MAGNETIC RECONNECTION IN HIGH-TEMPERATURE PLASMA OF SOLAR FLARES

III. *Stabilizing Effect of the Transverse Magnetic Field in a Non-Neutral Current Sheet*

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Abstract. Quasi-steady high-temperature current sheets are an energy source during the 'main' or 'hot' phase of solar flares. Such sheets are shown to be stabilized with respect to the tearing instability by a small transverse component of magnetic field existing in the sheets.

1. Introduction

Any current sheet (CS), e.g., the Syrovatskii pinch current sheet (Syrovatskii, 1976, 1979), is a two-dimensional and (essentially) two-scale formation even in the simplest models. On the one hand, being wide enough as CS may accumulate a considerable quantity of free-magnetic energy. On the other hand, being thin enough it may provide rapid dissipation of this energy by converting it into the kinetic energy of plasma flows and accelerated particles. Due to these properties of a CS, its investigation is of great importance for many problems of cosmic and laboratory plasma physics (e.g., Priest, 1982, 1985; Hones, 1984).

For the explanation of a wide class of interconnected non-stationary phenomena in the solar corona, – coronal transients, transient coronal holes, and coronal particle acceleration, – the high-temperature turbulent current sheet (HTCS) model was suggested (Somov, 1981). The main feature of a HTCS is that heat flows play an essential role in its energetics.

The presence of a small transverse component of the magnetic field in HTCS increases essentially the efficiency of the sheet cooling by anomalous heat flows and convective plasma flows. Moreover, in a HTCS (Somov and Titov, 1983, 1985a, b) it is not only the plasma outflow that increases, but also the plasma inflow into the sheet. Together with a plasma inflow increase, the magnetic energy dissipation in a HTCS increases also. It makes it possible to achieve a sufficiently big energy release power in a non-neutral (i.e., with nonvanishing magnetic field transverse component) HTCS even when the typical reconnection rates are relatively small.

The conditions described above are those that are realized during the 'main', or 'hot'

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phase of solar flares (see, for example, Somov, 1985, 1986; Somov, Titov, and Verneta, 1987). This phase is called 'hot' because of its bright emission by a high temperature relatively dense plasma, and it is called 'main' because during this phase most of the flare energy is probably released.

The applicability of the non-neutral HTCS model to conditions in solar flare was analyzed in several papers (see the review by Somov, 1986). Particularly, the marginal ion-acoustic turbulence regime was shown to be the best advantageous. It allows one to obtain an energy release power and magnetic reconnection rate necessary for the explanation of the 'main', or 'hot' phase. However, an essential question is whether the HTCS as a power source for the energy is stable with respect to the tearing instability (TI). The answer to this question will be given in the present work (see also Verneta and Somov, 1987).

2. Tearing Instability Stabilization Mechanisms

Since the work of Furth, Killeen, and Rosenbluth (1963) it is known that current sheets are unstable with respect to long-wave perturbations ($\lambda > 2\pi L$) which cause the sheet to fragment to parallel current filaments. Here λ is the perturbation wavelength, L is the thickness of the sheet. In other words, according to the theory, a CS is often unstable. However, laboratory and space research (see, for example, Hones, 1984; Priest, 1982, 1985) suggests that current sheets exist during a long time, being rather wide and thin. For solar flares, for example, a CS with width to thickness ratio of 10^7–10^8 is needed.

Different factors that stabilize the CS tearing instability have been considered: the surrounding plasma (Syrovatskii, 1976); the plasma outflow (Bulanov, Sakai, and Syrovatskii, 1978); the transverse component of the magnetic field (in the collisionless limit: Schindler, 1974; Galeev and Zeleny, 1975a, b; Coroniti, 1980; in the MHD limit: Verneta and Somov, 1988a, b, and references therein) and others.

The stabilizing influence of the surrounding plasma is because in the tearing place a new current sheet begins to form (Syrovatskii, 1976). We can introduce the following quantitative criterion of stabilization. If the instability growth rate $\gamma_e < V_d/L$, where V_d is the velocity of the plasma drift into the sheet, the tears of the sheet have no time to be built up and are filled by the plasma flowing in and the instability is thus stabilized. For a HTCS we have $\gamma_e \sim 10^6\ \mathrm{s}^{-1}$ (see below) and $V_d/L \sim 10^2$–$10^4\ \mathrm{s}^{-1}$ (see Somov, 1986). Thus we see that TI in a HTCS cannot be stabilized by the surrounding plasma.

