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Overview of open issues in the physics of large solar flares

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A broad variety of observational methods allows us to see the effect of magnetic reconnection in high-temperature strongly-magnetized plasma of the solar corona. Some specific features of the large-scale reconnection in large solar flares are summarized in this review but they are not investigated in detail yet. For example, an analysis of the topological peculiarities of magnetic field in active regions clearly shows that the so-called topological trigger phenomenon is necessary to allow for in order to construct realistic models for large solar flares and Coronal Mass Ejections (CMEs). However this is not a simple task. We discuss also some new analytical models of magnetic reconnection in a current layer with attached MHD discontinuities. These models take into account the possibility of a current layer rupture in the region of anomalous plasma resistivity. In the context of the numerical simulations of reconnection, a question of their interpretation is considered. Some new results obtained recently are briefly reviewed together with new questions of the solar flare physics to be studied.

Keywords: Sun; Solar flares; Magnetic reconnection; Shock waves

1 Introduction

Large solar flares strongly influence the interplanetary and terrestrial space by virtue of shock waves, hard electromagnetic radiation and high-energy accelerated particles [1, 2]. Early studies of solar flares showed that flares were associated with magnetic fields [3]. Estimates of the energy required to power large flares led to the conclusion that flares must be electromagnetic in origin. However even much earlier it became more clear, step by step, that a solar flare is a result of the effect of reconnection of magnetic fields, the *magnetic reconnection* [4–6].

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The principal flare process is contingent on the accumulation of the *free magnetic energy* in the corona. By 'free' we mean the surplus energy above that of a potential magnetic field. This field has the sources (sunspots, background fields) in the photosphere. The free energy is related to electric currents in the corona. A flare corresponds to rapid changes of the currents. It is of principal importance to distinguish the currents of different origin because they have different physical properties and, as a consequence, different behaviors in the pre-flare and flare processes (see Sec. 14.5 in [7]). The actual currents conventionally comprise two different types. (a) The *smoothly-distributed* currents that are necessarily parallel or nearly parallel to the field lines, since magnetic field is strong in the solar atmosphere. So, the magnetic field is locally force-free (FFF [8]). (b) The *strongly-concentrated* electric currents like a reconnecting current layer (RCL [9]. It was a question whether or not it is possible to explain the pre-flare energy storage in a FFF. However the smoothly-distributed currents dissipate too slowly in a low-resistivity plasma of the solar atmosphere. Hence the highly-concentrated currents are necessary to explain an extremely high power of energy release in the impulsive phase of a flare. The RCLs allow an active region to overcome this difficulty.

We distinguish between two processes: a slow accumulation of energy and its fast release, a flare. An interaction of magnetic fluxes (and an excess of energy) appears as a result of slow changes of the field sources. The changes are an emergence of a new flux from below the photosphere and other flows of photospheric plasma, in particular the *shear* flows along the neutral line of the photospheric magnetic field. So, an actual reconnection in the corona is always a 3D phenomenon (Sec. 2).

Accumulation of energy in the form of magnetic field of RCLs and rapid dissipation of the field necessary for a flare can be explained by the theory of super-hot turbulent-current layers (SHTCL [7, 10]).

In general, the potential field determines a large-scale structure of the flare-active regions while the RCL at separators together with the other non-potential components of field determine energetics and dynamics of a large eruptive flare. To understand the relative role of different currents, it is necessary to study the evolution of its magnetic structure in and above the photosphere. This would allow us to determine not only the magnetic fluxes of certain magnetic links but also their changes – redistribution and reconnection. Such a study would also give us an information about the structure and evolution of the electric field in active regions. In this article, some new theoretical results obtained recently are briefly reviewed together with new questions of the solar flare physics to be studied.

2 The topological models of 3D reconnection

In the simple topological model [11], four field sources – the magnetic "charges" $e_{\rm N}$ and $e_{\rm S}$, $e_{\rm n}$ and $e_{\rm s}$, located in the plane Q under the photosphere Ph (Fig. 1) – are used to reproduce the main features of the observed field in the photosphere related to the four most important sunspots: N, S, n and s. As a consequence, the *quadrupole* model reproduces only the large-scale features of the actual field in the corona related to these sunspots. As a minimum, the four sources are necessary to describe

