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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:

$$\mathbf{B} = \{B_x; B_y; B_z\} = \{-hy; -hx; 0\}\,; \tag{1}$$

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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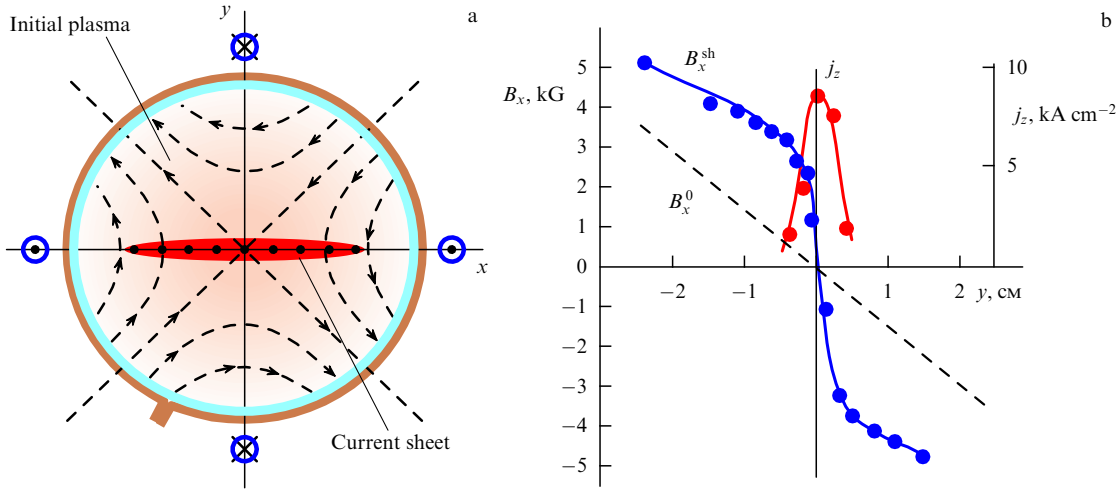

Figure 1. (a) A cross section of the 'current sheet' setup (Lebedev Physical Institute). A 2D magnetic field with the field lines (dashed lines) in the (x, y) plane and a neutral line on the z axis is created by the four straight conductors, which are parallel to the vacuum chamber axis. The initial plasma in the magnetic field is created by theta discharge in the neutral gas. The current excitation directed along the z axis results in current sheet formation. (b) The magnetic field increase and concentration of the magnetic energy in the vicinity of the neutral line as a result of the current sheet formation. B_x^{sh} is the magnetic field component tangential to the sheet surface; B_x^0 is the same component before the development of the current sheet; j_z is the current density in the sheet. Shown are the dependences of these parameters in the direction of the normal to the sheet, i.e., along the y axis.

a current sheet would develop. But the first experiments performed at the Lebedev Physical Institute gave negative results, i.e., the accumulation was not achieved. Currents in the plasma resulted in a sharp conductivity decrease due to plasma instabilities, such that the freezing-in condition for the plasma magnetic field did not hold.

To check the freezing-in condition, a dimensionless parameter, the magnetic Reynolds number $\mathrm{Re_m}$ is typically used. If

$$\mathrm{Re_m} = \frac{4\pi\sigma L v}{c^2} \gg 1\,, \tag{2}$$

then the magnetic field moves with the plasma, i.e., it is frozen in the substance. Here, σ is the plasma conductivity, and L and v are a characteristic scale of the plasma and its characteristic velocity. Condition (2) is certainly valid for almost all astrophysical objects, first of all due to their giant sizes L, while in laboratory experiments, it is necessary to create a plasma with a high conductivity σ to satisfy condition (2). To solve this problem, a crucial idea was suggested that the plasma conductivity can be increased by a considerable increase in the initial electron density. This allowed increasing the conductivity to $\sigma \approx 2 \times 10^{14}$ s^{-1}, such that the freezing-in condition held for several microseconds [6].

