NUMERICAL SIMULATION OF THE EFFECTS OF MAGNETIC FIELD INDUCED BY PLASMA FLOW PAST NONMAGNETIC PLANETS

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ABSTRACT

The interaction of a nonstationary plasma flow with a model ionosphere is studied. On the basis of a numerical simulation, the calculation yields results of the distribution of the plasma concentration and magnetic field in the transition region.

INTRODUCTION

Three models of the solar-wind interaction with the upper atmosphere of planets not having their own magnetic field sufficient for deceleration of the solar wind are known:

1. Solar plasma deceleration in the atmosphere,
2. The boundary between the solar wind and atmosphere is considered as a tangential discontinuity, and
3. The induced magnetosphere excitation [1, 2].

The first and the second models were studied in detail [3, 4, 5], but there are only qualitative estimates of the model with magnetic field induction [6, 7].

This paper is an attempt to study the structure of the magnetic field excited by currents in the solar wind and the ionosphere.

FORMULATION OF THE PROBLEM

The Solar-Wind Model

The solar-wind parameters are such that $\omega_e \gg D/Dt \, \ell n \, H$, $v_i \ll W \ll v_e$, $\rho_e \ll \rho_i \leqslant R_v$ where $\rho_{i,e}$ is Larmor radius of ions and electrons, R_v is the radius of the ionosphere, ω_e is the gyrofrequency of electrons, $v_{i,e}$ and W are the thermal and directed velocity of ions and electrons, and H is the modulus of the magnetic field. To describe the electrons, the drift approximation is applied, and the electron distribution is thus approximated by a Maxwell-Boltzmann function:

$$f_e \sim \exp\left[-\frac{m(v_\parallel - w_\parallel)^2}{2KT} - \frac{M_e H}{KT} - \frac{e}{KT}\int_\infty^r d\vec{r}\left(\vec{E} + \frac{\vec{V}\times\vec{H}}{C}\right)\right] \quad (1)$$

In the approximation considered, the ions are assumed to be cold and their motion, in dimensionless form, is defined by the equation:

$$\frac{D}{D\tau}\vec{V}_i^* = \frac{\omega_i R_v}{W_\infty}(\vec{E}^* + \vec{V}_i^* \times \vec{H}^*)$$

where (2)

$$V_i^* = \frac{V_i}{W_\infty}, \quad \tau = t\cdot\frac{W_\infty}{R_v}, \quad E^* = \frac{E\cdot C}{H_\infty \times W_\infty}, \quad H^* = \frac{H}{H_\infty}$$

where W_∞ and H_∞ are the plasma velocity and the magnetic field in the incoming flow.

Maxwell's equations, in dimensionless form, are as follows [8]:

$$\bar{\nabla}\times\vec{H}^* = 0, \qquad \bar{\nabla}\vec{E}^* = \frac{4\pi e\, n_\infty C\, R_v\,(n_i^* - n_e^*)}{H_\infty W_\infty} \quad (3)$$

$$\frac{\partial}{\partial\tau}\vec{H}^* + \bar{\nabla}\times\vec{E}^* = 0 \quad (4)$$

$$\bar{\nabla}\times H^* = \left\{\left[\frac{\beta_e}{2}(-\bar{\nabla}n^* + \chi n^*\vec{K}) - \frac{M_a^2\,\omega_i R_v\, n^*\vec{E}^*}{H^* W_\infty}\right]\times\hat{e}_1 + M_a^2\frac{\omega_i R_v}{W_\infty}n^*\vec{V}_i^*\right\}\Big/\left(1 + \frac{\beta_e}{2}\frac{n^*}{H^*}\right), \qquad \bar{\nabla} = R_v\nabla \quad (5)$$

where

n_∞ = the plasma concentration in the incoming flow ($n^* = n/n_\infty$),

β_e = $8\pi P_{\perp e\infty}/H_\infty^2$, the ratio of thermal pressure to magnetic pressure,

χ = $P_{\parallel e}/P_{\perp e}$, the anisotropy of the pressure,

M_a = $W_\infty\sqrt{4\pi n_\infty M/H_\infty}$, Alfvén Mach number,

$\vec{K}$ = the curvature of the magnetic field.

To calculate the electric field, the condition of quasineutrality of plasma $n_e \approx n_i$ is used.

The Ionosphere Model

Two models of a planetary ionosphere are considered. In the first model, the ionosphere is simulated by a motionless spherical ring $R_v \leqslant r \leqslant r_0$ with an effective homogeneous isotropic conductivity σ. (See figures 1 and 2.) In this case, the equations of the field are as follows:

$$\bar{\nabla} \times \vec{H}^* = R_e \vec{E}^*, \qquad \frac{\partial}{\partial \tau} \vec{H}^* + \bar{\nabla} \times \vec{E}^* = 0 \tag{6}$$

$$R_e = \frac{4\pi W_\infty R_v \delta}{C^2} = \text{the magnetic Reynolds number.}$$

The boundary conditions on the outer and inner surface of the ionosphere are

$$[H_n] = [E_\tau] = 0, \qquad H_n = E_\tau = 0.$$

In the second model, the ionosphere is simulated by a motionless, magnetized, ideally-conducting, plasma-like, hemispherical cap with a right circular cylinder on the nightside (figures 3 and 4). In this model, the characteristics of the ionosphere are defined by the parameters

$$\beta_i = \frac{8\pi P_{1i}}{H_i^2}, \quad M_{ai} = \frac{W_\infty \sqrt{4\pi n_i M}}{H_i}$$

For simplification, the index * of the dimensionless values will be omitted.