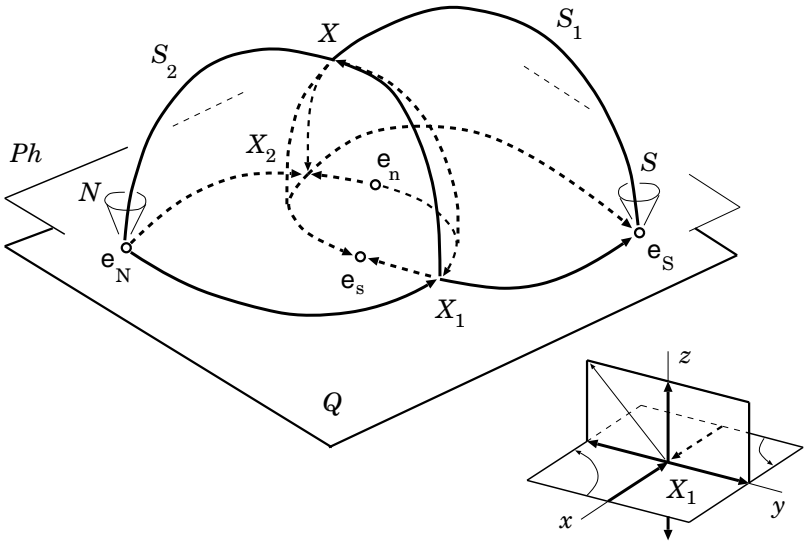


Figure 1 The simplest topological model for magnetic field of four sunspots of pairwise opposite polarity.

two interacting magnetic fluxes having the two sources per each. The larger number of sources are not necessarily much better.

The main features are two magnetic surfaces called the *separatrices*: S_1 and S_2 (Fig. 1). They divide the whole space above the plane Q into four regions and, correspondingly, the whole field into four magnetic fluxes having different linkages. The field lines are grouped into four regions according to their termini. The separatrices are formed from lines beginning or ending at magnetic zeroth points X_1 and X_2. For example, the field lines originating at the point X_1 form a separatrix surface S_1.

The topologically singular field line X_1XX_2, lying at the intersection of the separatrices, belongs to all four fluxes (the two reconnecting and two reconnected fluxes) that interact at this line, the 3D magnetic *separator*. So the separator separates the interacting fluxes by the separatrices. Such situation is of fundamental importance for solar physics. On the other hand, direct detection of a separator, as a field line that connects two zeroth points in the Earth magnetotail, by the four *Cluster* spacecraft [12] provides an important step towards establishing an observational framework of 3D reconnection.

3 What is topological trigger?

Near a separator the longitudinal component $B_\parallel$ dominates because the orthogonal field $\mathbf{B}_\perp$ vanishes at the separator. Reconnection in the RCL at the separator just conserves the flux of the longitudinal field, see Sec. 6.2 in [7]. At the separator, the orthogonal components are reconnected. Therefore they actively participate in the connectivity change, however the longitudinal field does not. Thus the longitudinal

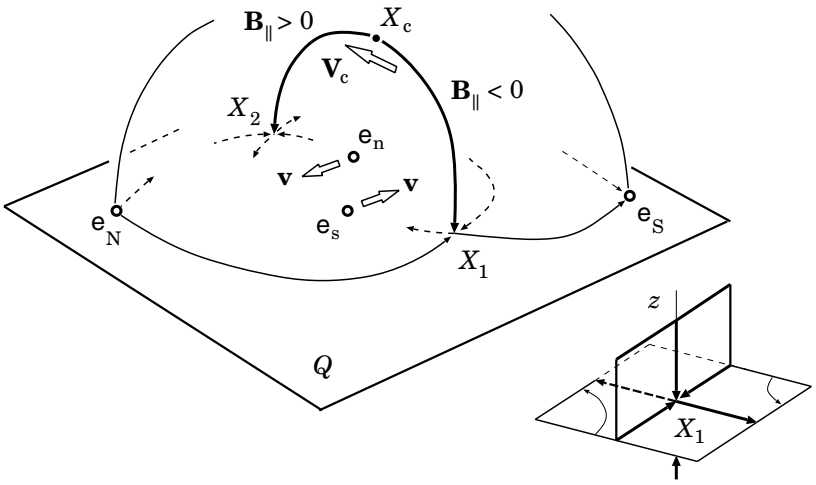


Figure 2 The zeroth point X_c rapidly moves along the separator and switches back the longitudinal component $\mathbf{B}_\parallel$ of magnetic field.

field plays a passive role in the topological aspect of the 3D reconnection process but it influences the physical properties of the RCL, in particular the reconnection rate. The longitudinal field decreases compressibility of plasma flowing into the RCL. When the longitudinal field vanishes at the separator, the plasma becomes "strongly compressible", and the RCL collapses, i.e. its width decreases substantially. As a result, the reconnection rate increases quickly. However this is not the whole story.

The important exception constitutes a zeroth point which can appear on the separator above the photosphere. In this case, even very slow changes in the configuration of field sources in the photosphere can lead to a rapid migration of such a point along the separator (Fig. 2) and to a *topological trigger* of a flare [13].

This essentially 3D effect is considered in mathematical detail in [14, 15].

