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Commemoration of the 85th birthday of S I Syrovatskii
(Scientific session of the Physical Sciences Division of the Russian Academy of Sciences, 26 May 2010)

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A scientific session of the Physical Sciences Division, Russian Academy of Sciences (RAS), was held on 26 May 2010 at the conference hall of the Lebedev Physical Institute, RAS. The session was devoted to the 85th birthday of S I Syrovatskii.

The program announced on the web page of the RAS Physical Sciences Division (www.gpad.ac.ru) contained the following reports:

(1) **Zelenyi L M** (Space Research Institute, RAS, Moscow) "Current sheets and reconnection in the geomagnetic tail";

(2) **Frank A G** (Prokhorov General Physics Institute, RAS, Moscow) "Dynamics of current sheets as the cause of flare events in magnetized plasmas";

(3) **Kuznetsov V D** (Pushkov Institute of Terrestrial Magnetism, the Ionosphere, and Radio Wave Propagation, RAS, Troitsk, Moscow region) "Space research on the Sun";

(4) **Somov B V** (Shternberg Astronomical Institute, Lomonosov Moscow State University, Moscow) "Strong shock waves and extreme plasma states";

(5) **Zybin K P** (Lebedev Physical Institute, RAS, Moscow) "Structure functions for developed turbulence";

(6) **Ptuskin V S** (Pushkov Institute of Terrestrial Magnetism, the Ionosphere, and Radio Wave Propagation, RAS, Troitsk, Moscow region) "The origin of cosmic rays."

Papers based on reports 1–4 and 6 are published in what follows.

Sergei Ivanovich Syrovatskii
(02.03.1925 – 26.09.1979)

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Metastability of current sheets

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1. Introduction

A current sheet (CS) is a universal plasma structure. The formation of current sheets is observed in numerous laboratory experiments [1, Vol. 1, Ch. 9], [2, p. 108], in the solar corona [2, p. 3], [3], and in astrophysical objects (magnetospheres of stars, galactic jets, etc.) [4, 5]. They exist in the tail of Earth's magnetosphere [1, Vol. 2, Ch. 4] and at its boundary, i.e., magnetopause [6]. The presence of CSs is associated with the accumulation of magnetic field energy. Therefore, revealing the mechanisms responsible for energy accumulation in CSs without its immediate release is of great interest. Among phenomena associated with the release of the accumulated magnetic energy, we first of all note solar flares. The idea of magnetic field reconnection has been suggested in the research on the accumulated magnetic energy release by conversion to the thermal energy and the energy of particle motion in solar flares [7].

A current sheet separates two regions where magnetic field lines have opposite directions, and reconnection of these

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lines is therefore accompanied by their disruption and the current sheet filamentation. But the first magnetic reconnection models were aimed at describing not the current sheets and their dynamics but a stationary region with the dissipation of the magnetic field (see [8] and review [9]). These models were based on the strong assumption of the existence of an equilibrium between the plasma flows incoming to the dissipation region and the fluxes of accelerated particles leaving this region. More rigorous calculations showed that the boundary conditions required for such stationary solutions in the framework of magnetohydrodynamics (MHD) cannot typically be well defined [10], and the reconnection in real problems is essentially nonstationary [11].

A more general dynamic CS formation scenario was considered by Syrovatskii [2, 12]. In solving the MHD problem of plasma flows in the vicinity of a neutral point of a magnetic field, he succeeded in developing a scenario of CS formation with a subsequent magnetic field reconnection. The finite lifetime of a CS results in the *concept of metastability*. In the framework of this concept, a CS accumulates energy during a relatively long time period, and only after that does it spontaneously release the energy during a rapid magnetic reconnection. This approach allowed explaining the alternating long-lasting periods when CSs are 'quiet' and the subsequent explosion-like releases of the accumulated energy [2, 13]; such an alternation is difficult to explain by stationary reconnection models.

Models of CSs in the solar corona and their disruption involve a mechanism of the magnetic field dissipation due to Coulomb collisions of plasma particles. Similar structures are also observed in the collisionless plasma of Earth's magnetosphere and in the solar wind. In 1965, Ness proved the existence of Earth's magnetic tail with oppositely directed magnetic fields in its northern and southern regions and a current sheet separating these regions [14]. The number density of particles in such a CS is about 1 cm^{-3}, which excludes collisional dissipation. The main mechanism responsible for the dissipation in collisionless plasmas is the kinetic effect of the resonance interaction of plasma particles with a developing unstable plasma mode in a CS (reverse Landau damping). To simulate a CS, a one-dimensional kinetic model by Harris [15] and its subsequent generalizations to the two-dimensional geometry [16, 17] are frequently used. The disruption of such a CS is related to a developing tearing instability, which was suggested in 1966 as the main candidate for the mechanism responsible for initiating the magnetic reconnection in the magnetotail [18]. Realizing the importance of kinetic effects for understanding the stability of extremely thin CSs in collisionless plasmas, Syrovatskii in cooperation with Bulanov worked out a model of the tearing instability developing in a CS of zero thickness [2, p. 88].

The transformation of the magnetic field energy into the energy of particles in collisionless plasmas is also essentially kinetic. Indeed, one of the main mechanisms of increasing the particle energy is by accelerating the particles with electric fields in the vicinity of the reconnection region. The modern theory of this process is based on the pioneering work of the Syrovatskii school [19–21], where the stationary electric field approximation was used, and the work of Galeev [22, 23], who considered the pulsed electric field approximation.

The concept of metastability was introduced in papers [24, 25] devoted to the stability theory for collisionless CSs in the magnetotail with the normal magnetic field component B_z taken into account. This component, which is nonvanishing in the CS center, magnetizes electrons and makes the field lines rigid (as if they were materialized), thereby stabilizing the tearing instability and delaying the CS filamentation. The theory of the tearing instability in Earth's magnetosphere developed in the 1970–1980s [26–29] was based on the Harris model. The above assumption was the weakest statement in the theory and then led to its abandonment (which was unjustified, as we show in what follows) as regards explaining the initialization of geomagnetic substorms (a phenomenon that is directly related to the magnetic field reconnection). In the 1990s, it was shown that the Harris CS is absolutely stable with respect to the tearing instability [30, 31]. This result favored developing alternative substorm scenarios based not on the disruption of field lines but on the disruption of current structures in the inner magnetosphere [32].