As a consequence, a neutral current sheet separating the regions with oppositely directed magnetic fields was obtained for the first time and a significant (several dozen-fold) increase in the magnetic energy density was achieved in the vicinity of the CS surface (Fig. 1b) [6]. The process of CS formation in the 2D magnetic field with a neutral line has been studied, from the linear stage with a propagating magnetosonic wave to the nonlinear stage of energy accumulation. The detailed structure of the magnetic field created by currents in the plasma was determined and it was shown that the currents are shaped as sheets [7]. These results provided an additional argument for resolving the dilemma of Syrovatskii's CS [8] or a Petchek-type flow [9], and favored the CS [10].

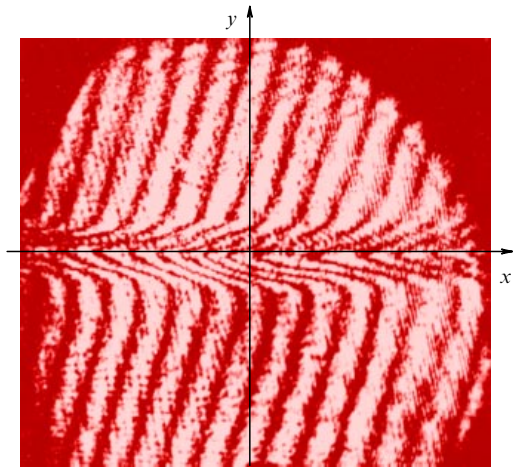

Figure 2. The interferogram characterizing the 2D electron density distribution in the current sheet. The double-exposure holographic interferometry technique was used.

An important stage of the experimental studies was the 'visualization' of the plasma compressed to a flat sheet, i.e., obtaining a vivid 2D plasma density distribution by means of holographic interferometry (Fig. 2) [11]. It was found that as a current sheet develops, a rapid and effective compression of the plasma occurs, resulting in a 10–15-fold density increase with respect to both the initial plasma density and the density outside the sheet. The electron and ion temperatures are also much higher in the sheet than outside. In other words, a current sheet is a spatial region where a dense and hot plasma is concentrated, with the plasma pressure being balanced by the magnetic pressure outside the layer and a characteristic plasma parameter $\beta \approx 1$. Here,

$$\beta = \frac{8\pi N_\mathrm{e}(T_\mathrm{e} + T_\mathrm{i}/Z_\mathrm{i})}{(B_x^{\mathrm{sh}})^2}\,, \tag{3}$$

N_e, T_e, T_i, and Z_i are respectively the electron density, electron and ion temperatures, and the mean ion charge in the middle plane of the sheet, and B_x^{sh} is the tangential component of the magnetic field near the sheet surface.

An unexpected but very important result was that the sheet is quite stable [11, 12]: it can exist without any changes in the magnetic field structure and distributions of plasma density over extended periods, which are much longer than the characteristic times for the tearing instability [13]. This result, which shows that the magnetic energy can be gradually increased in the vicinity of current sheets over prolonged periods, is extremely important for astrophysical applications [14].

Thus, in the experiments that were carried out in 1970–1980s and dedicated to studies of the plasma dynamics in 2D magnetic fields with neutral lines, the processes typical for pre-flare conditions were realized, namely, a considerable accumulation of the magnetic energy resulting from the emergence of metastable current sheets, the plasma heating in the sheets, and the generation of plasma fluxes.

3. Transition to three-dimensional magnetic configurations

In Nature, just as in plasma laboratory setups (for instance, in tokamaks), the magnetic configurations are usually three-dimensional (3D), i.e., have all three components of the magnetic field. In addition, 3D configurations are not only more common in the real world but are also more general in comparison with the 2D configurations with a neutral line and enhanced symmetry. In this connection, an obvious question arises of whether it is possible to accumulate the magnetic energy in 3D configurations.

The problem of a 3D generalization of the results obtained for 2D magnetic fields with neutral lines was widely discussed in the literature. Using the magnetohydrodynamic (MHD) equations describing the plasma dynamics in the vicinity of X-type neutral lines, Syrovatskii proved the possibility of current sheets forming in 3D configurations that combine 2D magnetic fields with neutral lines and a relatively uniform longitudinal field B_z:

$$\mathbf{B} = \{B_x; B_y; B_z\} = \{-hy; -hx; B_z\}\,, \tag{4}$$

$$\frac{\partial B_z}{\partial z} \ll h\,. \tag{5}$$

Under condition (5), the longitudinal component can play a role analogous to that of thermal pressure. These ideas by Syrovatskii were confirmed by subsequent experiments.

