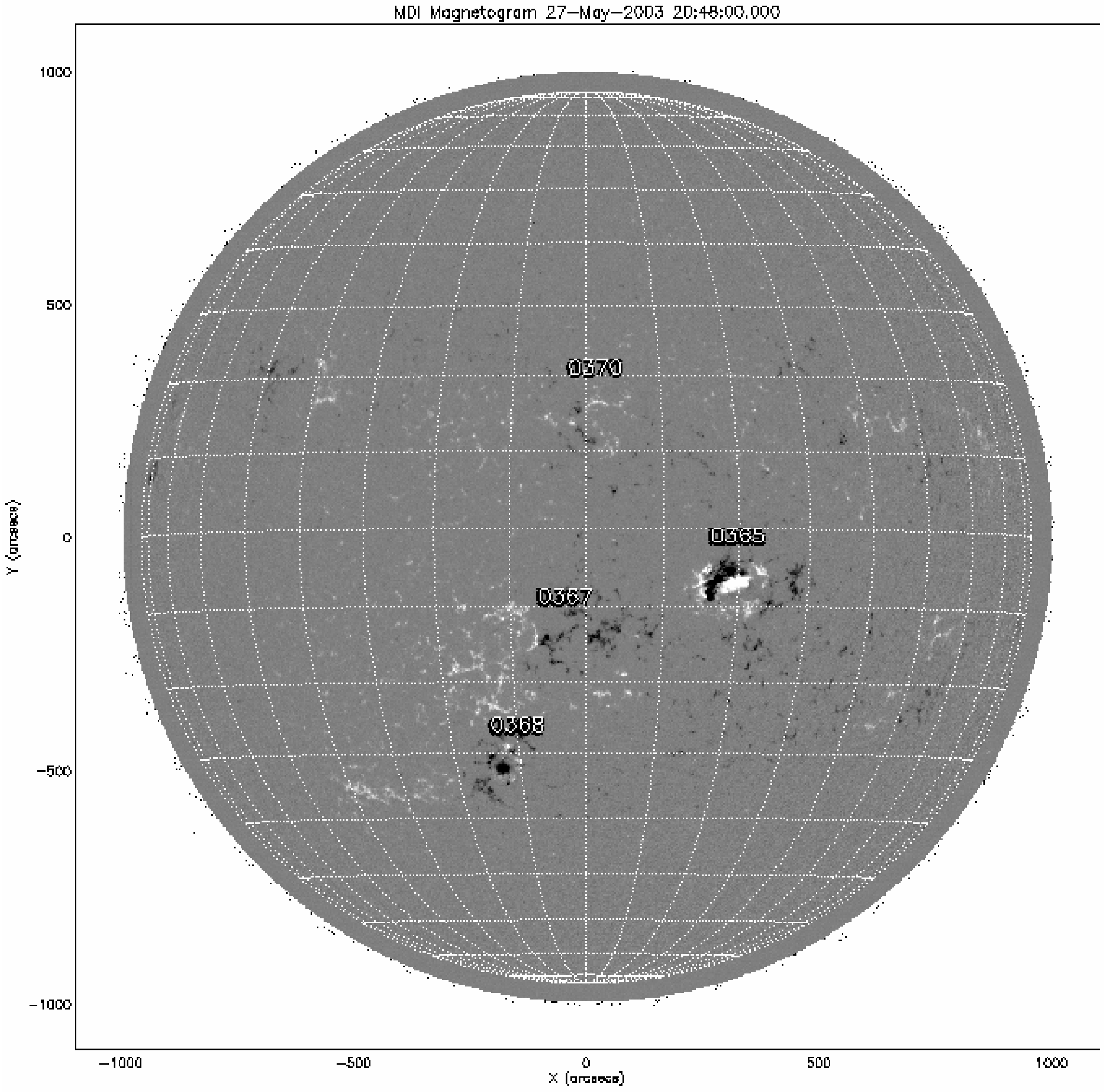
Sources of solar flare X-ray - MHD simulations and comparison with observation

A. I. Podgorny[1] and I. M. Podgorny[2]

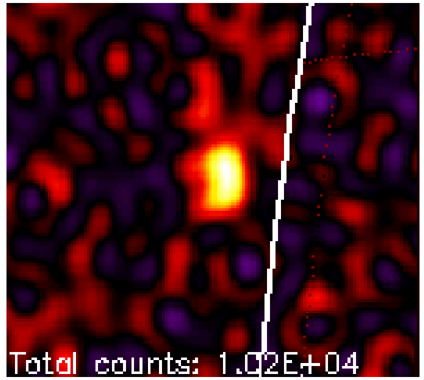
[1]Lebedev Physical Institute RAS, Moscow, podgorny@lebedev.ru
[2]Institute for Astronomy RAS, Moscow, podgorny@inasan.ru

The primordial energy release takes place in the solar corona above an active region at the height 15 - 30 thousands kilometers. Flare energy accumulation can occur in the current sheet magnetic field created by disturbances focusing in the vicinity of an X-type singular line. Majority of others solar flare mechanisms are based on assumption of a magnetic rope appearance in the corona. To define what mechanism is responsible for solar flare, the 3D MHD simulations are done in the solar corona without any assumptions about the flare physics. The initial and boundary conditions are taken from observations of a real active region before the flare. The main goal of MHD simulation in the solar corona is finding-out of the physical mechanism of solar flare. The simulation shows that the current sheet appears in the preflare state in the corona above an active region. The electrodynamical model of the solar flare based on current sheet mechanism, which explains main flare manifestations, is proposed. The positions of sources of X-ray radiation can be found from magnetic field configuration obtained by MHD simulation. According to the solar flare electrodynamical model the position of thermal X-ray is situated in the current sheet, and positions of nonthermal hard X-rays are places of crossing of photosphere with the magnetic lines, which are going out of the current sheet. The graphical system is developing, which can find these positions of sources of X-ray radiation.

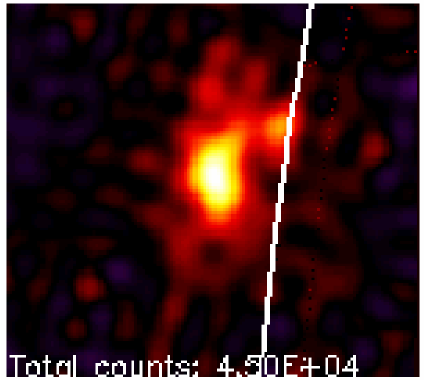
SOLAR FLARE OCCURS IN THE SOLAR CORONA ON HEIGHTS 15 - 30 THOUSANDS KILOMETERS, WHICH IS 1/40 – 1/20 OF SOLAR RADIUS.

