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Exo-plasmaspheric refilling due to ponderomotive forces induced by geomagnetic pulsations

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Abstract. The effect of exo-plasmaspheric refilling due to ponderomotive forces induced by geomagnetic pulsations is considered. It is shown that two maxima of high-density cold plasma can appear on field lines near the dayside magnetospheric boundary, located symmetrically with respect to the equator. When moving away from the noon meridional plane the plasma density distribution along the field line undergoes a smooth transition from two off-equatorial maxima to one maximum at the equator. We calculate the plasma condensation due to the ponderomotive forces in this region. On the other hand, the satellite data have shown that exo-plasmaspheric Pc1 pulsations have a maximum in the noon-dusk sector. These facts bring us to a conclusion that the formation of high-density cold plasma outside plasmasphere in the magnetospheric trough in the noon-dusk sector may be accelerated by ponderomotive effects of Pc1 pulsations.

1. Introduction

An extensive literature has been devoted to the study of ponderomotive forces induced by geomagnetic pulsations in the magnetospheric plasma [e.g., *Allan*, 1992, 1994; *Guglielmi et al.*, 1993, 1995; *Witt et al.*, 1995; *Pokhotelov et al.*, 1995]. These investigations were recently reviewed by *Guglielmi and Pokhotelov* [1994, 1995]. It has been shown that if the amplitude of geomagnetic pulsations exceeds a certain critical value, a pronounced maximum of plasma density is formed at the equator [*Guglielmi et al.*, 1993]. At high altitudes, due to the deformation of the Earth's magnetic field caused by the solar wind pressure, even two maxima may appear [*Pokhotelov et al.*, 1995]. It is evident that the positions of plasma maxima coincide with the minima of magnetic field intensity along the trajectory of geomagnetic pulsations. However, the previous studies have been limited to the noon meridional plane only.

In this paper we consider the effect of ponderomotive forces induced by Pc1 geomagnetic pulsations outside the noon meridional plane. We shall demonstrate that the effect of ponderomotive forces will result in the formation of high-density plasma (condensed plasma) even outside the noon sector and at high latitudes. According to AMPTE/CCE measurements [*Anderson et al.*, 1992], the exo-plasmasperic Pc1 pulsations maximize in the postnoon sector, forming a significant ponderomotive pressure in this region. This gives us the possibility to suggest a new interpretation for the appearance of detached high-density plasma observed mainly in the noon-dusk sector at distances $L = 6 - 10$ [*Chappel et al.*, 1970; *Chappel*, 1974]. The formation of detached plasma is generally attributed to dusk detachment and subsequent sunward plasma drift. However, this process may be significantly accelerated by the ponderomotive wave pressure caused by Pc1 pulsations.

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2. Basic Equations

As in our previous study [*Pokhotelov et al.*, 1995], we shall make use of the magnetic field model by *Antonova and Shabanskii* [1968]. According to this model, Earth's magnetic field is formed by a superposition of two dipoles: the internal dipole and another dipole at a certain distance a along the Earth-Sun line. The need of introducing the additional dipole is connected with the fact that the Earth's magnetic field is compressed at dayside by the solar wind pressure. According to this model, the total magnetic field and its components in the spherical coordinate system can be written in the following form:

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

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

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

$$B_\lambda = -\frac{B_E}{r^3}\gamma \tag{4}$$

where

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

$$\beta = 1 + \frac{kr^3[(a^2 + r^2)\sqrt{1-x^2} - ary(2 + x^2)]}{\sqrt{1-x^2}(a^2 + r^2 - 2ary\sqrt{1-x^2})^{5/2}} \tag{6}$$

$$\gamma = \frac{3kar^4x\sqrt{1-y^2}}{(a^2 + r^2 - 2ary\sqrt{1-x^2})^{5/2}} \tag{7}$$

The equation of the field line yields

$$\frac{dr}{dx} = -\frac{2rx}{1-x^2}\frac{\alpha}{\beta} \tag{8}$$

where $x = \sin\varphi$ (φ is the geomagnetic latitude), $y = \cos\lambda$ (λ is the geomagnetic longitude measured from the line which connects the two dipoles; $\lambda = 0°$ corresponds to the noon), a stands for the distance between the original and additional dipole measured in units of the Earth's radius R_E, r is the geocentric radial distance (in units of R_E), k is the ratio of the additional dipole magnetic moment to the Earth's magnetic moment, and B_E is the equatorial magnetic intensity at 1 R_E (3×10^{-5} T). The expressions (1)-(8) are different from those given by *Pokhotelov et al.* [1995] by the additional terms describing the longitudinal dependence of the external magnetic field. Here we consider the case where the axes of the original and additional dipoles are parallel.

