New Trends in the Physics of Solar Flares

Boris V. Somov
Solar Physics Department
Astronomical Institute
Moscow State University

10 minute review

ИКИ РАН 2014, February 10

New physical problems:

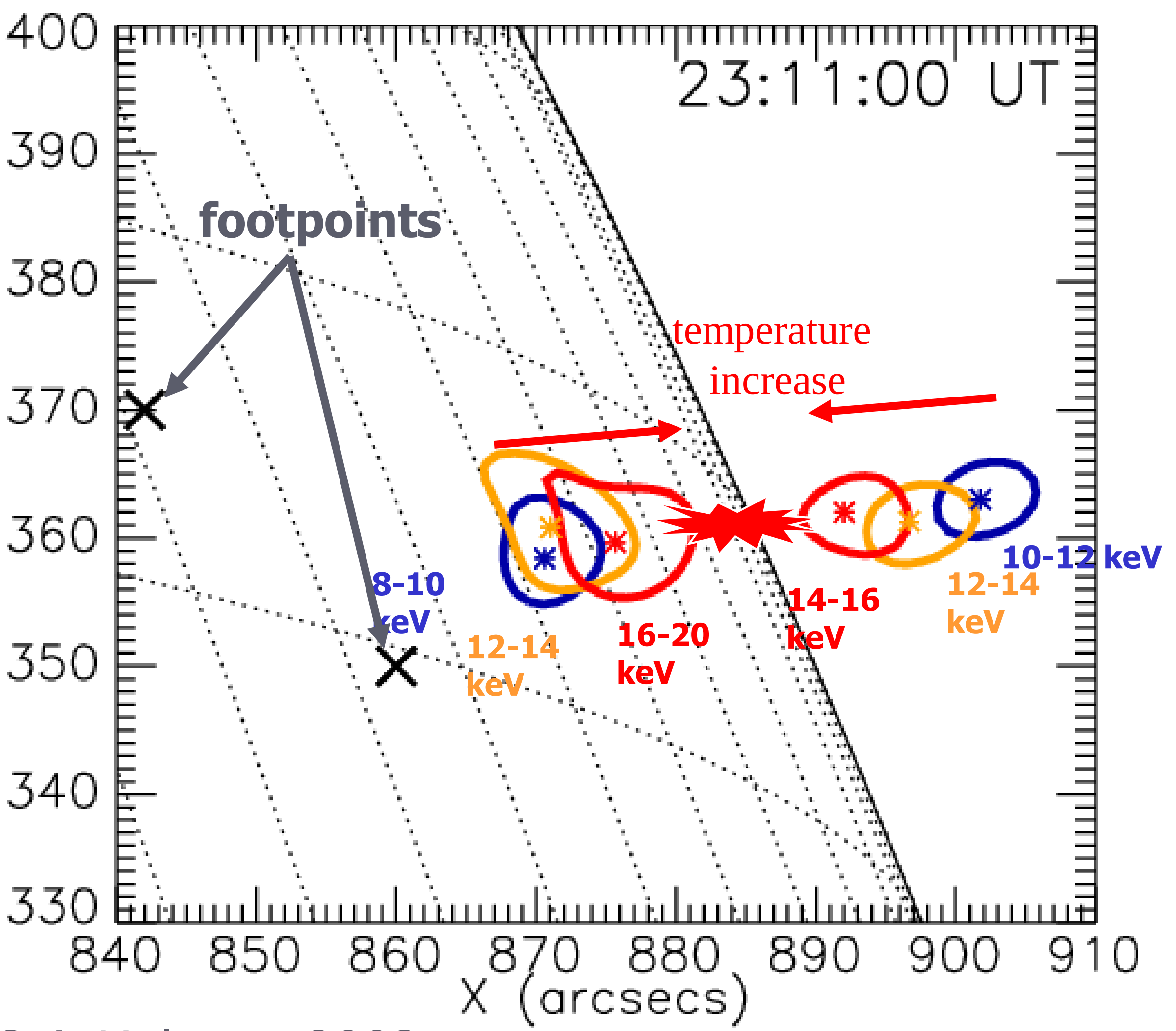
(a) Theoretical investigations addressed to future space experiments,

(b) Fundamental theoretical research related to observations, laboratory and numerical modeling of magnetic reconnection

Some new observational problems

- A) Observations of the primary energy release in solar flares
- B) Studies of electric currents in active regions (reconnection of currents)
- C) Observations related to the new methods of flare predictions

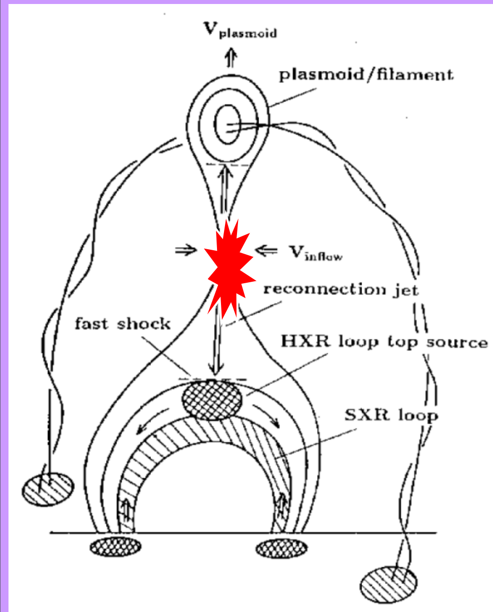
1. A) RHESSI: The first quantitative evidence of reconnection



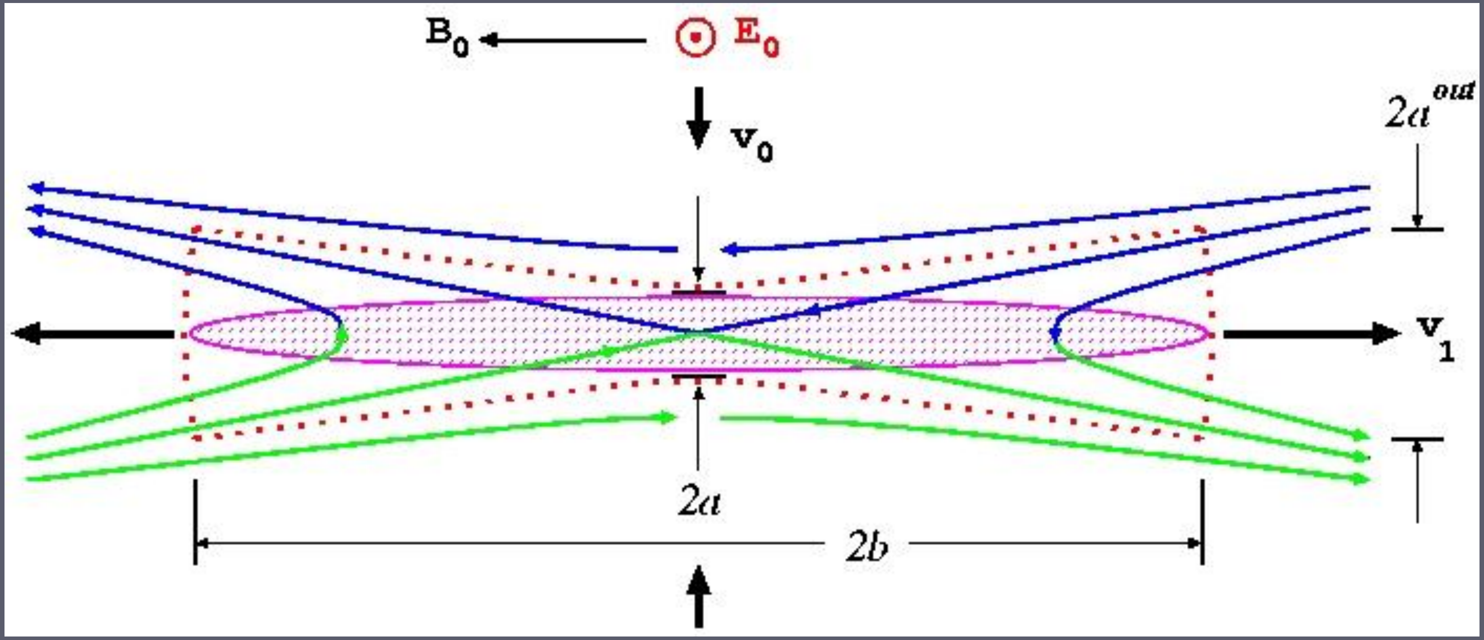
Sui, Holman, 2003

Thanks to S. Krucker

How can we observe the **super-hot turbulent-current layer** (**SHTCL**, Somov, 2013) ?



