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PROBLEMS OF MAGNETOSPHERIC DYNAMICS AND FEATURES OF MAGNETOSPHERIC MAGNETIC FIELD STRUCTURE

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Abstract
Different models are frequently used for the description of large-scale magnetospheric dynamics without analysis of the scope of their applicability. The traditional approaches based on the ideal MHD approximation, which is violated only in narrow local regions, encounter fundamental difficulties in the regions with large turbulent fluctuations and laminar slow bulk flow. Therefore, before the selection of the proper scheme for the description of definite magnetospheric region, it is necessary to know properties of its turbulence, plasma parameter and the relation of the Alfvén velocity to bulk flow velocity. We obtain and analyze the distribution of the ratio of the Alfven velocity to the plasma flow velocity averaged under magnetically quiet conditions at geocentric distances up to 20 R_E using THEMIS mission data. It is shown, that this ratio is much higher than unity inside the magnetosphere. The applicability of magnetohydrodynamic models for describing equilibrium and nonequilibrium processes is considered. We argue that the use of models based on the approximation of magnetostatic equilibrium has a number of advantages in the formation of the structure of the magnetospheric magnetic field. A number of problems connected with the comparatively stable local magnetic field decrease and increase are discussed.

1. Introduction

Magnetospheric plasma is a collisionless medium (the mean free path of particles with respect to Coulomb collisions exceeds the distance from the Earth to the Sun). Full kinetic modelling of magnetospheric dynamics requires the self-consistent analysis of every particle motion, particle interactions and the creation of self-consistent electric and magnetic fields. Such problem cannot be solved now. At the same time, nonequilibrium distribution functions formed in the collisionless processes, relatively quickly relax to kappa distributions and later to Maxwell distributions (see [*Espinoza et al.*, 2018; *Kirpichev and Antonova*, 2020; *Kirpichev et al.*, 2021]), which is associated with the development of various instabilities, wave-particle interactions and plasma turbulization. Such feature gives the possibility to use the magnetohydrodynamic description of large-scale magnetospheric dynamics. This formalism is based on the solving a system of simplified magnetohydrodynamic equations (MHD). It is assumed, that the absence of Coulomb collisions makes it possible to use the suggestion about the validity of the frozen-in condition of a magnetic field into a plasma. At the same time, the applicability of this approach frequently is not verified. According to popular concepts, the frozen-in condition can be violated only in relatively thin local regions with scales of the order of the ion Larmor radius or the ion inertial length. However, the scale of these regions is determined not only by the plasma and magnetic field parameters. It strongly depends on the relation of Alfvén speed and bulk flow velocity (see [*Antonova and Stepanova*, 2021] and references therein). Therefore, it is of interest to obtain the distribution of the ratio of the Alfven velocity to the plasma velocity and to analyze the applicability of widely used magnetohydrodynamic models.

2. The relation of Alfvén speed to plasma flow velocity

The value of the Alfvén speed is equal $V_A=B/(\mu_0 mn)^{1/2}$, where B is the magnetic field, μ_0 is the magnetic permeability of vacuum, mn is the plasma density, $m\approx m_i$, $n=(m_i n_i + m_e n_e)/m$, n is the concentration, m_i and m_e are ion and electron mass. The value of plasma flow velocity $\mathbf{V}=(m_i n_i \mathbf{v}_i + m_e n_e \mathbf{v}_e)/mn$ practically coincide with ion velocity. To obtain averaged V_A/V we used data of the THEMIS mission for the period from 2007 till 2011 at geocentric distances smaller than 20 R_E available online at the following sites: (http://themis.ssl.berkeley.edu/) and (http://cdaweb.gsfc.nasa.gov/). The averaged picture was obtained for all IMF and all solar wind dynamic pressures, densities and velocities. We selected the intervals of quite geomagnetic conditions when Dst>-20 nT, Al>-300. The layer $\pm 3R_E$ was selected for averaging. THEMIS data have no discrimination between different ion species and we assumed that all measured ions are H.

Figure 1 shows the picture V_A/V near the equatorial plane and illustrate the well-known information. As it can be easily seen, the super-alfvénic solar wind is a region where $V_A/V<<1$ (dark blue sectors). A comparatively sharp transition from $V_A/V<<1$ to $V_A/V>1$ is observed in the magnetosheath region before the magnetopause shown by red line in accordance with *Shue et al.* [1998] model. The averaged flow velocity in the subsolar magnetosheath and in all of the magnetosphere is much smaller than the Alfvén velocity. The value of averaged V cannot reach V_A in all magnetospheric regions. It is necessary to mention that $V_A/V<<1$ only in the solar wind flow direction. This corresponds to the super-alfvénic flows of the solar wind. However, it is necessary to remind that different turbulent flow velocities are observed in the reference frame of the solar wind. At geocentric distances smaller than $8R_E$ strong magnetic field provides $V_A/V<<1$ which is taken into account in the inner magnetospheric modelling of plasma flows.