However, a growing amount of experimental data was still showing that the magnetic reconnection is the most probable mechanism of the magnetic energy transformation into the energy of particle fluxes in Earth's magnetosphere [33–35]. Moreover, using the results obtained aboard the Themis spacecraft aimed at finding substorm initialization sites, it was shown that the reconnection of field lines occurs in a region with a thin current sheet in the night-side magnetosphere at the radial distance about 16 Earth radii [36]. Thus, there was an obvious contradiction between the observational data and theoretical predictions of the absolute stability of CSs. In this paper, we discuss ways to overcome this misunderstanding regarding one of the most important phenomena in space physics.

2. Modern satellite data and theoretical models

The Syrovatskii hypothesis that thin current sheets (TCSs) play a crucial role in the accumulation and release of magnetic energy is fully confirmed by modern spacecraft data. Using the magnetic field measurements aboard two ISEE (International Sun–Earth Explorer) spacecraft, it was found that a TCS with a complicated internal structure may develop at the substorm initiation phase. A characteristic feature of such a current sheet is the distinction between the amplitude of the CS magnetic field B_0 and the field B_{ext} at the boundary of the plasma sheet. Hence, a TCS with small-scale currents is embedded into a much wider plasma sheet (the plasma of this sheet can be represented as a background of the TCS). Syrovatskii considered this model in his papers, where the background plasma was called a fur [2].

The most detailed information about CSs in Earth's magnetosphere was provided by the four-device project Cluster [38–40]. Simultaneous measurements of the magnetic field $\mathbf{B}$ at four different locations allow determining the current density $\mathbf{j} = (c/4\pi)\,\mathrm{rot}\,\mathbf{B}$ and thereby revealing the CS structure. It was found that most current sheets in the magnetotail are embedded structures [38] and cannot be described by the Harris model [40].

The embedding of CSs assumes that a small fraction of particles (10–20% of the total) creates a TCS current responsible for the magnetic field $\sim B_0$. The remaining 80–90% develop the magnetic field $B_{ext} - B_0$. In this case, a typical ratio is $B_0/B_{ext} \sim 0.4$ [41]. Such a CS is schematically shown in Fig. 1. Characteristic TCS scales are of the order of 1000 km, and if $B_{ext} \approx 30-40$ nT, then the current density is large enough to prevent the TCS formation due

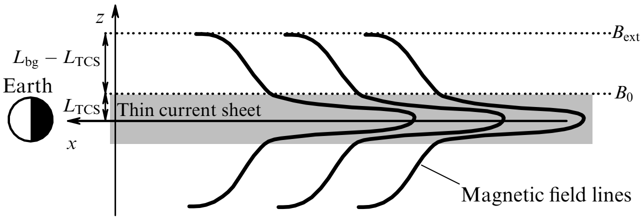

Figure 1. Schematic representation of a TCS. Shown are the thickness L_{TCS} of the current sheet and the thickness L_{bg} of the background sheet embedding the TCS. The positions corresponding to the magnetic fields B_0 and B_{ext} are also shown.

to the diamagnetic drift of plasma particles. On the other hand, it is known that transit ions with 'Speiser's trajectories' may exist in a TCS [42, 43]; because their orbits are open, such ions create a current and the projection of their flow velocities on the current direction is comparable to the thermal speed. Because the normal component of the magnetic field in a TCS is small ($B_z \ll B_0$), the ion equations of motion are integrable, and it is possible to introduce the quasiadiabatic invariant $I_z = \oint v_z \, dz$, which is conserved along the trajectories of transit particles [43]. The conservation of I_z and of the total energy H_0 allows developing a self-consistent one-dimensional model of TCSs [44, 45].

The normal component B_z of the magnetic field in the magnetotail is too small to magnetize the ions; but is large enough to regard the electrons as magnetized and to analyze their trajectories in the drift approximation. By summing the currents of the transit ions with the electron drift currents, a model of two-component TCS can be developed [46].

To write the basic equations for the one-dimensional TCS model, we choose the coordinate system shown in Fig. 1. The current is directed along the y axis; the magnetic field, which is directed along the x axis, changes its sign in the plane $z = 0$. The only spatial coordinate on which all parameters of the system depend is z. The ion distribution function at the boundary of the system can be chosen as a shifted Maxwell distribution,

$$f \sim \exp\left(-\frac{v_\perp^2 + (v_\parallel - v_D)^2}{v_T^2}\right),$$

and the main parameter of the problem is the ratio of the thermal and bulk flow velocities of ions, $\varepsilon = v_T/v_D$. In the central part of the TCS, the distribution function can be expressed in terms of the integrals of motion,

$$f \sim \exp\left[-\frac{\omega_0 I_z}{m v_T^2} - \left(\sqrt{\frac{2H_0}{m v_T^2} - \frac{\omega_0 I_z}{m v_T^2}} - \varepsilon^{-1}\right)^2\right].$$

Using the Liouville equation ($df/dt = 0$), the ion current $j_i = q_i \int v_y f \, d^3 v$ can then be calculated at each point. Here, m and q_i are the ion mass and charge, and ω_0 is the ion gyrofrequency at the TCS boundary. The quasiadiabatic invariant I_z is then a nonlocal function of the magnetic field B_x:

$$I_z \sim m \oint \sqrt{v_y^2 + v_z^2 - \left(v_y - \frac{q_i}{mc}\int_{z'}^{z} B_x(z'')\, dz''\right)^2}\, dz'.$$

The z' integration limits are determined by the points where the integrand vanishes (see [45, 46]).