Such a model has two local minima of magnetic field intensity located away from the equator along the field line near the dayside magnetospheric boundary. When moving away from the meridional plane (at constant L), the influence of the additional dipole, imitating the action of the solar wind, becomes weaker and the two minima finally join to one equatorial minimum. Below we shall use the values $a = 33$ and $k = 13$ which locate the dayside magnetospheric boundary in the noon meridional plane to 10 R_E.

Let us consider the action of the ponderomotive force induced by ion-cyclotron waves propagating along the magnetic field lines. The parallel component of this force $f_\parallel$ may be written in the form [*Guglielmi et al.*, 1993]

$$f_\parallel = -\frac{n^2E^2}{4\mu_0 c^2}\left[\frac{\omega}{\omega_{ci} - \omega}\nabla_\parallel \ln B + \nabla_\parallel \ln\rho\right] \tag{9}$$

where

$$n^2 = 1 + \frac{\omega_{0i}^2}{\omega_{ci}(\omega_{ci} - \omega)} \tag{10}$$

Here E is the wave electric field, ρ is the plasma mass density, ω_{ci} is ion cyclotron frequency, n is the refractive index, and ω_{0i} stands for the Langmuir frequency. In the WKB approximation $E \sim (B/n)^{1/2}$, where B and n are evaluated at the equator. The latter relation follows from Faraday's law and the conservation of wave energy flux through the magnetic field tube.

In order to determine the plasma distribution along the geomagnetic field line we consider the force balance in the field-aligned direction:

$$\nabla_\parallel P = \rho g_\parallel + f_\parallel \tag{11}$$

where $P = \rho c_S^2$ is the plasma pressure and $c_S = (T_{\text{eff}}/M_i)^{1/2}$ is the sound velocity. The plasma is supposed to be composed of one ion species (protons) with mass M_i and electrons. T_{eff} is the effective plasma temperature. The operator $\nabla_\parallel$ can be replaced by $(dx/dl)d/dx$, where dl is the element of the field line arc determined by

$$\begin{aligned} dl &= R_E[r^2/(1-x^2) + (dr/dx)^2 \\ &+ r^2(1-x^2)(d\lambda/dx)^2]^{1/2}dx \end{aligned} \tag{12}$$

where

$$d\lambda/dx = -(1-x^2)^{-3/2}(\gamma/\beta) \tag{13}$$

Finally, the parallel component of the gravitational force is

$$g_\parallel = \frac{B_r g_E}{Br^2} \tag{14}$$

where $g_E = 9.8$ m/s^2 and B and B_r are defined by the relations (1) and (2).

The parallel component of the ponderomotive force is thus reduced to

$$\begin{aligned} f_\parallel &= -\frac{b_0^2(1-\nu_0)^{1/2}}{4\mu_0 c^2 N^{1/2}(1-\nu_0 B_0/B)^{1/2}} \\ &\times \left[\frac{\nu_0 B_0 N}{(1-\nu_0 B_0/B)B^2}\nabla_x B + \nabla_x N\right]\left(\frac{dx}{dl}\right) \end{aligned} \tag{15}$$

where b_0 is the oscillation amplitude of the magnetic field, $\nu_0 = \omega/\omega_{ci}$ the ratio of wave frequency and cyclotron frequency, and B_0 is the magnetic field, all calculated at the equator (labeled by subindex 0); $N = \rho/\rho_0$, ρ_0 is the equatorial plasma mass density, and $\nabla_x = d/dx$. Substituting (10)-(13) into (9), we find the first-order differential equation which determines the distribution of the plasma density along the field line:

$$\frac{dN}{dx} = \frac{A_1 N^{3/2} + A_2 N}{N^{1/2} + A_3} \tag{16}$$

where

$$A_1 = \frac{2g_E R_E x}{c_s^2(1-x^2)r}\frac{\alpha}{\beta} \tag{17}$$

$$A_2 = -\frac{\nu_0 A_3}{(1-\nu_0 B_0/B)}\frac{B_0}{B^2}\frac{dB}{dx} \tag{18}$$

$$A_3 = \frac{b_0^2(1-\nu_0)^{1/2}}{4\mu_0 c^2 \rho_0 c_s^2(1-\nu_0 B_0/B)^{1/2}} \tag{19}$$