At the same time, several theoretical studies [16–19] considered the plasma flows in spatially nonuniform 3D magnetic fields with isolated neutral points. From self-similar solutions of the MHD equations, it was possible to conclude that the existence of a region with a vanishing magnetic field is necessary for the formation of a current sheet in a 3D magnetic configuration.

Experimental studies of plasma dynamics and energy transformations in 3D configurations were commenced in the 1990s in different laboratories worldwide, including the Plasma Physics Department of the Prokhorov Institute for General Physics, Russian Academy of Sciences, with a new-generation CS-3D facility (Fig. 3). One of the main goals of the experiments was to find the 3D magnetic field characteristics that are required for energy accumulation in plasmas.

Three-dimensional magnetic configurations with topological peculiarities such as neutral points or neutral lines are

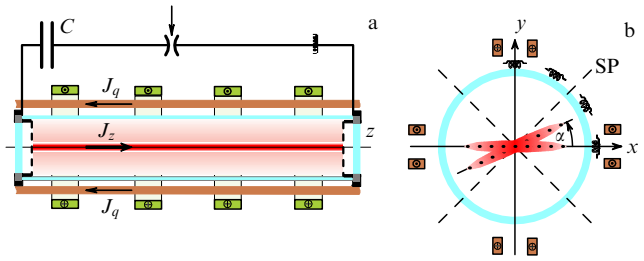

Figure 3. The design of the 3D CS experimental facility. (a) The side view. (b) A cross section [22]. The dashed lines in panel (b) show the orientation of the separatrix planes (SP) for the 2D magnetic field with a neutral line.

created in the 3D CS setup by superposing two magnetic fields with different (translational and axial) symmetries [20]. A magnetic field with the translational symmetry is the 2D field given by (1), with a neutral line on the z axis. As axially symmetric magnetic fields with the z axis directed along the neutral line, three types of fields were used: uniform magnetic fields B_z satisfying condition (5), 3D nonuniform magnetic fields with one or several neutral points, and 3D nonuniform fields without neutral points. The intensities of each of the two fields, as well as the structure of the axially symmetric field, can be changed independently of one another, thereby providing both a variety of initial configurations and a gradual transition between different configurations.

In a 3D magnetic configuration, a plasma is created and then an electric current J_z is generated along the neutral line of the 2D magnetic field, the line coinciding with the symmetry axis of the axially symmetric field. The energy used in the 3D CS facility to create the magnetic fields is $W \approx 400$ kJ, the initial plasma density varies in the range $\approx 10^{16} - 10^{14}$ cm^{-3}, magnetic fields can reach ≈ 10 kG, and the plasma current is $J_z \approx 100$ kA.

4. Current sheets in 3D magnetic configurations with neutral points

The first experiments on the 3D CS setup were performed for 3D magnetic fields with isolated neutral points, when the axially symmetric field was that of the 'anti-mirror machine,'

$$\mathbf{B}^{\mathrm{A}} = \{h_{\mathrm{A}}x;\ h_{\mathrm{A}}y;\ -2h_{\mathrm{A}}z\}\,. \tag{6}$$

Here, the neutral line of the anti-mirror machine is at the origin, and h_{A} is the radial gradient of the magnetic field in the vicinity of the neutral point.