Let us arbitrary fix the positions of three charges, while we move the fourth one along an arbitrary trajectory in the plane Q. Let an initial position of the moving charge corresponds to the zeroth points X_1 (with the eigenvalue $\lambda_z > 0$) and X_2 (with $\lambda_z < 0$) respectively (Fig. 1). The separator is the field line connecting these points without a coronal null. This field line emerges from the point X_1 and is directed along the separator to the point X_2.

The moving charge can arrive in a narrow region (let us call it the region TT) such that both points in the plane Q will have the same sign of λ_z (Fig. 2). In this case there must also exist two zeroth points outside the plane. They are arranged symmetrically relative to the plane Q (the plane $z = 0$). Figure 3 illustrates how these additional points appear.

Before the start of trigger, the moving charge is outside of the region TT, and $\lambda_z > 0$ at the nondegenerate zeroth point X_1 (Fig. 3a). When the moving charge crosses the boundary of the region TT, the eigenvalue λ_z at the point X_1 vanishes (Fig. 3b):

$$\lambda_z(X_1) = 0\,. \tag{1}$$

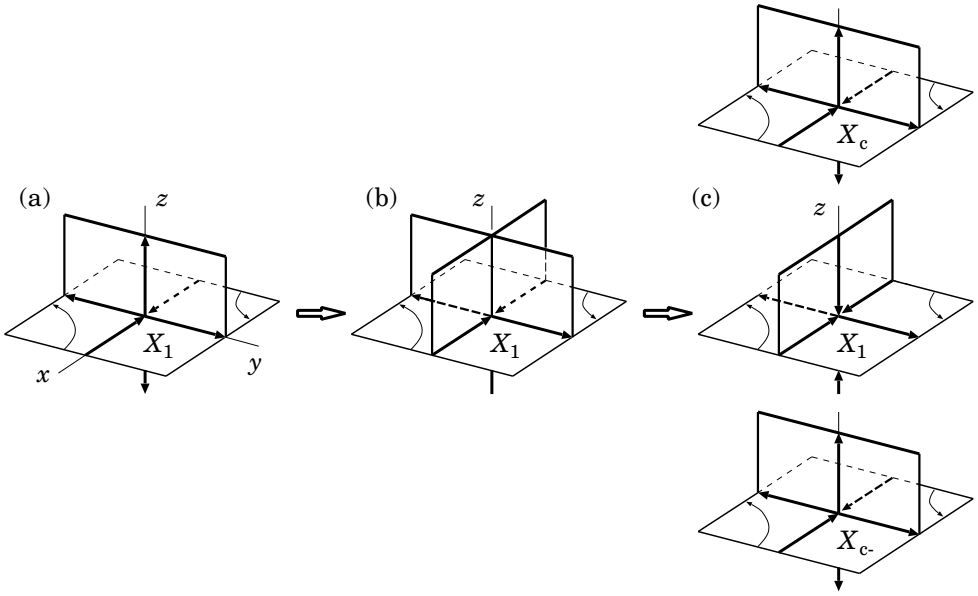


Figure 3 Changes of the field pattern at the zeroth point X_1. (a) An initial state is the nondegenerate point with $\lambda_z > 0$. (b) A *degenerate* hyperbolic point (line) with $\lambda_z = 0$ at the beginning of trigger. (c) After the beginning of trigger, the pattern of field is the nondegenerate point with $\lambda_z < 0$ and two zeroth points outside the plane $z = 0$.

The point becomes degenerate. At this instant, another pair of zeroth points is born from the point X_1 (Fig. 3c). Consider one of them, the point X_c in the upper half-space $z > 0$. This nondegenerate point travels along the separator and merges with the point X_2 in the plane $z = 0$ when the moving charge emerges from the region TT. At this instant λ_z vanishes:

$$\lambda_z(X_2) = 0\,. \tag{2}$$

As a result of the process described, the direction of the field at the separator is reversed with the point X_2 with $\lambda_z > 0$. After that, the moving charge is located outside the region TT, there are no zeroth points outside the plane $z = 0$. Thus Equations (1) and (2) determine the boundaries of the topological trigger region TT.

Typically the region TT is very narrow. That is why small shifts of the moving charge within this region lead to large shifts of the zeroth point X_c along the separator above the plane $z = 0$ just creating a *global bifurcation*. By analogy with hydrodynamics [16], the separatrix plane (y, z) in Fig. 3a, which plays the role of a 'hard wall' for 'flowing in' magnetic flux, is quickly replaced by the orthogonal hard wall, the separatrix plane (x, z) in Fig. 3c. Thus the topological trigger drastically changes directions of magnetic fluxes in an AR as illustrated by Fig. 4.

During the quick process of topological trigger, another rigid wall, the separatrix plane of the coronal zeroth point X_c running along the separator, turns the large-scale magnetic field of an active region like a page in a book.

