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Standing slow magnetosonic waves in a dipole-like plasmasphere

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ABSTRACT

A problem of the structure and spectrum of standing slow magnetosonic waves in a dipole plasmasphere is solved. Both an analytical (in WKB approximation) and numerical solutions are found to the problem, for a distribution of the plasma parameters typical of the Earth's plasmasphere. The solutions allow us to treat the total electronic content oscillations registered above Japan as oscillations of one of the first harmonics of standing slow magnetosonic waves. Near the ionosphere the main components of the field of registered standing SMS waves are the plasma oscillations along magnetic field lines, plasma concentration oscillation and the related oscillations of the gas-kinetic pressure. The velocity of the plasma oscillations increases dramatically near the ionospheric conductive layer, which should result in precipitation of the background plasma particles. This may be accompanied by ionospheric F2 region airglows modulated with the periods of standing slow magnetosonic waves.

1. Introduction

Electromagnetic oscillations of planets' magnetospheres in the low-frequency part of the spectrum are MHD waves. The typical spatial scales of most low-frequency MHD oscillations are comparable with the magnetospheric scales. There are two modes of MHD oscillations capable of propagating almost exactly along magnetic field lines—the Alfven waves and slow magnetosonic (SMS) waves. Propagation of the fast magnetosonic (FMS) waves is not related to the magnetic field direction. Since magnetic field lines are closed, they cross the ionosphere twice (in the case of the Earth—in the Northern and Southern hemispheres). Because it is highly conductive, the ionosphere is an almost ideally reflecting boundary for the waves under consideration. Therefore the Alfven and SMS oscillations can form standing (along magnetic field lines) waves in the magnetosphere. Many papers have been devoted to the structure and spectrum of the standing Alfven waves in dipole-like model magnetospheres (see Radoski, 1967; Cummings et al., 1969; Leonovich and Mazur, 1989; Chen and Cowley, 1989; Lee and Lysak, 1991; Wright, 1992 etc.).

Meanwhile, investigations of standing SMS waves are fairly few: Taylor and Walker (1987), Leonovich et al. (2006), and Klimushkin and Mager (2008). Insufficient attention paid to the waves is probably due to their rather large decrement (Leonovich and Kozlov, 2009), thanks to which the eigen-SMS-oscillations decay rapidly making them difficult to register. Nevertheless, if there is a rather strong source capable of generating such waves, they may well be observed in the magnetosphere. Resonant SMS waves excited in a dipole magnetosphere by a monochromatic fast magnetosonic wave penetrating from the solar wind into the magnetosphere were studied in Leonovich et al. (2006). The typical wavelength of such SMS oscillations both in the direction along magnetic field lines and in the azimuthal direction is of the order of the characteristic scale of magnetospheric plasma inhomogeneity. Across the magnetic shells, they have a typical resonance structure with a characteristic scale that is much smaller than the scale of magnetospheric plasma inhomogeneity. Their amplitude decreases dramatically from the magnetospheric equatorial plane to the ionosphere. Therefore, such oscillation is possible to register at high-orbit spacecraft only.

Total electronic content (TEC) oscillations were registered by Afraimovich et al. (2009) in GPS observations over Japan concerning the terminator transit over the Earth's ionosphere in regions connected with the observation region through the geomagnetic field lines. Such oscillations are best registered at times close to the summer solstice. The oscillations appear in the ionospheric region under consideration 20–30 min after the evening terminator passes over the magnetoconjugated region of the Southern hemisphere. The terminator passes through the observation regions only 1 h after the TEC oscillations start. Since the terminator at the latitudes under consideration moves at supersonic velocity, the ÒÅÑ oscillations in the period in question cannot be related to the inner gravity waves generated by the terminator. These waves are most likely responsible for the oscillations of the total electronic content after the terminator passes over the observation point. The periods of the observed

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TEC oscillations were within the 15–30 min range. Lower-frequency oscillations were filtered artificially so as to eliminate the effect of the GPS satellite movement.

Thus, a relationship is clearly traceable between the TEC oscillations and processes in the magnetoconjugate region of the ionosphere. Therefore it was suggested that the magnetoconjugate regions of the ionosphere interact through the Alfven or SMS waves moving along the geomagnetic field lines. Both these wave types are capable of disturbing the electron concentration near the ionosphere. The disturbance of the concentration is an essential property of the SMS waves. Whereas the Alfven waves can disturb the concentration when they impinge onto the ionosphere, by generating a FMS oscillation in the ionospheric conducting layer (Pilipenko and Fedorov, 1995).

However, the specific periods of the first harmonics of standing Alfven waves at the magnetic shells under consideration (~ 10 s) are very far from the periods of the observed TEC oscillations. Therefore the generation of the observable oscillations by the Alfven wave appears to be ineffective. The periods of the first harmonics of standing SMS waves (~ 20 min) fit exactly in the required range. Therefore the conclusion has been made in Afraimovich et al. (2009) that the TEC oscillations related to the terminator transit in the magnetoconjugated region of the ionosphere are, in fact, one (or a few) of the first harmonics of standing SMS waves.

The assumption was based on the periods of the several first harmonics of these oscillations as calculated in the WKB approximation. More rigorous substantiation is needed, however. For the purpose, we will calculate the total field of standing SMS waves in the dipole model of the Earth's plasmasphere and compare the results with the observational data. SMS waves related to the terminator transit are likely to have a rather large typical wavelength across magnetic shells (comparable with the typical scale of magnetospheric inhomogeneity) while being fairly small-scale in the azimuthal direction. This paper is devoted to calculating the spectrum, structure and amplitude of the wave field components of such azimuthally small-scale standing SMS waves observed near the ionosphere. The calculations are done both analytically—in the WKB approximation—and numerically. The results of the analytical calculations are compared to the numerical results, and both these results are also compared to observational data.

