmi, Feygin, 2018; Feigin, Guglielmi, 2023] that under the influence of Alfvén and ion-cyclotron waves a noticeable redistribution of plasma occurs along geomagnetic field lines. The ponderomotive force "rakes" the plasma toward the minimum of the magnetic field, i.e. toward the plane of the geomagnetic equator with a dipole approximation of the external magnetic field, resulting in an equatorial compaction of plasma.

On theoretical grounds, the traveling Alfvén wave is of particular interest. The wave trajectory coincides with the geomagnetic field line, and at each point of the trajectory the relation holds

$$\nabla_\parallel E_\perp^2 = E_\perp^2\nabla_\parallel \ln\left(B^2\big/\sqrt{\rho}\right), \qquad (4)$$

where $\rho = \sum m_i N_i$ is the plasma density; m_i and N_i are the mass and concentration of i-type ions, and the summation is made over ions of all types (see, e.g., [Guglielmi, 1992]).

From (1), in view of (4), a simple expression for the ponderomotive force follows

$$f_{\|} = -\frac{1}{8}\left(\frac{cE_{\perp}}{B}\right)^2 \nabla_{\|}\rho, \qquad (5)$$

which is convenient for calculations.

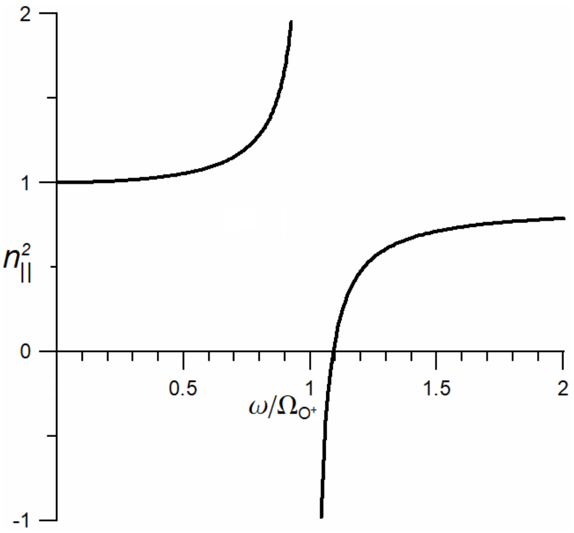
Formula (5) is applicable when the strong inequality $\omega \ll \min\{\Omega_i\}$ holds, where $\Omega_i = e_i B / m_i c$ is the ion gyrofrequency. In this case, the dispersion equation for Alfvén waves has the form $n_{\|}^2 = \varepsilon_{\perp}$, with $\varepsilon_{\perp} = c^2 / c_{\mathrm{A}}^2$, where $c_{\mathrm{A}} = B / \sqrt{4\pi\rho}$ is the Alfvén velocity; $n_{\|} = ck_{\|} / \omega$, , $k_{\|}$ is the longitudinal component of the wave vector. It is assumed that $c_{\mathrm{A}} \ll c$ (dense plasma) and $k_{\|} \ll k_{\perp}$ (quasi-transverse propagation).

When $\omega \ll \min\{\Omega_i\}$ all ions move with the same acceleration under the action of the Alfvén wave. This limits the range of problems to be solved analytically, in particular, does not allow us to analyze the ponderomotive separation of ions with different charge-to-mass ratios.

However, the strong inequality $\omega \ll \min\{\Omega_i\}$ can be reduced. For example, it suffices to assume that in a two-component plasma containing electrons, protons, and oxygen ions O^+, $\omega < \Omega_{\mathrm{O}^+}$ provided always that the above inequality is not violated at any point on the trajectory of the traveling wave. If the additional condition is violated, the wave field structure is sharply complicated, which makes the analytical study of the ponderomotive redistribution of ions more difficult.

Let us explain this with the help of Figure. It shows the dispersion curve for Alfvén waves at the Clarke value of oxygen $\kappa = \rho_{\mathrm{O}^+} / \rho_{\mathrm{H}^+} = 0.2$, where ρ_{O^+} and ρ_{H^+} are the densities of oxygen and hydrogen ions respectively. Hereinafter, the term "Clarke number", or simply "Clarke", is used. It is common in the geophysical and cosmophysical literature. Classical Clarke expresses the average content of chemical elements in a certain system in relation to the total mass of this system. We have somewhat expanded the meaning of this term to utilize it as an indicator of plasma metallicity. In this paper, Clarke, in fact, represents the ratio of Clarke of oxygen to Clarke of hydrogen. By the corresponding system we mean a rather small volume of plasma within which the densities of ions of both types are uniform. Recall that metallicity in astro- and cosmophysics is commonly referred to as the relative concentration of elements heavier than hydrogen and helium in stars or other astronomical objects [https://www.aanda.org/glossary/194- metallicity].

