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HIGH-BETA PLASMA JET IN THE SPACE

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Abstract. Injection of dense plasma from an explosive source in the magnetosphere is numerically simulated. Plasma motion along and across the magnetic field is considered. Comparison with an injection without magnetic field is presented.

Introduction

Plasma flows play an important role in space phenomena. High beta plasma ejection from the Sun (CME), its propagation in the solar wind, and interaction with the magnetosphere are critical problems of modern solar-terrestrial physics. The attempt to solve this problem in single numerical MHD experiment meets many difficulties. Another example of important problems in the magnetospheric physics is plasma injection from the tail during a substorm. These problems are very complicated, and conditions in the space usually unknown. In such situation it is very desirable to understand the jet behavior under strong determinated conditions, as the jet interaction with the background plasma in the magnetic field depends on many parameters (β in the jet and background plasma, Mach number, the angle between **V** and **B**, et al.). For solving these problems the results of active experiments in the space can be used (*Gavrilov at al., 1998, 1999*). But in such investigations only restricted amount of instrumental containers (usually one) are employed. As a result the complete picture of jet dynamics can not be obtained.

In previous papers (*Podgorny and Podgorny, 1997, 1998, 1999*) we have considered low β plasma jet interaction with the magnetosphere. Here some results of high β jet interaction with low β plasma are presented.

Numerical method

The system of 3D MHD equations in dimensionless form:

$$\frac{\partial \mathbf{B}}{\partial t} = \mathrm{rot}(\mathbf{V}\times\mathbf{B}) - \frac{1}{\mathrm{Re}_m}\mathrm{rot}\left(\frac{\sigma_0}{\sigma}\mathrm{rot}\mathbf{B}\right) \tag{1}$$

$$\frac{\partial \rho}{\partial t} = -\mathrm{div}(\mathbf{V}\rho) \tag{2}$$

$$\frac{\partial \mathbf{V}}{\partial t} = -(\mathbf{V},\nabla)\mathbf{V} - \frac{\beta_0}{2\rho}\nabla(\rho T) - \frac{1}{\rho}(\mathbf{B}\times\mathrm{rot}\mathbf{B}) + \frac{1}{\mathrm{Re}\rho}\Delta\mathbf{V} + G_g\mathbf{G} \tag{3}$$

$$\frac{\partial T}{\partial t} = -(\mathbf{V},\nabla)T - (\gamma-1)T\mathrm{div}\mathbf{V} + (\gamma-1)\frac{2\sigma_0}{\mathrm{Re}_m\sigma\beta_0\rho}(\mathrm{rot}\mathbf{B})^2 - (\gamma-1)G_q L'(T)\rho +$$
$$+\frac{\gamma-1}{\rho}\mathrm{div}\left(\mathbf{e}_\parallel\frac{\kappa}{\Pi\kappa_0}(\mathbf{e}_\parallel,\nabla T) + \mathbf{e}_{\perp1}\kappa_{\perp dl}(\mathbf{e}_{\perp1},\nabla T) + \mathbf{e}_{\perp2}\kappa_{\perp dl}(\mathbf{e}_{\perp2},\nabla T)\right) \tag{4}$$

is solved numerically. The last term in equation (4) takes into account anisotropy of thermal conductivity. Here $\mathbf{e}_\parallel$ and $\mathbf{e}_\perp$ are the unity vectors along and across the magnetic field respectively. κ and $\kappa_\perp$ are thermal conductivity along and across the magnetic field. $\kappa_{\perp dl} = \dfrac{(\kappa\kappa_0^{-1}\Pi^{-1})(\kappa_B\kappa_{0B}^{-1}\Pi_B^{-1})}{(\kappa\kappa_0^{-1}\Pi^{-1}) + (\kappa_B\kappa_{0B}^{-1}\Pi_B^{-1})}$ The main dimensionless parameters of background plasma are: $\beta=8\pi nkT/B^2 = 10^{-4}$, the magnetic Reynolds number $\mathrm{Re}_m = 10^2$, the Peclet number $\Pi=VL/V_{Te}\lambda_e=1$, Peclet number across the magnetic field, $\Pi_B=10^6$. The high density jet is injected from the X=0 plane along the X axis with the velocity $\mathbf{V}_0=(V_x, 0, 0)$. The jet diameter (d=0.12) center is Y= 0.5, Z=0.5. All results are presented in dimensionless units: the numerical region dimension L is the unit of length, Alfvenic velocity V_A is the velocity unit, Alfvenic time L/V_A is the time unit, initial magnetic field B_0 is the magnetic field unit, the background plasma density ρ_0 is the density unit. The PERESVET code (*Podgorny, 1995*) is used. The initial conditions correspond to subalfvenic jet injection in the magnetosphere at the altitude of 150-500 km. The results permit to compare measurements in active experiments.