Figure 4b shows that a loop e_1X_c quickly grows up. If it reaches a height in the corona, where the solar wind becomes important and pools the magnetic field lines

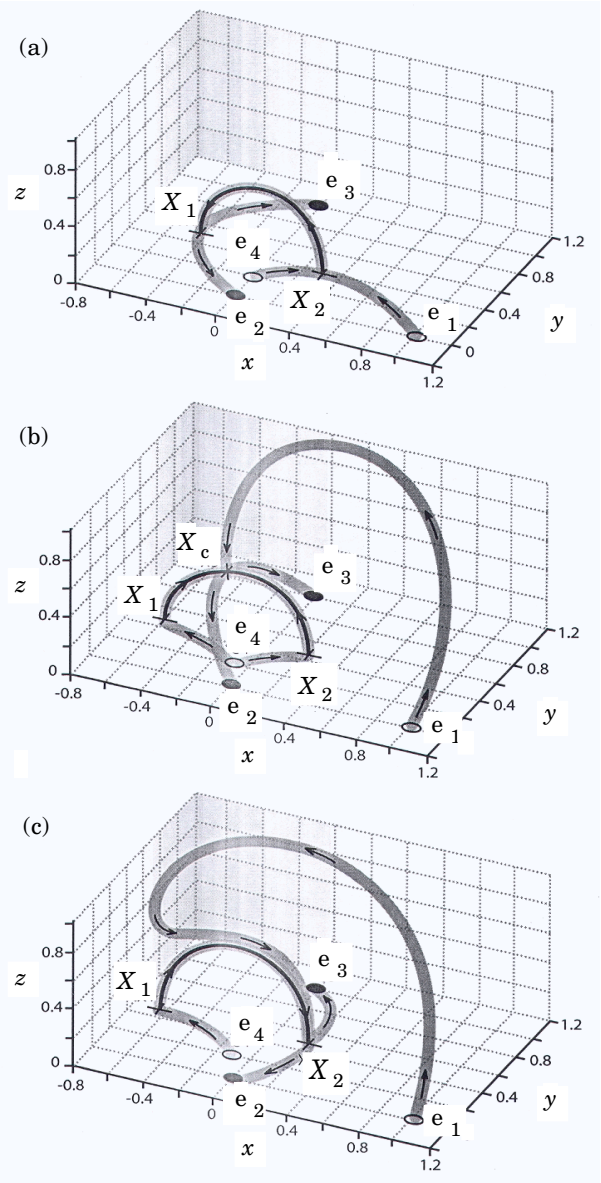


Figure 4 Drastic changes of the large-scale structure of magnetic field in a model of active region. (a) An initial state without a coronal null of magnetic field. (b) The coronal null X_c runs along the separator during the topological trigger process. (c) After the end of the trigger process.

in the interplanetary space [17], then a fast motion appears as an upward collimated jet along a coronal streamer structure.

We have considered the travel of one charge while the coordinates and magnitudes of the other three charges were fixed. It is obvious however that all the foregoing

remains in force in a more general case of variation of the charge configuration. A slow evolution of the configuration of field sources in the photosphere can lead to a rapid rearrangement of the global topology in active regions in the corona. So the phenomenon of topological trigger is necessary to model the large eruptive flares.

Note that the topological trigger effect is *not* a resistive instability which leads to a change of the topology of the field configuration from pre- to post reconnection state. On the contrary, the topological trigger is a quick change of the global topology, which dictates the fast reconnection of collisional or collisionless origin. Thus the term 'topological trigger' is the most appropriate nomenclature to emphasize the basic nature of the topological effect involved, and it is a welcome usage.

In close relation to the effect of topological trigger, we have to undertake a series of extensive researches to elucidate the electrodynamic processes in the photosphere, chromosphere and corona, related to magnetic field concentration and dissipation, plasma heating and acceleration of electrons and ions. A major thrust of this work is the development of a unified model for electrodynamic coupling at all levels in the solar atmosphere starting from the photosphere. This is what we need to involve the topological trigger in a mechanism of the geoeffective solar events and to develop their physics. Such investigations will also give us the possibility of applying the theory of large solar-type flares to astrophysical phenomena (like the flares in accretion disk coronae) accompanied by fast plasma ejections, powerful fluxes of heat and radiation, impulsive acceleration of electrons and ions to high energies [18].

4 New analytical models of reconnection

In the approximation of a strong magnetic field, Syrovatskii [19] constructed a simple 2D analytical RCL model in the form of a discontinuity surface that separates the oppositely directed magnetic fluxes (Fig. 5a).