Super-Hot (T_e >/~ 100 MK) Turbulent-Current Layer (SHTCL)



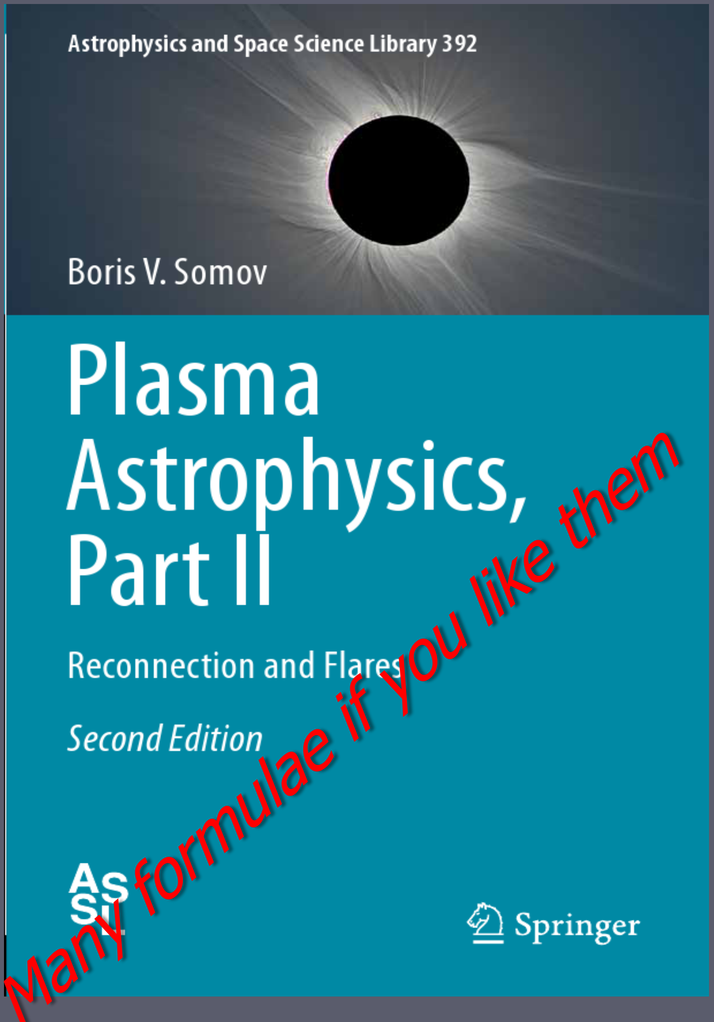
- Powerful heating of electrons results from wave-particle interactions

Somov, 2013,
Plasma Astrophysics, Part II, Reconnection and Flares,
Springer SBM, New York

What does follow from the theory?

Thermal and non-thermal HXR emissions from the corona can be interpreted involving a reconnecting super-hot turbulent-current layer as the source of flare energy

Somov, *Plasma Astrophysics, Part II, Reconnection and Flares*, *Second Edition*, Springer SBM, New York, 2013



What has to be understood?

Heat-transfer problem → Predictions for observations (Classical and relaxed heat conduction)

Проблема переноса тепла

В спокойном переходном слое между короной и хромосферой (вне вспышки)

применима обычная столкновительная теплопроводность.

Доклад

Птицына О.В., Сомов Б.В.,

«Течения плазмы в переходном слое…»

Reconnection creates flares

but

the specific properties of a SHTCL are important

~~Gold age of MHD~~

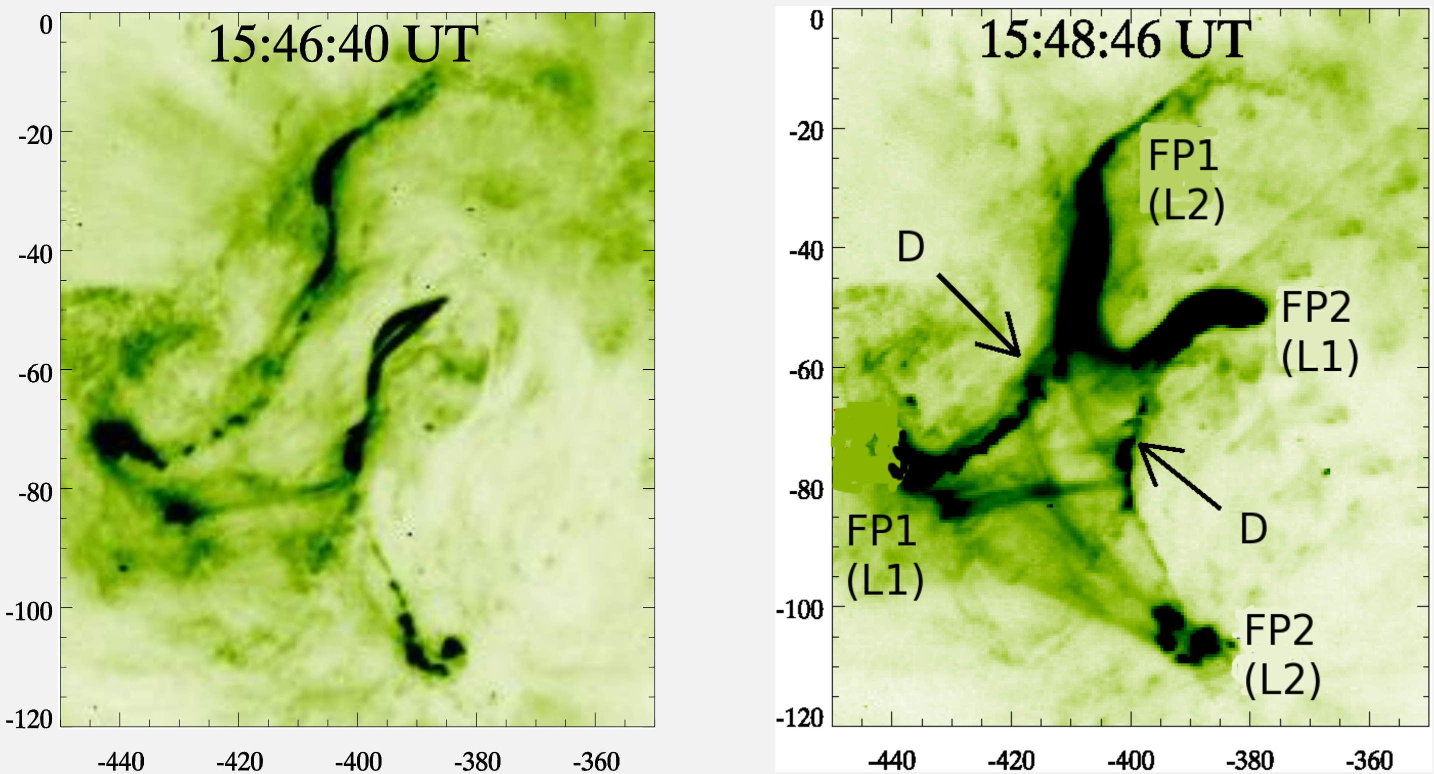
- Collisionless non-MHD reconnection with wave-particle interaction inside the SHTCL
- Particle acceleration in 3-component magnetic field plus electric field
- Non-classic heat transfer
- Reverse-current electric field