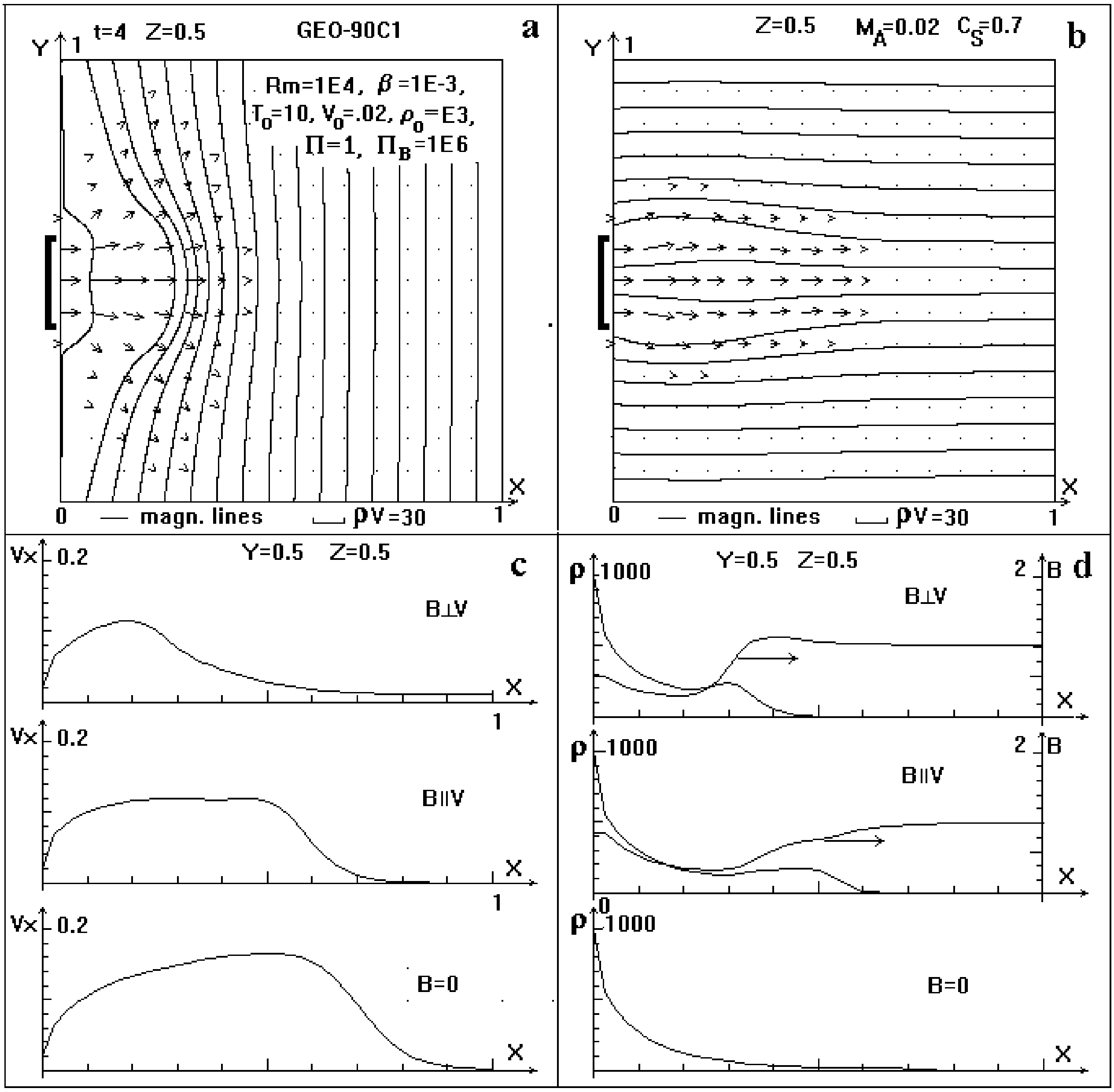

Fig. 1. (a) and (b) Magnetic field lines and momentum vectors for the time t=4. (c) Distributions of the jet velocity along the jet axis. (d) Distributions of magnetic field lines and density.