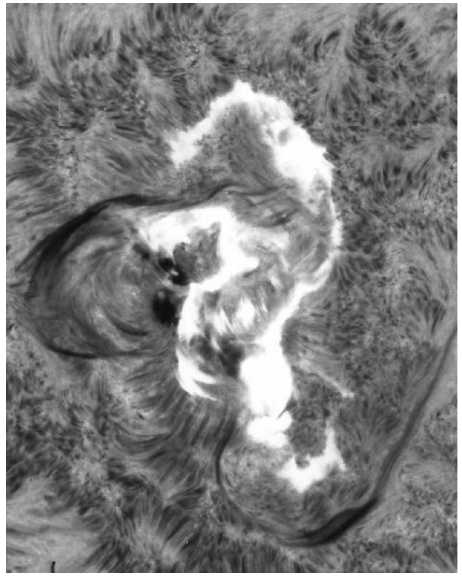


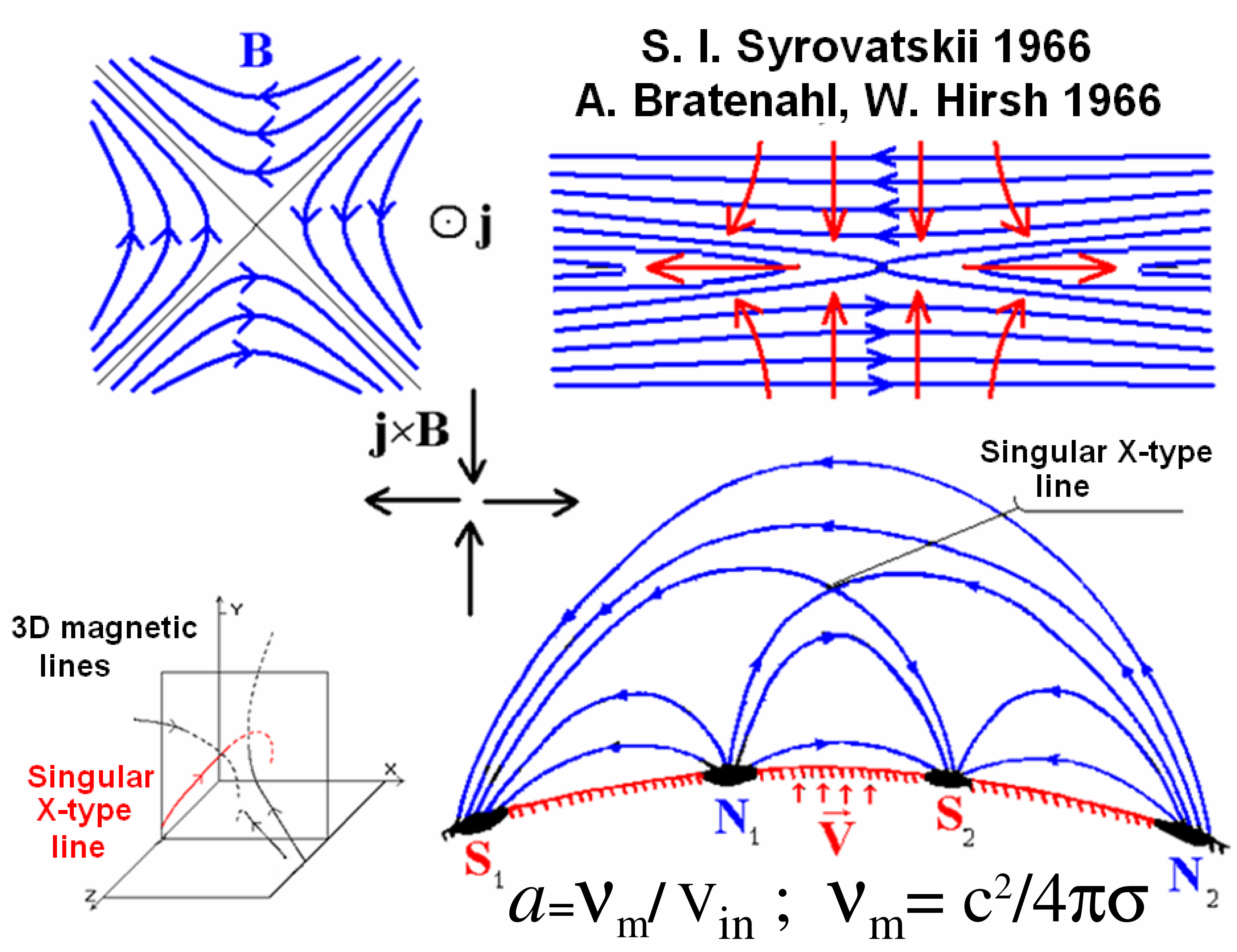
3 - 6 кэВ



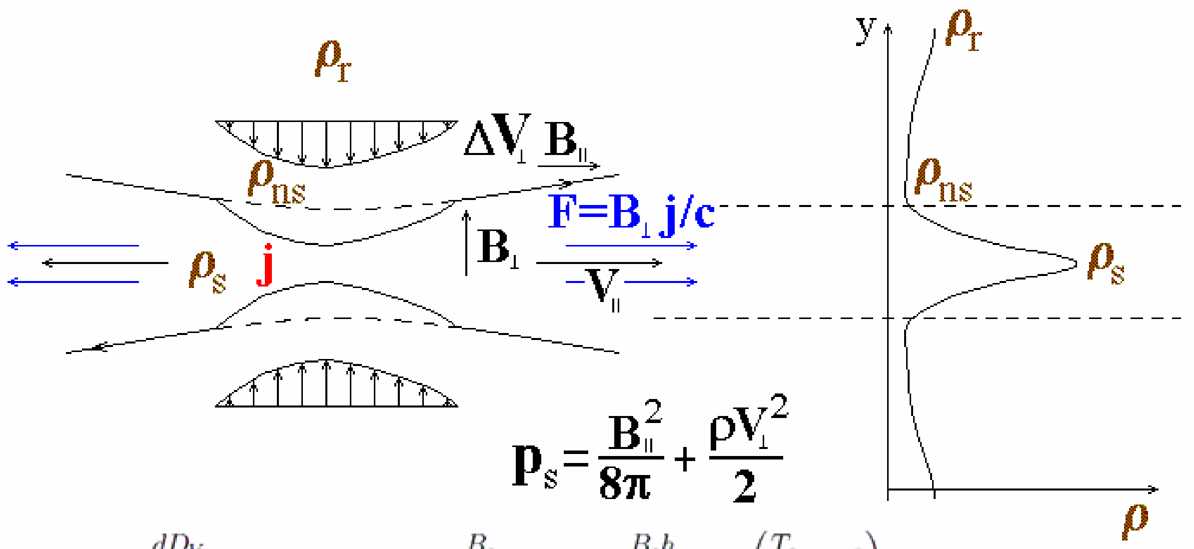
12 - 25 кэВ






S. I. Syrovatskii 1966
A. Bratenahl, W. Hirsh 1966
B
⊙j
j×B
Singular X-type line
3D magnetic lines
Y
X
Z
Singular X-type line
S1
N1
V
S2
N2
a=νm/ Vin ; νm= c2/4πσ