The obtained picture clearly shows that modelling different magnetospheric regions it is necessary to use different approximations as the contribution of different terms in the generalized Ohm's law, as was mentioned in the Introduction, strongly depends on the relation V_A/V. In the collisionless plasma the generalized Ohm's law has the form:

$$\mathbf{E}[\mathbf{V}\times\mathbf{B}] = \frac{[\mathbf{j}\times\mathbf{B}]}{ne} - \frac{\nabla p_e}{ne}\left[\frac{\partial\mathbf{j}}{\partial t}\nabla\cdot(\mathbf{jVVj})\right]\frac{m_e}{ne^2}, \quad (1)$$

where **E** is the electric field, **j** is the current density, m_e and n_e is the mass and concentration of electrons, m_i and n_i is the mass and concentration of ions. The third and fourth terms are of interest in the cases of analysis of electron diffusion regions (see the results of MMS observations) and will not be discussed here. It is small in the case of large-scale motions. If the right-hand side of equation (1) is smaller than [**V**×**B**], then the equation (1) represents the frozen-in condition.

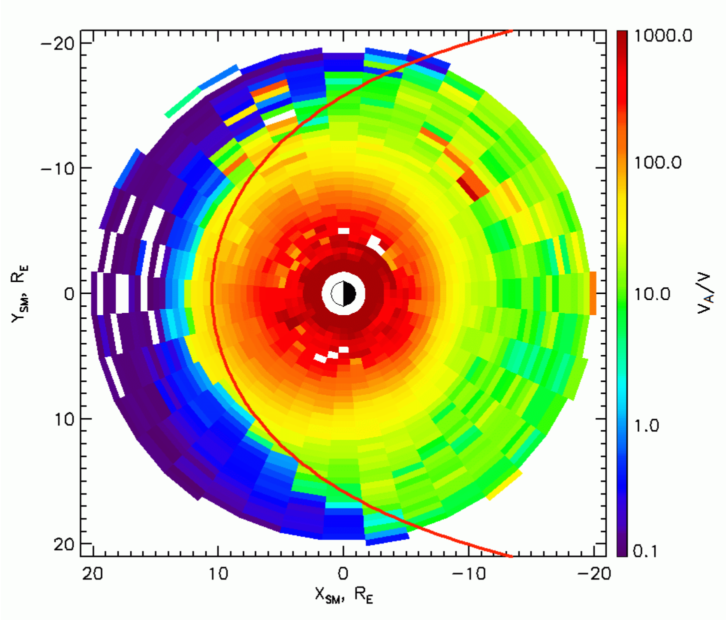

Figure 1. The ratio V_A/V near the equatorial plane at geocentric distances smaller than 20 R_E.

The contribution of the right-hand side of equation (1) to the generalized Ohm's law becomes especially significant in the regions of high current density due to the Hall term. The region where **E[V×B]**≠0 due to a large value of the Hall term is named the ion diffusion region. Its scale is equal $L_{Hall}=\lambda_i V_A/V$, where $\lambda_i=c/\omega_{pi}$ is the ion diffusion region, c is the velocity of light, $\omega_{pi}=[(e^2n)/(\varepsilon_0 m_i)]^{1/2}$ is the ion plasma frequency, ε_0 is the vacuum dielectric constant. Therefore Fig. 1 shows that during quite conditions when $V\to 0$ physics of magnetosphere cannot be described by MHD suggesting the validity of the frozen-in condition. Plasma motions with Alfvén velocities are typical only for fast processes.

3. Tail turbulence and magnetostatic equilibrium

The velocity of plasma flows in the geomagnetic tails can be comparable with Alfvén velocity [*Borovsky et al.*, 1997]. However, such flows are the part of observed plasma sheet turbulence or the result of Alvén-like wave propagation. This turbulence has the intermitten character. Fig. 2 shows three examples of hodograms of the bulk velocity in the (Vx,Vy) and (Vy,Vz) planes observed 26 February 2008 between 5 and 8 UT by satellite THEMIS-C (THC) during three 12 min intervals [*Eyelade et al.*, 2021]. The colors represent 12 min intervals centered at the time indicated in the lower left corner by the same color together with the average bulk velocity calculated for each interval. It is possible to see that velocity fluctuations have the random character. The level of velocity fluctuations is ordinarily smaller than the Alvén speed and analysis of such turbulent fluctuations can be done with the inclusion of terms in the right-hand side of the equation (1). However, fast flows with the Alvén speed are also observed. Such fast flows can lead to scenarios described by reconnection theories. It is necessary to mention that in accordance with [*Lazarian et al.*, 2019] for solar wind and astrophysical turbulence and [*Antonova and Steanova*, 2021] for turbulence in the geomagnetic tail, reconnection events can be considered as the intrinsic properties of turbulent cascade.

The most important feature of velocity scattering is the existence of flow fluctuations across the plasma sheet in Z direction which was first time demonstrated due to INTERBALL/Tail probe observations [*Yermolaev et al.*, 2000]. Such turbulent velocity fluctuations create the diffusion flux which can destroy the plasma sheet (see the reviews

[*Ovchinnikov and Antonova*, 2017; Antonova and Stepanova, 2021]). The problem was theoretically solved and gave the possibility to predict the value of the eddy diffusion coefficient, which was measured experimentally. It was based on the observed pressure balance across the plasma sheet [*Baumjohann et al.*, 1990; *Petrukovich et al.*, 2011], its dependence on IMF Bz and large-scale plasma flow form the tail lobes to its center when IMF Bz<0.