Results of numerical simulation

Behavior of the plasma jet with an injection along and across the magnetic field is presented in Fig. 1a and Fig. 1b respectively. Arrows show the plasma momentum ρV. Parameters of the jet are written in the right upper corner of Fig. 1a. The dense plasma jet is expanded and expels the magnetic field lines because of the high conductivity. A diamagnetic cavity is created. During the injection along the field lines, plasma flow is guided along magnetic lines, and magnetic pressure prevents its fast expansion in the radial direction. This effect is also found in density distributions with and without magnetic field (Fig. 1d). During the injection across the field the plasma deceleration is more effective. The velocity distributions for both cases (B⊥V and B||V) are presented in Fig. 1c. A strong jet deceleration is seen with regard to the motion across the magnetic field. Distributions of the magnetic field and plasma density along the jet axis are seen in Fig. 1d. The magnetic field inside the jet drops in both magnetic field directions. For V parallel to B, the magnetic field depletion propagates ahead of jet. Magnetic field lines displacement from the axis occurs , because of Alfven wave moving before the jet front. For B⊥V magnetic field increasing before the jet front appears because magnetic lines envelopment of the jet. The background plasma begins to move ahead of the jet, as it is seen in Fig. 1c. This is typical for the magnetosonic wave generation. Apparently, for a jet of very high density, when magnetic field is expelled completely, the magnetosonic waves generation is the main mechanism of plasma jet deceleration.

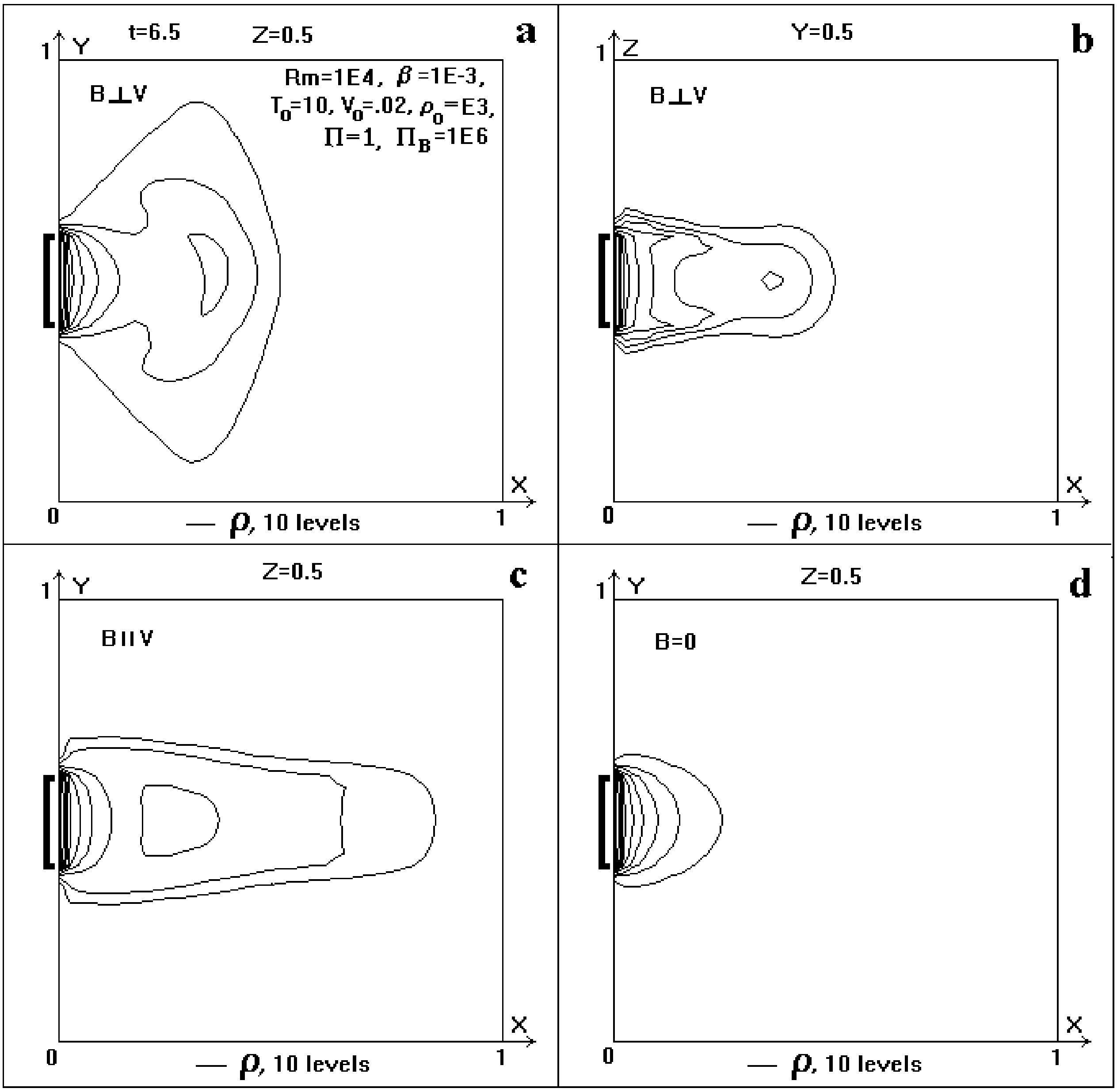

Fig. 2. Ten levels of   =const for injections across the field (a and b), along the field (c), and (d) at B=0. All data for t=6.5.