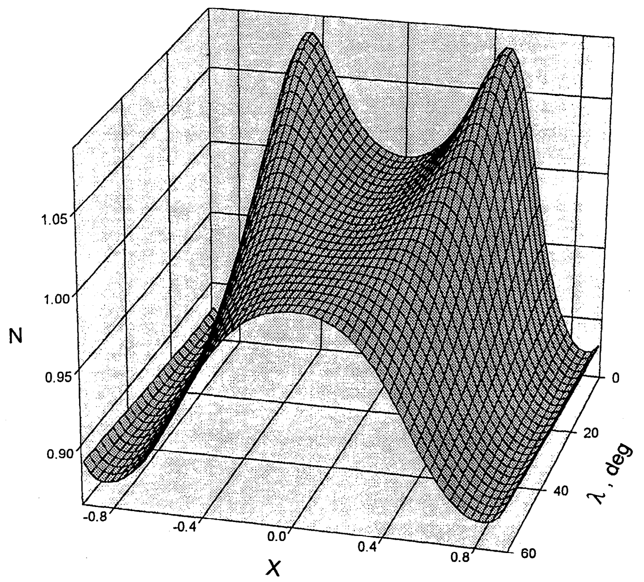

Figure 1. The (normalized) plasma density along the geomagnetic field line for different longitudes λ at $L = 9.5$.

3. Numerical Analysis

The integration of the equation (16) has been carried out by means of the Runge-Kutta method using the boundary condition $N = 1$ at $x = 0$. The results are shown in Figures 1-4. For Figures 1-3 we assume that the square of the sound velocity c_s^2 is 10^9 m^2/s^2. The plasma mass density at the equator ρ_0 was chosen to be 2×10^{-20} kg/m^3 .

Figure 1 displays the results for the plasma mass density along the field line as a function of x, assuming ν_0, b_0, and L to be constant ($\nu_0 = 0.5$, $b_0 = 5$ nT and $L = 9.5$), and varying the geomagnetic longitude λ from 0° to 60°. At high altitudes, when we move from the noon meridional plane, the W structure of the magnetic field intensity with two minima transforms into the V structure with one minimum due to the weakening of solar wind effect with λ. Such a behavior of the magnetic field at high altitudes results also in the plasma density modification along the field line due to the action of ponderomotive forces. The results presented in Figure 1 show that with increasing longitude there exists a smooth transition from the structure with two density maxima to one wide maximum. For still larger longitudes the wide maximum becomes more narrow, approaching the form which is typical for the dipole approximation. Note also that the magnitude of the plasma density maximum decreases with increasing longitude λ.

Figure 2 shows an example of the plasma density at constant λ, ν_0, and b_0, ($\lambda = 15°$, $\nu_0 = 0.5$, and $b_0 = 5$ nT) while varying the L value from 5 to 9.5 . Note that the numerical example presented here corresponds to the case where the distance to the magnetopause is about 10 R_E (at $\lambda = 0°$). In this case the bifurcation, i.e., the transition from the density distribution with one maximum to a distribution with two maxima occurs at a distance of 8.5 R_E which is different from that corresponding to $\lambda = 0°$. The variation of the solar wind pressure leads to a change of the magnetopause position and the position of the magnetic field minima along the field line and finally results in a subsequent change of the distance where bifurcation occurs. Moreover, this position may be much closer to the Earth during magnetospheric storms than in the case presented in Figure 2.

The density distribution along the field line when varying the pulsation amplitude b_0 from 1 to 7 nT ($L = 9.5$, $\nu_0 = 0.5$, and $\lambda = 15°$) is given in Figure 3. Similar to *Pokhotelov et al.* [1995], the increase of pul-

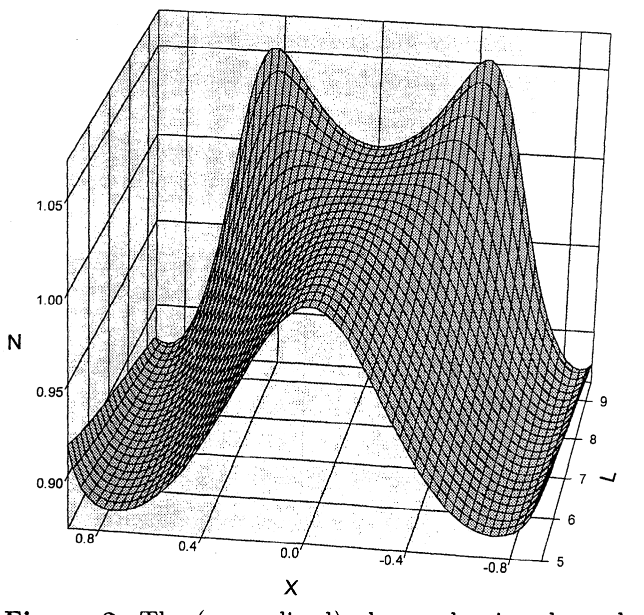

Figure 2. The (normalized) plasma density along the geomagnetic field line for different L values at $\lambda = 15°$.

