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Magnetic reconnection in solar flares

B V Somov

1. Introduction

I was privileged to work under the supervision of Sergei Ivanovich Syrovatskii from 1966 to 1979, first as a graduate and postgraduate student, and then as a scientist at the Theoretical Department of the Lebedev Physics Institute. During those years, which quickly flew by, Syrovatskii was mostly interested in the solar flare problem.

The essence of the problem, its scientific and applied value, is determined by two facts. First, solar flares are a nonstationary electromagnetic phenomenon, typical for space plasmas but accessible to the most detailed investigations, in contrast to other stellar flares and bursts of objects in the Universe. Second, solar flares strongly influence interplanetary and near-Earth space, Earth's atmosphere, and even the biosphere. It is no coincidence that solar flares are interesting for not only astronomers and physicists but also specialists in cosmonautics/astronautics and power engineering, as well as biologists and medics. Syrovatskii made a fundamental contribution to establishing and successfully developing theoretical and experimental solar flare science in our country and abroad. In this communication, I touch upon only one key issue of this science, the role of the

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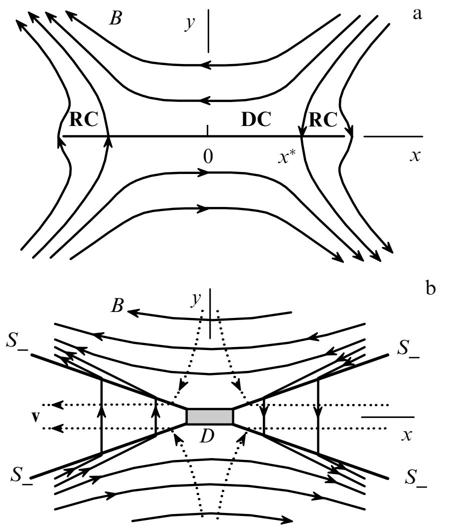

Figure 1. Two classic reconnection models: (a) the Syrovatskii current layer, and (b) the Petschek flow.

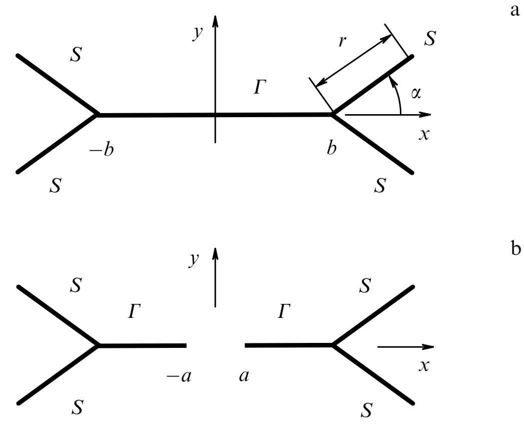

Figure 2. Current configuration containing a current layer Γ and four attached discontinuous MHD flows S with a finite width r: (a) the current layer without discontinuity, and (b) the current layer with a discontinuity of width $2a$.

magnetic field line reconnection (magnetic reconnection) in the flares [1, 2].

2. Syrovatskii's current layer

Magnetic reconnection is a redistribution of magnetic fluxes resulting in a change in the field topology. In both the medium and the vacuum, this process induces an electric field that is manifested depending on the medium properties. In the vacuum, for example, it can be merely measured or used to accelerate a charged particle. In plasma, the electric field generates an electric current; to be more precise, a current structure, which is typically fairly complex.

In a highly conducting plasma, the electric field forms a narrow current layer impeding redistribution of interacting magnetic fluxes [3, 4]. This leads to an energy excess in the form of the magnetic field in the current layer. The wider the layer is, the more energy is accumulated, and this is extensively used in astrophysical applications of the magnetic reconnection effect.

In a strong magnetic field, its structure near the current layer in a highly conducting plasma can be described by a simple analytic model [7], namely, as a discontinuity surface separating oppositely directed fields (Fig. 1a). This model is called the Syrovatskii current layer. The layer contains a direct current (DC) region and two attached reverse current (RC) regions. The magnetic field outside the current layer is considered to be potential, or more precisely, a two-dimensional field whose complex potential is an analytic function.

Another classic reconnection model, called the Petschek flow [8], is usually regarded as an alternative to the Syrovatskii current layer. In the Petschek model, the magnetic field line reconnection process is essentially separated from the field dissipation process. Reconnection occurs in a small diffusion region D (Fig. 1b). Energy release in this small region can be neglected, in contrast to the magnetic field energy that is converted into the plasma thermal and kinetic energy on four associated slow magnetohydrodynamic (MHD) shock waves S_- of infinite length.