The comparison of density distributions for plasma injection at V⊥B and V||B with the distribution for B=0 shows that focusing of plasma density occurs in both cases, when the magnetic field is present. During the injection across the magnetic field the force **j**x**B**/c compressed the plasma and concentrated it in the axis vicinity, because magnetic lines are arranged along the jet surface. This effect is demonstrated in Fig. 2 for t=6.5 The idea of density distributions in 3D can be obtained from the distributions of ten levels of ρ=const in planes perpendicular and parallel to undisturbed **B** (Fig. 2a and 2b). The jet expands mostly along the field lines, and becomes flat. The density distribution for injection along the **B** (Fig. 2c) is axial symmetrical. The levels of ρ=const for the same time, but calculated at B=0, is shown in Fig. 2d.

Measurements in the space

In active experiments a set of sensors is placed on the separated container for measurements plasma and field parameters inside the jet in a single point. It is well known that magnetized plasma flow interaction with a container produce disturbances, because of container conductivity. To avoid their influence the sensors are placed on long booms. Calculations has been carried out for estimation the region ahead of container where the disturbances are significant. In Fig. 3a magnetic field and density distributions along the jet axis are presented. The conductive obstacle is placed at X=1. For comparison the same calculation has been performed without the obstacle. Their results are also shown. The length of disturbed region is an order of the obstacle dimension.

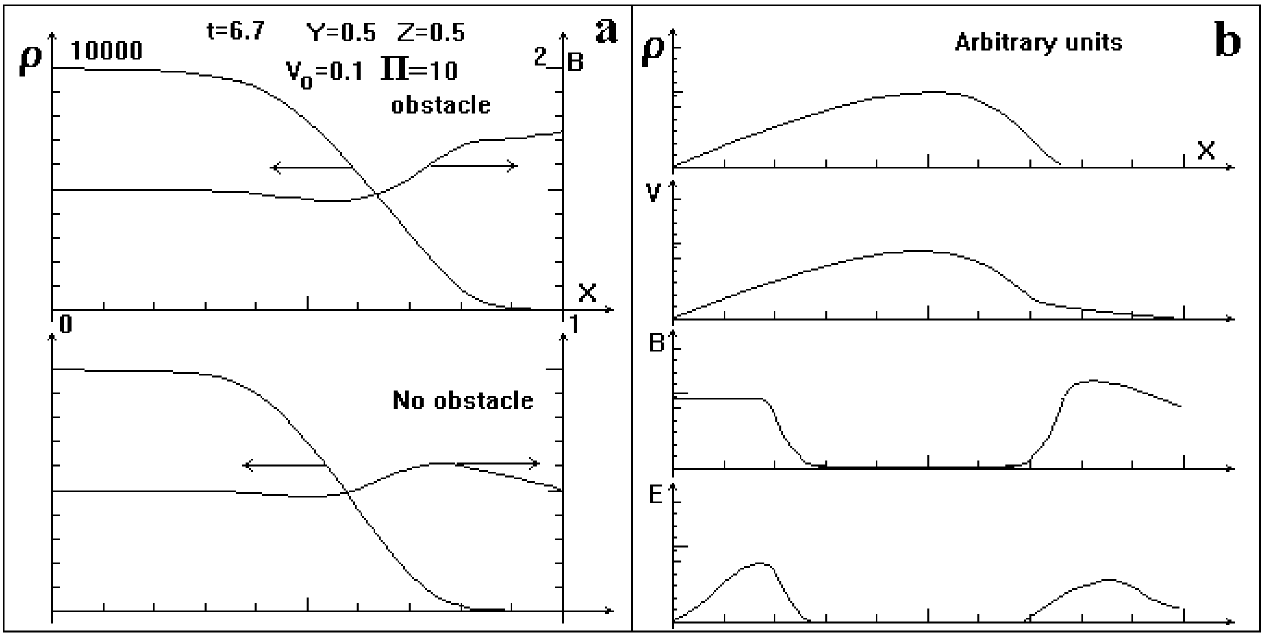

Fig. 3. (a) The velocity and magnetic field disturbance under the jet interaction with a conductive obstacle. (b) The schematic presentation of the results of plasma and field parameters under measurements with a container.

The electric field sensor in the magnetized plasma must measure E=–VxB/c. In the case of complete magnetic field expelling E=0. Ahead of the jet front the magnetosound wave disturbs plasma. In the wave the electric field is $\mathbf{E}=\mathbf{V}_w x\mathbf{B}/c$, here $\mathbf{V}_w$ is the velocity in the wave. In the rear front the plasma density drops, the diamagnetic effect is weak, and the sensor must show the electric field of the same direction. The schematic distributions of the measured parameters in strong magnetic field expelling are presented in Fig. 3b.

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