The current of magnetized electrons can be expressed as

$$j_e = q_e n_e c \frac{[\mathbf{E}\times\mathbf{B}]}{B^2} + \frac{c}{B^2}[\mathbf{B}\times\nabla_\perp p_{e\perp}] + c(p_{e\parallel} - p_{e\perp})\frac{[\mathbf{B}\times(\mathbf{B}\nabla)\mathbf{B}]}{B^4},$$

where q_e and n_e are the electron charge and number density, $p_{e\parallel}$ and $p_{e\perp}$ are the parallel and perpendicular components of the electron pressure, and $B = \sqrt{B_z^2 + B_x^2}$. Because the large-scale electric field E_y in the sheet can be eliminated by passing to a moving reference frame (the so-called de Hoffmann–Teller frame), only one nonvanishing electric field component $E_z = -d\varphi/dz$ is taken into account. The quasineutrality equation is used to find the scalar potential, $q_i n_i + q_e n_e = 0$. Hence, the TCS model is reduced to the Grad–Shafranov equation

$$\frac{dB_x}{dz} = \frac{4\pi}{c}\left[j_e(B_x, z) + j_i(B_x, z)\right],$$

where B_z can be considered a free parameter. The model obtained has a triple embedded structure. The electron current density profile with a sharp peak at the center is embedded into a wider profile of the ion current density. This structure as a whole is in turn embedded into a plasma sheet (the plasma density does not vanish at the CS boundary) (Fig. 2). The central peak of the electron current density is caused by the curvature drift, $\sim (p_{e\parallel} - p_{e\perp})/R_{curv}$, where the curvature radius R_{curv} is proportional to the ratio $(B_z/B_0)^2 \ll 1$.

Comparison of the model predictions with current sheets observed in the magnetotail showed that the model with transit particles allows describing the experimental data with a much better accuracy than the Harris model. Figure 3 shows an example of comparison of the current density profiles

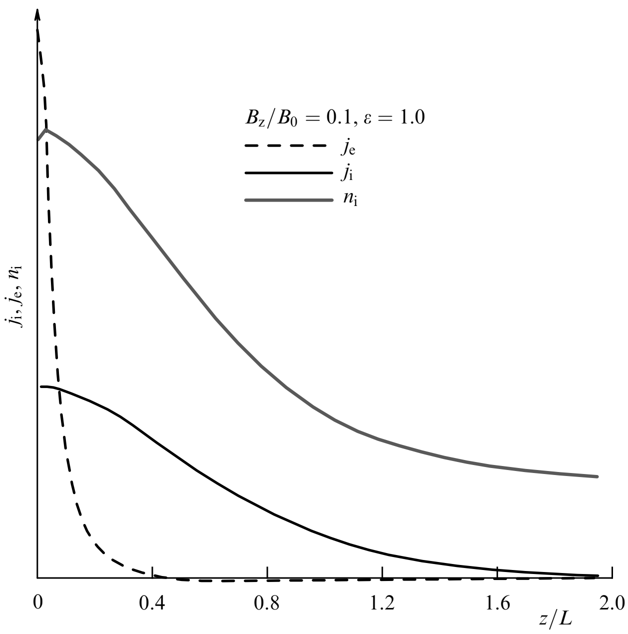

Figure 2. The profiles of the ion and electron current densities and plasma density for the TCS model.

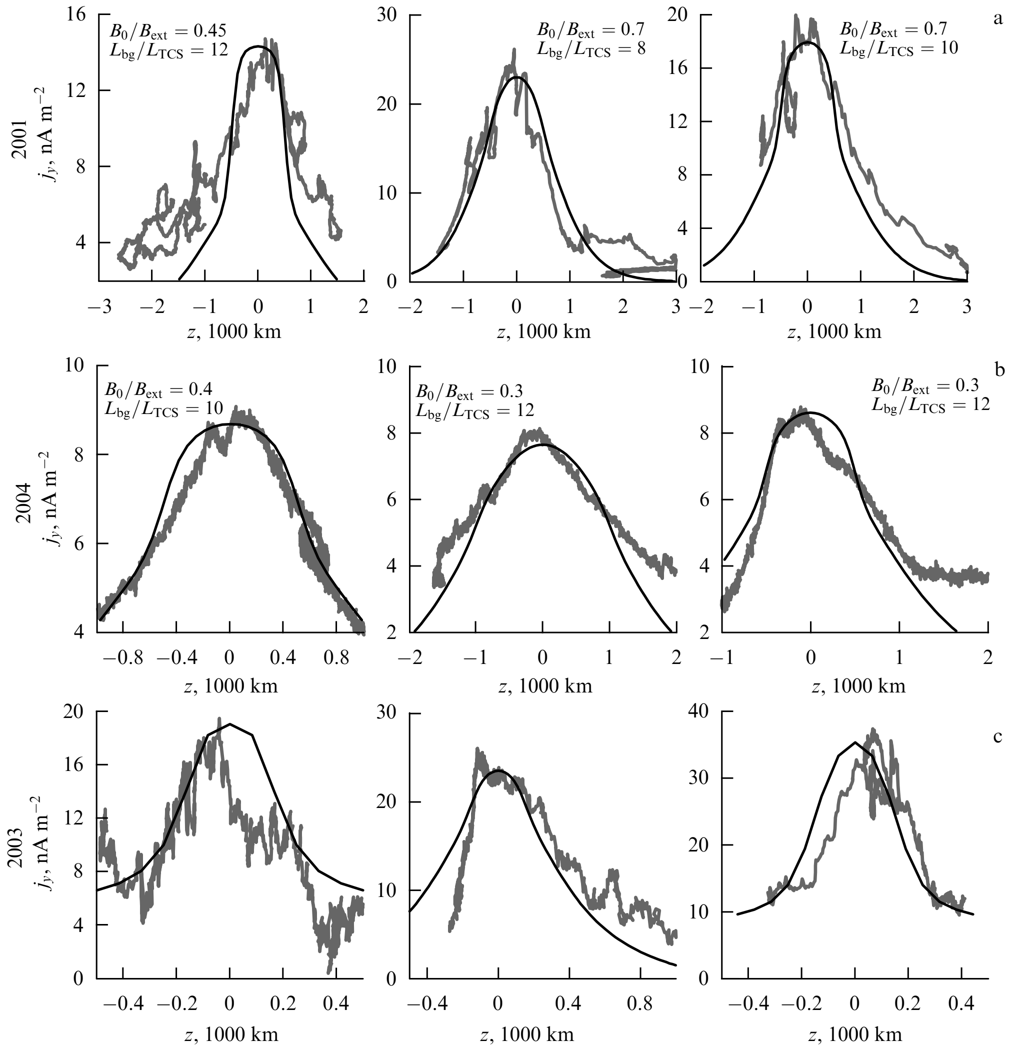

Figure 3. Profiles of the current density for the TCS model (black curves) and experimental observation (gray curves).

