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Numerical modelling of the Earth's magnetosheath for different IMF orientations

Andrey Samsonov *

Earth Physics Department, Physical Faculty, St. Petersburg State University, Ulyanovskaya 1, St. Petersburg, 198504, Russian Federation

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Abstract

A new magnetosheath numerical MHD model has been developed which calculates solar wind flow around a paraboloidal obstacle. Steady-state solutions have been obtained for different interplanetary magnetic field orientations, namely for the strictly northward and southward interplanetary magnetic fields, and for the case of a large B_x component. It has been found that the magnetic field magnitude and values of other MHD parameters in the magnetosheath depend on the direction of the interplanetary magnetic field. Particularly, the magnetic field near the magnetopause is weaker for the southward interplanetary magnetic field than for the northward interplanetary magnetic field due to the magnetopause reconnection, and the magnetic barrier may almost disappear for a special interplanetary magnetic field orientation nearly aligned with the solar wind velocity. Three electric current systems are simulated in this work: the currents at the bow shock, in the magnetosheath, and on the magnetopause.

Keywords: Magnetosheath; Magnetopause; Numerical modelling; Solar wind–magnetosphere interaction

1. Introduction

Numerical modelling of the Earth's magnetosheath was begun in 60th of the last century (Spreiter et al., 1966). Those models were mainly hydrodynamic or kinematic. The latter allows to calculate the magnetic field using the frozen-in condition, but does not take into account the influence of magnetic field on plasma flow. Simulating flow in the magnetic field tubes, (Zwan and Wolf, 1976) found that the increase of the magnetic field in the inner magnetosheath close to the magnetopause results in depletion of plasma. Similar results were obtained by Pudovkin et al. (1982), who compared also the behaviour of MHD parameters in the magnetosheath for the northward and southward IMFs. They assumed for the first time that the magnetopause magnetic reconnection may influence the magnetosheath flow. They found that the magnetic barrier (i.e., the increase of magnetic field near the magnetopause due to draping effect) is weaker for the northward IMF than for the southward IMF. However, the flow geometry in that two-dimensional (2D) MHD model does not correspond well to the results obtained later by three-dimensional MHD models (Erkaev, 1989). Moreover, (Siscoe et al., 2002) using results of the global MHD modelling have found that the plasma depletion near the magnetopause is largest for the northward IMF, while the plasma depletion layer appears to be absent for the southward IMF.

The model of open magnetosphere developed by Dungey (1961) supposes that the solar wind plasma may enter in the magnetosphere through the dayside magnetopause for a southward IMF due to the magnetopause magnetic reconnection. The Petchek's theory of magnetic reconnection (Petschek, 1964) allows to obtain

* Tel.: +7 812 151 0834; fax: +7 812 4287 240.
E-mail addresses: samsonov@geo.phys.spbu.ru, yasam00@mail.ru

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the estimation of the reconnection rate and, correspondingly, the flow velocity on the magnetosheath side of the reconnection region. In this paper, we use this assumption to determine the boundary conditions between the magnetosheath and magnetopause for the southward IMF and to study the influence of the magnetopause magnetic reconnection on a stationary MHD flow in the magnetosheath. We also simulate the magnetosheath parameters for the IMF direction nearly aligned with the Sun–Earth line and for a most typical orientation along the Parker's spiral.

2. Numerical model

In order to simulate the interaction of the supersonic solar wind with a paraboloid obstacle, we use the non-stationary three-dimensional (3D) MHD equations

$$\partial\rho/\partial t = -\nabla\cdot(\rho\mathbf{V}), \tag{1}$$

$$\frac{\partial}{\partial t}(\rho\mathbf{V}) = -\nabla\cdot\left[\rho\mathbf{V}\mathbf{V} + I\left(p+\frac{B^2}{8\pi}\right) - \frac{\mathbf{B}\mathbf{B}}{4\pi}\right], \tag{2}$$

$$\partial e/\partial t = -\nabla\cdot\mathbf{q}, \quad e = \frac{\rho V^2}{2} + \frac{B^2}{8\pi} + \frac{p}{\gamma-1},$$