1. B) Studies of electric currents in active regions

* * *

Interaction and reconnection of currents

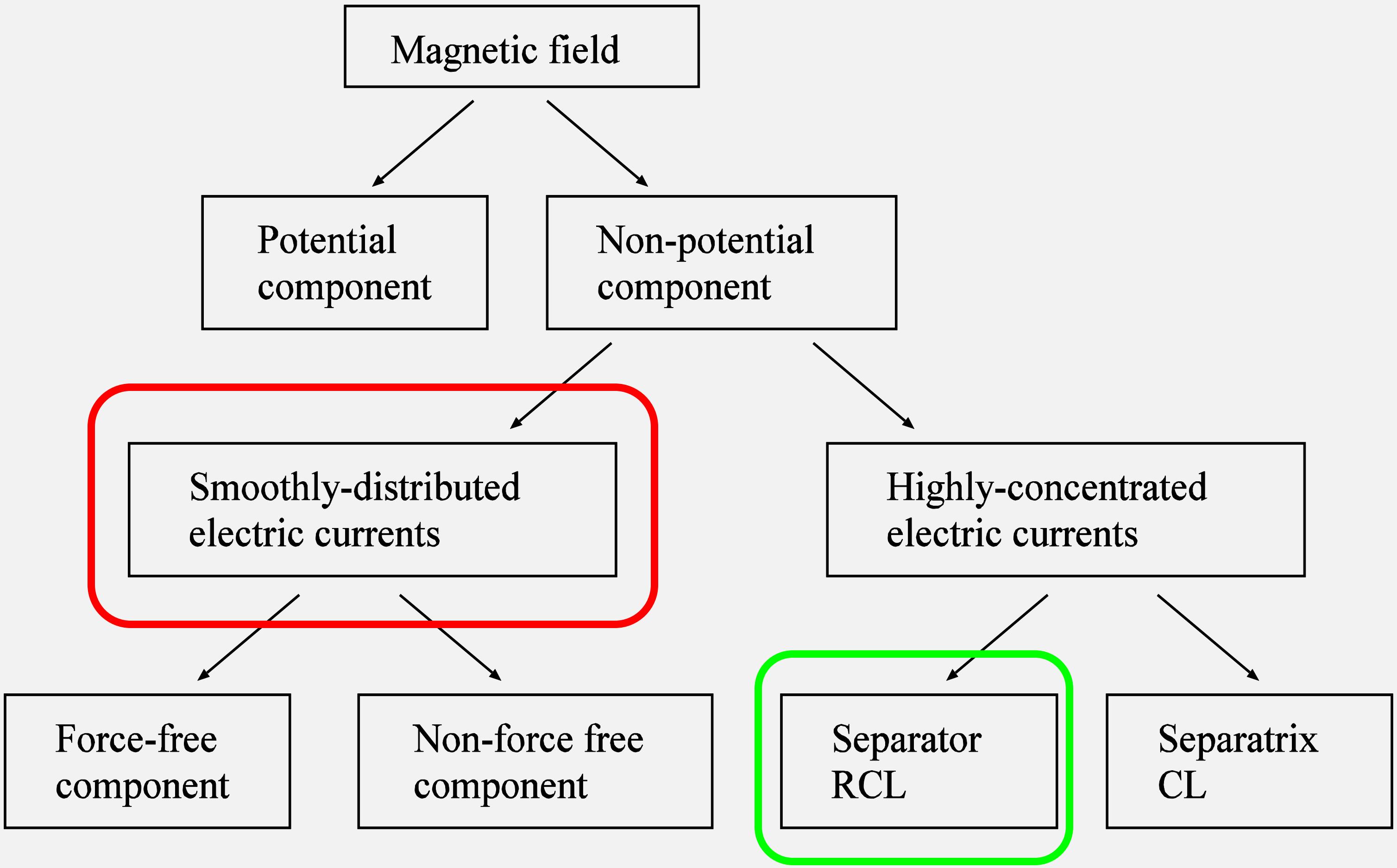
Interaction of two coronal loops in the M7.9/1N flare on 2006 April 27



TRACE 195 A images: Left panel – start of the flare, Right panel – max of the *GOES* soft X-ray flux. D is the thickness of an interaction region

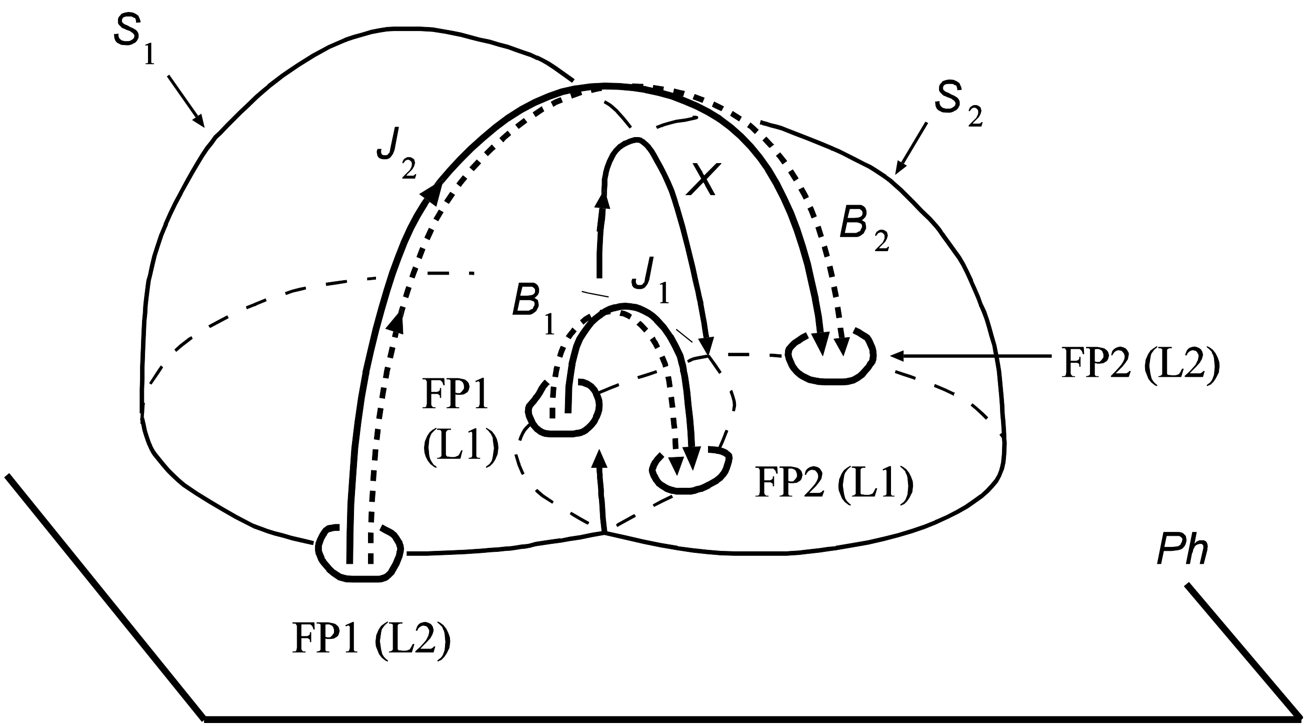
Kumar et al., 2010, ApJ **723**, 1651

Magnetic fields and electric currents in an AR, depending on their physical properties



What is a role of distributed currents in solar flares?

A couple of distributed currents J_1 and J_2 are involved in the classic topological model of a large-scale magnetic field