Another classical model (Fig. 5b) is called Petschek's flow [20] and is commonly considered as an alternative to Syrovatskii's current layer. Markovskii and Somov [21] suggested a stationary reconnection model that is a generalization of both models. This model consists of an infinitely thin current layer of length $2a$ with four MHD shock waves of length r attached to its endpoints like whiskers. The normal magnetic field component vanishes on the current layer and is equal to a given constant β on the shock waves inclined to the current layer at angle α.

An asymptotics of the solution to this problem corresponding to a small whisker length r was found in [21]. We present the general solution of the problem with arbitrary length r as illustrated by Fig. 6 taken from [22]. This solution is found in an analytical form that admits of efficient numerical implementation. So we can analyze in detail the structure of the magnetic field and its variation with reconnection-model parameters.

In the center part of the pattern we see the thin-wide current layer with the region of direct current and two regions of reverse current in a good agreement with Syrovatskii's model. In addition, four MHD discontinuities are attached to the edges of the layer. Note that a character of discontinuous flows is not prescribed but determined from a self-consistent solution of the problem in the approximation of strong field. Should the discontinuous flows be similar to the slow MHD shock waves in Petschek's

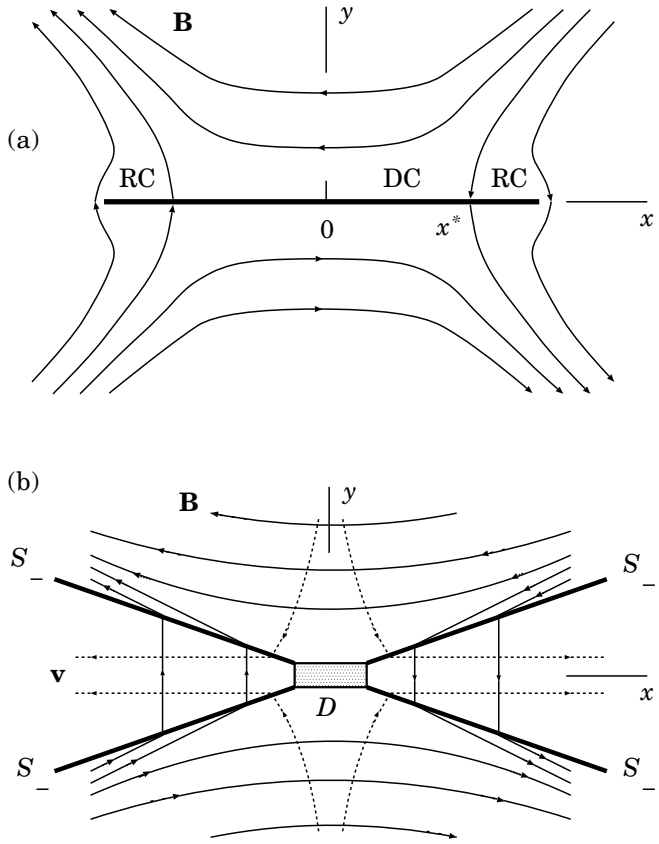


Figure 5 Two classical models of reconnection. (a) Syrovatskii's current layer contains a region of direct current (DC) and two regions of reverse current (RC). (b) Petschek's flow consists of a small diffusive region D and four attached slow MHD shocks S_-.

flow? – No, these discontinuities are not so simple. The general solution shows that a situation is more complicated.

In different parts of the attached discontinuities, different types of discontinuous solutions present. For example, slow shocks associated with the reconnection process in Petschek's flow are separated from the current layer by fast MHD shocks. Moreover, near the edges of the layer with return currents inside it, there appears the regions of trans-Alfvénic shock waves (TASW) [23]. The distinctive feature of TASW is that they do not exist as stationary shocks: they disintegrate, transform to time-dependent compound waves, or evolve to Alfvén waves in a diffusion-like manner [24, 25]. As a consequence, some parts of the attached discontinuities become non-evolutionary (see Ch. 17 in [26]). This fact gives us the principal possibility to understand general properties of reconnection in the framework of 2D resistive theory and direct numerical simulations, e.g., [27, 28].

The most interesting problem is the behavior of magnetic field and plasma in the edge region of a RCL, i.e. in a complicated transition from the RCL to the exterior