We can see that at $\omega > \Omega_{\mathrm{O}^+}$ there is a reflection point ($n_{\|} = 0$) of a wave propagating into a stronger magnetic field. This leads to the formation of a specific resonator in the magnetosphere in the vicinity of the geomagnetic equator [Guglielmi et al., 2000; Guglielmi and Potapov, 2012]. The waves in the resonator are standing. Simple self-consistency condition (4) is not met for them. Nonetheless, self-consistency is necessary since the ponderomotive modification of plasma affects the intensity of the wave whose action causes this modification.



Dispersion curve for Alfvén waves in quasi-transverse propagation in hydrogen-oxygen plasma. The longitudinal refractive index $n_{\|} = ck_{\|} / \omega$ is expressed in c/c_{A}

We deal with the effect of traveling Alfvén waves on plasma; therefore, we assume that the condition of the form $\omega < \Omega_{\mathrm{O}^+}$ is fulfilled along the entire wave trajectory. We show that the ponderomotive forces acting on ions with different charge-to-mass ratios are greater the lower the specified ratio. As a result, ponderomotive separation of ions occurs, and the chemical composition of the plasma changes. In particular, heavy ions accumulate in the vicinity of the geomagnetic equator in the dipole model of the magnetosphere, i.e. plasma metallicity increases. Thus, we can talk about metallization of magnetospheric plasma in magnetic field minima on the field lines along which Alfvén waves propagate.

1. PARTIAL FORCES

Decompose ponderomotive force (1) into the sum of partial ponderomotive forces: $f_{\|} = \sum f_{\|s}$. Here $s=e$, i; the subscripts e and i denote electrons and ions. Take into account the relation

$$\varepsilon_{ik} = \delta_{ik} + \frac{4\pi i}{\omega}\sigma_{ik} \qquad (6)$$

and use the additivity of the complex electrical conductivity tensor: $\sigma_{ik} = \sum \sigma_{iks}$. Then, we express $f_{\|s}$ through σ_{iks}; σ_{iks} is the contribution of charged s-type particles to electrical conductivity.

Select the geomagnetic field line along which the Alfvén wave propagates and introduce a concomitant coordinate system (x, y, z) in the vicinity of the line such that the X-axis is directed along the binormal, and the Z-axis is tangential. Using (1), (3), (4), (6), we get

$$f_{\|s} = -\frac{E_{\perp}^2}{8\pi}\left(\frac{\omega_{0s}^2}{\Omega_s^2 - \omega^2}\right)\left[\partial \ln \rho^{1/4} + \left(\frac{\omega^2}{\Omega_s^2 - \omega^2}\right)\partial \ln B\right], \qquad (7)$$

where $\partial \equiv \partial / \partial z$.

Let us give expressions for the partial forces acting on electrons, protons, and singly charged oxygen ions in a two-component plasma:

$$f_{\|\mathrm{e}} = -\frac{1}{8}\left(\frac{cE_\perp}{B}\right)^2 \rho_\mathrm{e}\partial \ln \rho, \tag{8}$$

$$f_{\|\mathrm{H}^+} = -\frac{1}{8}\left(\frac{cE_\perp}{B}\right)^2 \rho_{\mathrm{H}^+}\partial \ln \rho, \tag{9}$$

$$f_{\|\mathrm{O}^+} = -\frac{E_\perp^2}{8\pi}\left(\frac{\omega_{0\mathrm{O}^+}^2}{\Omega_{\mathrm{O}^+}^2-\omega^2}\right)\times \left[\partial \ln \rho^{1/4} + \left(\frac{\omega^2}{\Omega_{\mathrm{O}^+}^2-\omega^2}\right)\partial \ln B\right]. \tag{10}$$