If the 2D magnetic field with the neutral line on the z axis is given by

$$\mathbf{B}^{\mathrm{q}} = \{hx;\ -hy;\ 0\}\,, \tag{7}$$

where h is the radial gradient, then it is easy to see that a superposition of fields (6) and (7) forms a new 3D magnetic field $\mathbf{B}^{\Sigma}$ with a neutral point. In the vicinity of the neutral point, the structure of the magnetic field depends on the ratio of the gradients h_{A} and h [20]:

$$\begin{aligned}\mathbf{B}^{\Sigma} = \mathbf{B}^{\mathrm{q}} + \mathbf{B}^{\mathrm{A}} &= \{(h + h_{\mathrm{A}})x; (-h + h_{\mathrm{A}})y;\ -2h_{\mathrm{A}}z\} \\ &= h\{(1+\gamma)x; (-1+\gamma)y;\ -2\gamma z\}\,,\end{aligned} \tag{8}$$

$$\gamma = \frac{h_{\mathrm{A}}}{h}\,. \tag{9}$$

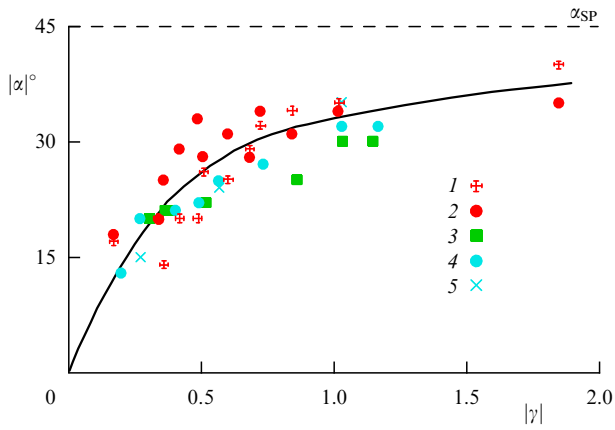

Figure 4. The dependence of the angular orientation $|\alpha|$ of the current sheet in the (x, y) plane on the parameter $|\gamma|$ for nonuniform 3D magnetic fields. Results *1* and *5* were obtained from the images of the radiating plasma, and *2–4* from the magnetic measurements. Data points *1* and *2* correspond to the sheet position in the vicinity of the magnetic neutral point, and data points *3–5* were obtained far away from the neutral point and in the magnetic field without neutral points [21].

It was found that a current sheet does form in the vicinity of the neutral point of the 3D magnetic field, and the plane of the sheet is rotated by an angle α with respect to the position of the sheet in the 2D field [21]. The angle α increases with increasing h_A and decreasing h, i.e., it depends on the parameter γ in (9) and varies in the range $0 \leqslant |\alpha| \leqslant \pi/4$ as $|\gamma|$ increases (Fig. 4, data points *1* and *2*) [21]. Therefore, the formation of current sheets in 3D magnetic fields with neutral points does occur; moreover, it occurs in a large variety of such configurations.

It was found that the current sheet is formed not only in the vicinity of the neutral point but also far from it, in regions with a sufficiently strong longitudinal magnetic field B_z, as well as in nonuniform magnetic fields without neutral points. In each cross section $z = \text{const}$, the angular orientation of the sheet is determined by the local value of the parameter $\gamma(z) = h_A(z)/h$ (see Fig. 4, data points *3–5*) [21]. The variation of the angular position of the sheet depending on the value of $\gamma(z)$ results the current sheet taking the form of a bended surface in a nonuniform magnetic field [22].

From the experimental data obtained, it was found that a critical condition for a sheet to develop in a 3D magnetic field is the presence of singular X-type lines with a saddle-like transverse structure [22]. We note that the 3D magnetic field with a neutral point also has an X-line. Without loss of generality, this allowed studying the evolution of current sheets in 3D fields (4) with a uniform longitudinal component $B_z \approx \text{const}$ directed along the X-line [23]. Such a field can be regarded as an element of a more complex 3D magnetic configuration with spatially varying components.

5. Current sheets in 3D magnetic configurations with X-lines

In passing from 2D configuration (1) to 3D configuration (4), a question arises as to how much the longitudinal component B_z affects the possibility of a current sheet developing and the current sheet parameters. Experiments performed with 3D magnetic fields (4) with different combinations of longitudinal and transverse components allowed establishing that a necessary condition for a current sheet to develop is that the gradient of the transverse field exceed a critical value, $h > h^{\text{cr}}$ [23]. In this case, the magnetic field B_z may exceed the transverse field in the entire region occupied by the plasma [24].