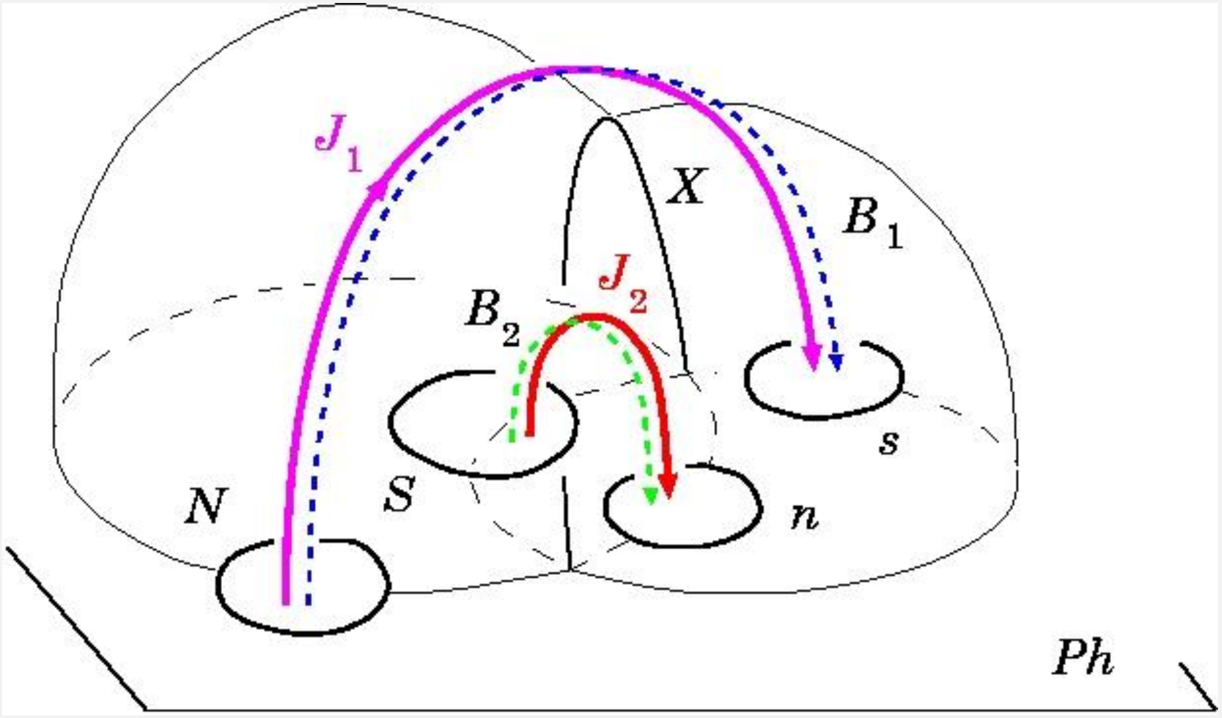


S_1 and S_2 – separatrices (domes), X – separator,

L_1 and L_2 – current-carrying magnetic-flux tubes.

How do the currents interact? How do they reconnect?

Reconnection of Electric Currents

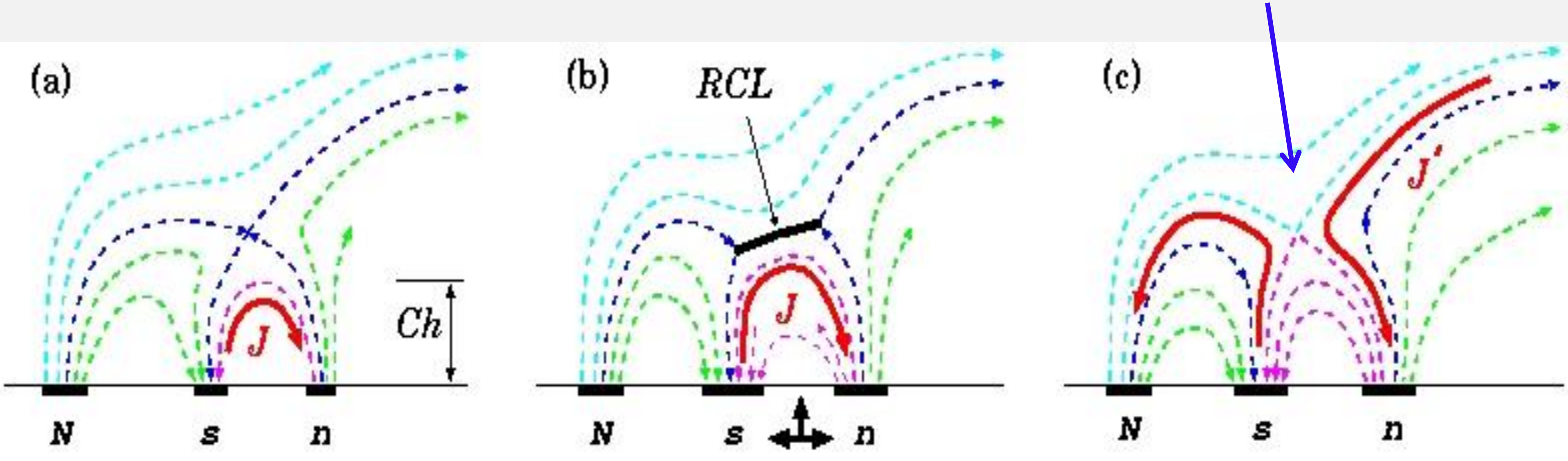


- In general, the reconnected currents are not equal among themselves
- Their topological disruption creates an electric field

Henoux and Somov, 1987, *Astron. Astrophys.*, 185, 306

Reconnection of an Electric Current

Topological disruption



- The initial state is mainly potential but contains a loop of new emerging flux with a current *J*
- The pre-reconnection (pre-flare) state with a *RCL*
- The final state after reconnection of magnetic field lines and field-aligned currents *J′*

Somov, *Plasma Astrophysics, Part II, Reconnection and Flares,*

Springer SBM, New York, 2013

Properties
of
reconnection of electric currents

- Reconnection changes the inductive energy of a current system and its inductive time scale
- A part of flare energy can be attributed to a change in the current pattern but not to a current dissipation

Сомов Б.В., О магнитном пересоединении электрических токов в солнечных вспышках, Письма в Астрон. журн., 38, 149, 2012

The M7/1N flare on 27 April 2006

- The mutual induction coefficient

$L_{12} \sim (1.2 - 3.4) \times 10^{10}$ cm

- The interaction energy of the coronal electric currents

$W_{12} \sim 1.6 \times 10^{31}$ erg

$J_1 \sim J_2 \sim 10^{11}$ Ampere

- the distributed currents do contribute significant energy to the flare, they should be observable in the photospheric magnetic field changes .

May these changes be seen by HMI/SDO ?

1. C) Observations related to the new methods in flare predictions

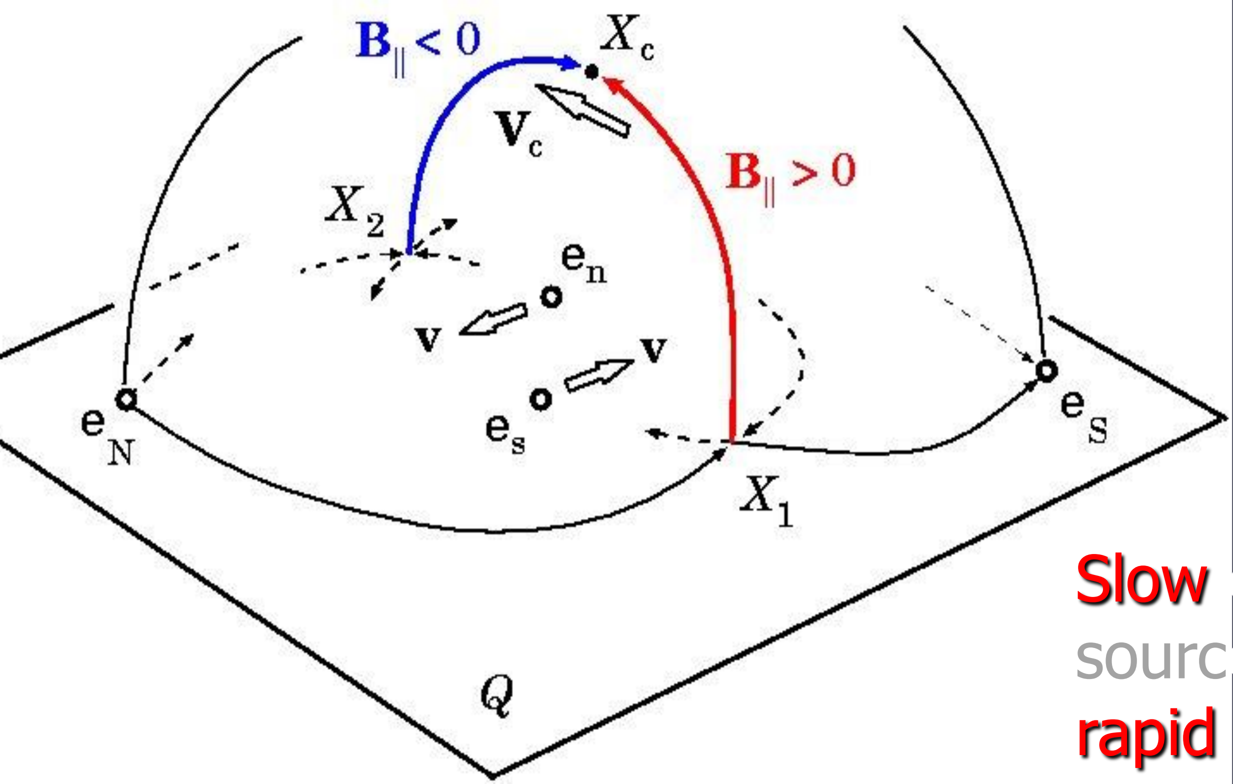
Topological Trigger of Large Eruptive Solar Flares