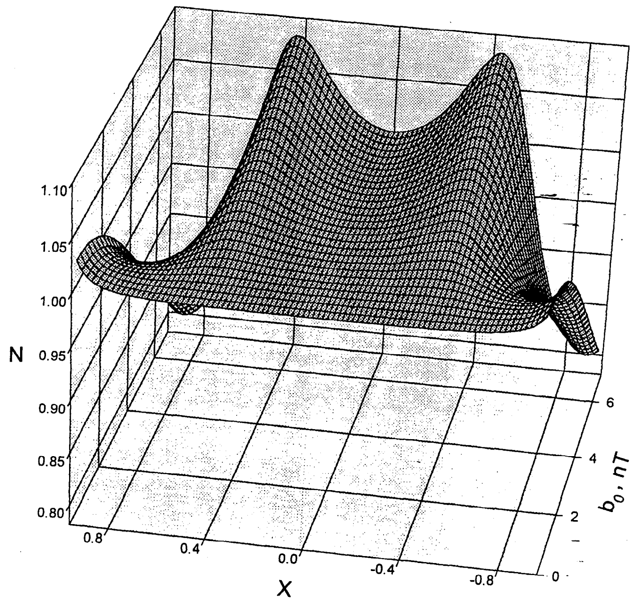

Figure 3. The (normalized) plasma density along the geomagnetic field line for different amplitudes b_o of the Pc1 pulsations at $\lambda = 15°$ and $L = 9.5$.

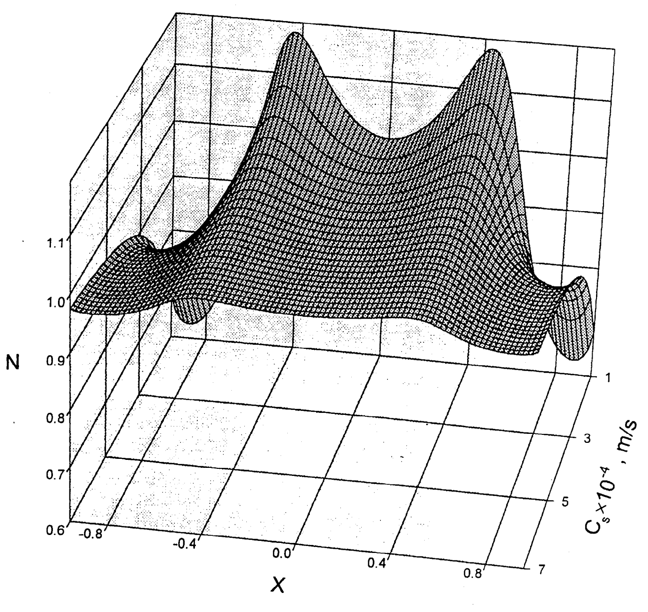

Figure 4. The (normalized) plasma density along the geomagnetic field line for different values of c_s at $\lambda = 15°$ and $L = 9.5$.

sation amplitude results in a significant enhancement of the ponderomotive effect. The critical amplitude at which the action of the ponderomotive force leads to plasma condensation for the given case is about 2 nT.

The ponderomotive effect essentially depends on the value of the sound velocity c_s^2. The measurements of plasma density and temperature at L = 6-10 in the dayside magnetosphere by IMP 6 [*Gurnett and Frank*, 1974], OGO 5 [*Serbu and Maier*, 1970; *Chappell*, 1974], and GEOS 1 [*Decreau et al.*, 1982] allow us to determine the range of the values for $c_s^2 = (10^8 - 5 \times 10^9)$ m^2/s^2. Figure 4 shows the dependence of the plasma density (at λ = 15°, ν_0 = 0.5, b_0 = 5 nT, L = 9.5) on c_s between 10^4 m s^{-1} and 7 $\times 10^4$ m s^{-1}. The results show that the ponderomotive effect increases when c_s decreases. Furthermore, Figure 5 displays the plasma density along the field line (at L = 9.5, λ = 15°, and b_0 = 5 nT) when varying ν_0 from 0.3 to 0.7. It is evident that the ponderomotive effect increases when ν_0 increases.