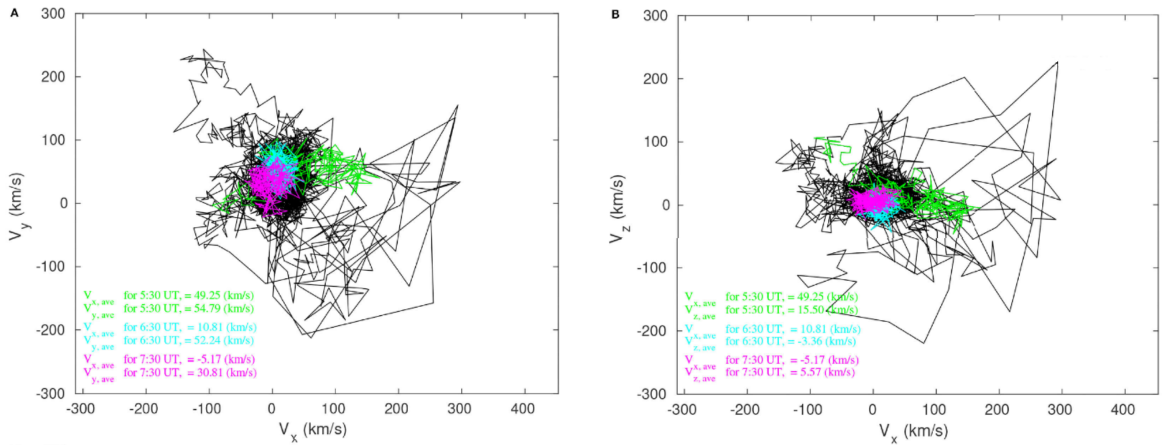

Figure 2. Hodograms of the bulk velocity in the (Vx, Vy) and (Vy, Vz) planes observed 26 February 2008.

3. The condition of magnetostatic equilibrium and the advantages of its use

The main differences of magnetospheric plasma from the plasma in the most of laboratory plasma devices is the absence of rigid walls. Magnetospheric dynamics are controlled by outer boundary conditions created in the process of turbulent solar wind interaction with the magnetic field of the Earth's dipole. The level of solar wind turbulence is greatly increased after the bow shock crossing forming the turbulent magnetosheath where $\mathbf{E}[\mathbf{V}\times\mathbf{B}]\neq 0$. In spite of great level of turbulence, the pressure balance at the magnetopause take place with rather high accuracy (see [*Znatkova et al.*, 2011] and references therein) and even can be used for calibration of electrostatic analyzers in flight [*McFadden et al.*, 2008]. The existence of pressure balance across the plasma sheet was mentioned earlier. This means that the relaxation of the magnetosphere to the condition of magnetostatic equilibrium when averaged flow velocity is much slower than Alfvén and sound velocity can be selected as the main mechanism of magnetospheric dynamics.

The condition of magnetostatic equilibrium when plasma pressure p is near to isotropic has the form:

$$[\mathbf{j}\times\mathbf{B}]=\nabla p. \qquad (2)$$

This condition is very useful for mapping the low latitude regions to the equatorial plane as in accordance with (2) isotropic plasma pressure has the constant value along magnetic field line. This approach was first used, as we know, in the paper [*Dubyagin et al.*, 2003] to demonstrate the near-Earth auroral breakup location (at ~$8R_E$). After the obtaining plasma pressure distribution at the equatorial plane [*Kirpichev and Antonova*, 2011] it became possible to compare plasma pressure distribution at the equatorial plane and at low latitudes. It was shown that the auroral oval is mapped to the surrounding the Earth plasma ring at geocentric distances till ~10-13 R_E. [*Antonova et al.*, 2014; 2015; 2018; *Kirpichev et al.*, 2016]. Latest results about distribution of plasma pressure in the low latitude boundary layer were published in [*Vorobjev et al.*, 2021].

4. Conclusions and discussion

Produced analysis leads to the next conclusions:

- The relation of Alfvén to averaged plasma flow velocity is larger than unity in the plasma sheet and very high in the inner magnetosphere which strongly limited the using of the frozen-in condition.
- Velocity fluctuations across the plasma sheet create the problem for its stability. However comparatively stable plasma sheet can be formed taking into account plasma regular flow form the tail lobes to the tail center.
- Magnetospheric dynamic is directed to the formation of stress balance which can coexists with large velocity fluctuations.
- Analysis of pressure distribution at low altitudes and at the equatorial plane provides the effective way of mapping.

However, the using of plasma pressure as the magnetic field market strongly complicates due to nonhomogeneous distribution of magnetic field and plasma pressure in the radial direction [*Saito et al.*, 2010; *Petrukovich et al.*, 2013; *Vovchenko et al.*, 2018].

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