Somov, Astronomy Lett., 2008, **34**, 635
Somov, Asian Journal of Physics, 2008, **17**, 421
Oreshina I.V., Somov B.V., Astronomy Lett., 2009, **35**, 207

Barnes, ApJ, 670, L53, 2007

The presence of a coronal null is an indication that an active region is more likely to produce an eruptive event

Topological Trigger



Slow evolution of magnetic sources leads to a rapid change of the coronal field topology

Coronal null X_c quickly moves along the separator and switches back the longitudinal field

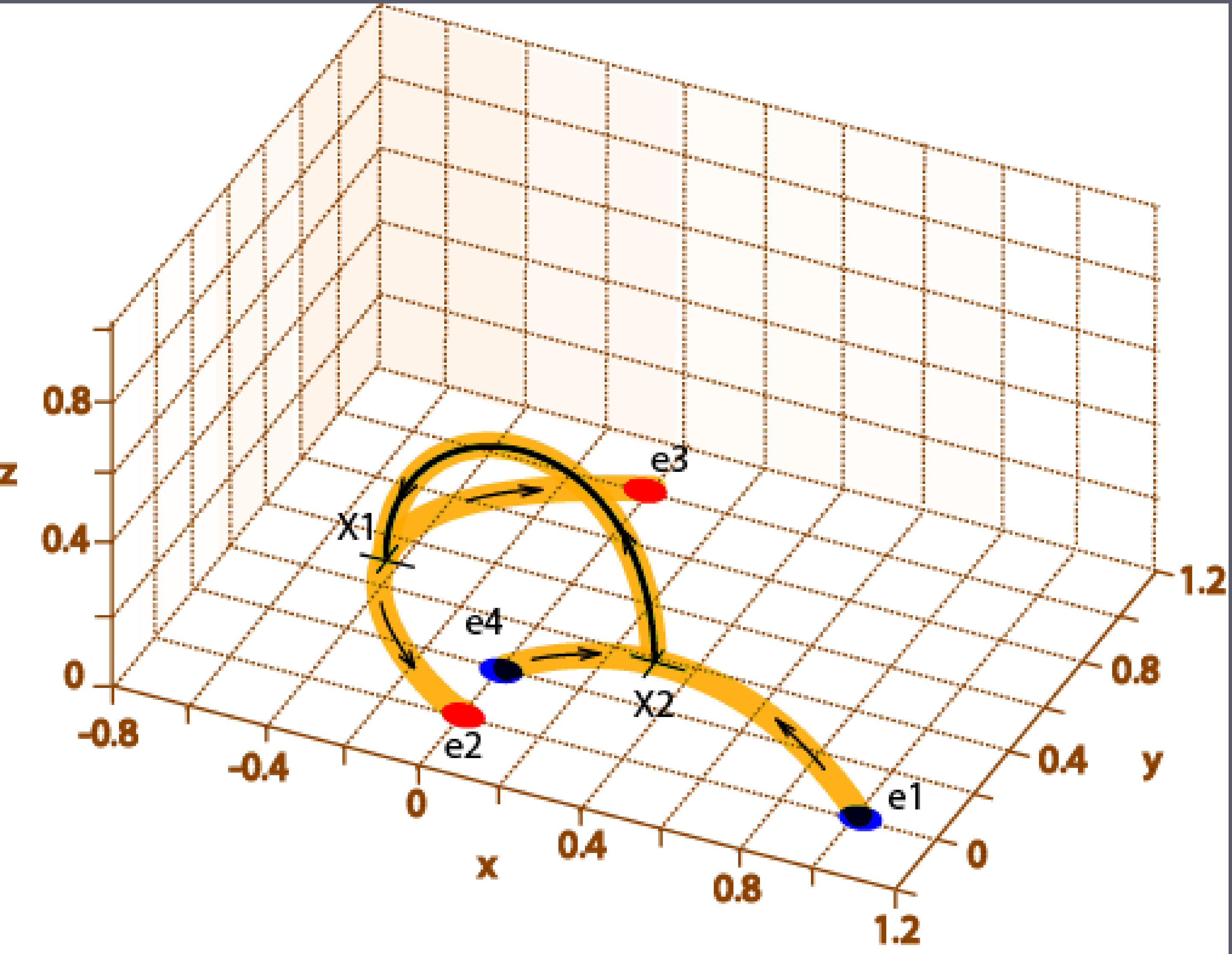
Reconnection and Topological Trigger

- Reconnection changes a topology of field lines *(step by step)* but conserves the global topology of the field in an active region
- Topological trigger is a **quick rearrangement** of **global topology**