deduced from the direct measurement of the magnetic fields aboard the Cluster spacecraft with those calculated from the TCS model. We first consider Figs 3a and b. The data show that both the observed and modeled TCSs have an embedded structure with $B_0 < B_{ext}$. This characteristic feature of TCSs manifests itself in two different effects. The first is that for the events shown, the current density decreases by more than an order of magnitude, to $\sim 1-3$ nA m^{-2}, over distances of 1000–2000 km. As a result, the remaining magnetic field $B_{ext} - B_0$ is supported by a relatively weak background current; hence, the thickness of the background sheet L_{bg} is much larger than that of the TCS, L_{TCS}. Figures 3a and b also show the values for the ratio L_{bg}/L_{TCS} for the given current density profiles. The existence of a local strong current in a CS (emergence of a TCS) is therefore related to the emergence of a narrow strong CS within a wide CS, rather than to the narrowing of the entire CS.

The second effect is the emergence of a thin electron current within the ion TCS. Such structures can be resolved in spacecraft observations if the distance between the spacecraft is very small (≈ 300 km) (the Cluster spacecraft were working in this regime in 2003 [39]). The measured current density profiles are compared with the model results in Fig. 3c. It is seen from these plots that the model electron current is in good agreement with the measurements for profiles wider than 200 km. Hence, the double embedded structure of CSs predicted by the model in [46] is confirmed by the experimental data. Obviously, stability criteria for such structures should be entirely different from those for the Harris model.

It is worth noting that observations of very thin current sheets, where the electron current is much stronger than the ion current, are in good agreement with the results of Frank's group on laboratory modeling [1, Vol. 1, Ch. 9], [2, p. 108] that had been initiated by Syrovatskii.

The TCS model can be compared with experimental results in more detail by considering the distribution function of ions responsible for the currents. In the TCS model, the current is transferred by transit particles with a distinctive half-ring distribution function (see [47, 48]). An example of such a distribution function is shown in Fig. 4. The corresponding measurements are complicated by the presence of the background plasma. But because the background density (and the distribution function) does not change across a TCS (over scales ~ 1000 km), it is possible to subtract the distribution function measured at the current sheet boundary from that in the center of the TCS. A positive result then indicates the distribution of protons in the TCS (Fig. 5). Comparison of the model and the observed distributions shows that they are in good qualitative agreement (see Figs 4 and 5).

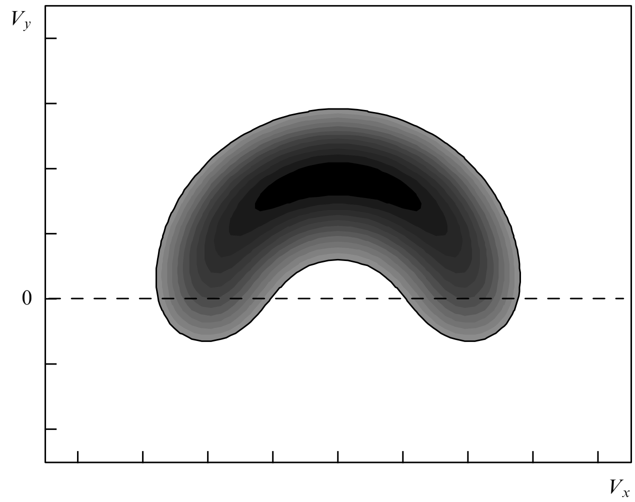

Figure 4. The distribution of the TCS transit particles.

Thus, a possible solution of the stability problem for the current sheet in the magnetotail may be found in using TCS models that are in better agreement with observations than the Harris model is.

3. Tearing instability

A comprehensive study of the tearing instability involves the variational method. To derive an equation for a perturbation of the vector potential $A_{1y} \sim \exp(ikx - i\omega t)$, the energy functional W_2 is calculated in the second order of the perturbation theory [49]. The functional W_2 contains three terms: the magnetic field perturbation energy W_B, the energy of the attraction of current filaments $W_{\rm free}$, and a stabilizing contribution $W_{\rm e}$ due to the presence of the magnetic field B_z. The term $W_{\rm free}$ represents the 'free energy' of the system because this term allows the tearing instability to develop. The term $W_{\rm e}$ contains the contributions of several effects. First, the electrons are magnetized by B_z and, as the instability develops, their density is perturbed, $n_{1\rm e} \sim B_{1z}/B_z$. Second, in order to maintain the plasma quasineutrality, the ions follow the electrons and this motion consumes a significant portion of the system free energy [26]. Third, the conservation of the canonical momentum $P_y = mv_y + qA_y/c \sim qB_z x/c$ implies additional restrictions on the tearing instability.