CURRENT SHEET INSTABILITY



$$p_s = \frac{B_{\parallel}^2}{8\pi} + \frac{\rho V_{\perp}^2}{2}$$

$$\begin{aligned}
\rho_s \frac{dD_V}{dt} &= -D_V A \rho_s + D_B \frac{B_s}{4\pi a} + V_{in1} K_I \frac{B_s h}{4\pi \nu_m} + \rho_1 \left(\frac{T_s}{b_1^2} - A^2 \right) \\
\rho_{ns} \frac{dV_{in1}}{dt} &= V_{in1} K_V \frac{\rho_{ns} V_{in0}}{a} - \rho_1 K_p \frac{T_s}{a} - D_B \frac{B_s}{4\pi} \\
\frac{d\rho_1}{dt} &= -\rho_1 A - D_V \rho_s + V_{in1} \frac{\rho_{ns}}{a} \\
\frac{dD_B}{dt} &= -2 D_V h - D_B \left(A + \frac{\nu_m}{b_1^2} + \frac{\nu_m}{a^2} \right) + V_{in1} \frac{B_s}{b_1^2} K_B
\end{aligned}$$

MAXIMAL INCREMENT OF CURRENT SHEET INSTABILITY:

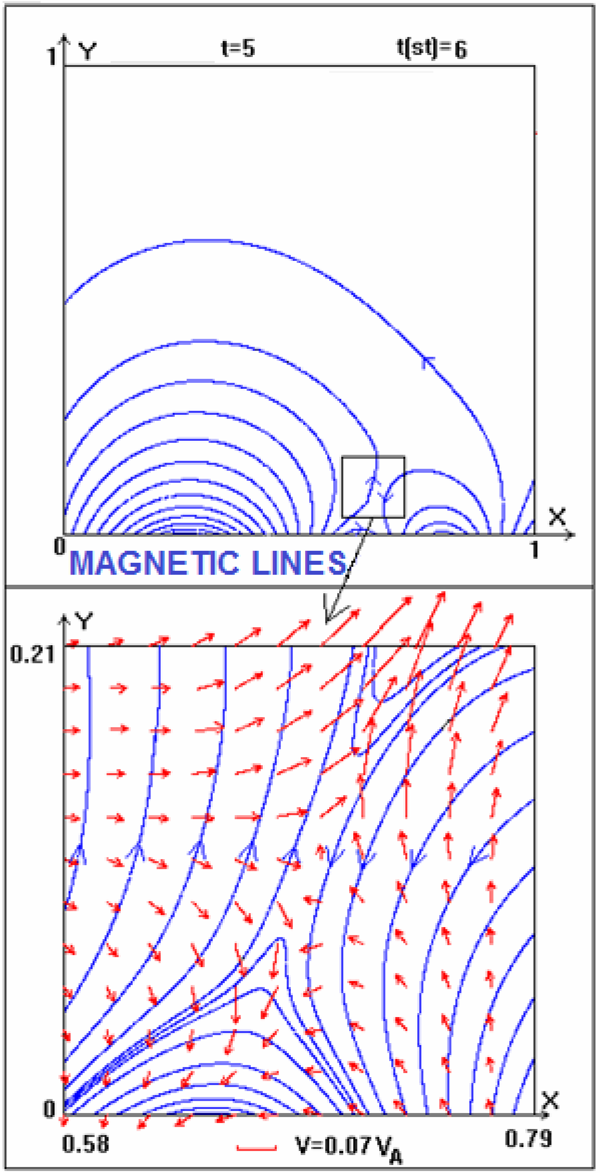
$$\gamma_{max} = \frac{1}{2}\mathrm{Re}_m^{-1}\varepsilon_v^{-2} + \sqrt{\left(\frac{1}{2}\mathrm{Re}_m^{-1}\varepsilon_v^{-2}\frac{\rho_r}{\rho_{ns}}\right)^2 + K_B \mathrm{Re}_m^{-1}\varepsilon_v^{-2}\left(\frac{\rho_r}{\rho_s}\right)^{1/2} - 2\frac{\rho_r}{\rho_s}} - \sqrt{\frac{\rho_r}{\rho_s}}$$

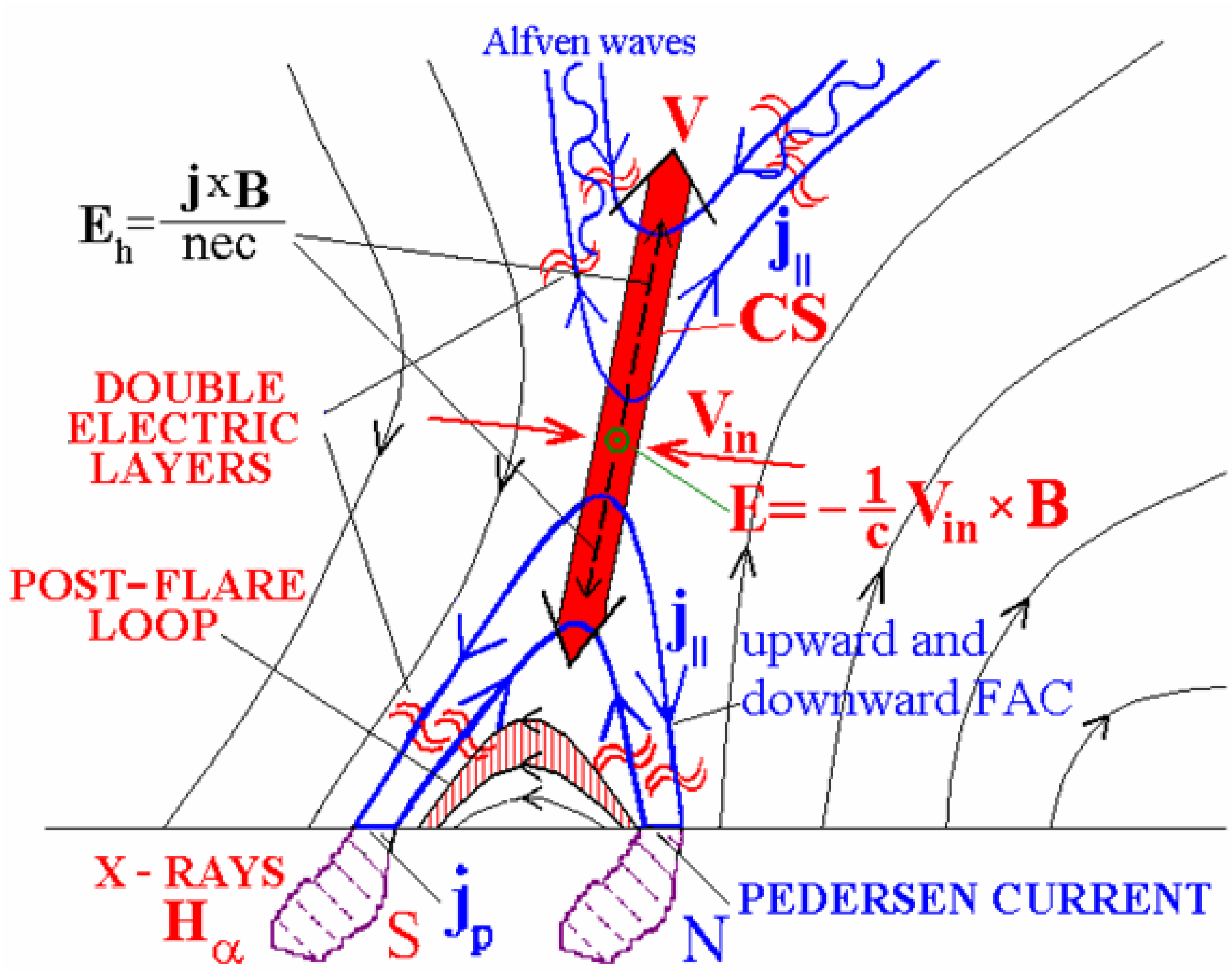
CONDITION OF CURRENT SHEET INSTABILITY $\gamma_{max} > 0$ HAVE A FORM:

