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About the equilibrium and stability of non-electroneutral current sheaths

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Abstract

In this paper, we prove the necessity of using the Cauchy problem, i.e., initial value problem, for solving the equilibrium (steady state) current sheet. In this connection, it appears that equilibrium current sheaths exhibit structural instability.

It is emphasized that during examination of the stability of a current sheath, the kinetic equation solution uses the angle integration technique (unlike the method of paths applied earlier). Therefore, in contrast to previous procedures of examination, this method demonstrates the possibility of studying tearing instability and also all the remaining eigenmodes of instability of a current sheath. The growth rate of tearing instability exceeds the values adopted previously by an order of magnitude or more. At this stage, we realize examination shortwave eigenmodes only.

Keywords: Kinetic theory; Distribution function; Polarization of magneto-active plasma; Equilibrium of magnetopause; Stability of magnetopause; Tearing instability

1. Introduction

To describe a steady state current sheet, Harris proposed a distribution function selected in such a way that it allowed passing into a system of coordinates where the electric field is zero (Harris, 1962). Further, the Coppi et al. (1966) investigate the stability of the sheet, and they arrived at the conclusion that the development of the tearing-instability, which enables reconnection of the magnetic field lines in the magnetoneutral plane, is possible under certain conditions. Those two papers became a basis for most of the further research of the dynamics of a magnetotail current sheet and energetics of magnetospheric substorm.

However, subsequent theoretical studies (Brittnacher et al., 1994, 1998; Lembège and Pellat, 1982; Pellat et al., 1991) showed that inclusion of the component of the magnetic field, which is normal to the sheet, changes the power balance of the system and the spontaneous development of the instability becomes energetically unfavorable. One of the lines of research of the dynamics of current sheets today is searching for such physical processes, which would contribute to the development of the tearing- and other instabilities. The instability of current sheets under disturbances such as bending, ballooning, combined, and drift modes are being studied (Sitnov and Lui, 1999; Buchner and Kuska, 1999; Daughton, 1998; Kuznetsova et al., 2001; Sitnov et al., 1999; Silin et al., 2002; Zelenyi et al., 2002; Mingalev et al., 2007). In the paper (Camporeale et al., 2004), the problem of starting of reconnection of the magnetic field lines was also studied, and it may be inferred that development of low-hybrid drift instability can contribute to solving this problem.

The Harris distribution function is generalized in the paper (Neukirch et al., 2009). In all the papers cited, the

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process of polarization of sharply inhomogeneous magnetic plasma of a current sheet was not considered. Only a small number of papers, such as (Schindler and Birn, 2002; Birn and Schindler, 2004; Yoon and Lui, 2004), were devoted to the study of the process of plasma current-sheet polarization. However, the research is within the limits of quasi-neutrality approximation. The quasineutral approximation is zero approximation of the method of singular perturbations. In this case, as small parameter for the thermal plasma serves the ratio of the electron temperature to the electron rest energy $\varepsilon_0\mu_0\theta_e/m_e = \theta_e/m_e c^2$. The quasineutrality condition is well satisfied at low temperatures and is worse performed at high temperatures. Finding of the next specifying first approximation is technically impossible. Therefore, it is impossible to make any definite physical conclusion about the polarizing electric field of sharply inhomogeneous magnetic plasma.

In the proposed paper, the kinetic theory of equilibrium and stability of non-electroneutral current sheets which formed at the arbitrary values of parameters of the environment is developed. The equilibrium distribution function (Harris function) that takes into account the anisotropy of plasma temperature along and across the sheet is generalized. The non-electroneutral equilibrium solution for the current sheet with anti-parallel magnetic fields is obtained. The effect of plasma polarization without any restrictions in a wide range of values of parameters and its influence on the stability of a current sheet are investigated.

In this paper, we generalized the results obtained in the papers (Lyahov and Neshchadim, 2012, 2013) as also we eliminated technical errors made by preparation of figures in those papers.