Topological trigger

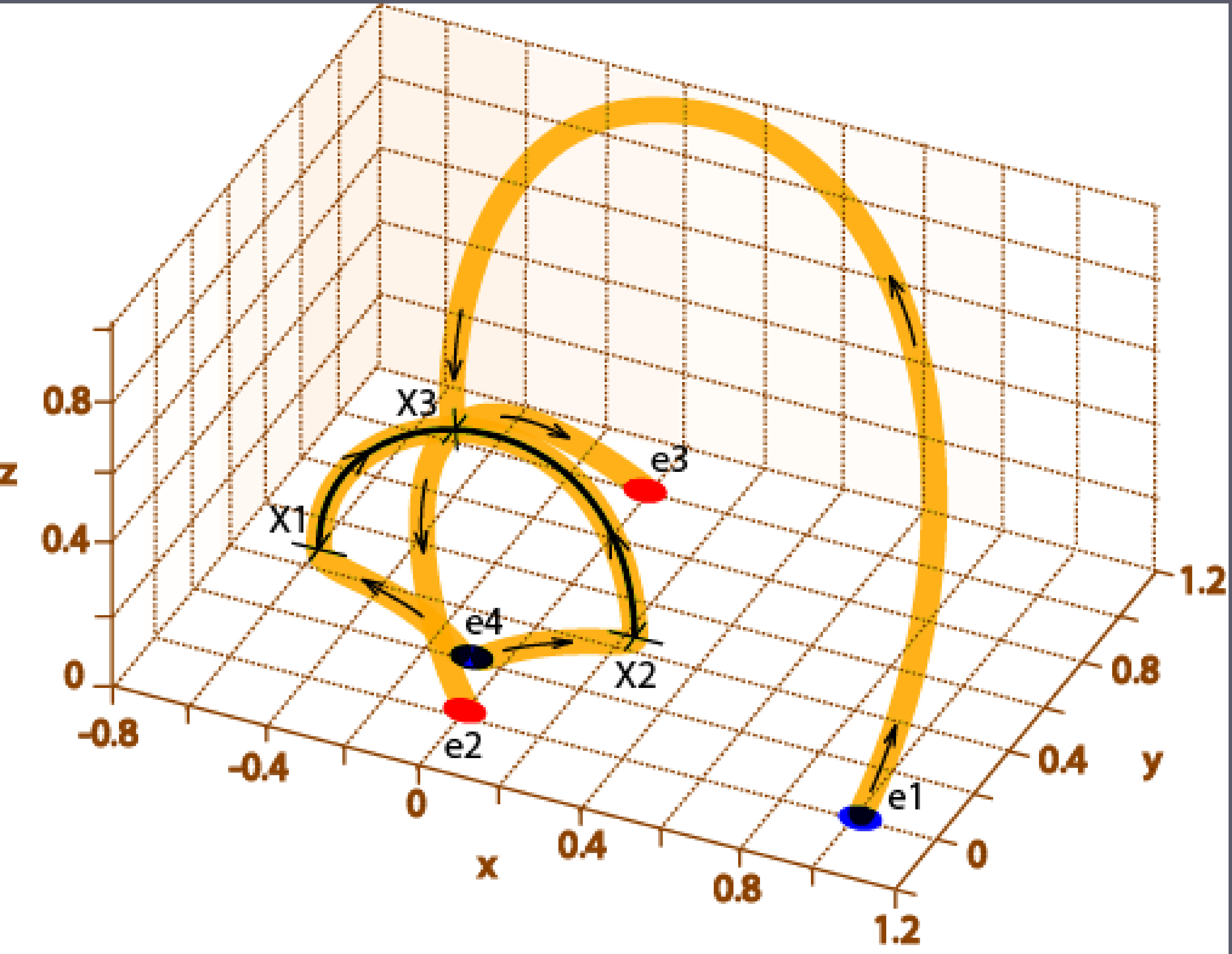
Reconnection in action

Structure of magnetic field in the corona before a trigger



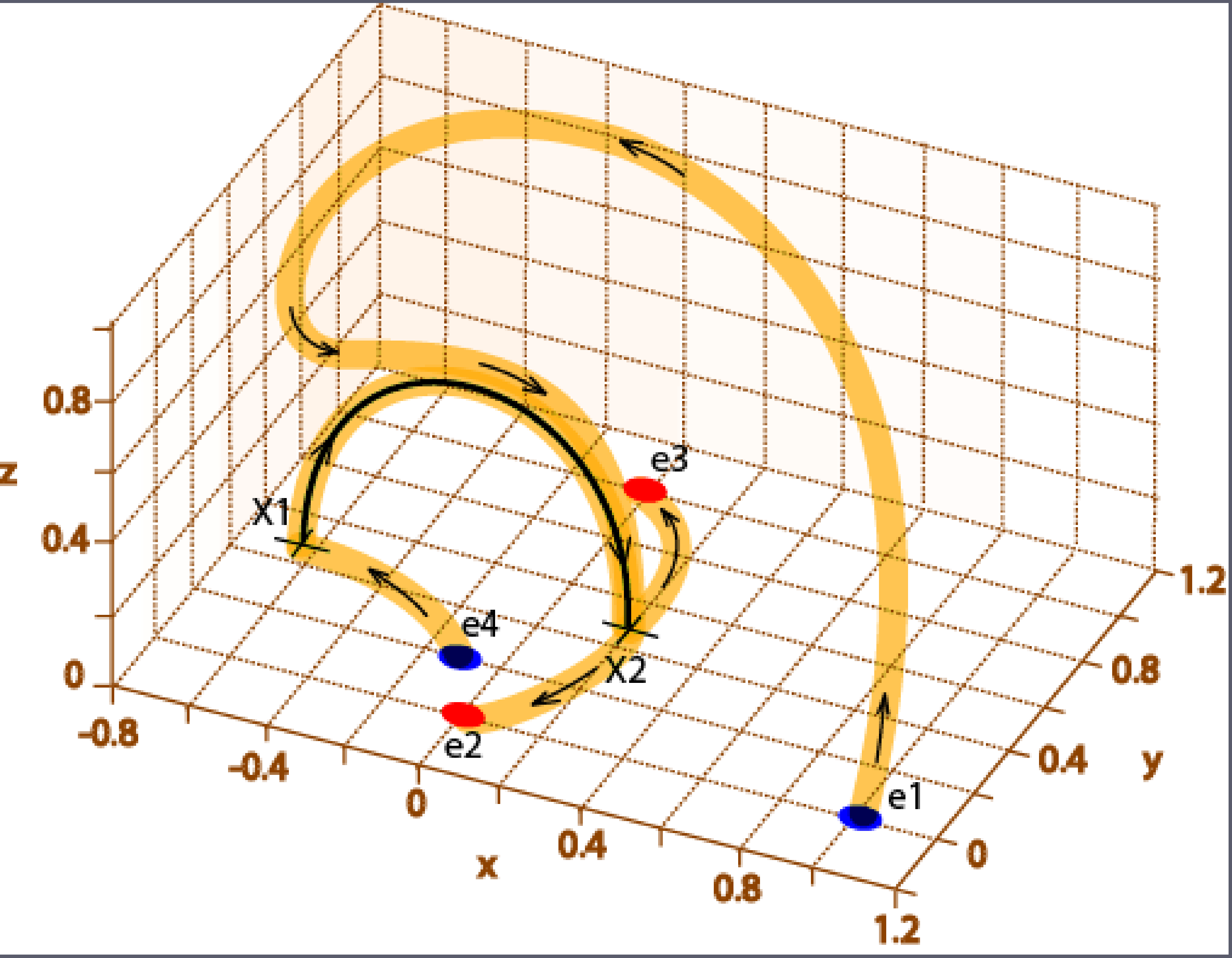
$\lambda_z(X1) < 0$
$\lambda_z(X2) > 0$

Change of the magnetic field structure in the beginning of trigger



$\lambda_z(X1) > 0$
$\lambda_z(X2) > 0$

Final stage of trigger



$\lambda_z(X1) < 0$

$\lambda_z(X2) < 0$

Criterion for the existence of magnetic null at the separator in the corona

$$I_{sep} = \text{sign}\ (\lambda_z (X_1) \cdot \lambda_z (X_2)) > 0,$$

where X_1 и X_2 are the null points at the separator footpoints.

Oreshina I., Somov, Astronomy Lett., **35**, 207, 2009

The Topologically Critical State
of coronal magnetic fields
has to found before a flare
by using photospheric magnetograms

- Even minor changes in the magnetic-source characteristics can lead to drastic changes in the topology of large-scale magnetic field.

- AR NOAA 10501 on 2003 November 18 was very close to the Topologically Critical State at 08:00 UT.

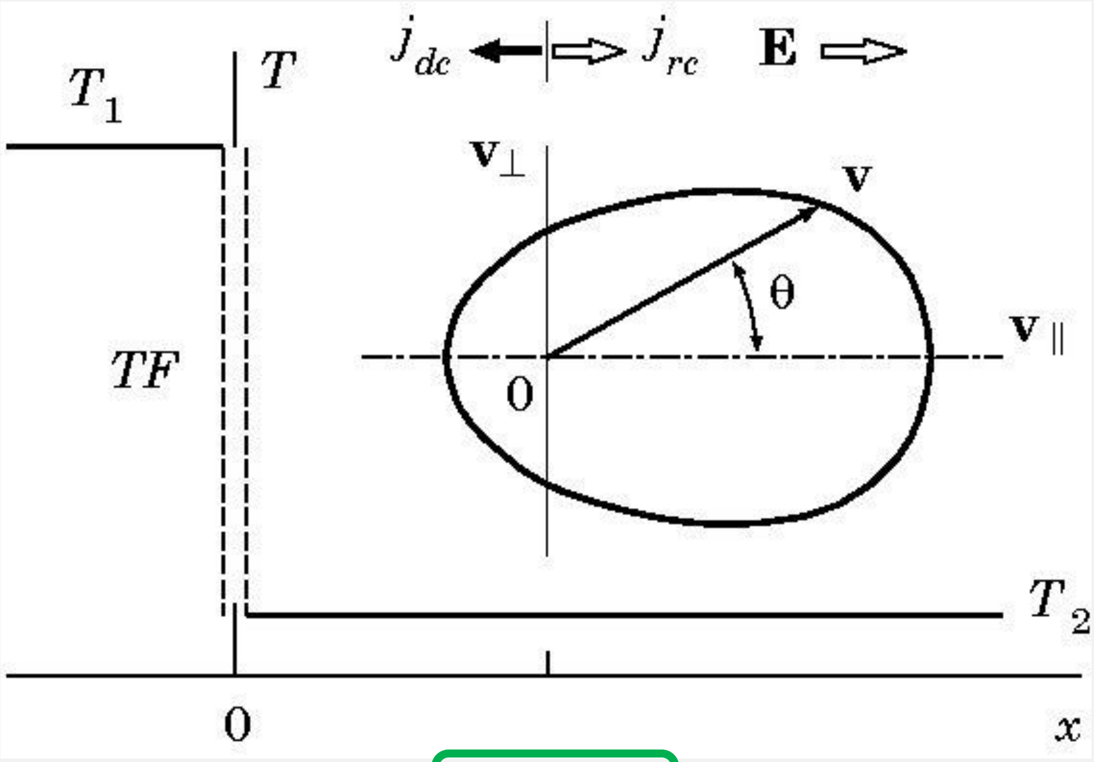
Somov, 2013,
Plasma Astrophysics, Part II, Reconnection and Flares,
Springer SBM, New York

Какова наиболее типичная геометрия
3D магнитного пересоединения ?
См.
стендовый доклад 23,
Думин Ю.В., Сомов Б.В.