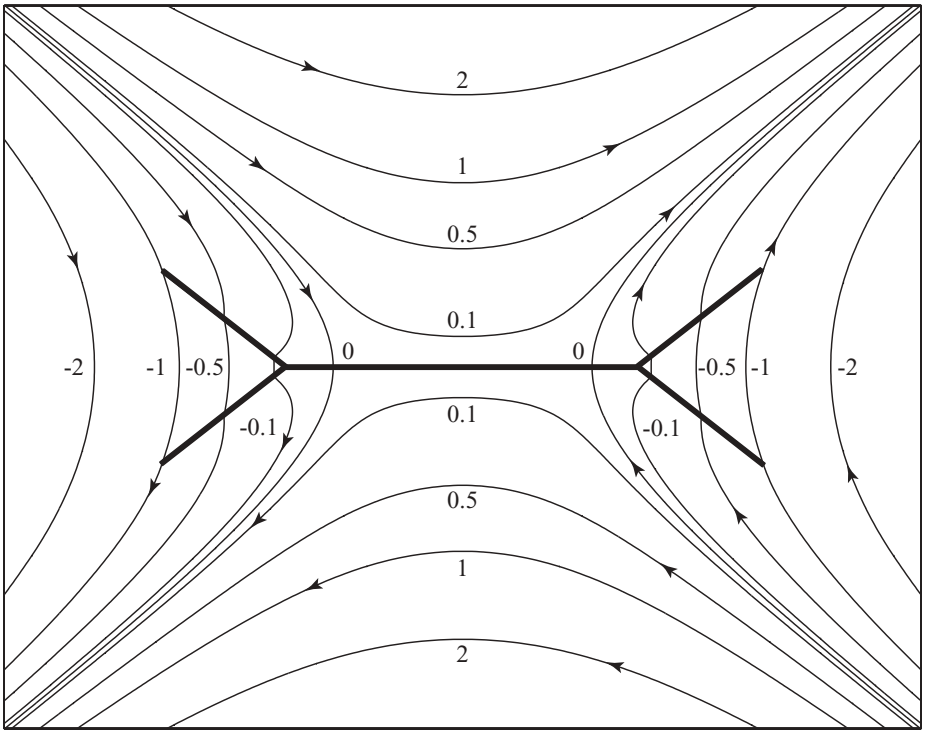


Figure 6 Magnetic field lines in the pattern which is typical for general case of physically meaningful solutions of the reconnection problem.

region of a 'downstream cone' between two attached MHD shocks. Another important problem is to find the generalized analytical solutions those take into account the possibility of the current-layer rupture (Fig. 7) in a place of anomalous resistivity of plasma [22]. The current layer rupture region is assumed to be the place of particle acceleration to high energies in solar flares [29]. The regions of direct and reverse currents and the refraction of magnetic field lines at the attached shocks are clearly seen in Fig. 7. Thus we can study the global structure of magnetic field in a reconnection region as well as the local properties of the field in the vicinity of the current layer and attached discontinuities.

5 New problems in the solar flare physics

The existing topological models are used to describe active regions, to reproduce the main features of magnetic fields leading to the large-scale reconnection in solar flares [30, 31]. To understand the 3D structure of reconnection in flares is one of the most urgent problems. *RHESSI*, *Hinode* and other modern space missions offer us the means to check whether phenomena predicted by topological models (such as the topological trigger) do occur. However some puzzling discrepancies may also exist, and further development of realistic 3D models is required.

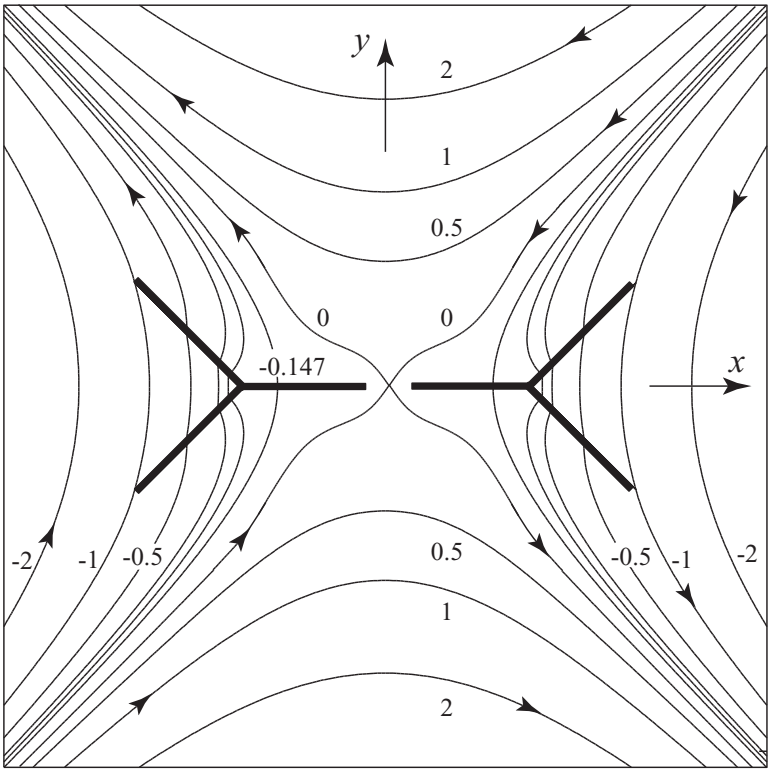


Figure 7 Magnetic field lines in the vicinity of a disrupted current layer with attached discontinuous MHD flows.