Detailed studies of the structure of current sheets developing in 3D configurations (4) showed that the distributions of currents are shaped like sheets, and the magnetic structures of the sheets in the 2D and 3D configurations are very similar [25]. As in the case of 2D fields, the plasma can be compressed by a factor of 5–10 compared with its initial density in 3D magnetic fields with the longitudinal component B_z [26].

In addition, the studies revealed that the compression ratio for the magnetic field and the current forming the sheet decreases as the magnetic field B_z increases [25, 26]. This effect manifests itself, first, in decreased values of the maximum current and plasma densities and, second, in an increased thickness of the sheet, i.e., in its smaller transverse size [25, 26]. The decreased compression ratio results in a sharp decrease in the plasma density gradient perpendicular to the sheet surface, whereas the total number of electrons per unit (1 cm) of thickness does not change considerably (Fig. 5a) [26]. In other words, as the B_z component increases in configuration (4), the plasma dynamics tend to those of incompressible plasmas.

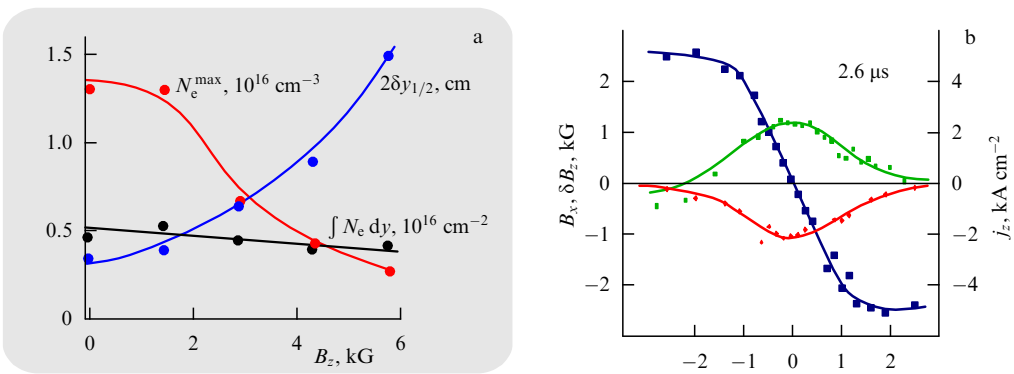

Figure 5. (a) The dependences of the maximum electron density N_e^{max} in the sheet, the sheet thickness $2\delta y_{1/2}$ (level $0.5N_e^{max}$), and the number of electrons per cm of the sheet thickness on the longitudinal magnetic field B_z [26]. (b) Transverse (along the y axis) distributions of the tangential component of the magnetic field B_x, the current density j_z, and the longitudinal magnetic field δB_z trapped in the sheet.

These results allowed suggesting that the decreased compression of the plasma on the sheet is caused by the increased B_z magnetic field component compared with its value outside the sheet [26]. Indeed, a gradual increase in the longitudinal component was observed in magnetic measurements [27]. The excess of the longitudinal magnetic field in the sheet compared with its initial value reached $\delta B_z \geqslant 1.2$ kG (Fig. 5b) and, importantly, the direction of the field δB_z captured in the sheet always coincided with the direction of the B_z component in the initial configuration (4).

The increased longitudinal magnetic field in the current sheet can exist only due to plasma currents in the (x, y) plane. In this case, the total current responsible for the δB_z field attained $J_x \approx 57$ kA, i.e., its order of magnitude was close to that of the main current, $J_z \approx 70$ kA. As a consequence, the current structure becomes three-dimensional as the current sheet develops in a 3D magnetic field.