Stabilization by the plasma outflow along a HTCS is not effective either. Actually, this stabilization mechanism works when the instability growth rate γ_e satisfies the condition $\gamma_e < V_0/b$, where V_0 is the plasma outflow velocity. In this case perturbations are carried away from the sheet and have no time for growth. For a HTCS we have $\gamma_e \sim 10^6\ \mathrm{s}^{-1}$ (see below) and $V_0/b \sim 0.1$–$1\ \mathrm{s}^{-1}$ (Somov, 1986). Consequently the collisionless tearing instability cannot be stabilized by this mechanism. (Here b is the half of the layer width.)

To clarify the influence of the transverse magnetic field component of the TI development in a HTCS we shall use the results obtained for collisionless current sheets (Shindler, 1974; Galeev and Zeleny, 1975a, see also Zeleny, 1986) (see Figure 1).

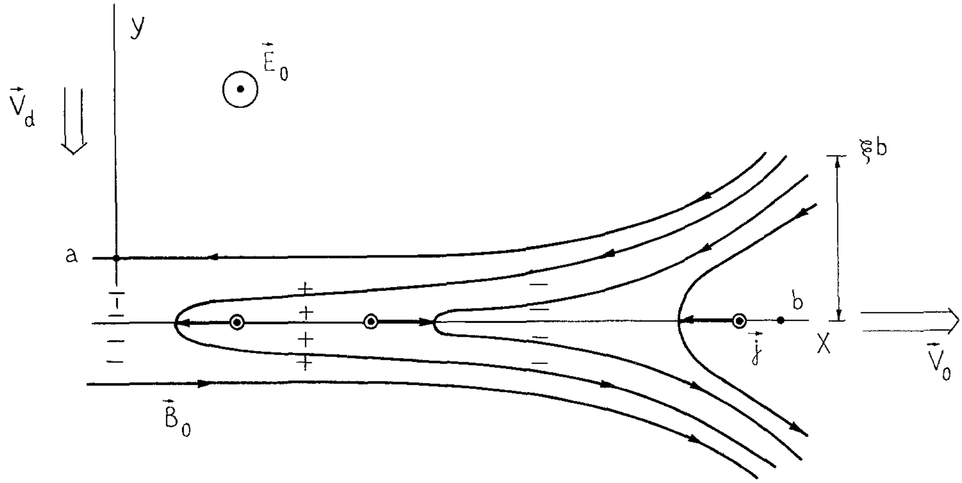

Fig. 1. The stabilizing influence of the transverse magnetic field component in HTCS. During the instability development currents j concentrating the additional energy for the transverse magnetic field compression is needed. The magnetic field is partially or totally frozen into the electron component of plasma.

The collisionless plasma approximation is valid if the characteristic time of TI processes is much less than that of collisions, i.e., if the condition

$$\gamma_e \gg \nu_e$$

is satisfied (Drake and Lee, 1977; Zeleny and Taktakishvili, 1981). Here γ_e is the instability growth rate, ν_e is the electron collision frequency:

$$\nu_e = \frac{8\pi n_e e^4 \ln \Lambda}{3\sqrt{3m_e}\,(kT_e)^{3/2}}$$

(see, e.g., Goland, Zhilinskii, and Sakharov, 1977), where the Coulomb logarithm $\ln \Lambda \sim 20$, the electron concentration $n_e \sim 10^{10}\ \mathrm{cm}^{-3}$ and the electron temperature $T_e \sim 10^7$ K (Somov, 1986), other notations being traditional. If the electrons are magnetized the effective collision frequency is

$$\nu_{e\,\mathrm{eff}} \lesssim \frac{1}{\xi^2}\left(\frac{r_e}{L}\right)^2 \nu_e = \Pi \nu_e$$