The local models of reconnection in flares take kinetic effects into account and allow us to develop the basic physics of reconnection in flares [7, 29]. Collisionless reconnection is a key process in flares. It was introduced by Syrovatskii [9] as a *dynamic dissipation* of field in a current layer and leads to fast conversion from field energy to particle energy. The problem of stable motion of particles in a RCL was considered in the adiabatic approximation with account of three components of magnetic field and an inductive electric field related to reconnection [32]. However the non-adiabatic behavior of accelerated particles in the RCL is a big issue here.

General properties and parameters of the collisionless reconnection can be examined in a frame of models based on the mass, momentum, and energy conservation laws. A particular feature of the models is that electrons and ions are heated by wave-particle interactions in a different way. The magnetic-field-aligned thermal flux becomes anomalous and plays the role in the cooling of electrons in a SHTCL [7]. These properties are typical for the conditions derived from the observations by *RHESSI* [33]. Unfortunately, the local models are not incorporated in the global consideration of reconnection in the corona. Only a few first steps have been made in this direction.

Modern spacecraft observations of collisionless reconnection in the magnetotail and magnetopause as well as recent simulations show the existence of *thin* current layers

with scale lengths of the order a few electron skin depth, e.g., [34]. In the electron MHD model of such current layers, reconnection is facilitated by electron inertia which breaks the frozen-in condition. The simulations demonstrate the instability of the whistler-like mode which presumably plays the role of the ion-cyclotron instability in the SHTCL model.

Future models of flares should join global and local properties of reconnection under coronal conditions. For example, chains of plasma instabilities, including kinetic instabilities, can be important for our understanding the types and regimes of plasma turbulence inside the collisionless current layers with a longitudinal magnetic field. In particular it is necessary to evaluate better the anomalous resistivity and selective heating of particles in such a SHTCL. Heat conduction is also anomalous in the superhot plasma. However the effect of collisional relaxation of heat fluxes (e.g., [35]) from SHTCL should be taken into account and presumably better describes heat transfer in flares than the classic Fourier law and the anomalous heat conduction [36].

Self-consistent solutions of the reconnection problem will allow us to explain the energy release in flares, including the open question of the mechanism or combination of mechanisms which explains the observed acceleration of electrons and ions to high energy. The problem of particle acceleration in the collapsing magnetic traps created by reconnection in the corona [37] is considered by taking into account the particle scattering and braking in the high-temperature plasma of solar flares [38]. The Coulomb collisions are shown to be weak in traps with life-times $\tau < 10$ s and strong for $\tau > 100$ s. For collisional times comparable to τ, the electron spectrum at energy above 10-20 keV is shown to be a double-power-law one. Such spectra in hard X-rays are often found by *RHESSI* in flares.

However note that the most sensitive tool to study behavior of the electron acceleration in the collapsing trap is radio-emission. At least, the simple gyrosynchrotron radio-emission has to be calculated for evolving electron distribution in a collapsing magnetic trap in order to understand how the magnetic trap and the particle distribution evolve [39]. Wave-particle interactions can presumably be important too; see Sec. 7.4.4 in [7]. Resonant scattering is likely to enhance the rate of precipitation of the trapped electrons with energy higher than 100 keV, generating microwave bursts.

The lose-cone instabilities of trapped mildly-relativistic electrons could provide excitation of waves with a very wide continuum spectrum. In a solar flare with a slowly-moving upward coronal HXR source, an ensemble of the collapsing field lines with accelerated electrons would presumably be observed as a slowly moving type IV burst with a very high brightness temperature and with a possibly significant time delay relative to the chromospheric footpoint emission. The second kind of wave-particle interactions in the collapsing trap-plus-precipitation model is the streaming instabilities (including the current instabilities related to a reverse current) associated with the precipitating electrons.

The reverse-current electric field results in an essential change of the fast electron behavior in the thick target. It leads to a quicker decrease of the fast-electron number with a column depth in comparison with the classical thick-target model. It makes the fast-electron distribution to be more isotropic and leads to a significant decrease of expected hard X-ray bremsstrahlung polarization; see Sec. 4.5 in [26]. Future models should incorporate such fine (or even subtle) effects like an initial nonuniform ionization of chromospheric plasma in the thick target, the time-of-flight effect etc.

with correct account taken of the reverse-current electric field as the effect of primary importance. Otherwise the accuracy of the existing models will be lower than the accuracy of new observations of solar flares in hard X-rays.