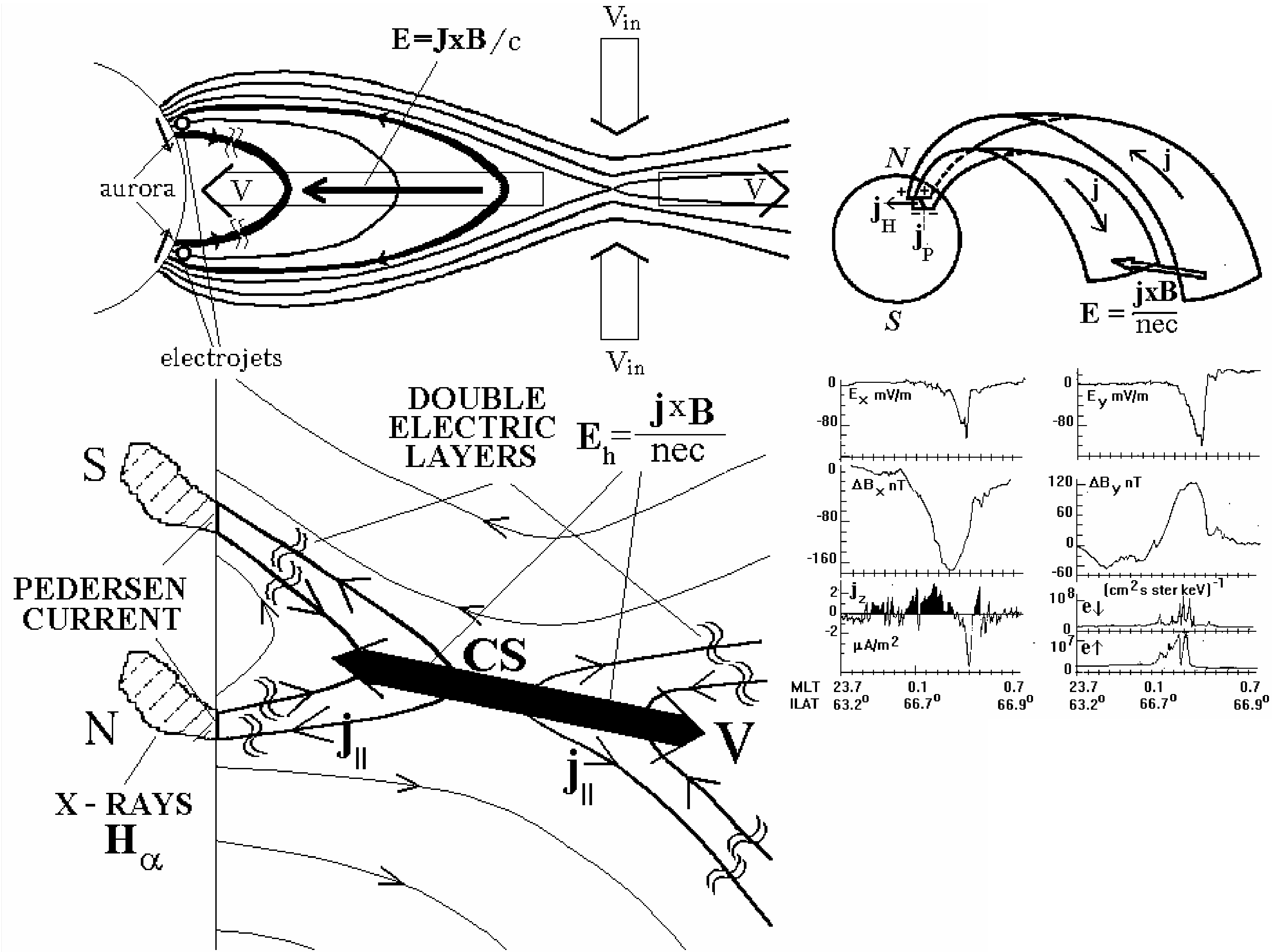
$$\varepsilon_v^2 \mathrm{Re}_m \sqrt{\frac{\rho_r}{\rho_s}} \frac{\rho_{ns}}{\rho_r} \frac{1}{K_B} < \frac{1}{2} \qquad (K_B \lesssim 1)$$

Electrodynamic model of solar flare

Igor M. Podgorny using results of measurements on the satellite Intercosmos-Bulgaria-1300

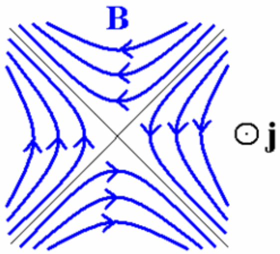


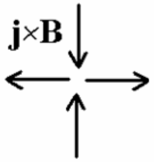


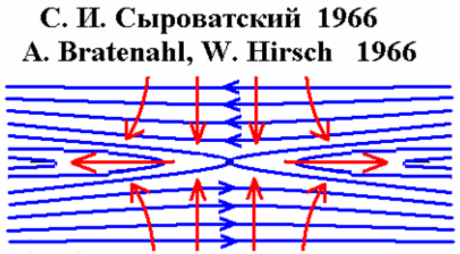


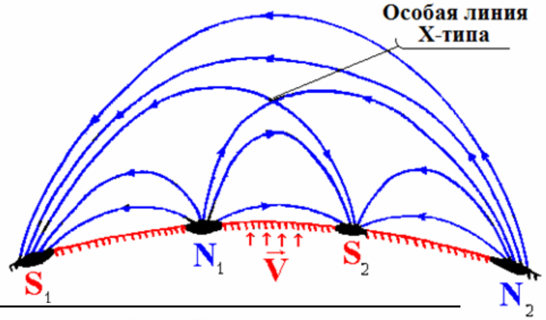
E=JxB/c
V_in
aurora
V
V
V_in
electrojets
N
j
j
j_H
j_P
S
E = jxB/nec
DOUBLE
ELECTRIC
LAYERS
E_h = jxB/nec
S
PEDERSEN
CURRENT
CS
N
j_||
j_||
V
X - RAYS
H_α
0
E_x mV/m
-80
0
E_y mV/m
-80
0
ΔB_x nT
-80
-160
120
ΔB_y nT
60
0
-60
2
j_z
0
-2
μA/m^2
10^8
(cm^2 s ster keV)^-1
e↓
0
10^7
e↑
0
MLT 23.7 0.1 0.7
ILAT 63.2° 66.7° 66.9°
23.7 0.1 0.7
63.2° 66.7° 66.9°