(Pitaevsky, 1963; Zeleny and Taktakishvili, 1987), where r_e is the electron gyroradius in the external magnetic field B_0, $\xi = B_n/B_0$ is the relative value of the transverse component B_n of the magnetic field. For a HTCS the ratio r_e/L which will play an important role in what follows, is equal to

$$\frac{r_e}{L} = \frac{m_e c^2}{2\pi e \sigma_a E_0 L^2}\left(\frac{2kT_e}{m_e}\right)^{1/2} = \text{const.} = 5.34 \times 10^{-2} \tag{1}$$

and does not depend on the external parameters in the HTCS model applicability region. Here σ_a is the conductivity in CS, E_0 is the electric field (see the expressions for σ_a, E_0 in Somov, 1986). Thus in a HTCS

$$\nu_e \lesssim 3 \times 10^{-7}\ \mathrm{s}^{-1};$$

$$5 \times 10^{-4} < \xi < 1\,, \quad \Pi < 10^4 \quad \text{(see Figure 2)};$$

$$\gamma_e \sim 10^6\ \mathrm{s}^{-1} \quad \text{(see below)}.$$

One can see that the inequalities

$$\gamma_e \gg \nu_e\,, \quad \gamma_e \gg \nu_{e\,\mathrm{eff}}$$

are valid.

Note that the influence of the turbulence can modify this result more essential, because the effective electron-ion sound collision frequency (for the HTCS with ion sound turbulence) is

$$\nu_{\mathrm{eff}} = \frac{\omega_{pe}^2}{4\pi\sigma_a} \sim 10^6\ \mathrm{s}^{-1}\,,$$

where ω_{pe} is the electron plasma frequency. However, as shown by Verneta and Somov (1988a, b) in the MHD approximation we may consider a HTCS to be stabilized by the transverse magnetic field and plasma flows from the sheet and in it.

We shall begin with sufficiently small values of ξ that the inequality $\Omega_e < \gamma_e$ holds, where Ω_e is the electron gyrofrequency in the transverse magnetic field. In this case the electrons in the region, where the reconnecting magnetic field components vanish, are in resonance with the magnetic field perturbation (inverse Landau damping). As a consequence an electron tearing mode is developed in a CS, with the growth rate

$$\gamma_e = \frac{V_{Te}}{L}\left(\frac{r_e}{L}\right)^{3/2}\,,$$

where V_{Te} is the electron heat velocity. In a HTCS for $\xi = 10^{-4}$ (see Figure 2) $\gamma_e \sim 10^6\ \mathrm{s}^{-1}$.

With the increase of ξ, Ω_e increases. When $\Omega_e > \gamma_e$ the electron resonance with the perturbation is broken and the electron TI mode is stabilized. This occurs when

$$\xi > \xi_{e1} = \left(\frac{r_e}{L}\right)^{5/2}\left(1 + \frac{T_i}{T_e}\right).$$

For a HTCS we get (see Equation (1))

$$\xi_{e1} = 7.6 \times 10^{-4}$$

which is independent of the external parameters in the HTCS model applicability region. Here the ratio $T_i/T_s = 1/6.5$ (Somov, 1986) was taken into account.