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References

[1] A. Hanslmeier, *The Sun and Space Weather* (Springer, Dordrecht, 2007), 315 pp.
[2] J. Lilensten (Ed.), *Space Weather* (Springer, Dordrecht, 2007), 330 pp.
[3] A.B. Severny, *Ann. Rev. Astron. Astrophys.* **2** 363 (1964).
[4] R.G. Giovanelli, *Mon. Not. Royal Astron. Soc.* **108** No. 2, 163 (1948).
[5] P.A. Sweet, *Nuovo Cimento Suppl.* **8**, *Serie* 10, 188 (1958).
[6] S.I. Syrovatskii, *Soviet Astronomy–AJ* **6** 768 (1962).
[7] B.V. Somov, *Plasma Astrophysics, Part II, Reconnection and Flares* (Springer Science + Business Media, LLC; New York, 2006a), 413 pp.
[8] J.J. Aly, 1991, *Astrophys. J.* **375** L61 (1991).
[9] S.I. Syrovatskii, *Soviet Physics–JETP* **23** 754 (1966).
[10] B.V. Somov, *Physical Processes in Solar Flares* (Kluwer Academic Publ., Dordrecht, 1992), 249 pp.
[11] V.S. Gorbachev and B.V. Somov, *Adv. Space Res.* **10**, No. 9, 105 (1990).
[12] C.J. Xiao, X.G. Wang, Z.Y. Pu, et al., *Nature Physics* **3** 609 (2007).
[13] V.S. Gorbachev, S.R. Kel'ner, B.V. Somov, et al., *Soviet Astronomy–AJ* **32** 308 (1988).
[14] B.V. Somov, *Astronomy Lett.* **34** 635 (2008a).
[15] B.V. Somov, *Asian Journal of Physics* **17** 445 (2008b).
[16] I.V. Oreshina and B.V. Somov, *Astronomy Lett.* **35** 207 (2009).
[17] B.V. Somov and S.I. Syrovatskii, *Soviet Physics–JETP* **34** 992 (1972).
[18] B.V. Somov, A.V. Oreshina, I.V. Oresina, and N.I. Shakura, 2003a, *Adv. Space Res.* **32** 1087 (2003).
[19] S.I. Syrovatskii, *Soviet Physics–JETP* **33** 933 (1971).
[20] H.E. Petschek, in *Proc. AAS-NASA Symposium on the Physics of Solar Flares*, NASA SP-50, p. 426 (1964).
[21] S.A. Markovskii and B.V. Somov, in *Solar Plasma Physics* (in Russian), Nauka, Moscow, p. 45 (1989).
[22] S.I. Bezrodnykh, V.I. Vlasov and B.V. Somov, *Astronomy Lett.* **37** 113 (2011).
[23] L.S. Ledentsov and B.V. Somov, *Astronomy Lett.* **37** 131 (2011).
[24] S.A. Markovskii and S.L. Skorokhodov, *J. Geophys. Res.* **105** 12,705 (2000).
[25] S.A.E.G. Falle and S.S. Komissarov, *J. Plasma Phys.* **65** 29 (2001).
[26] B.V. Somov, *Plasma Astrophysics, Part I, Fundamentals and Practice*, (Springer Science+Business Media, LLC; New York, 2006b), 437 pp.
[27] D. Biskamp, *Nonlinear Magnetohydrodynamics*, (Cambridge Univ. Press, Cambridge, 1997), 378 pp.

[28] J. Büchner, C.D. Tum and M. Scholer (Eds.), *Space Plasma Simulation*, (Springer-Verlag, Berlin, 2003), 351 pp.
[29] B.V. Somov, *Physics – Uspekhi* **53** 954 (2010).
[30] B.V. Somov, T. Kosugi, H.S. Hudson, et al., *Astrophys. J.* **579** 863 (2002).
[31] B.V. Somov, *Astronomy Lett.* **36** 514 (2010).
[32] A.V. Oreshina and B.V. Somov, *Astronomy Lett.* **35** 195 (2009).
[33] W. Liu, V. Petrosian, B.R. Dennis, et al., *Astrophys. J.* **676** 704 (2008).
[34] A. Zeiler, D. Biskamp, J.F. Drake, et al., *J. Geophys. Res.* **107** No. A9, p. SMP 6-1 (2002).
[35] V.E. Golant, A.P. Zhilinskii, I.E. Sakharov, I.E. *The Basis of Plasma Physics*, (Atomizdat, Moscow, 1977), 384 pp. (in Russian).
[36] A.V. Oreshina and B.V. Somov, *Moscow University Physics Bull.* **66** (2011).
[37] B.V. Somov and T. Kosugi, *Astrophys. J.* **485** 859 (1997).
[38] S.A. Bogachev and B.V. Somov, *Astronomy Lett.* **35** 57 (2009).
[39] Y. Li and G.D. Fleishman, *Astrophys. J.* **701** L52 (2009).