2. New physical problems:

A) To future space experiments

The accurate quantitative model of propagation of accelerated electrons in solar flares



D + 2D

The kinetic equation takes into account Coulomb collisions of the accelerated electrons with thermal electrons and protons in the corona and chromosphere.
The electric field of a reverse current determines the beam dynamics.

Somov, Gritsyk, 2012, Moscow Univ. Physics Bull., 67, 102

См.
Стендовый доклад 32
Грицык П.А., Сомов Б.В.,
«Моделирование
коронального источника…»

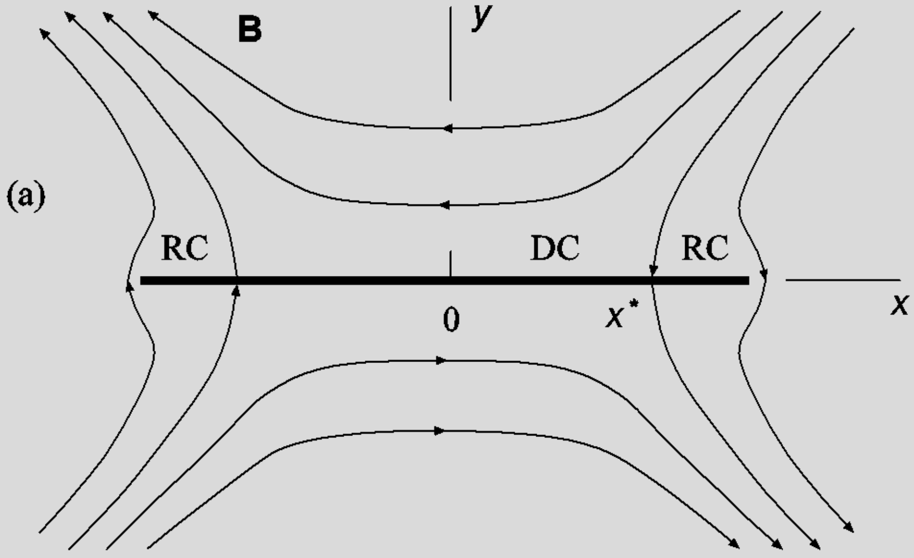
2. B) Fundamental theoretical research related to numerical and laboratory experiments on reconnection

New Analytical Models of Magnetic Reconnection

Bezrodnykh, Vlasov, Somov, Astronomy Lett. 37, 113, 2011.

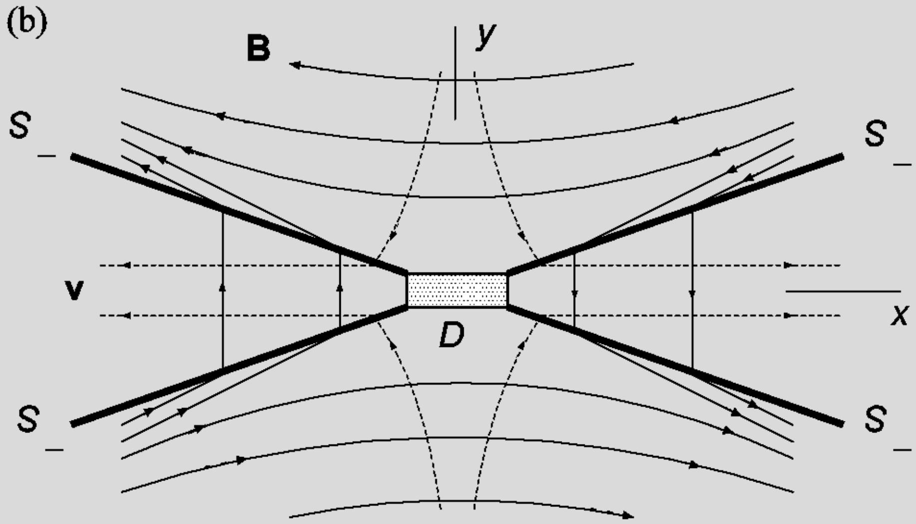
Ledentsov, Somov, Astrophys. Space Sci. Proc. 30, 117, 2012

Two classic models of reconnection



Current layer by Syrovatskii:

direct current (DC) and return currents (RC) inside thin current layer



Petschek Flow:

compact diffusion region *D* and 4 attached MHD slow shock waves of infinite length

Динамическая роль обратного тока в физике неравновесных магнитосфер компактных релятивистских объектов.

См.
Стендовый доклад 33

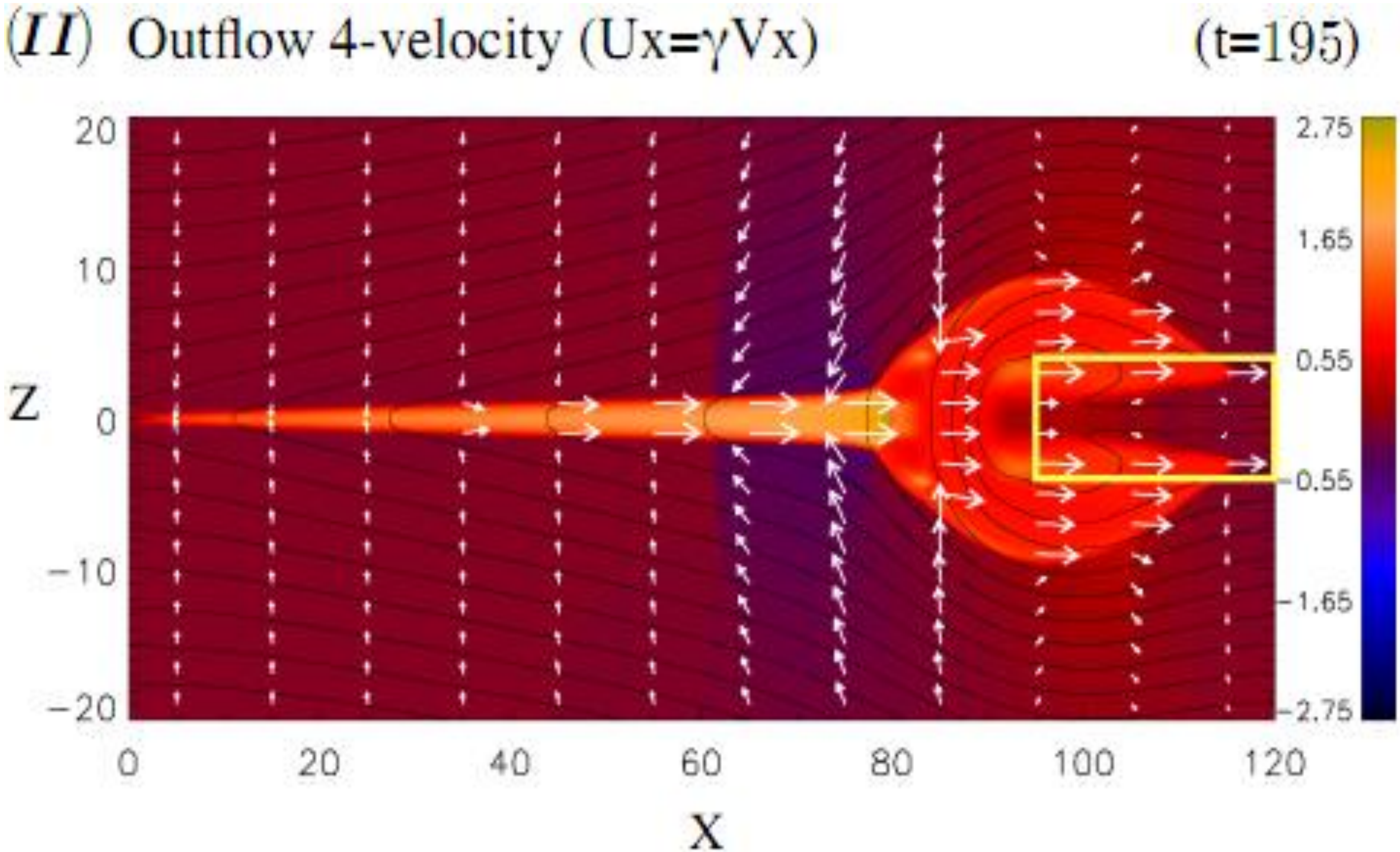
Безродных С.И., Сомов Б.В.

