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► To cite this version:

O. Pokhotelov, F. Feygin, L. Stenflo, P. Shukla. Ponderomotive Forces Near the Dayside Magnetospheric Boundary. Journal de Physique IV Proceedings, 1995, 05 (C6), pp.C6-49-C6-52. 10.1051/jp4:1995609 . jpa-00253972

HAL Id: jpa-00253972

<https://hal.science/jpa-00253972>

Submitted on 1 Jan 1995

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Ponderomotive Forces Near the Dayside Magnetospheric Boundary

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Abstract. It is shown that the existence of the so-called “magnetic holes” (magnetic field minima) along the field lines play a significant role in the plasma pressure balance in the Earth’s magnetosphere. Ponderomotive forces induced by the Pc1 geomagnetic pulsations propagating through these regions can lead to a significant plasma accumulation there.

1. INTRODUCTION

Investigations of ponderomotive forces induced by geomagnetic pulsations have shown that they can significantly contribute to the plasma balance in the Earth’s magnetosphere [1-4]. It is known [2-4] that if the amplitude of the Pc1 pulsations exceeds some critical value then a pronounced maximum of the plasma density is formed in the vicinity of the apex of the Pc1 trajectory. It is evident that its position coincides with a minimum of the dipole magnetic field along that trajectory.

In previous studies this effect was analyzed with the dipole approximation in the close vicinity of the equatorial plane and near high latitudes where the geomagnetic field lines are nearly radial. However, such approximations are justified only at small altitudes. The magnetic data collected by satellites, and theoretical models of the geomagnetic field show a complex structure of the geomagnetic field at the midday boundary of the Earth’s magnetosphere. This structure is characterized by a smooth transition from a “V” to a “W” magnetic field shape with two minima in the magnetic field along the field lines [5]. This brings up the question whether the existence of two maxima in the distribution of the geomagnetic field along the field lines leads to the appearance of two maxima in the distribution of the plasma density along the Pc1 trace, and, consequently, how this will influence the conditions for Pc1 generation and propagation. In this paper, we shall consider the ponderomotive force action induced by the geomagnetic pulsations in the dayside magnetosphere.

2. GOVERNING EQUATIONS

In a spherical coordinate system, the magnetic field components for the two-dipole model in the meridional noon-midnight plane have the form

$$B_r = -\frac{2B_E x}{r^3} \alpha, \quad (1)$$

and

$$B_\varphi = \frac{B_E}{r^3} \sqrt{1-x^2} \beta, \quad (2)$$

where r is the geocentric radial distance (r is measured in units of the Earth's radius R_E), $x = \sin \varphi$, φ is the geomagnetic latitude, B_E is a constant ($B_E = 0.3$ gauss), and

$$\alpha = 1 - \frac{kr^3(a^2 - 2r^2 + ar\sqrt{1-x^2})}{2(a^2 + r^2 - 2ar\sqrt{1-x^2})^{5/2}}, \quad (3)$$

and

$$\beta = 1 + \frac{kr^3(\sqrt{1-x^2}(a^2 + r^2) - ar(2+x^2))}{\sqrt{1-x^2}(a^2 + r^2 - 2ar\sqrt{1-x^2})^{5/2}}, \quad (4)$$

where k and a are two constant model parameters [5]. Thus, the magnetic field at an arbitrary point at the field lines and the equation for the field line are determined by

$$B = \frac{B_E}{r^3} [4x^2\alpha^2 + (1-x^2)\beta^2]^{1/2}, \quad (5)$$

and

$$dr/dx = -\frac{2rx}{(1-x^2)} \frac{\alpha}{\beta}. \quad (6)$$

Here we consider the case where the axis of the original and the additional dipoles are parallel to each other. The analysis will then reveal the existence of two minima of the magnetic field which are shifted from the equator of the field line near the dayside boundary of the magnetosphere. This is in contrast to the one-dipole model with the minimum of the magnetic field at the equator. That picture is also confirmed by satellite observations. Below we choose the parameters $a = 33$ and $k = 13$, which corresponds to the dayside boundary of the magnetosphere at $10R_E$. When a is approaching infinity, we have a limiting transition to the one-dipole approximation.

Let us now consider the action of the ponderomotive force $f_{||}$ induced by the ion-cyclotron waves propagating along the magnetic field lines [6]. The longitudinal component of this force can be written in the form [2]

$$f_{||} = -\frac{n^2 E^2}{16\pi} \left[\frac{\omega}{\Omega_i - \omega} \nabla_{||} \ln B + \nabla_{||} \ln \rho \right], \quad (7)$$

where

$$n^2 = \frac{\omega_{0i}^2}{\Omega_i(\Omega_i - \omega)} + 1.$$

Furthermore, E is the wave electric field, ρ is the plasma mass density, Ω_i is the ion cyclotron frequency, n is the refractive index and ω_{0i} is the ion plasma frequency. In the WKB approximation $E \sim (B/n)^{1/2}$, where B and n are evaluated at the axis of the field tube.