3. Necessary generalizations of classic models

Already the first numerical simulations [9, 10] of the dissipative MHD magnetic reconnection have shown that there are finite-length discontinuous MHD flows near the current layer edges. The observed pattern of the flows is quite complex and, of course, depends on the initial and boundary conditions. Moreover, natural restrictions intrinsic for finite-difference methods do not allow investigating the current layer structure in the reconnection regime corresponding to the so-called super-hot turbulent current layers in solar flares [6]. The above conditions require that generalized analytic models should be constructed and reasonably simplified, and should explicitly depend on the physical parameters of the reconnection region. For solar flares, such parameters are, first of all, the geometric features of the region: a characteristic width b of the current layer, the angle α between the layer and the attached shock waves, and their length r (Fig. 2a).

The question of boundary and initial conditions in a general magnetic reconnection problem is not trivial. In the generalized model in [11, 12], as well as in Syrovatskii's model [7], the normal component of the magnetic field vanishes on the layer, i.e., the current layer is neutral. Accounting for a small transverse field component related to the reconnection process inside the layer is generally necessary and possible; however, that complicates the problem significantly. Taking the current layer symmetry into account, the problem can be reduced to a mixed Riemann–Hilbert boundary value problem [13] (see also Section 3.4 in Ref. [14], where a particular solution in the framework of the Keldysh–Sedov problem [13] is given). The transverse component of MHD shock waves is equal to a given constant β. This last assumption somewhat restricts the class of possible solutions; but it is necessary to limit the complexity regarding the formulation of the mathematical problem.

Another generalization of Syrovatskii's model is necessary in relation to the narrow layer decay into parallel current ribbons. Such a layer tearing can occur as a result of the tearing instability or when a higher resistivity occurs in the layer region, for example, anomalous resistivity owing to the excitation of some plasma turbulence. A simple analytic model of a decaying layer of infinite width was suggested in Ref. [15]. The magnetic tension force acts on the discontinuity sides in the layer; the force is proportional to the discontinuity width and tends to widen it. A powerful electric field is induced inside the discontinuity; in astrophysical conditions (e.g., in solar flares), this field is capable of accelerating charged particles to high energies. A generalized problem for a finite-width current layer in the presence of attached discontinuous flows, taking the current layer discontinuity into account, was formulated and solved in Ref. [16].

4. New analytic models

The generalized model described in Section 3 assumes that the two-dimensional magnetic field is potential in the region g outside the current configuration represented by a set of cuts $\Gamma + 4S$ on the complex plane $z = x + \mathrm{i}y$ (see Fig. 2). The magnetic field itself is also written in the complex form

$$B(z) = B_x(x, y) + \mathrm{i}B_y(x, y)\,. \qquad (1)$$

The field component B_n normal to the line $\Gamma + 4S$ vanishes on the current layer Γ, and is equal to a given constant β on the cuts S corresponding to shock waves. Herewith, B_n is expressed in terms of B as

$$B_n = \mathrm{Re}\left[v(z)\,\bar{B}(z)\right], \qquad (2)$$

where $v(z)$ is the complex unit normal, Re is the real part of the quantity in square brackets, and the bar over B denotes complex conjugation.

At infinity, the function $B(z)$ satisfies the condition

$$B(x, y) \sim \mathrm{i}h\,\bar{z}\,, \qquad z \to \infty\,, \qquad (3)$$

where h is the magnetic field gradient. Such behavior of the field corresponds to the pattern of lines observed far away from the hyperbolic null point in Syrovatskii's model [7].

To find the magnetic field function B, it is convenient to use its complex conjugate,

$$\mathcal{F}(z) = u(x, y) + \mathrm{i}v(x, y) = \bar{B}(z)\,, \qquad z \in g\,, \qquad (4)$$

because it follows from the potential character of the field that the function $\mathcal{F}(z)$ defined this way is an analytic function of the complex variable z in region g. Replacing B with $\bar{\mathcal{F}}$ in (2) and taking the boundary conditions on the $\Gamma + 4S$ cuts into account, we obtain the Riemann–Hilbert problem for $\mathcal{F}(z)$:

$$\mathrm{Re}\left[v(z)\mathcal{F}(z)\right] = c(z) \quad \text{on} \quad \Gamma + 4S\,. \qquad (5)$$

Here, $c(z)$ is a known function: $c(z) = 0$ on the current layer Γ and $c(z) = \beta$ on the cuts S.