For the TCS model in [46], the three terms of the energy functional W_2 are as follows [51]:

$$W_B = \int \frac{(\nabla A_{1y})^2}{8\pi}\, {\rm d}^3 r\,,$$

$$W_{\rm free} = -\frac{1}{2c} \int \frac{\partial j_0}{\partial A_{0y}}\, A_{1y}^2\, {\rm d}^3 r\,,$$

$$W_{\rm e} = \int \left(\frac{q_{\rm i} n_{0\rm i}^2}{\partial n_{0\rm i}/\partial \varphi_0}\, \frac{k^2}{B_z^2} \right) A_{1y}^2\, {\rm d}^3 r + W_H\,.$$

Here, the subscripts 0 denote the CS macroparameters in the unperturbed state (j_0 is the current, $n_{0\rm i}$ is the ion density, A_{0y} is the only component of the vector potential, and φ_0 is the scalar potential). The term W_H is due to the dependence of P_y on B_z in the initial state and the corresponding additional restrictions for perturbations (see [49, 50]). The only component of the perturbed vector potential is A_{1y}. Actually, W_2 is the difference in the energies of the perturbed system and of the system in the initial state. Therefore, if there exists a function A_{1y} such that $W_2 < 0$, then the tearing instability development is energetically favorable and the CS is macroscopically unstable.

To verify this condition, it is necessary to solve the equation $\delta W_2/\delta A_{1y} = 0$, which determines A_{1y} for the minimum possible value of W_2. The solution of this equation is presented in [50]; here, we consider only the final result, i.e., the instability parameter domain shown in Fig. 6a. It is seen that thin and elongated current sheets with small ε and $B_z/B_0 \sim 0.1-0.2$ are unstable. Hence, the TCSs with an embedded structure not only resemble those in the experimental data but also allow solving the problem of the disruption of the magnetic field lines and substorm initialization due to a large amount of 'free' energy. In addition, predictions of the stability theory can be compared with experimental data.

We first see whether the observed TCSs have the properties that make the TCS model unstable. One of the main reasons for the TCS instability is a large amount of 'free energy,' which in turn manifests itself in the embedded structure of the sheet. A large difference between the spatial scales for the plasma density profile and those for the current density allows $\partial j_0/\partial A_{0y}$ to reach a large value, such that the energy variation W_2 becomes negative.

The effect considered can be estimated as follows. We first construct a simple empirical CS model that has an embedded structure and can be conveniently compared with experi-

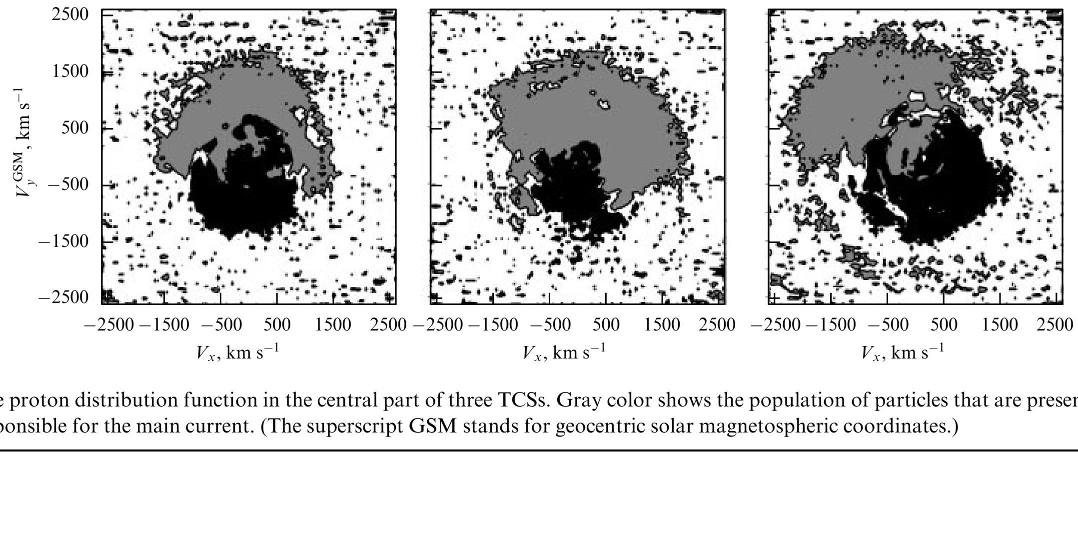

Figure 5. The proton distribution function in the central part of three TCSs. Gray color shows the population of particles that are present in the central part and responsible for the main current. (The superscript GSM stands for geocentric solar magnetospheric coordinates.)

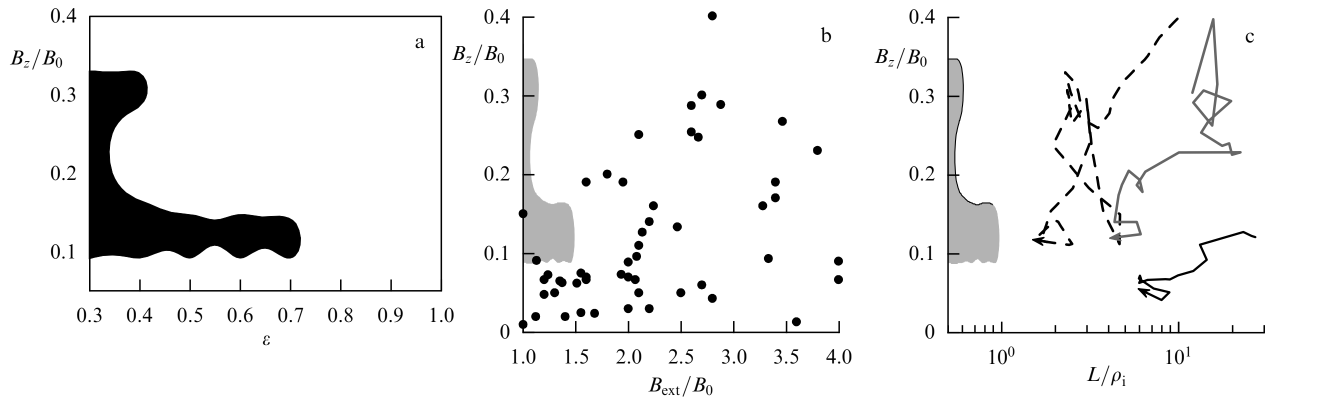

Figure 6. (a) A parametric map. Black color shows the region where $W_2 < 0$. (b) Map of the instability regions with the positions of the observed TCS. (c) A parametric instability map with the trajectories corresponding to CS evolution during the substorm growth phase.