$$\mathbf{q} = \mathbf{V}\left(\frac{\rho V^2}{2} + \frac{\gamma}{\gamma-1}p\right) + \frac{1}{4\pi}[\mathbf{B}\times(\mathbf{V}\times\mathbf{B})], \tag{3}$$

$$\partial\mathbf{B}/\partial t = \nabla\times[\mathbf{V}\times\mathbf{B}], \tag{4}$$

where all parameters are used in their usual notation, and $\gamma = 5/3$. Two coordinate systems have been applied: the parabolic coordinates in the main part of the numerical box, and the spherical coordinates near the subsolar region in order to avoid the singularity of the parabolic coordinates at the Sun–Earth line. The two coordinate systems intersect and the values from inner points of one coordinate system have been used to determine the boundary conditions for the other system. At the external boundaries, typical supersonic solar wind conditions have been taken: the sound Mach number equal to 6.95, and the Alfven–Mach number equal to 8.13. The solar wind velocity directs along the Sun–Earth line. At the internal boundary near the magnetopause, we change the boundary conditions in dependence on the IMF orientation, what reflects our assumptions about the magnetic reconnection process. Thus, for the northward IMF the magnetopause is a non-penetrable obstacle with V_n and B_n (the normal components of velocity and magnetic field) equal to zero, but for the southward IMF it is supposed that the normal components at the magnetosheath–magnetopause boundary are determined by the conditions

$$V_n = k\times f(\theta,\phi)\times B_\tau/\sqrt{4\pi\rho}, \quad B_n = k\times f_1(\theta,\phi)\times B_\tau,$$

where f and f_1 are functions in the range $0 < f < 1$ and $-1 < f_1 < 1$ determining the reconnection region at the magnetopause (our determination of this region is similar to that in Semenov and Pudovkin, 1985), B_τ is the tangential component of the magnetic field near the internal boundary, and k is a constant equal to 0.15.

The IMF cone angle (i.e., the angle between the IMF and the Sun–Earth line) is influence on a stationary MHD solution in the magnetosheath too. We have simulated two other cases with IMF $B_z = 0$, and the cone angles equal to 45° and 20°. In other words, in first of these cases the IMF is nearly along the Parker's spiral, and in the second case the direction of the IMF is close to the direction of the solar wind velocity.

We have used the TVD Lax-Friedrichs II-order scheme for the numerical calculations. Stationary solutions in every case have been found by the relaxation method. For a given stationary solution in the magnetosheath, we have calculated the magnetopause current. This current has been determined by the difference between the calculated magnetosheath magnetic field near the inner boundary and the magnetospheric magnetic field obtained by the Tsyganenko's model (Tsyganenko, 2002).

3. Results

Fig. 1 shows the modulus and direction of magnetic field in the magnetosheath for different IMF orientations projected on the plane which contains the IMF and the OX-axis (i.e., the Sun–Earth line). Fig. 2 shows the $|B|$, the density, and the velocity at the OX-axis, while different lines correspond to different IMF orientations. The magnetic barrier is located usually in the subsolar region near the magnetopause obstacle. The magnetic field magnitude in the magnetic barrier is largest for the strictly northward IMF. For the southward IMF, the magnetic field magnitude is about 10–25% less than for the northward IMF, but this value may vary in dependence on the chosen reconnection rate. There is a dip of the $|B|$ in the subsolar region in the vicinity of reconnection line formed on the dayside magnetopause.

For two other cases, with the cone angles 45° and 20°, the behaviour of the MHD parameters is different in the regions downstream of the quasi-parallel and quasi-perpendicular bow shocks (below and above the Sun–Earth line, correspondingly). It is known from the Rankine–Hugoniot conditions that the magnetic field does not change across the parallel bow shock. Thus, an increase of the magnetic field downstream of the parallel bow shock takes place only near the magnetopause due to the draping effect. The magnetic field geometry may be complicated in this case, since the magnetic field near the magnetopause may be directed nearly oppositely with respect to the magnetic field just downstream of the bow shock at the same radial profile. Also for small cone angles, there is a region in the magnetosheath