In order to determine the plasma distribution along the geomagnetic field line we consider the force balance in the longitudinal direction with respect to the geomagnetic field, or

$$\nabla_{||} P = \rho g_{||} + f_{||}, \quad (8)$$

where $P = \rho c_s^2$ is the plasma pressure and c_s is the sound velocity. The plasma is supposed to be isothermal and to be composed of ions of one species (protons) and electrons. The operator $\nabla_{||}$ can be replaced by $(dx/dl)d/dx$, where dl is the element of the field line arc. It is determined by $dl = [r^2/(1-x^2) + (dr/dx)^2]^{1/2} dx$. Finally, the longitudinal component of the gravity force is

$$g_{||} = \frac{B_r g_E}{B r^2}, \quad (9)$$

where $g_E = 980 \text{ cm/s}^2$ and B_r and B are defined by the relations (1) and (5).

Substituting (7) and (9) into (8) we find a differential equation of first order which determines the distribution of the plasma density along the field line. Thus

$$\frac{dN}{dx} = \frac{A_1 N^{3/2} + A_2 N}{N^{1/2} + A_3}, \quad (10)$$

where

$$A_1 = \frac{2g_E R_E x}{c_s^2(1-x^2)r} \frac{\alpha}{\beta},$$

$$A_2 = -\frac{\nu_0 A_3}{(1-\nu_0 B_0/B)} \frac{B_0}{B^2} \frac{dB}{dx},$$

and

$$A_3 = \frac{b_0^2(1-\nu_0)^{1/2}}{16\pi\rho_0 c_s^2(1-\nu_0 B_0/B)^{1/2}}.$$

Here b_0 is the oscillation amplitude of the magnetic field, $\nu_0 = \omega/\Omega_{i0}$ is the ratio of the wave frequency to the ion-cyclotron frequency in the apex of the field line, B_0 is the magnetic field at the equator and $N = \rho/\rho_0$, where ρ_0 is the plasma mass density at the equator.

3. NUMERICAL RESULTS

The integration of eq. (10) has been carried out by means of the Runge–Kutta method by assuming that the square of the sound velocity c_s^2 was $3 \times 10^{11} \text{ cm}^2/\text{s}^2$. The plasma mass density at the equator ρ_0 was chosen as $1.67 \times 10^{-23} \text{ g/cm}^3$. Furthermore, we take ν_0 and b_0 to be constant ($\nu_0 = 0.7$, $b_0 = 3 \text{ nT}$). The McIlwain parameter L varies here from 6.1 to 9.5. Our results for the plasma mass density redistribution show a smooth transition from a plasma condensation in the equatorial plane (the one-dipole approximation) to the appearance of plasma density maxima far from the equator along the field line in the vicinity of the field minima. Moreover, both the plasma density and the position of the maxima along the field line (with respect to the equator) increase when we move away from the Earth. This should be expected because the deviation of the geomagnetic field from the one-dipole structure is significant due to the influence of the surface currents on the magnetopause. Let us recall that the numerical example presented here corresponds to the case where the distance from the center of the Earth to the magnetopause is of the order of $10R_E$. In this case the bifurcation, i.e., the transition from a $N(x)$ distribution with one minimum to a distribution with two maxima occurs at a distance of $8R_E$. The variation of the solar wind pressure leads to a change of the magnetopause position and a subsequent change of the distance where bifurcation occurs.

The plasma density variations along the field line at $L = 9.5$ and $b_0 = 3 \text{ nT}$ for different values of ν_0 exhibit that the ponderomotive effect increases when ν_0 increases. Finally, we observe that the increase of the pulsation amplitude leads to a significant amplification of the ponderomotive effect.

4. DISCUSSION

In this paper, we have performed analytical and numerical studies of the influence of the geomagnetic field structure near the dayside magnetospheric boundary on the plasma density redistribution due to the ponderomotive force action induced by the ion-cyclotron waves. We have demonstrated that the picture of plasma condensation may be significantly altered with a more general geometry for the magnetic field of the Earth. The transition from a "V" to a "W" structure of the Earth's magnetic field may lead to the appearance of so called "magnetic holes" playing a significant role in the plasma density redistribution in the magnetosphere. Based on the Antonova and Shabansky model [5] for the geomagnetic field we have thus found a new effect which results in the appearance of two plasma density maxima in the regions of the "magnetic holes". The existence of such regions can also lead to anomalous resonant absorption of the ion-cyclotron waves (the "magnetic beach" effect), which may be the reason for the partial (or even complete) absence of ion-cyclotron wave spectra at high latitude observatories.

Acknowledgments

This work was partially supported by the Commission of the European Union (Brussels) through Research Grant No. INTAS-94-870, and through the network "Microphysics of Nonlinear Phenomena in Collisionless Plasmas: Application to Space and Laboratory Plasmas" of the Human Capital and Mobility Program under Contract no. CHRX-CT-93-0356. The authors are grateful to Prof. A. V. Guglielmi, Dr. E. N. Fedorov, and Dr. G. Brodin for useful discussions.

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