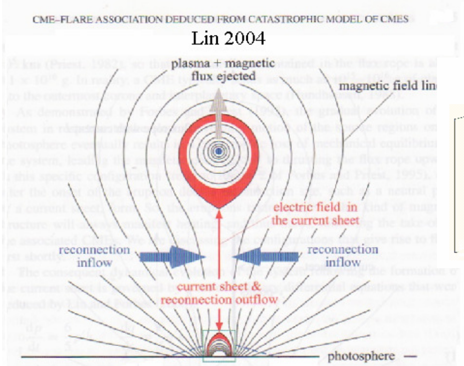
Flare meshanizms

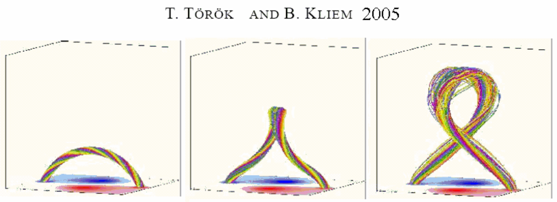


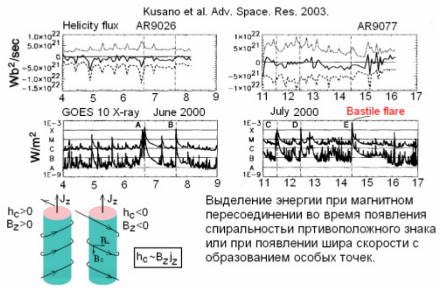


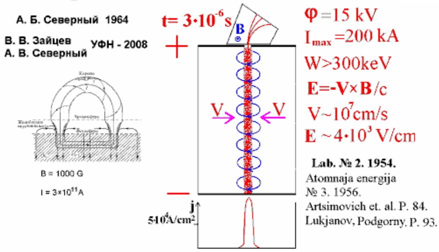




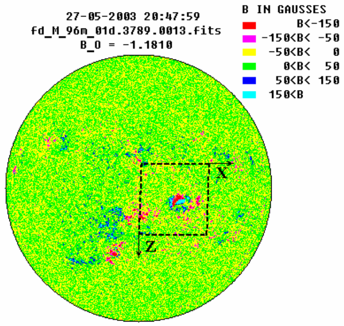


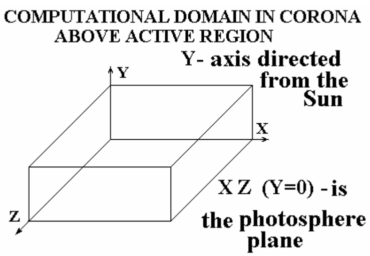






Now our aim is: To find solar flare mechanism directly by MHD simulation in real active region.



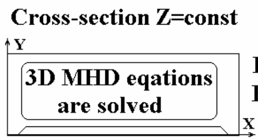


Photospheric boundary:

$B_{\parallel}$ from calculated potential field for observed $B_{\text{line-of-site}}$

$B_{\perp}$ from $\text{div}\mathbf{B} = 0$;

$\rho = \text{const}$; $\partial V/\partial n=0$; $\partial T/\partial n=0$



Nonphotospheric boundary:

$B_{\perp}$ from $\text{div}\mathbf{B} = 0$

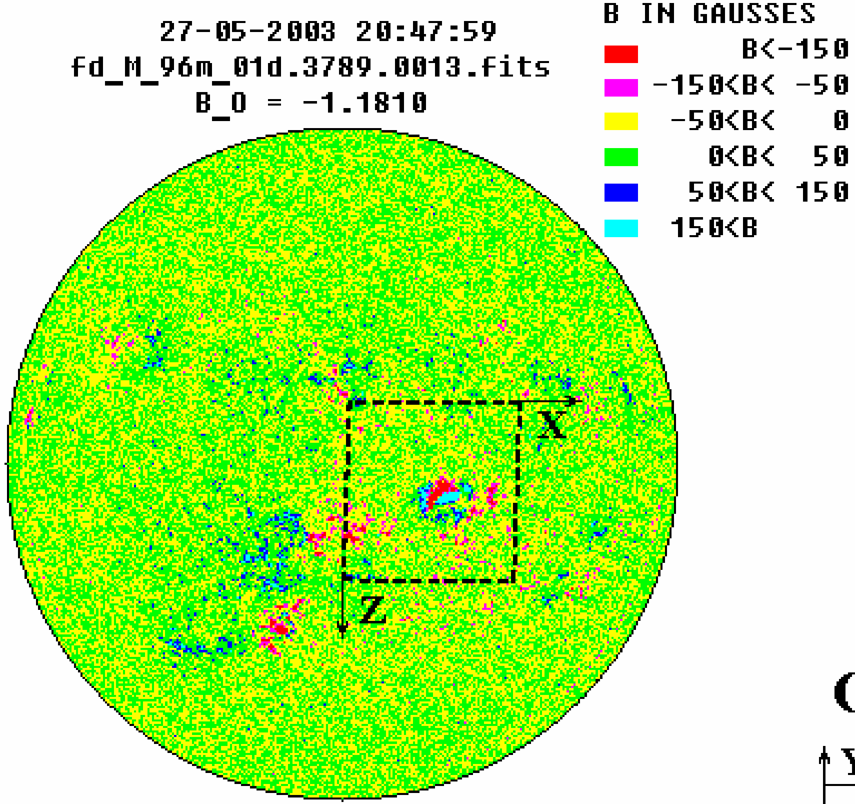
$B_{\parallel}$ from $\partial j/\partial n=0$

$\partial \rho/\partial n=0$

$\partial V/\partial n=0$

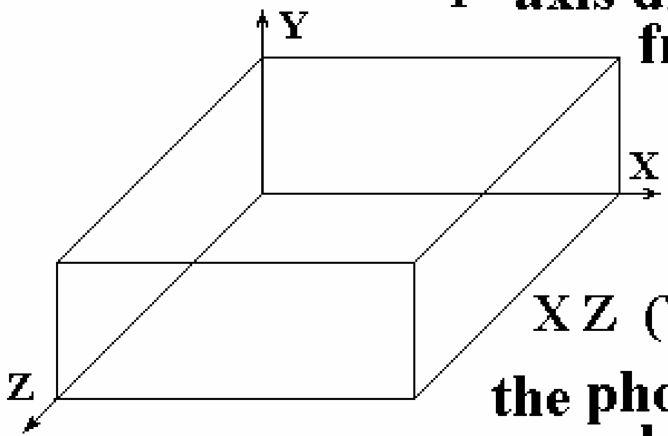
$\partial T/\partial n=0$

Earlier: Hypothesized the mechanism of the solar flare, which is then tested.