A current sheet that forms in 3D magnetic field (4) appears as a region with concentrated hot and dense plasma, like sheets in 2D fields. The electron temperature and plasma density, the ion temperature, and the effective ion charge attain maximum values in the middle plane of the sheet and increase with time [28]. But the increase in the longitudinal magnetic field in the sheet by δB_z changes the condition of the transverse equilibrium of the sheet,

$$N_e\left(T_e + \frac{T_i}{Z_i}\right) + \frac{(\delta B_z)^2}{8\pi} \approx \frac{(B_x^{sh})^2}{8\pi}\,, \qquad (10)$$

$$\beta < 1\,.$$

It follows from this equation that the magnetic pressure of the transverse field B_x^{sh}, which compresses the plasma and current onto the sheet, is balanced by the sum of the thermal plasma pressure $N_e(T_e + T_i/Z_i)$ and the magnetic pressure due to the field δB_z [28]. It is worth emphasizing that the analogy between the pressure of the longitudinal magnetic field and the plasma pressure was substantiated by Syrovatskii in [15].

Hence, in 3D nonuniform magnetic fields with X-lines of different structures, extended current sheets may develop, with a considerable amount of magnetic energy concentrated in their vicinity. The sheets may exist for a long time without changes in their structure and parameters, i.e., they are metastable.

6. Two-fluid effects in current-sheet plasmas

In studies of current sheets developing in 3D magnetic configurations with an X-line and a longitudinal magnetic field B_z, the emergence of deformed (i.e., bended and asymmetric) current sheets was observed [29]. The asymmetry became more prominent as the ion mass was increased in the plasmas under study. This phenomenon was interpreted as a manifestation of two-fluid effects in the current-sheet plasma, namely, the generation of Hall currents in the sheet. In the presence of the B_z component, these currents give rise to additional dynamic effects causing sheet deformation [29]. As the direction of the B_z component was changed, the current sheet orientation changed as well, thereby confirming this hypothesis.

The analysis of the plasma parameters showed that the sheet deformation and consequently the generation of Hall currents occurred under the condition that the velocity u_c of the electrons carrying the current is several times larger than the characteristic Alfvén speed v_A,

$$u_c \gg v_A\,. \qquad (11)$$

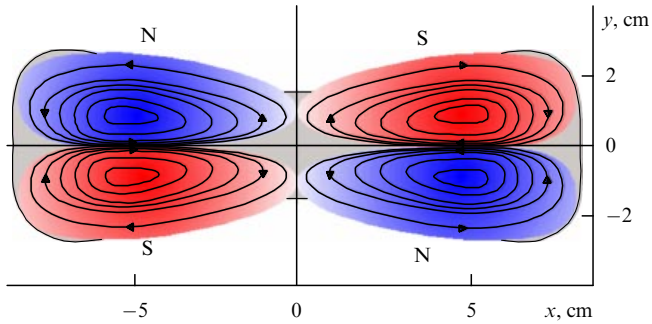

Figure 6. The structure of the Hall currents in the cross section of a current sheet. In the (x, y) plane, the Hall currents form four closed contours, which create a quadrupole longitudinal magnetic field B_z in the sheet [30]. In two quadrants placed diagonally, the B_z component is directed to the observer (N), while in the others it is directed from the observer (S).

Obviously, condition (11) can hold not only in 3D configurations (4) with B_z components but also in 2D fields with neutral lines (1), when $B_z = 0$ and the plasma sheets are planar and symmetric. It would appear reasonable that in the symmetric current sheets, Hall currents could be generated by the electrons moving with respect to heavy and slow-moving ions. In this case, the sheet remains symmetric because in the absence of the B_z component, there are no forces deforming the sheet.

Direct measurements revealed the generation of a longitudinal magnetic field B_z in the current sheets developing in 2D magnetic configurations. It is worth emphasizing that the B_z component was absent in both the initial 2D field and the magnetic field created by the main current J_z in the sheet [30]. Emerging in the current sheet, the longitudinal B_z component has a characteristic quadrupole structure and its appearance is direct evidence of the generation of Hall currents in the sheets.

The structure of Hall currents was determined for the first time and it was shown that in the current sheet cross section, i.e., in the (x, y) plane, the Hall currents form four current contours that create a quadrupole longitudinal magnetic field B_z (Fig. 6) [30]. The magnitude of the total Hall current along the current sheet reaches $J_H \approx 130-150$ kA. The Hall currents exist in the sheet for a limited time, which increases with the ion mass. The acceleration of ions along the surface of the current sheet, from the center to the lateral borders, results in the damping of the Hall currents. Thus, the generation of Hall currents in a sheet created in a 2D magnetic field considerably complicates the current and magnetic field structures, making them three-dimensional.