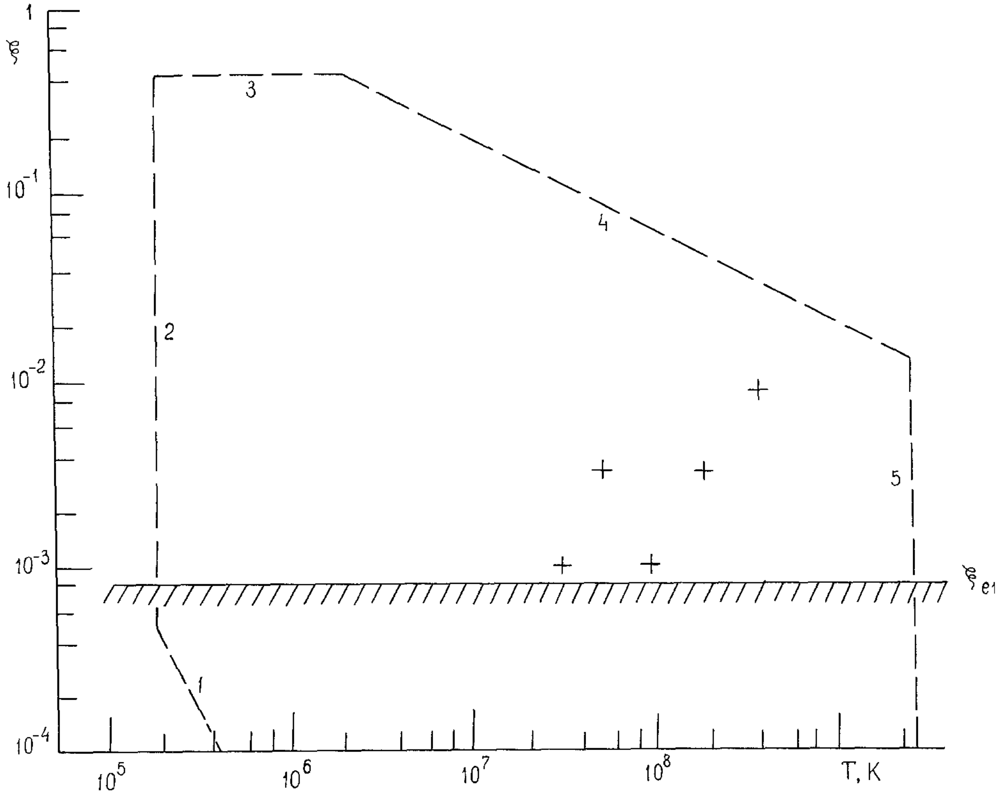

Fig. 2. ξ and T parameter region where the HTCS model is applicable (dashed line). The stability region lies above the line ξ_{e1}. By the crosses the different states of a HTCS are shown which correspond to solar flares of different power.

If the electron TI mode is stabilized, there remains the possibility for the ions to become the resonant particles accumulating the energy of the waves. The gyro-rotation of the electrons, however, stabilizes the ion tearing mode provided

$$\xi < \xi_{e2} = \left(\frac{r_e}{L}\right)^{1/4}\left(1 + \frac{T_i}{T_e}\right)^{-1/2} .$$

For a HTCS we find (see Equation (1))

$$\xi_{e2} = 4.5 \times 10^{-1} .$$

The treatment used above is valid for

$$\xi < \left(\frac{r_j}{L}\right)^{1/2}$$

(Galeev and Zeleny, 1975a; Zeleny and Taktakishvili, 1981; Zeleny, 1986). Here r_j is the gyroradius of particles of j-type. At

$$\xi > \left(\frac{r_e}{L}\right)^{1/2} = 2.3 \times 10^{-1}$$

electrons become 'frozen' into the magnetic field, and that is a strong stabilizing factor (Coroniti, 1980; Zeleny, 1986). For HTCS with ion-acoustic turbulence the condition for ion-acoustic instability excitation implies $r_i \sim L$. From this it follows that the condition $\xi_{e2} \sim \xi_{i1}$ is valid, which is equivalent to $r_i/L \sim (m_e/m_i)^{1/18}$. (The definition of ξ_{i1} is similar to that of ξ_{e1}.) In the interval $\xi_{e2} < \xi < \xi_{i1}$ ion instability could arise (Galeev and Zeleny, 1975a). However, as $\xi_{e2} > (r_e/L)^{1/2}$, this instability is suppressed for $\xi > \xi_{e2}$ by the stabilizing influence of the frozen-in electrons (Coroniti, 1980).

The value obtained ξ_{e2} lies on the boundary of applicability of the HTCS model itself (see Figure 2). The boundaries 1 and 4 are determined by the assumption that the conductivity (in the HTCS) is due to scattering of electrons only on ion-acoustic turbulence in a marginally stable-state. The boundaries 2 and 3 correspond to the strong magnetic field approach. The line 5 marks the upper limit of the temperature, under which the magnetic field B_0 may affect the plasma turbulence.

3. Summary

An analysis of the problem of CS tearing instability in a collisionless plasma applied to the high-temperature turbulent current sheet (HTCS) model with a small transverse magnetic field component (Somov and Titov, 1985) shows that such a sheet is stabilized with respect to tearing instability when the transverse component ξ is sufficiently large.

On the (T, ξ) diagram the stability region lies above the ξ_{e1} (Figure 2). Here the HTCS applicability boundary (Somov, 1986) is shown by the dashed line and the crosses denote five different states of a HTCS corresponding to solar flares of the different power (see Table I).

TABLE I

Parameters of a HTCS

Parameters	Notation	Units	Values				
Electron temperature	T	10^7 K	3.3	10	5.6	6	33
Drift velocity	V_d	km s^{-1}	3.8	6.7	15	25	72
Power released per unit sheet length	p/l	10^{18} erg (cm s)$^{-1}$	0.1	1.2	8	72	1.2×10^3

Therefore, for very wide range of flare energy release power, the tearing instability of the HTCS is stabilized by a small transverse component of magnetic field.

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