--- REGION IN PICTURE PLANE

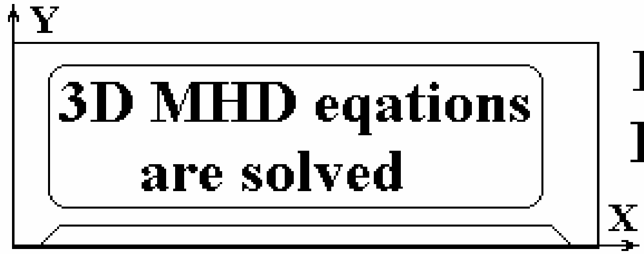
COMPUTATIONAL DOMAIN IN CORONA ABOVE ACTIVE REGION



Y- axis directed from the Sun

X Z (Y=0) - is the photosphere plane

Cross-section Z=const



Nonphotospheric boundary:

$\mathbf{B}_\perp$ from div$\mathbf{B} = 0$

$\mathbf{B}_\parallel$ from $\partial j/\partial n=0$

$\partial \rho/\partial n=0$

$\partial V/\partial n=0$

$\partial T/\partial n=0$

Photospheric boundary:

$\mathbf{B}_\parallel$ from calculated potential field for observed $\mathbf{B}_{\text{line-of-site}}$

$\mathbf{B}_\perp$ from div$\mathbf{B} = 0$; $\rho = \text{const}$; $\partial V/\partial n=0$; $\partial T/\partial n=0$

The numerical 3D simulation in corona above active region. The system of MHD equations for compressible plasma with dissipative terms and anisotropy of thermal conductivity is solved.

$$\frac{\partial \mathbf{B}}{\partial t} = \mathrm{rot}(\mathbf{V}\times\mathbf{B}) - \frac{1}{\mathrm{Re}_m}\mathrm{rot}\left(\frac{\sigma_0}{\sigma}\mathrm{rot}\mathbf{B}\right)$$

$$\frac{\partial \rho}{\partial t} = -\mathrm{div}(\mathbf{V}\rho)$$

$$\frac{\partial \mathbf{V}}{\partial t} = -(\mathbf{V},\nabla)\mathbf{V} - \frac{\beta}{2\rho}\nabla(\rho T) - \frac{1}{\rho}(\mathbf{B}\times\mathrm{rot}\mathbf{B}) + \frac{1}{\mathrm{Re}\rho}\Delta\mathbf{V} + G_g\mathbf{G}$$

$$\frac{\partial T}{\partial t} = -(\mathbf{V},\nabla)T - (\gamma-1)T\mathrm{div}\mathbf{V} + (\gamma-1)\frac{2\sigma_0}{\mathrm{Re}_m\sigma\beta\rho}(\mathrm{rot}\mathbf{B})^2 - (\gamma-1)G_q\rho L'(T) +$$
$$+\frac{\gamma-1}{\rho}\mathrm{div}\left(\mathbf{e}_\parallel\kappa_{dl}(\mathbf{e}_\parallel,\nabla T) + \mathbf{e}_{\perp 1}\kappa_{\perp dl}(\mathbf{e}_{\perp 1},\nabla T) + \mathbf{e}_{\perp 2}\kappa_{\perp dl}(\mathbf{e}_{\perp 2},\nabla T)\right)$$

The PERESVET program was developed

MAIN PUBLICATIONS:

A.I. Podgorny Solar Phys. 156,41,1995.

A.I. Podgorny, I.M. Podgorny

Solar Phys. 139, 125, 1992; 161, 165, 1995; 182, 159, 1998; 207, 323, 2002

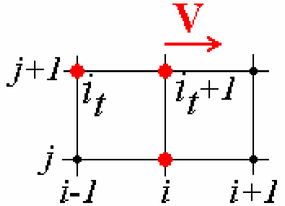
Cosmic Research 35, 35, 1997; 35, 235, 1997; 36, 492, 1998

Astronomy Reports 42, 116, 1998; 43, 608, 1999; 44, 407, 2000; 45, 60, 2001; 46, 65, 2002; 47,696,2003; 48, 435, 2004; 49, 837, 2005; 52, 666, 2008; 54, 645, 2010

Comput. Mathem. Mathematical Phys 44, 1784, 2004

The principal difference between the numerical methods implemented in the program PERESVET and others. The main goal is to build the mostly stable finite-difference scheme. Stability must remain for maximally possible step Δt, to accelerate calculations maximally. The scheme must be stable even, if the Courant condition ($\boldsymbol{\Delta t V_w / \Delta x < 1}$) is violated, which is reached only for **implicit** schemes. But here there is no purpose to achieve high precision of approximation of differential equations by finite-difference scheme.

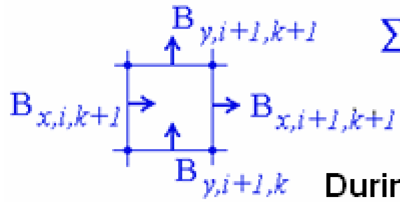
In the PERESVET program:



- Finite-difference scheme is upwind for diagonal terms.
- The scheme is absolutely implicit, it is solved by iteration method ($\Delta t V_w / \Delta x < 1$ is not necessary).

$$\overset{(i_t+1)}{u}{}_i^{j+1} = u_i^j - v\frac{\Delta t}{\Delta x}\left(\overset{(i_t+1)}{u}{}_i^{j+1} - \overset{(i_t)}{u}{}_{i-1}^{j+1}\right)$$

- The scheme is conservative relative to magnetic flux [divB]=0



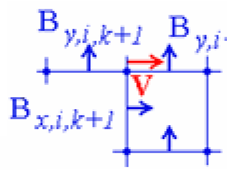
$$\sum B_n \Delta S = 0$$

Equivalency of equations

$\partial \mathbf{B} / \partial t = \mathrm{rot}(\mathbf{V} \times \mathbf{B}) + \nu_m \Delta \mathbf{B}$ and $\partial \mathbf{B} / \partial t = \mathrm{rot}(\mathbf{V} \times \mathbf{B}) - \nu_m \mathrm{rot}(\mathrm{rot}\mathbf{B})$

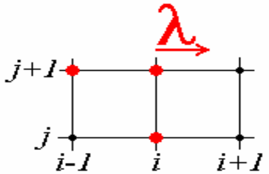
During dissipation relaxation of magnetic field, the current density $[\mathrm{rot}\ \mathrm{B}] \to 0$

- Nonsymmetrical (upwind) approximation V×B.



$\mathbf{V} \times \mathbf{B}$ contains $\mathrm{V} \mathrm{B}_{y,i,k+1}$

Other methods:



- Explicit finite-difference schemes
- Often Godunov type (Riemann waves)

$$w_i^{j+1} = w_i^j - \lambda\frac{\Delta t}{\Delta x}\left(w_i^j - w_{i-1}^j\right)$$

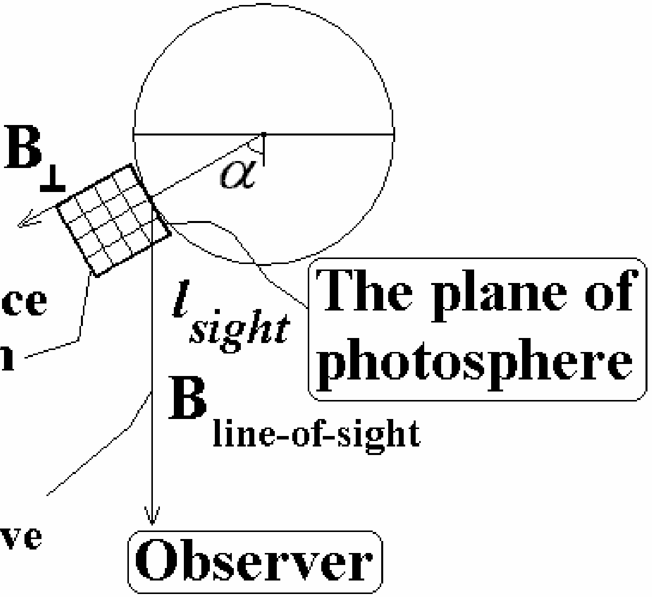
- The special methods are used to obtain high order approximation (FCT, TVD)
- Also Lagrangian schemes with further recalculation by interpolation on each step.
- Some schemes are also conservative relative to magnetic flux [divB]=0, but with symmetrical approximation V×B.