Figure 3 illustrates the problem solution method [17]. Because the problem is symmetric with respect to the x and y axes, it is sufficient to consider one quarter of region g, e.g., the first quadrant with cut CDE, the region G (Fig. 3a). Because region G is an infinite pentagon, it can be mapped on the upper half-plane $\mathbb{H}^+$ (Fig. 3b) by using a conformal map $\zeta = \Phi(z)$ whose inverse can be represented as the Christoffel–Schwarz integral [18]

$$\Phi^{-1}(\zeta) = \mathscr{K}\int_0^{\zeta} t^{-1/2}(t-\lambda)^{-\alpha}(t-1)\,(t-\tau)^{\alpha-1}\,\mathrm{d}t\,. \qquad (6)$$

The problem solution $\mathscr{P}(\zeta)$ in the upper half-plane $\mathbb{H}^+$ can be obtained by standard methods [13]; it is shown in Fig. 3c. Substituting $\zeta = \Phi(z)$ in $\mathscr{P}(\zeta)$, we finally write the general solution $\mathcal{F}$ in the form $\mathcal{F}(z) = \mathscr{P}[\Phi(z)]$.

An analytic solution of the problem of a current layer with attached shock waves (Fig. 4) was obtained in Ref. [12]. The model allowed studying a global arrangement of the magnetic field and the behavior of the total current and reconnection rate determined by the magnetic field as functions of the parameters β and h. The character of the magnetic field refraction on the shock wave, i.e., on cut CDE (Fig. 3a), was considered in Ref. [16].

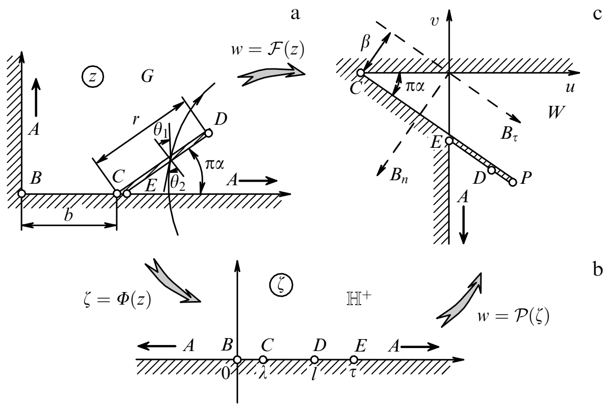

Figure 3. Sketch to solve the Riemann–Hilbert problem. (a) Initial region. (b) Upper half-plane. (c) Magnetic field locus region.

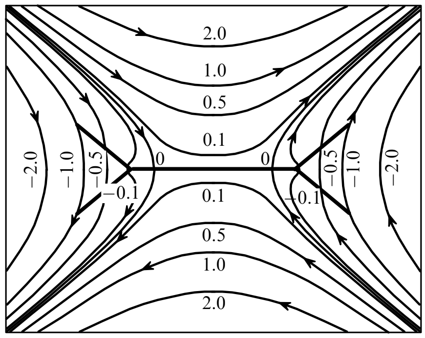

Figure 4. Current structure (bold straight line segments) and magnetic field lines (thin curves, with arrows showing the field direction) in the model of a current layer with attached shock waves [12] for characteristic parameter values $b = r = 1$, $\alpha = 1/4$, $\beta = 1$, and $h = 1$.

We let θ_1 and θ_2 be the respective deviation angles of the magnetic field vector from the interior (with respect to region G) normals to boundary segments CD and DE. The ratio of these two angles determines the MHD wave type (see Ref. [19]). For example, if both angles are positive and $\theta_2 > \theta_1$, the wave is fast, and in the case $\theta_1 > \theta_2$, slow. As demonstrated in Ref. [16], near the attachment point of a shock wave to a current layer, there is always a segment of cut S where the wave is a trans-Alfvénic shock. It increases the tangential field component and changes its direction to the opposite (see Ref. [20]). Trans-Alfvénic waves are non-evolutionary (see Ref. [19]). The analysis of the evolutionary character of a current layer itself (see Ch. 10 in Ref. [6]) has shown that in reverse-current regions, the layer, as an MHD discontinuity, is not evolutionary [21] and can therefore split into other discontinuities observed in the numerical simulations in [22, 23]. Figure 5 shows the magnetic field pattern for the model with a decaying current layer in the presence of attached shock waves (Fig. 2b). Clearly seen are the direct and reverse current regions, and the field line refraction on shock waves.