Initial and Boundary Conditions

Initially, the solar-wind plasma density and the electromagnetic field in the calculation region are absent (in the first model, it is a sphere; in the second model, it is a cylinder). Then, the plasma with a frozen-in magnetic field is ejected against the ionosphere.

On the outer boundary of the calculation region, the parameters of the field and plasma are assumed to be undisturbed. In the case where $\vec{W}_\infty \perp \vec{H}_\infty$, mirror symmetry relative to equatorial and meridional planes takes place. Let us expand the parameters in Fourier series of Φ, relative to the Z-axis, and consider the homogeneous solution described by the first harmonic.

The solution of equations 1 through 6 was determined by the "guiding center in the cell" method, a description of which can be found in Lipatov [8].

The solution of Maxwell's equations was determined by the alternating-direction method [9] on the spherical (first model) and cylindrical (second model) grid.

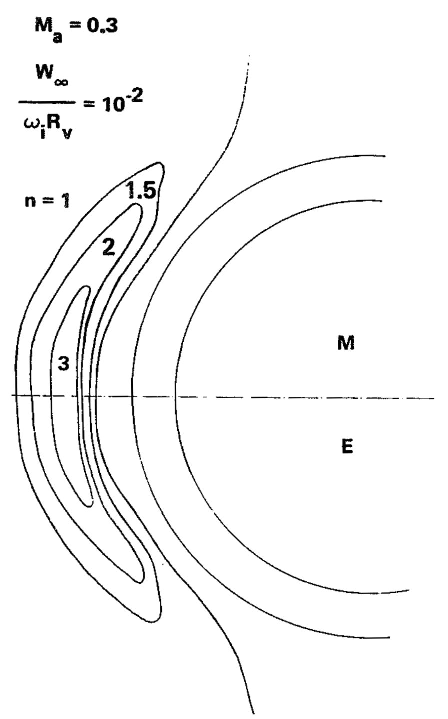

Figure 1. The distribution of the normalized plasma concentration n/n_∞ in the case of a spherical model of the ionosphere (first model).

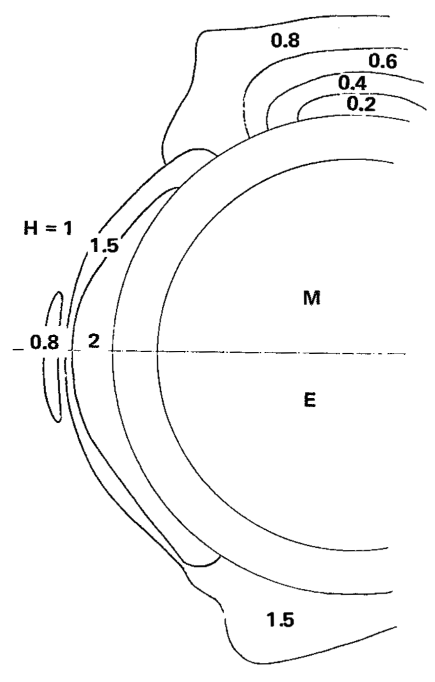

Figure 2. The distribution of the magnetic field H/H_∞ in the case of a spherical model of the ionosphere (first model).

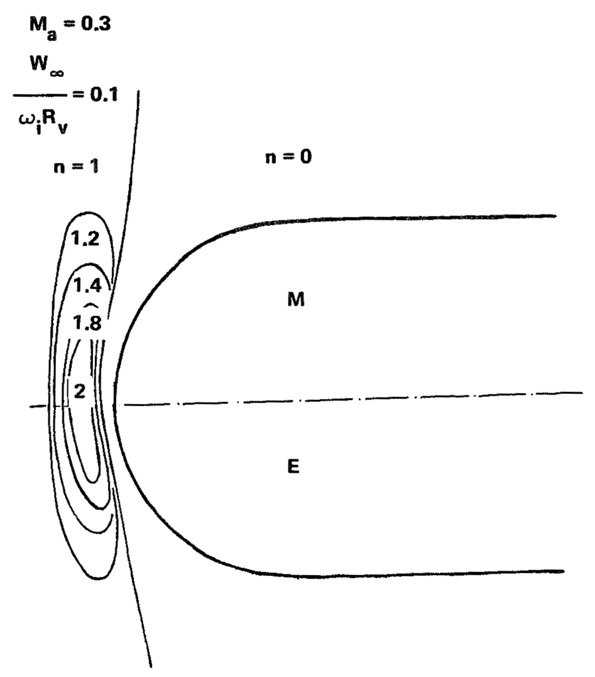

Figure 3. The distribution of the normalized plasma concentration n/n_∞ in the case of the existence of the ionospheric tail (second model).