$\mathbf{V} \times \mathbf{B}$ contains $\mathrm{V}(\mathrm{B}_{y,i+1,k+1} + \mathrm{B}_{y,i,k+1})/2$

Initial potential magnetic field

$$\mathbf{B} = \nabla \varphi_m$$

$$\Delta \varphi_m = 0$$ is solved using finite-difference scheme in the region



Boundary condition on the plane of photosphere:

$$\frac{\partial \varphi_m}{\partial l_{sight}} = \mathbf{B}_{line\text{-}of\text{-}sight}$$ - inclined derivative

On the net corresponded to conservative relative to magnetic flux finite-difference scheme for solving MHD equations

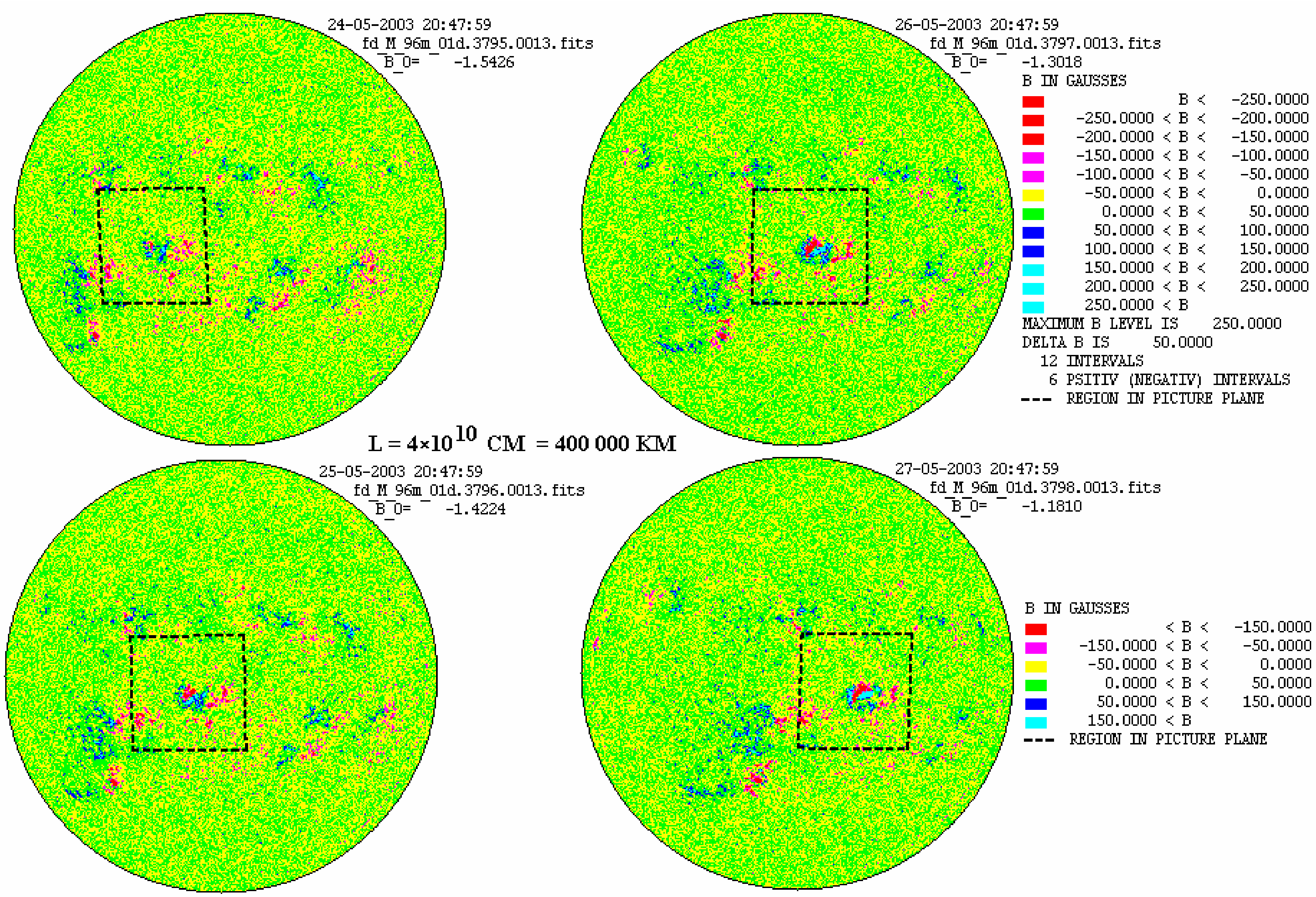
$$[\text{rot}]\mathbf{B}=0 \quad [\text{div}]\mathbf{B}=0$$