Currently, manifestations of two-fluid effects in the magnetic reconnection in current sheets, including the process in Earth's magnetosphere, are attracting particular attention.

7. Disruption of the current sheet and flare phenomena

The long-lasting phase in which a current sheet is stable and accumulates a considerable amount of magnetic energy created serious complications for laboratory experiments aimed at disrupting the sheet, releasing the accumulated

energy, and thereby realizing a flare event. Regarding this problem, Syrovatskii suggested that the relatively tenuous external plasma surrounding the current sheet prevents the disruption of the sheet by repairing the emerging disruptions [31]. Using this concept and experimental data on the dynamics of the peripheral plasma [32], it has been possible to find current sheet formation conditions such that a pulsed phase of magnetic reconnection occurs spontaneously and results in a catastrophic disruption of the current sheet [12]. The typical features of the pulsed phase are an abrupt change in the magnetic field topology, redistribution of currents in the sheet, the appearance of super-Alfvénic waves, and the generation of plasma flows [33, 34].

Rapid rearrangement of the magnetic field in the sheet result in excitation of the inductive electric fields and acceleration of the plasma particles. Indeed, the generation of accelerated electrons with energies exceeding 10 keV always correlated in time with the pulsed phase of the magnetic reconnection, i.e., with the current sheet disruption [35]. The most energetic particles were observed at the initial phase of the sheet disruption, thereby demonstrating a qualitative analogy with the particle acceleration during solar flares.

Thus, at the pulsed phase of the magnetic reconnection in current sheets in laboratory plasmas, all main nonstationary processes typical for flare events were observed; these include a rapid sheet disruption and release of accumulated magnetic energy, strong plasma heating and ejection from the sheets, and acceleration of charged particles [36, 37]. Recent preliminary results have demonstrated a possibility of rapid disruption of the current sheets created in 3D magnetic configurations.

The question of the physical mechanisms responsible for the long-lasting metastable phase of the current sheet evolution, initiation of the rapid disruption of the sheet, and flare phenomena is still open. On the one hand, at the pulsed phase of the magnetic reconnection, a decrease in the plasma conductivity [38] and increase in anomalous electric fields [39] are observed, thereby giving evidence of turbulent processes in the sheet plasma. But there are reasons to suppose that the plasma turbulence does not initiate the reconnection; rather, the turbulence is a consequence of reconnection.

It was found that an unusually rapid increase in the electron and ion temperatures occurs in a relatively small region within the current sheet just before the pulsed phase of the magnetic reconnection [40–42]. From the experimental data collection, a conclusion can be made that the pulsed plasma heating in the 'hot spots' of the current sheet is probably the main reason for violation of the transverse equilibrium of the sheet, its disruption, and, finally, release of the accumulated magnetic energy [42]. It is worth emphasizing that the crucial role of thermal processes causing the current sheet disruption is similar to the role of the 'thermal trigger' for solar flares considered by Syrovatskii [43].

8. Conclusions

The results of experimental studies allow arguing that flare phenomena in plasmas may have their origin in the evolution and dynamics of current sheets, as was predicted by Syrovatskii. Accumulation of the magnetic energy in plasmas occurs in the vicinity of metastable current sheets as they are forming in both 2D and 3D magnetic fields with neutral X-lines. A rapid disruption of the current sheet results in the release of the accumulated magnetic energy, which transforms into the thermal plasma energy and the energy of suprathermal fluxes of the plasma and of accelerated particles. The most probable cause of the termination of the metastable stage and the beginning of the pulsed phase of the magnetic reconnection seems to be thermal processes related to the pulsed local plasma heating.

Currently, a number of laboratories in different countries are deeply involved in experimental studies targeted at the investigation of the current sheets and magnetic reconnection in plasmas (for details, see [44] and the references therein). These studies commenced in the 1970s under the influence of the ideas of Syrovatskii.