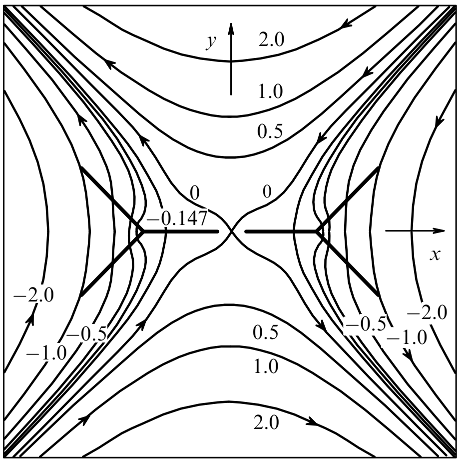

Figure 5. Pattern of magnetic field lines near a decaying current layer with attached shock waves [16].

5. The physics of reconnecting current layers

In space and laboratory plasmas, the magnetic reconnection effect underlies many nonstationary phenomena accompanied by fast plasma flows and shock waves, powerful heat fluxes, and fluxes of charged particles accelerated to high energies. Among these phenomena are, first of all, solar flares accessible for comprehensive investigation and detailed modeling [24]. On the Sun, reconnecting current layers naturally appear in the corona, in the magnetic fields of the so-called active regions, where magnetic fields are strong and the reconnecting current layer electric fields reach enormous values.

The analytic models considered above do not describe physical processes inside a current layer. In the strong-field approximation, a current layer is an infinitely thin MHD discontinuity. Due to the two-dimensional character of the reconnection effect, such a discontinuity essentially differs from one-dimensional MHD discontinuities included in the standard classification [25]. The field structure in its vicinity is described by Syrovatskii's solution [7]. The plasma dynamics near a current layer can be investigated in the same approximation (see Ch. 3 in Ref. [26]). In particular, it is possible to find velocities of plasma flows together with the frozen magnetic field and identify the inflow velocity in the layer with the reconnection rate in it. Thus, Syrovatskii's solution, describing the two-dimensional magnetic field structure near a current layer, plays the same role as the Hugoniot adiabate that determines parameters of a stationary one-dimensional gas flow through a hydrodynamic shock wave front. The corresponding MHD generalizations of the Hugoniot adiabate are applicable to MHD shock waves attached to a current layer.

In the framework of the above models, the parameters of a current layer and shock waves are considered fixed. In specific astrophysical applications, for example, solar flares, a particular physical model should be used to determine these parameters (such as the current layer half-width b), namely, the high-temperature turbulent current layer model (the shaded oval area in Fig. 6) (see Ch. 6 in Ref. [6]). This two-dimensional self-consistent model is based on the mass, momentum, and energy conservation laws (as well as on Ohm's law) written as order relations.

The temperature of the current layer is so high that Coulomb collisions can be neglected there. Direct heating of electrons and ions as a result of particle–wave interactions inside the turbulent layer and the electron cooling by anomalous thermal fluxes from the layer are the dominant physical processes in such a 'super-hot' layer [27, 28]. The model allows estimating characteristic values of the turbulent layer thickness $2a_{\text{tur}}$ and width $2b_{\text{tur}}$ (see Fig. 6), the plasma density, the electron and ion temperature in it, and the energy release power and other parameters that are interesting for astrophysical applications of the magnetic reconnection theory.

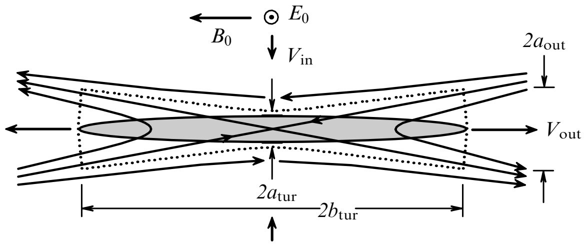

Figure 6. A high-temperature turbulent current layer [6] as a physical model of the direct current region in a reconnecting current layer.

However, a significant advantage of analytic models is the possibility of investigating general relations independent of detailed assumptions regarding the physical reconnection model in strong magnetic fields. This is highly analogous to the Hugoniot adiabate, which describes the initial and final gas state at its transition through a shock wave front irrespective of how exactly the transition occurs.