Resistive MHD Simulations of Reconnection

Zenitani, Hesse, Klimas, 2010,

ApJ Letters, 11/10/09

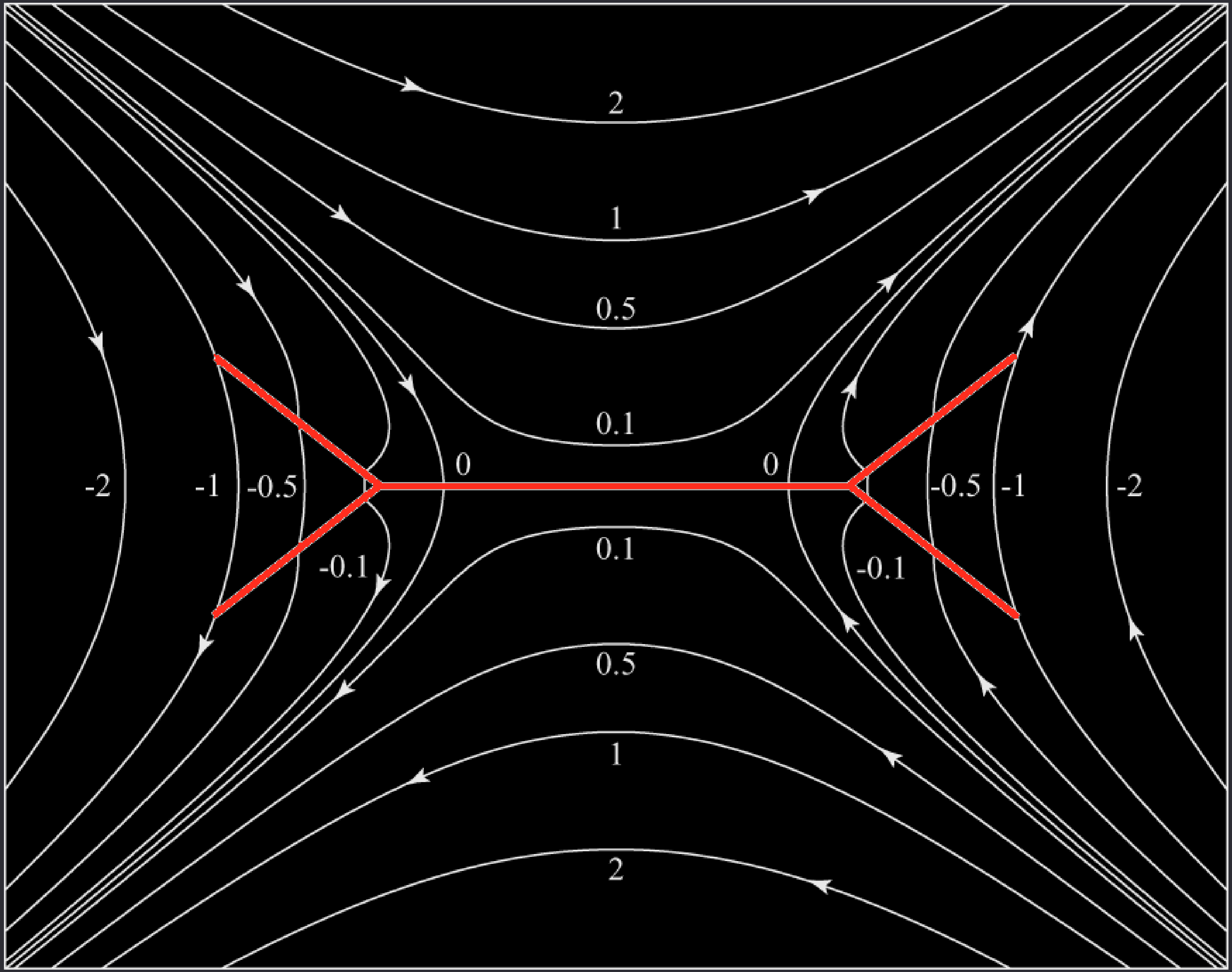
Reconnection of open magnetic field lines



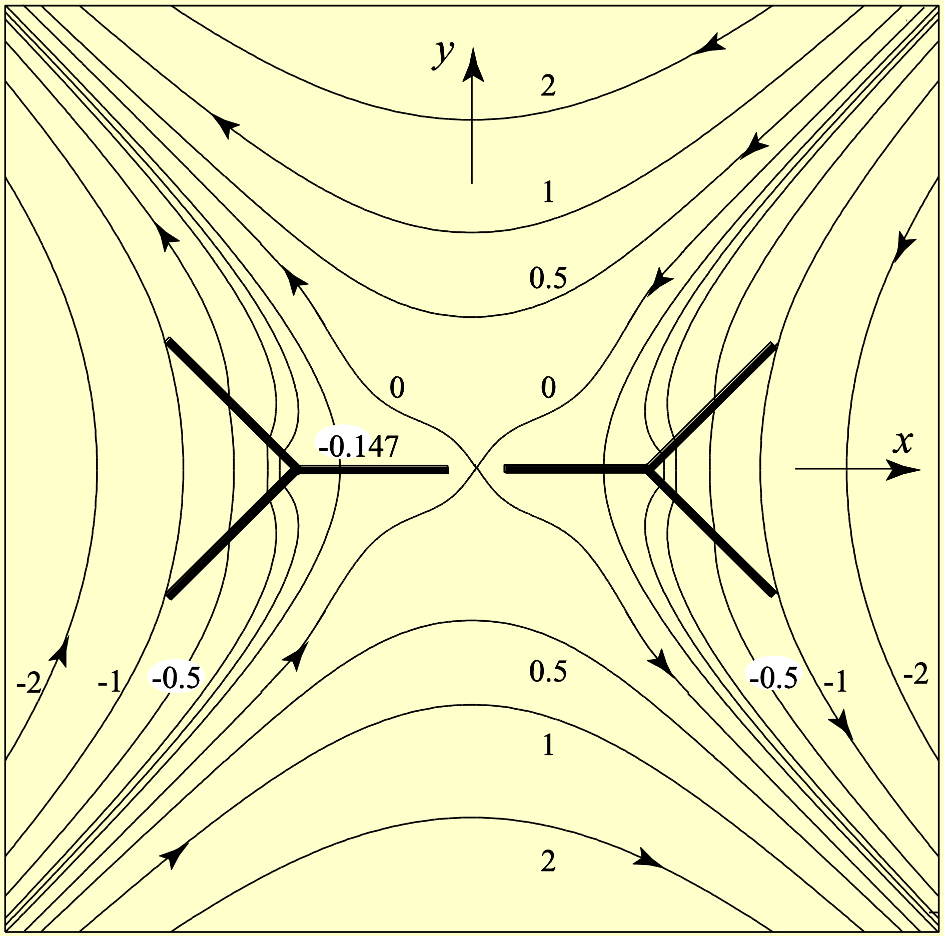
Our new analytical solution

- Thin current layer of the Syrovatskii type with attached discontinuous MHD flows of finite length
- A character of flows is not prescribed but determined from a self-consistent solution
- Global structure of magnetic field and local properties of the field near current layer and discontinuities have been investigated

Bezrodnykh, Vlasov, Somov,
Astronomy Lett. 37, 113, 2011;
Astrophys. Space Sci. Proc., 30, 133, 2012



Magnetic field lines



Generalized analytical model

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

Bezrodnykh, Vlasov, Somov, Astronomy Lett. 37, 113, 2011

The MHD approximation of a strong magnetic field is very good in reproducing the large-scale structures in the corona, its flows and density:

$$\Delta A = 0\,, \quad \frac{d\mathbf{v}}{dt} \times \nabla A = 0\,, \quad \frac{dA}{dt} = 0\,, \quad \frac{\partial \rho}{\partial t} + \operatorname{div} \rho\mathbf{v} = 0\,.$$

Here the scalar function $A(x, y, t)$: $\mathbf{A} = \{\,0,\ 0,\ A\,(x, y, t)\,\}$ for the field $\mathbf{B} = \operatorname{rot}\mathbf{A}$.

Система уравнений в частных производных сводится к системе обыкновенных дифференциальных уравнений

Доклад

Колесников Н.П., Безродных С.И., Сомов Б.В.,

Течения плазмы вблизи пересоединяющего токового слоя:

приближение сильного поля.

(14 февраля, 11.45)


Winter Sun
Thanks for Your Attension