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Space research of the Sun

V D Kuznetsov

1. Introduction

When speaking about solar studies, we first mean the Sun, our nearest star, as an astrophysical object that interests us because of both purely scientific (astrophysical) and practical aspects (since the Sun influences Earth and our life). Solar physics embraces various physical areas: nuclear physics, plasma physics and magnetic hydrodynamics (MHD), radiophysics, atomic physics and spectroscopy, and so on. All these physical directions are currently part of modern astrophysics as well.

The Sun is a natural space laboratory accessible for detailed investigation. Solar observations provide vast valuable data for understanding the Sun's composition and workings, and testing current theories and models applied for describing plasma, MHD, and other processes in space conditions, in particular, in distant astrophysical objects (e.g., convection, dynamo, and active phenomena). Currently, we can speak of heliophysics science, because solar and heliospheric physics are inseparably linked with each other [1]. It is appropriate that to mark the 50th anniversary of the International Geophysical Year, 2007 was named the International Heliophysical Year. Recently, the most significant progress in solar studies has been due to spacecraft studies; spacecraft allow observing the Sun in electromagnetic spectral ranges inaccessible from Earth, in the X-ray and ultraviolet ranges (extraterrestrial astronomy), as well as carrying out local measurements of plasma fluxes and particles emitted directly from the Sun. Elimination of the atmospheric influence for observations from space have provided a higher quality of optical observations, even though the size of space telescopes is always limited in comparison with ground-based terrestrial ones.

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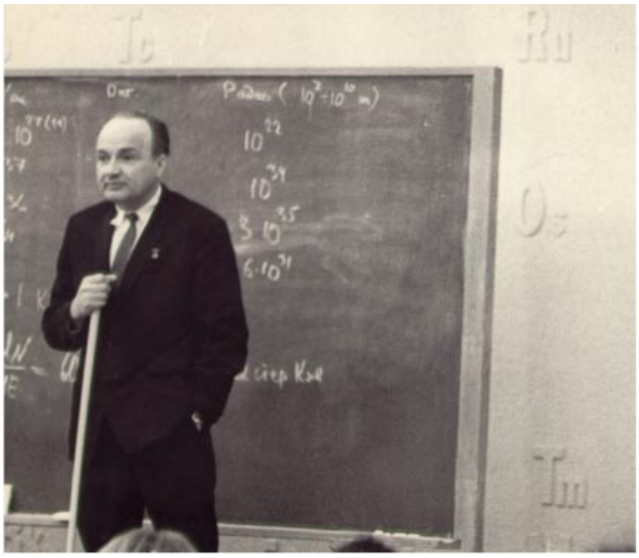

Sergei Ivanovich Syrovatskii. A seminar talk.

In the 1970s, Sergei Ivanovich Syrovatskii's main scientific interests were related to solar studies, magnetic reconnection and solar flares, and space, mostly solar, MHD — the fields where he is one of the classics. He paid considerable attention to observations of the Sun and its active atmospheric phenomena, whose origin and physics were quite interesting and not fully understood. Observations were regularly discussed at his seminar, and the theory of current sheets and magnetic reconnection was originated [1, 2], which was the basis for developed models of solar flares [3, 4] and other active phenomena. Observations with a high spatial resolution were not available at that time; this, on the one hand, provided a base for different approaches to explanations of phenomena and for discussions, and, on the other hand, set out the task of developing high-resolution space observations, which were eventually realized and have confirmed Syrovatskii's ideas.

2. Solar space projects

The current period in solar studies is called the golden era of solar physics in space, because such numbers of spacecraft and related results have never been seen before in the history of space research. Table 1 presents solar space projects of previous years, separated into four parts: recently completed, current, in preparation, and under development. A separate column shows the worthy contributions of Russian projects to this area of research.

In Sections 3–7, a brief review is given of the main results of solar space studies, from the solar interior to the solar wind. In Section 8, future solar space projects are described. A more detailed account can be found in Refs [5–7].

According to the current model, the Sun has a core where energy releasing thermonuclear fusion reactions occur; a radiation zone, throughout which the radiation energy released in the core is transferred to outer regions; the convective zone, the most outward invisible shell where the