mental data, and then estimate its free energy. We fix the amplitude of the external magnetic field B_{ext} (the value of the magnetic field where the plasma pressure vanishes), and the current density amplitude j_{max}. Then the term corresponding to the TCS 'free energy' is given by

$$W_{free} = -\frac{1}{2c} \int_{-\infty}^{+\infty} \frac{\partial j_0}{\partial A_{0y}} A_{1y}^2 \, dz = -\frac{j_{max}}{cB_{ext}} \int_0^1 \frac{\partial j}{\partial b} \frac{1}{b} A_{1y}^2 \, db \,,$$

where $b = B_x/B_{ext}$ and $j = j_0/j_{max}$. We next consider the structure of the current sheets on the (b, j) plane. In the Harris model, the current density is $j = \cosh^{-2}(z)$ and the magnetic field is $b = \tanh(z)$. Hence, the model is represented by the parabola $j = 1 - b^2$. The simple model of an embedded TCS has the only free parameter, the value of the magnetic field at the TCS boundary, $b_0 < 1$. The current density in this model is the sum of two currents if we consider that in the region $b > b_0$, there is only the background current $j_{bg} = j_1(1 - b^2)$ and in the region $b < b_0$, the TCS current $j_{TCS} = j_0(1 - b^2/b_0^2)$ is added to that current. In this case, a relation between the model parameters can be established: at the TCS center ($z = 0$, $b = 0$), the total current is equal to 1, $j_1 + j_0 = 1$, and at the boundary ($b = b_0$), it is equal to a number μ. With j_1 and j_0 expressed in terms of the model parameters, it is possible to find an equation for the total current both in the central region and outside the sheet:

$$j = 1 - \left(\frac{b}{b_0}\right)^2 (1 - \mu) \,, \quad b < b_0 \,,$$

$$j = \frac{\mu(1 - b^2)}{1 - b_0^2} \,, \quad b > b_0 \,.$$

Hence, the 'free energy' is given by

$$W_{free} \sim -\frac{2j_{max}}{cB_{ext}} \left(\frac{1 - \mu}{b_0^2} + \frac{\mu}{1 - b_0^2}\right) .$$

On the other hand, in the Harris model, $\partial j/\partial b = -2b$ and

$$W_{free} = -\frac{2j_{max}}{cB_{ext}} \int_0^1 A_{1y}^2 \, db \sim -\frac{2j_{max}}{cB_{ext}} \,.$$

Therefore, the ratio of the estimated free energies of a TCS and a Harris CS is determined by the coefficient $s = (1 - \mu) b_0^{-2} + \mu(1 - b_0^2)^{-1}$. As $\mu \to 0$ and $b_0 \to 1$, the TCS transforms into the Harris CS and $s \to 1$. This coefficient can be found for all observed TCSs. We have chosen eight TCS events observed by Cluster and calculated s using the empirical model (Fig. 7). It follows from the plots that the free energy estimates obtained with such a crude technique are larger by a factor of 2–3 for some observed TCSs than the estimates for the Harris CS.

Another possibility of comparing theoretical results with experimental data is provided by the obtained parametric map with instability regions (Fig. 6a). The positions of observed CSs can be shown on this map. For this, it is necessary to transform the parameter ε into an observed parameter. The pressure balance at the TCS boundary allows obtaining a relation between the amplitude of the TCS magnetic field B_0 and the plasma pressure P_b at the TCS boundary (see [45]). Using this relation and the definition of the field B_{ext} ($P_b + B_0^2/8\pi = B_{ext}^2/8\pi$), we obtain

$$\frac{B_{ext}^2}{B_0^2} = 1 + \varepsilon^2 \left\{ 1 + \frac{\varepsilon \exp(-\varepsilon^{-2})}{\sqrt{\pi}\left[1 + \mathrm{erf}(\varepsilon^{-1})\right]} \right\}^{-1} .$$

We note that the electron contribution to the pressure balance is neglected here (this contribution is small because the ion temperature should be larger than that for electrons by a factor of 5–7). Hence, the parameter ε can be transformed into measurable parameters.

We now use statistical data [51] for observed TCSs and show their positions on the instability parameter map. We can argue that a TCS observed under quiet conditions should fall outside the instability region. It can be seen from Fig. 6b that this statement is true. Only two observed events fall into the instability region. Most observed events occupy a zone around the instability region in the parameter space, thereby confirming the metastability concept, i.e., the current sheets 'live' in the magnetotail for several tens of minutes; however, the observations show that they are close to the instability region. This means that a quasistationary state of the system can change spontaneously (in $\sim 1-2$ min) to a rapid development of the tearing instability.

The obtained instability map can be compared with the observed evolution of the CS at the substorm growing phase. In this case, it is more convenient to use a theoretical relation between the parameter ε and the TCS thickness measured in the ion gyroradii L/ρ_i (see [45]). For this, we can use experimental observations [52] of the CS evolution before a substorm. A summary is presented in Fig. 6c: during this