2. Examination of the structural stability of the non-electroneutral current sheath

Let the plasma is concentrated in the $z = 0$ plane (see Fig. 1), and anti-parallel magnetic fields are present in the top and bottom half-spaces. In this plane, a self-consistent

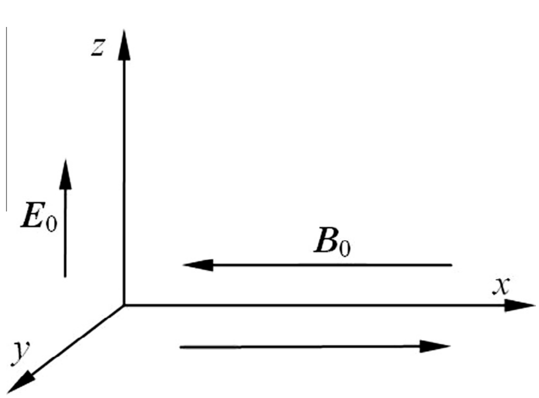

Fig. 1. The coordinate system of the current sheet.

current sheet dividing the areas with oppositely directed magnetic fields is formed.

We have a one-dimensional problem. All the values depend on the variable z. For an exposition of the equilibrium of a current sheath in Lyahov and Neshchadim paper (2012), we introduced the anisotropic distribution function which generalizes the Harris distribution (Harris, 1962):

$$f_{0\alpha} = \frac{m_\alpha}{2\pi\theta_{\alpha z}} n_0 (1+\alpha_\alpha)^{\frac{1}{2}} \exp\left[\frac{m_\alpha}{2\theta_{\alpha z}}(1+\alpha_\alpha)U_\alpha^2\right] \cdot \exp\left[-\frac{W_\alpha}{\theta_{\alpha z}} - \frac{\alpha_\alpha P_{y\alpha}^2}{2\theta_{\alpha z} m_\alpha} + U_\alpha(1+\alpha_\alpha)\frac{P_{y\alpha}}{\theta_{\alpha z}}\right]. \quad (1)$$

Here,

$$\alpha_\alpha = \frac{\theta_{\alpha z}}{\theta_{\alpha y}}\text{-}1 \quad \text{degree of the temperature anisotropy} \quad (2)$$

U_α – the macroscopic velocity directed along a sheath perpendicular to the magnetic field.

Integrals of motion are the total energy and generalized momentum:

$$W_\alpha = \frac{1}{2} m_\alpha (v_x^2 + v_y^2 + v_z^2) + e_\alpha \varphi(z), \quad P_{y\alpha} = m_\alpha v_y + e_\alpha A_y(z). \quad (3)$$

If we suppose that electric and magnetic potentials fulfill the condition

$$\phi(z=0) = A_y(z=0) = 0, \quad (4)$$

then, the distribution function (1) at the boundary $z = 0$ is the physically meaningful anisotropic shifted Maxwell distribution:

$$f_{0\alpha} = \frac{m_\alpha}{2\pi\theta_{\alpha z}} n_0 (1+\alpha_\alpha)^{\frac{1}{2}} \exp\left[-\frac{m_\alpha}{2\theta_{\alpha z}}[v_{\alpha z}^2 + (1+\alpha_\alpha)(v_{\alpha y} - U_\alpha)^2]\right]. \quad (5)$$

To describe the equilibrium of the current sheath, apart from the requirements of (4) at a point $z = 0$, it is necessary to ask for implementation of the inversion of magnetic field $A_y'(z=0) = 0$ and the absence of an electric field polarization (plasma at this point is electrically neutral) $\varphi'(z=0) = 0$. Thus, it is necessary to set the initial value problem, i.e., the Cauchy problem, as it is described in Harris (1962).

The equations for the dimensionless electromagnetic potentials obtained in Lyahov and Neshchadim (2012) are:

$$\frac{d^2\psi}{d\xi^2} = \exp\left(\frac{\psi}{\gamma} - \frac{\omega_e}{\gamma}a - \frac{\alpha_e}{1+\alpha_e}\frac{\eta a^2}{2\gamma\mu}\right) - \exp\left(-\psi + \omega_i a - \frac{\alpha_i}{1+\alpha_i}\frac{\eta a^2}{2}\right), \quad (6)$$

$$\frac{d^2 a}{d\xi^2} = \left(\omega_e + \frac{\alpha_e}{1+\alpha_e}\frac{\eta a}{\mu}\right)\exp\left(\frac{\psi}{\gamma} - \frac{\omega_e}{\gamma}a - \frac{\alpha_e}{1+\alpha_e}\frac{\eta a^2}{2\gamma\mu}\right) - \left(\omega_i - \frac{\alpha_i}{1+\alpha_i}\eta a\right)\cdot \exp\left(-\psi + \omega_i a - \frac{\alpha_i}{1+\alpha_i}\frac{\eta a^2}{2}\right) \quad (7)$$