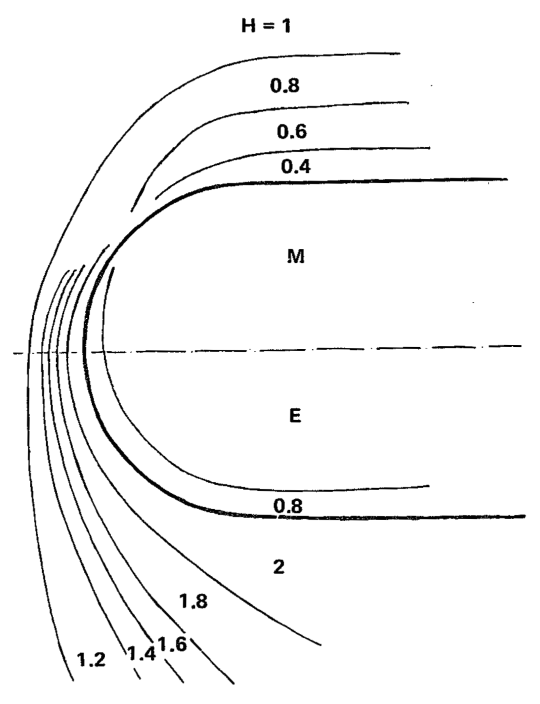

Figure 4. The distribution of the magnetic field H/H_∞ in the case of the existence of the ionospheric tail (second model).

Calculation Results

The calculations were made for the following values of the solar-wind parameters:

- $\beta_e = 1$,
- $\chi = 1$ to 1.5,
- $M_a = 0.3$ to 1,
- $W_\infty/(\omega_i R_v) = 0.01$ to 0.1.

Figures 1 and 2 show the distribution of the normalized plasma concentration n/n_∞ and magnetic field H/H_∞ near the ionosphere in the meridional and equatorial planes in the case of a spherical model of the ionosphere (first model). The directed velocity of the solar-wind flow near the nose of the ionosphere reaches $\sim W_\infty/10$, evidence of the plasma flow deceleration. The conductivity of the ionosphere is considered to be rather high ($R_e \sim 10^3$) so that the time of penetration of the interplanetary field into the ionosphere is high compared with the time of the particles' transit past the planet.

Figures 3 and 4 give the distribution of the normalized plasma concentration n/n_∞ and magnetic field H/H_∞ near the ionosphere in the meridional and equatorial planes in the case of the existence of the ionospheric tail (second model). The parameters of the ionosphere model have the values $\beta_i = 10$, $M_{ai} = 10^3$. Drift currents in this model create an intense magnetic field between the solar wind and the ionosphere and screen the ionosphere from penetration by the interplanetary field.

In the models of flow considered, the amplification of the magnetic field at the nose of the ionosphere is defined, in general, by compression of the lines of force of the field on the equator by analogy with plasma flow around the Moon [8].

The induced magnetosphere size is defined by the balance of the total pressure of the solar wind $H_\infty^2/8\pi + 2\rho W_\infty^2$ and of the pressure of the induced field $H_i^2/8\pi$. However, the calculated model of the induced magnetosphere does not take into account all the processes of the real deviated flow (see [10]), that is, the situation when the solar-wind ions can penetrate the ionosphere. In this case, an additional current system is set up coupling the solar wind into the ionosphere. These currents, according to estimates [7], may be important for determination of the magnetic field.

Filling up the induced magnetosphere by plasma will have an influence on the characteristics of the magnetosphere (duration of change of sign of the magnetic field and so on).

CONCLUSION

Preliminary calculations of decelerating plasma flow on the model ionosphere show that the induced magnetic field, in general, is determined by the conductivity of the ionosphere and can reach high values.

However, the model of an induced magnetosphere considered does not take into account the effect of the closing of currents from the solar wind into the ionosphere and the motion of ions of the ionosphere, both of which may influence the interaction of the solar wind with the ionosphere.

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QUESTIONS

Lipatov/Ness: Your diagram shows an increased field near the equatorial plane and a decreased field near the polar region assuming that the equator is defined by the plane containing the field lines and the solar wind velocity. Can you indicate the geometry of the field lines around the obstacle to the plasma flow? Do you expect the increased field to persist as the Mach number increases from subsonic to supersonic?

Lipatov: In the calculated model, we give the configuration of the magnetic lines of force, which is similar to the configuration of the lines of force near the Moon. As the Mach number increases to a supersonic value, the increased magnetic field remains near the nose of the ionosphere. But in the polar regions we can see an increase of the tangential component of the magnetic field.