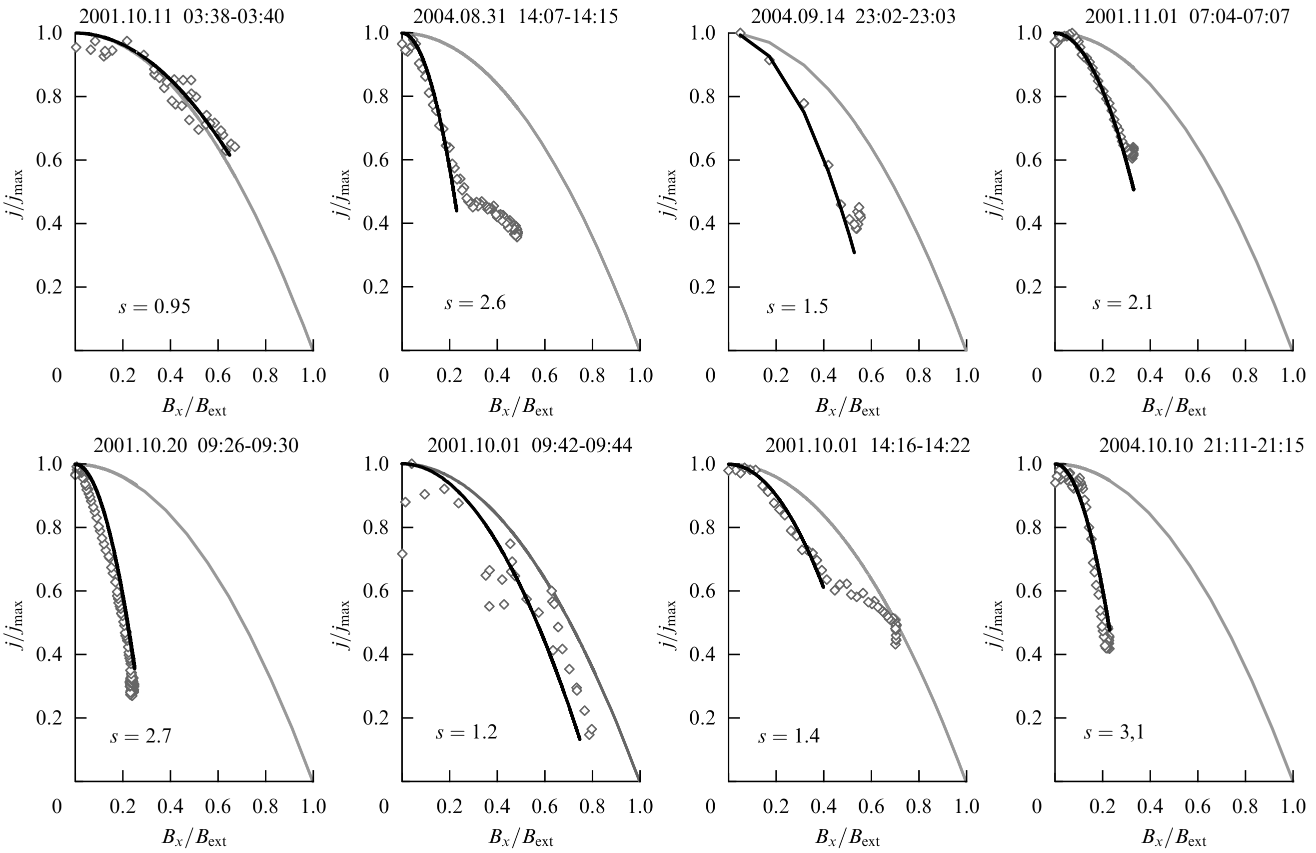

Figure 7. The profiles for the observed TCSs (open rhombi), approximation of the profiles by the function $j = 1 - \alpha b^2$, $\alpha = \text{const}$ (black curve) and profile for the Harris model (gray curve). Also shown are the corresponding values of s.

evolution, both the thickness and the ratio B_z/B_0 decrease, with the CS approaching the instability region. All the experimental observations used here show that at the next stage of the CS evolution, the disruption of magnetic field lines is unavoidable.

In summary, the TCS stability theory, which accounts for the mechanisms of their metastability, is strongly supported by experimental data.

4. Discussion: dynamics of a current sheet

A stability analysis of TCSs showed that in addition to the tearing instability, various drift modes with $k_y \neq 0$ can also develop [53]. This may lead to the pinching of magnetic surfaces, as well as to their bending. In this process, the growth rates for drift modes are larger than those for the tearing mode. This is closely related to the fact that the drift modes only deform magnetic surfaces without breaking them. As a result, the electron density perturbations and, consequently, the stabilizing contribution of the electrons to the energy functional W_2 becomes negligible. Under realistic conditions with a three-dimensional CS, the drift modes develop first, and then the tearing instability can develop in the background of the deformed magnetic surfaces. Hence, instead of infinite one-dimensional X-lines, which emerge during the current filamentation in the sheet and the corresponding field line reconnection, the system contains magnetic islands, which are bounded not only in the x direction but also in the y direction. This fact is not so important for substorm initialization. But it is more important for the nonlinear phase of various instabilities in the tail and particle acceleration, which are influenced by such a complicated topological structure of the magnetic surfaces.

Because the influence of the magnetic field on the particle motion in the vicinity of an X-line is small, the particles can be accelerated by an inductive electric field emerging in dynamical processes in the CS. If the electric field is regarded as a uniform external field acting on particles in the region of an X-line, then the plasma particles can be considerably accelerated (up to hundreds of keV in the magnetotail [54] and several MeV in the solar corona [55]) and non-Maxwellian particle distributions can be formed. The applications of such models to the solar [19, 21] and magnetospheric [56, 57] plasmas are widely discussed. On the other hand, it is possible to consider a nonstationary field line reconnection directly. In this case, the electric field is induced and the particle acceleration occurs in pulses [23, 58]. A comparison of spacecraft observations in the magnetotail with theoretical predictions confirms the validity of this approach to the interpretation of short-lived bursts of accelerated charged particles [59].

However, the spatial localization of X-lines does not allow accelerating large numbers of charged particles. This restriction may be obviated if there exists a magnetic field $B_y \neq 0$. In this case, the magnetic field disruption may result in a number of X-lines [60]. The particle acceleration in such structures was previously studied in the context of magnetopause CSs [61].

The drift-mode instabilities developing in a TCS with a subsequent deformation of the magnetic surfaces may result in a similar complex web-like structure of X-lines in the current sheet in the magnetotail. In this case, the development and interaction of different unstable modes result in a turbulent electromagnetic field [62]. The particle acceleration by these fields is efficient enough in the approximation of strongly disrupted magnetic surfaces, when the particles stay near the CS neutral plane for a long time [63], as well as when the turbulence only deforms the magnetic field lines, allowing particles to escape from the CS after a short time [64]. In both cases, the populations of accelerated particles may form high-energy 'tails' of non-Maxwellian distributions, which are often observed in Earth's magnetosphere and solar corona.