2. DIFFUSION EQUILIBRIUM

Examine the static equilibrium of a two-component isothermal plasma in the quasi-hydrodynamic approximation. The balance of forces acting along the geomagnetic field line is described by the equations

$$\partial p_\mathrm{e} = \rho_\mathrm{e} g_\| - eNE_\| + f_{\|\mathrm{e}}, \tag{11}$$

$$\partial p_i = \rho_i g_\| + eN_i E_\| + f_{\|i}. \tag{12}$$

Here $p_\mathrm{e}=NT$ and $p_i=N_iT$ are the partial pressures of electrons and ions; T is the temperature; N is the electron density; $g_\|$ is the longitudinal projection of gravitational acceleration; $E_\|$ is the electric field of ambipolar diffusion. The index i takes values 1 and 2 for quantities related to light and heavy ions respectively. Equations (7)–(11), in view of the quasi-neutrality condition $N = N_1 + N_2$, yield an expression for the ambipolar electric field

$$E_\| = -\frac{m_+}{2e}\left(g_\| + a_\|\right), \tag{13}$$

where $a_\| = \left(f_{\|1} + f_{\|2}\right)/\rho$ is the ponderomotive acceleration; $m_+ = \rho / N$ is the average ion mass. By substituting (13) into (12), we obtain two first-order nonlinear differential equations

$$T\partial N_i = \left(m_i - \frac{m_+}{2}\right)N_i g_\| - \frac{N_i}{2N}\left(f_{\|1} + f_{\|2}\right) + f_{\|i}, \tag{14}$$

describing the distribution of ions i=1, 2 along the geomagnetic field line.

3. DISCUSSION

We have compiled system of differential equations (14) describing the ponderomotive effect of Alfvén waves on the distribution of ions with different charge-to-mass ratios along geomagnetic field lines. It is advisable to conduct a general study of (14), taking into account rather cumbersome formulas for partial forces (7), using numerical methods. In this preliminary study, we limit ourselves to qualitative analysis of two extreme cases.

In the case of sufficiently small Clarke numbers $\kappa = \rho_2 / \rho_1$, the system of equations is simplified and allows an analytical solution. Examine the so-called magnetic well, i.e. the small neighborhood of the point on the magnetic field line at which the field strength is minimum. The magnetic field increases quadratically with distance from the bottom of the well. From (7), (14), omitting cumbersome calculations, we get the dependence $\kappa(z)$:

$$\kappa(z)=\kappa(0)\exp(-\alpha z^2). \tag{15}$$

Here,

$$\alpha = \frac{e^2E_\perp^2}{4m_2T}\left(\frac{\omega}{\Omega_2^2-\omega^2}\right)^2\frac{1}{B}\frac{d^3B}{dz^2}. \tag{16}$$

The distance z is measured along the field line from the point z=0, where the field B is minimum. The quantities Ω_2, $E_\perp$, B, and d^3B/dz^2 refer to z=0.

In the dipole magnetosphere, minimum B is located at the point of intersection of the field line with the equatorial plane. We can see that the number κ characterizing plasma metallicity is maximum at the top of the field line along which the Alfvén wave propagates. The value κ is proportional to the square of the wave amplitude; and the larger is the value, the smaller is the frequency difference $\Omega_2-\omega$.

Thus, we come to the conclusion that the density distribution of O^+ ions exhibits a maximum at the magnetic equator of the field line. It is interesting to compare our conclusion with satellite data on ion density in the magnetosphere. For obvious reasons, direct observations of ion distribution along geomagnetic field lines are extremely difficult; therefore, an indirect measurement method was employed in [Takahashi et al., 2004]. The idea is that the structure of the spectrum of toroidal MHD oscillations in the magnetosphere depends crucially on plasma distribution along geomagnetic field lines. By measuring the frequency ratios of electric and magnetic oscillation spectrum harmonics, we can judge the plasma density distribution along magnetic field lines. The CRRES satellite was used for observations and thorough analysis of oscillations in the afternoon sector of the magnetosphere (12–18 MLT) in the range of magnetic shells L from 4 to 8. The results [Takahashi et al., 2004] suggest that the distribution of mass ion density over shells $4<L<6$ does not differ from the electron density distribution measured earlier by radio sounding: both are minimum in the region of the magnetic equator. At higher shells ($L\geq6$), the electron density behavior remains the same, whereas the ion density has a local maximum at the intersection of the magnetic shell with the equatorial plane. This can only be the case if (while maintaining the plasma quasi-neutrality) heavy ions, primarily oxygen ions, make a significant contribution to the total ion density. The fact that Takahashi et al. [2004] did not see a local maximum of O^+ ions at lower L does not mean that it is absent there. It may turn out that on lower shells the O^+ concentration also has a maximum at the equator, yet it is not large enough to cause a significant change in the ion density distribution along the magnetic field line and hence the formation of a local maximum at the magnetic equator. According to [Fuselier, 2020], in the dayside magnetosphere, where Takahashi et al. [2004] carried out measurements, the concentration of oxygen ions is maximum in the region adjacent to the magnetopause and decreases at lower shells. In general, the study into the *L*-parameter dependence of the effect of heavy ion accumulation at the top of the magnetic field line requires both a separate theoretical study and a more accurate statistically justified experimental assessment of plasma ion density profiles at various heights. We, therefore, only state that our theoretical results do not contradict the CRRES satellite indirect measurements.