4. Discussion

Similar to *Pokhotelov et al.* [1995], the magnetic field model used was chosen by the requirement of simplicity. It allows us to calculate the ponderomotive force action at various locations of the dayside magnetosphere analytically. Moreover, this model is in agreement with the HEOS 1 and 2 data [*Antonova et al.*, 1983]. The use of more complex models [e.g., *Tsyganenko*, 1987] is necessary when analyzing some specific situations. However, the results for the presently shown distributions would be qualitatively the same.

Let us now consider the possibility of forming high-density plasma clouds far from the plasmasphere, similar to the formation of detached plasma. *Chappel et al.* [1970] and *Chappel* [1974] discovered regions containing clouds of high-density plasma outside the plasmasphere in the magnetospheric trough. These clouds are located in the dayside magnetosphere with maximum plasma density in the noon-dusk sector.

The study of Pc1 pulsations in the outer magnetosphere has shown that the maximum of wave events is found in the afternoon sector [*Anderson et al.*, 1992], i.e., in the same local time where detached plasma appears. Figure 6 presents the Pc1 occurrence rate at synchronous orbit [*Bossen et al.*, 1976] and the dis-

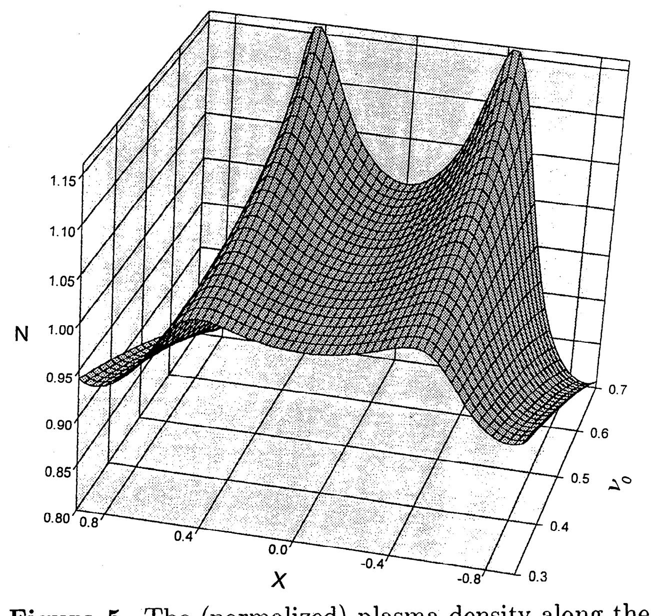

Figure 5. The (normalized) plasma density along the geomagnetic field lines for L = 9.5 with different values of $\nu_0 = \omega/\omega_{ci}$ at λ = 15° and L = 9.5.

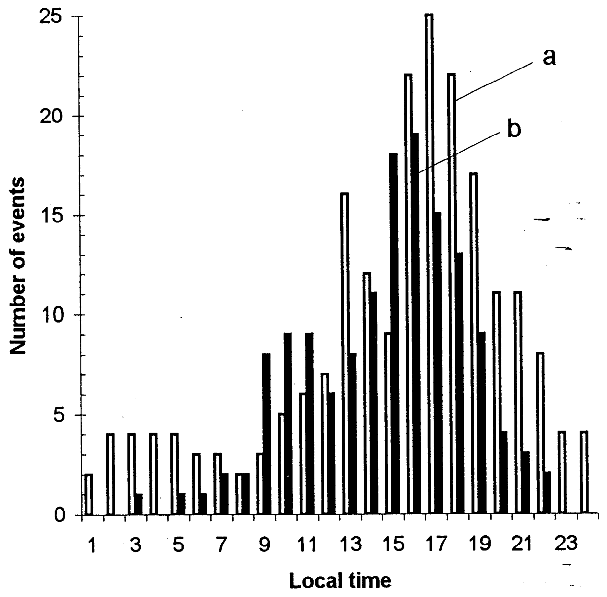

Figure 6. (a) Distribution of Pc1 activity at geosynchronous orbit versus local time [*Bossen et al.*, 1976]; (b) Distribution of detached plasma events versus local time [*Chappel*, 1974].

tribution of high-density plasma on board the OGO 5 satellite [*Chappel,* 1974] versus local time. These data were obtained in different years by different satellites, which reduces the correlation coefficient. However, comparing the plots in Figure 6 leads to the conclusion that the appearance of high-density clouds of the background plasma may be connected with the appearance of Pc1 pulsations in the same magnetic local time sector. The appearance of detached plasma was interpreted by *Chappel* [1974] in the framework of the model of dusk detachment and subsequent sunward drift. Naturally, both mechanisms can act simultaneously, but ponderomotive effects may significantly enhance the exo-plasmaspheric refilling.

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