When a multimode instability develops, the formation of large-scale magnetic structures (plasmoids) may result from the interaction of individual small magnetic islands formed by the disruption of CS magnetic surfaces. Using the kinetic [65] and magnetohydrodynamic [66] approaches, it was shown that a nonlinear stage exists such that the attraction of currents carried by a number of magnetic islands make the islands merge and form a large-scale structure.

5. Conclusions

We have reviewed modern models and experimental data related to thin current sheets and studied the effect of the coexistence of different scales in its structure on the tearing instability. It was shown that experimental observations of the evolution of current sheets in the magnetotail and, on the other hand, theoretical models for TCSs lead to the metastability concept suggested by Syrovatskii [2, 12] and Galeev [26]. Theoretical results show that a region exists in the parameter space where the tearing instability can develop. Outside this region, stable current sheets may exist for very long periods of time and accumulate the solar wind energy, even if the sheets are strongly squeezed and stretched. Then, when they enter the instability region, the energy is released and transformed into the kinetic energy of fluxes of accelerated particles. The experimental data confirm that most TCSs observed in the magnetotail are metastable, and their positions on the parameter map determine the limits of the time periods when they are stable with respect to the tearing instability. In addition, experimental data on the evolution of current sheets in the substorm growing phase indicate that the sheets approach the instability region as they move on the parameter map.

Summarizing the results of this paper, we note that the metastability concept, which explains the alternation of long-lasting preparatory phases and rapid releases of accumulated energy, is now used in the modern theory of magnetospheric substorms [1].

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Dynamics of current sheets underlying flare-type events in magnetized plasmas

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1. Introduction

Sergei Ivanovich Syrovatskii was a remarkable physicist who made an outstanding contribution to magnetohydrodynamics, the physics of cosmic rays, astrophysics, and solar physics. His classic review on magnetohydrodynamics [1] published in *Physics–Uspekhi* in 1957 is well known. At the end of the 1950s and in the 1960s, Syrovatskii, in close collaboration with V L Ginzburg, actively worked on astrophysical problems related to cosmic rays. *The Origin of Cosmic Rays* by Ginzburg and Syrovatskii [2] was published in 1963, republished several times in this country and abroad, and is still widely cited.

In the early 1960s, Syrovatskii focused on processes on the Sun, especially those involving considerable numbers of particles accelerated during solar flares. By that time, it had been discerned from observational data that the source of tremendous energies released during solar flares is the energy of the magnetic fields generated by electric currents in the solar corona. In 1966, Syrovatskii wrote a pioneering paper on this subject, ''Dynamic dissipation of a magnetic field and particle acceleration'' [3], where he considered a general nonstationary problem of compressible plasma flows in a two-dimensional inhomogeneous magnetic field with a neutral line. He reached the fundamental conclusion that the flows of a highly conductive plasma in such a field results in a considerable energy accumulation and the emergence of a current sheet separating the oppositely directed magnetic fields [3, 4]. The magnetic energy concentrated in the vicinity of the current sheet can be released in the case of rapid sheet disruption resulting in the emergence of strong electric fields, which accelerate charged particles. In accordance with Syrovatskii's concept, the cumulation of magnetic energy and the formation of current sheets precedes the flares. A flare occurs when the sheet is disrupted and the magnetic reconnection releases the accumulated energy, which is transformed into the thermal and kinetic energy of the plasma, fluxes of energetic particles, and radiation in different parts of the electromagnetic spectrum.

Syrovatskii suggested the idea that a cumulative acceleration occurs during the flares, when all particles in a small region are accelerated, regardless of their properties; the acceleration is therefore spatially nonuniform. The cumulative acceleration differs considerably from statistical acceleration, when a small population of particles that differ from other particles by some parameters, for instance, by the initial energy, mass, or charge, is accelerated. In addition, Syrovatskii emphasized that ''a process of the rapid dissipation of the magnetic field, which is accompanied by the emergence of energetic particles'' is quite ubiquitous and may occur not only in solar flares but also in many other dynamic phenomena in space and laboratory plasmas [3].

The first experiments on plasma dynamics in two-dimensional (2D) magnetic fields with neutral lines were performed in the early 1970s in the USA, Japan, and the USSR, in the Laboratory of Accelerators at the Lebedev Physical Institute. Although these studies were independent of each other, they were quite similar in many aspects and, as it turned out later, all the experiments were inspired by Syrovatkii's papers published in 1966–1971.

One of the investigation directions in the Laboratory of Accelerators, Lebedev Physical Institute in that period was related to the development of physical principles for new plasma methods for acceleration of charged particles. That is why Syrovatskii's ideas were of special interest. Syrovatskii and the head of the laboratory M S Rabinovich pioneered the decision to make a relatively small experimental setup and to investigate the possibility of cumulative acceleration. It is difficult to describe the enthusiasm with which Syrovatskii participated in the discussions of the basic principles, parameters, and construction of this setup. We note that experimental decisions suggested at the initial stage of the studies stood the test of time and were used in all subsequent setups from the 'current sheet' (CS) family.

2. Is it possible to accumulate the magnetic energy in the laboratory?

Experiments performed at the Lebedev Physical Institute were focused on studies in a parameter range as wide as possible. With this aim, three independent electrotechnical systems were used in the CS setup [5]. These were, first, a system responsible for the 2D magnetic field with a neutral line on the z axis, field lines in the (x, y) plane, and a radial gradient h of the field:

$$\mathbf{B} = \{B_x; B_y; B_z\} = \{-hy; -hx; 0\}; \qquad (1)$$

second, a system that created an initial plasma in the magnetic field; and third, a system creating an electric current J_z parallel to the neutral line (Fig. 1a).

It was expected that two-dimensional plasma flows emerging with currents would result in the accumulation of the magnetic energy in the vicinity of the neutral line, and that

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