This paper has the following structure. Section 2 deals with describing the model medium, deriving the basic equation for calculating the structure and spectrum of azimuthally small-scale standing SMS waves as well as obtaining analytical expressions for the oscillation field components. An analytical WKB solution to the basic equation describing the structure of the oscillation field along a magnetic field line is obtained in Section 3. A numerical solution to the basic equation is found, the distributions of the oscillation field components along a magnetic field line are constructed and the results are discussed in Section 4. The Conclusion lists the main results of the paper.

2. The model medium and the basic equations

Let us consider a model plasmasphere with dipole-like magnetic field in Fig. 1. Let us introduce a curvilinear orthogonal coordinate system (x^1,x^2,x^3) associated with the magnetic field lines. The x^3 coordinate is directed along the field line, x^1 across the magnetic shells, and x^2 makes the coordinates system a right-handed one. The square of the length element in this coordinate system is determined as

$$ds^2 = g_1(dx^1)^2 + g_2(dx^2)^2 + g_3(dx^3)^2,$$

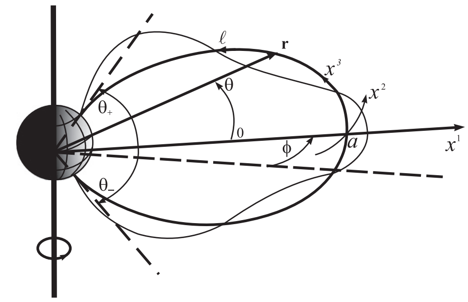

Fig. 1. The curvilinear orthogonal coordinate system (x^1,x^2,x^3) associated with magnetic field lines and the nonorthogonal coordinate system (a,ϕ,θ) used in numerical calculations. The structure of the fifth harmonic of standing SMS-waves along a magnetic field line is shown schematically.

where g_1,g_2,g_3 are the metric tensor components of the curvilinear coordinate system under study. Let us assume the plasma and magnetic field to be homogeneous with respect to the x^2 coordinate. We will describe the MHD oscillations using the equation system for the ideal MHD:

$$\rho\frac{d\mathbf{v}}{dt} = -\nabla P + \frac{1}{4\pi}[\mathrm{curl}\,\mathbf{B}\times\mathbf{B}], \tag{1}$$

$$\frac{\partial\mathbf{B}}{\partial t} = \mathrm{curl}[\mathbf{v}\times\mathbf{B}], \tag{2}$$

$$\frac{\partial\rho}{\partial t} + \nabla(\rho\mathbf{v}) = 0, \tag{3}$$

$$\frac{d}{dt}\frac{P}{\rho^\gamma} = 0, \tag{4}$$

where $\mathbf{B}$ and $\mathbf{v}$ are the magnetic field intensity and plasma motion velocity vectors, respectively, ρ and P are the plasma density and pressure, γ is the adiabatic index. Moreover, we will determine the oscillation electric field $\mathbf{E}$ using the drift approximation

$$\mathbf{E} = -\frac{[\mathbf{v}\times\mathbf{B}]}{c}.$$

In steady state $(\partial/\partial t = 0)$ the system (1)–(4) describes the distribution of parameters of an unperturbed magnetosphere: $\mathbf{B_0},\mathbf{v_0},\ \mathbf{E_0},\rho_0,P_0$. We will assume the plasma to be immobile $(\mathbf{v_0}=\mathbf{E_0}=0)$. Let us linearize the system (1)–(4) with respect to small disturbances: $\mathbf{B}=\mathbf{B_0}+\tilde{\mathbf{B}}$, $\mathbf{v}=\mathbf{v_0}+\tilde{\mathbf{v}}, \mathbf{E}=\tilde{\mathbf{E}}, \rho=\rho_0+\tilde{\rho}$, $P=P_0+\tilde{P}$, where $\tilde{\mathbf{B}},\tilde{\mathbf{v}},\tilde{\mathbf{E}},\tilde{\rho},\tilde{P}$ are the field components related to the plasma MHD oscillations. Let us present each disturbed component as an expansion over the Fourier harmonics of the form $\exp(ik_2x^2 - i\omega t)$, where ω is the oscillation frequency, k_2 is the azimuthal wave number (if $x^2\equiv\phi$ is the azimuthal angle, $k_2\equiv m = 1,2,3,\ldots$). From (1) we have

$$-i\omega\rho_0 v_1 = -\nabla_1\tilde{P} + \frac{B_0}{4\pi}\frac{1}{\sqrt{g_3}}(\nabla_3 B_1 - \nabla_1 B_3), \tag{5}$$

$$-i\omega\rho_0 v_2 = -ik_2\tilde{P} - \frac{B_0}{4\pi}\frac{1}{\sqrt{g_3}}(ik_2 B_3 - \nabla_3 B_2), \tag{6}$$

$$i\omega\rho_0 v_3 = \nabla_3\tilde{P}, \tag{7}$$

where v_i,B_i $(i=1,2,3)$ are the covariant components of the disturbed velocity $\tilde{\mathbf{v}}$ and magnetic field $\tilde{\mathbf{B}}$ vectors, $\nabla_i\equiv\partial/\partial x^i$. From (3), (4) we obtain

$$\tilde{P} = -i\frac{\gamma}{\omega}\frac{P_0^{1-\sigma}}{\sqrt{g}}\left[\nabla_1\left(\frac{\sqrt{g}}{g_1}P_0^\sigma v_1\right) + ik_2\frac{\sqrt{g}}{g_2}P_0^\sigma v_2 + \nabla_3\left(\frac{\sqrt{g}}{g_3}P_0^\sigma v_3\right)\right],$$

where $g=\sqrt{g_1g_2g_3}$, $\sigma = 1/\gamma$.