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The origin of cosmic rays

V S Ptuskin

1. Introduction

Cosmic ray studies constitute an important part of Sergei Ivanovich Syrovatskii's scientific heritage. The famous book published in 1963 by Ginzburg and Syrovatskii, *The Origin of Cosmic Rays* [1], has become a 'Bible' for scientists working in high-energy astrophysics. Already in this book, which was written before the discovery of quasars, cosmic background radiation, and pulsars, during the days when information on cosmic rays beyond the Solar System was based primarily on radio astronomy data, the foundations of the cosmic ray origin model were formulated, which remain firm up to this day. The model developed in Ref. [1] is based on the following assumptions: the main component of cosmic rays is of galactic origin, the cosmic rays diffuse in interstellar magnetic fields and fill a vast halo, the cosmic ray sources are supernova explosions, and the highest-energy particles (according to the modern nomenclature, cosmic rays with energies above $10^{18}-10^{19}$ eV) have an extragalactic origin. In 1979, shortly after Syrovatskii's death, Ginzburg suggested to several colleagues working in this field to jointly write a book on this topic. The book *Astrophysics of Comic Rays*, edited by Ginzburg, was published in 1984, and a second edition appeared in 1990. It included new chapters such as gamma-ray and neutrino astronomy, and a kinetic description of cosmic ray acceleration and propagation processes. In a certain sense, that book was a comprehensive summary of many years of collaborative work of Ginzburg, Syrovatskii, and their colleagues in the field of cosmic ray astrophysics.

In this brief communication, we describe, some recent results of research into the origin of cosmic rays.

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2. Galactic cosmic rays: acceleration in supernovae and propagation in galactic magnetic fields

Because of their energy characteristics, supernovae and their remnants are the most suitable galactic cosmic ray sources [1]. To obtain the observed energy density of cosmic rays, ≈ 1.5 eV cm^{-3}, approximately 10–20% of the kinetic energy of a supernova burst should be converted into the energy of relativistic particles. It is assumed that the kinetic energy of a supernova explosion is 10^{51} erg and that galactic supernova outbursts occur every 30 years on average. Direct evidence of the presence of relativistic particles in supernova remnants follow from nonthermal radiation observations in the radio, X-ray, and gamma-ray ranges. Synchrotron radio emission data indicate that there are electrons with energies 50 MeV–30 GeV in supernova remnants such as Cas A, IC 433, Cygnus Loop, and many others [3]. In the case of Cas A, the synchrotron radiation was detected in the infrared range, which indicates that there are electrons with energies up to 200 GeV. The nonthermal X-ray radiation with a characteristic power-law spectrum and energy up to a few dozen keV detected from bright rims in approximately ten young galactic supernova remnants, including SN1006, Cas A, RXJ 1713.7-3946, RX J08852-46/Vela Jr, RCW86, and G266.2-1.2 can be explained by synchrotron emission of very-high-energy electrons, up to 10–100 TeV (see review [4]). The inverse Compton scattering of background photons by such high-energy electrons, and gamma-ray emission via π^0-meson production and decays in interaction processes of protons and nuclei with energies up to ~ 100 TeV with gas nuclei, explain the presence of TeV gamma emissions detected from a number of young shell-type supernova remnants [5]. Spatial distribution of nonthermal emission in all frequency ranges demonstrates that particle acceleration occurs directly on the shock wave produced by the supernova explosion.

Cosmic ray composition data also confirm that particle acceleration occurs on a shock wave propagating in the interstellar medium or presupernova wind (see [6] for the details). In particular, it turns out that after accounting for the atomic properties such as the first ionization potential or volatility (the composition of matter deposited on the interstellar dust is volatility dependent), the chemical composition of cosmic ray sources is close to the typical composition of the local interstellar medium or solar photosphere. The ion and dust acceleration probably occurs in the partially ionized interstellar gas and/or hot interstellar gas bubbles with a high rate of supernova outbursts. The relatively high abundance ratio of $^{59}Co/^{56}Fe$ isotopes in the material of cosmic ray sources shows that most ^{59}Ni isotopes synthesized in a supernova explosion have time to decay into ^{59}Co isotopes due to orbital electron capture before the particle acceleration begins. It therefore follows that the acceleration occurs no less than 10^5 years after the nucleosynthesis process.

The mechanism of cosmic ray acceleration in supernova remnants is a version of the first-order Fermi acceleration. Acceleration of fast particles occurs in a gas flow that is compressed on the shock wave owing to multiple shock wave front crossings by diffusing fast particles [7, 8] (see also