Additional evidence for our theory is in [Denton et al., 2006] in which the dependence of the ion distribution along magnetic field lines on the geomagnetic activity indices and the intensity of toroidal oscillations has been analyzed. The authors also found a maximum density of heavy ions at the equator of the magnetic shell. At the same time, a nonmonotonic change in the plasma mass density with a local maximum at the equator was observed for *L* from 6 to 8, and the degree of nonmonotonicity increased with *L*. The question arises as to at what values of *L* our theory can work. If we talk about fundamental equations (7)–(14), the applicability of our theory is in no way related to *L*. The conditions for the applicability of these equations are defined in the text. The equations can be applied not only to the magnetosphere, where the spatial structure of the magnetic field depends crucially on *L*, but also (with some reservations) to other plasma formations in space, where a parameter similar to *L* may not exist. As for the magnetosphere, we do not see any fundamental limitations on *L*. The limitations may be associated with the conditions for the applicability of the fundamental formulas, but we have already mentioned this.

Thus, our theory works for any *L*, but the degree of accumulation of heavy ions at the top of the magnetic field line depends on their concentration. Fuselier [2020] has shown that the highest concentration of oxygen ions in the dayside magnetosphere is observed in the region of the low-latitude warm plasma cloak on the inner side of the magnetopause. It was there that Takahashi et al. [2004] and Denton et al. [2006] have found the most distinct peaks of mass ion density near the magnetic equator. Note that Denton et al. [2006] consider ponderomotive forces to be the most likely driver of the upward motion of heavy ions that causes the ion density to increase near the equator.

The second extreme case refers to regions of the magnetosphere with large Clarke numbers far exceeding unity. It would seem that we can only talk about plasma sheets directly adjacent to the F2 layer of the ionosphere from above, but this is not entirely true. A relatively high content of O^+ ions was detected at the periphery of the dayside magnetosphere during geomagnetic disturbances. For example, the review [Fuselier, 2020] indicates that concentrations of protons and singly charged oxygen ions are 0.5 and 0.2 cm^{-3} respectively. These values correspond to $\kappa = 6.4$. The review [Kronberg et al., 2014] and the papers [Roberts et al., 1987; Fuselier et al., 1989; Nosé et al., 2009, 2011; Denton et al., 2019] also contain information indicating the abundance of the oxygen ions of ionospheric origin in the magnetosphere.

When $\kappa \gg 1$, Equations (14) can be simplified. The distribution of O^+ almost completely determines the distribution of plasma density along geomagnetic field lines. If $\omega < \Omega_{O^+}$, as we assume, a situation arises that is formally similar to that analyzed in detail when solving the problem of the effect of ponderomotive forces on a two-component plasma consisting of electrons and H^+ ions. With the dipole configuration of the geomagnetic field, the ion distribution pattern is qualitatively as follows: three density extremes are formed with a maximum at the magnetic equator of the field line and two symmetrically located minima [Guglielmi, 1992; Lundin, Guglielmi, 2006].

CONCLUSION

We have examined the problem of ponderomotive separation of ions with different charge-to-mass ratios under the influence of Alfvén waves and have derived formulas for partial ponderomotive forces acting on light and heavy (metallic) ions. A system of equations describing the distribution of ions along magnetic field lines in Earth's magnetosphere is obtained in the quasi-hydrodynamic approximation. We have found that the Clarke number characterizing plasma metallicity is maximum at the magnetic field minimum on the field line along which the Alfvén wave propagates.

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