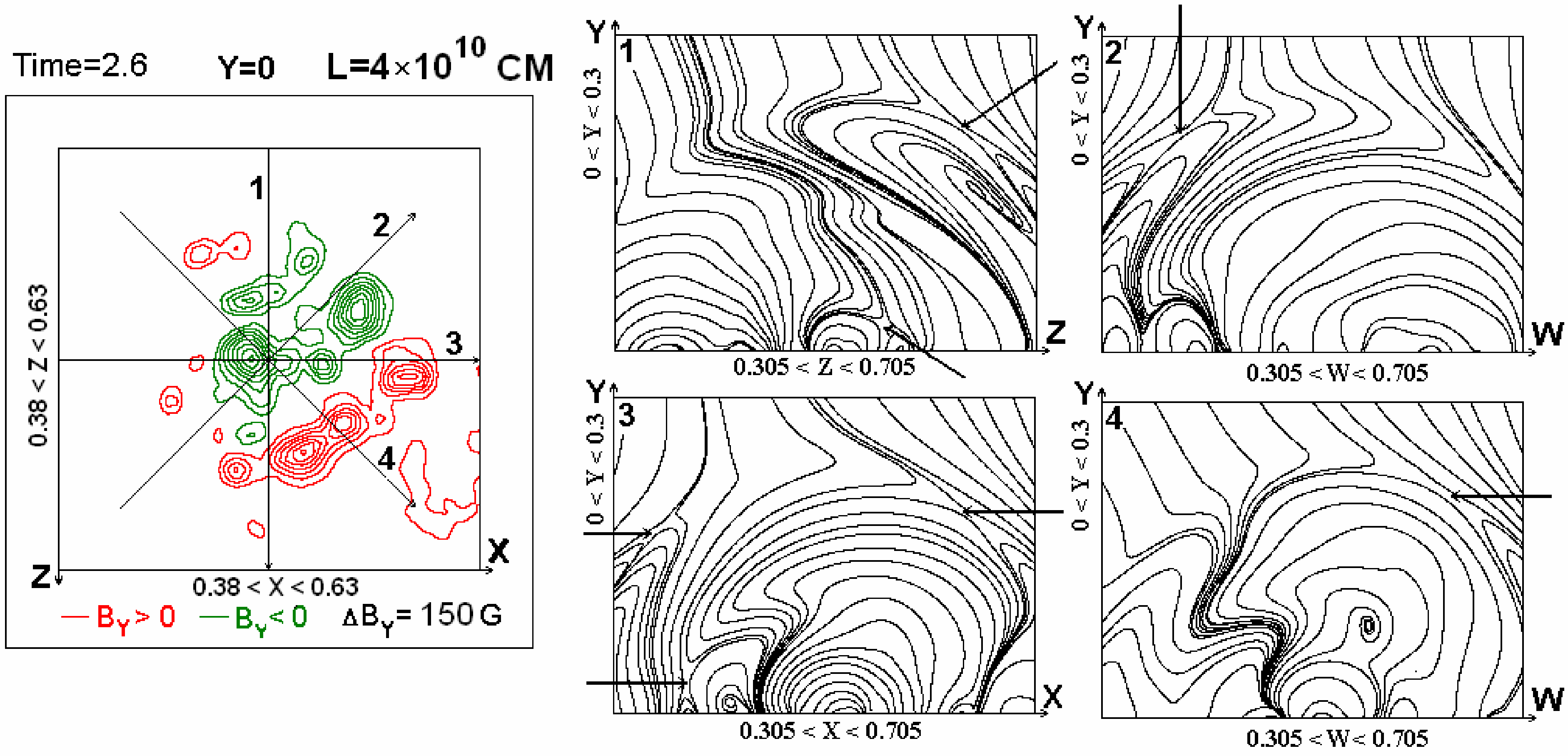
2 methods of $\Delta \varphi_m = 0$ solution:

1. $\Delta \varphi_m = 0$ directly by iterations
2. By relaxation of diffusion equation $\frac{\partial \varphi_m}{\partial t} = \Delta \varphi_m$

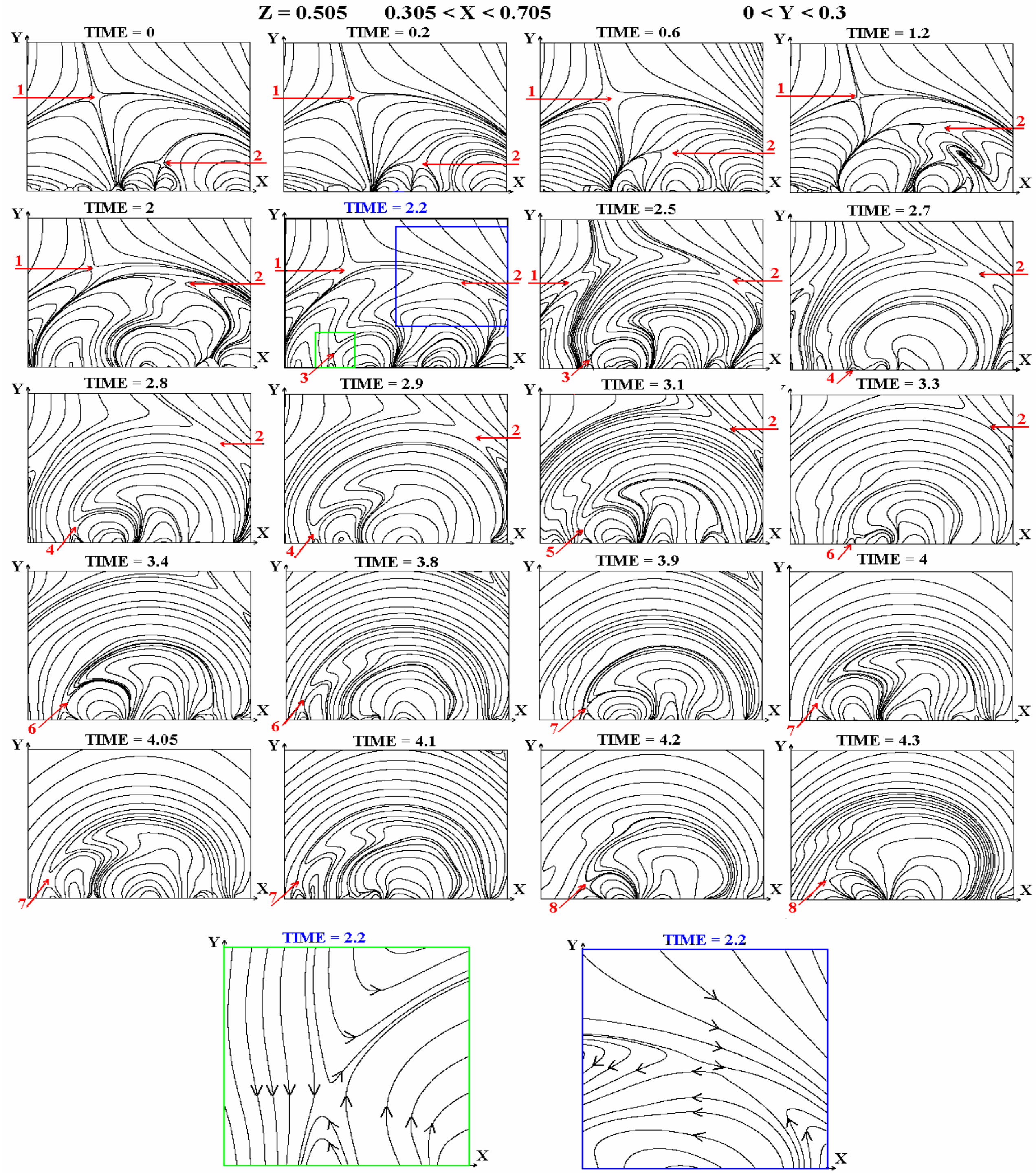
SET OF FLARES MAY 27, 2003

AR 0365





Time=2.6
Y=0
L=4×10^10 CM
1
2
3
4
0.38 < Z < 0.63
0.38 < X < 0.63
Z
X
B_Y > 0
B_Y < 0
ΔB_Y = 150 G
Y
0 < Y < 0.3
0.305 < Z < 0.705
0.305 < W < 0.705
0.305 < X < 0.705
W



Z = 0.505
0.305 < X < 0.705
0 < Y < 0.3
TIME = 0
TIME = 0.2
TIME = 0.6
TIME = 1.2
TIME = 2
TIME = 2.2
TIME =2.5
TIME = 2.7
TIME = 2.8
TIME = 2.9
TIME = 3.1
TIME = 3.3
TIME = 3.4
TIME = 3.8
TIME = 3.9
TIME = 4
TIME = 4.05
TIME = 4.1
TIME = 4.2
TIME = 4.3
TIME = 2.2
TIME = 2.2
X
Y
1
2
3
4
5
6
7
8

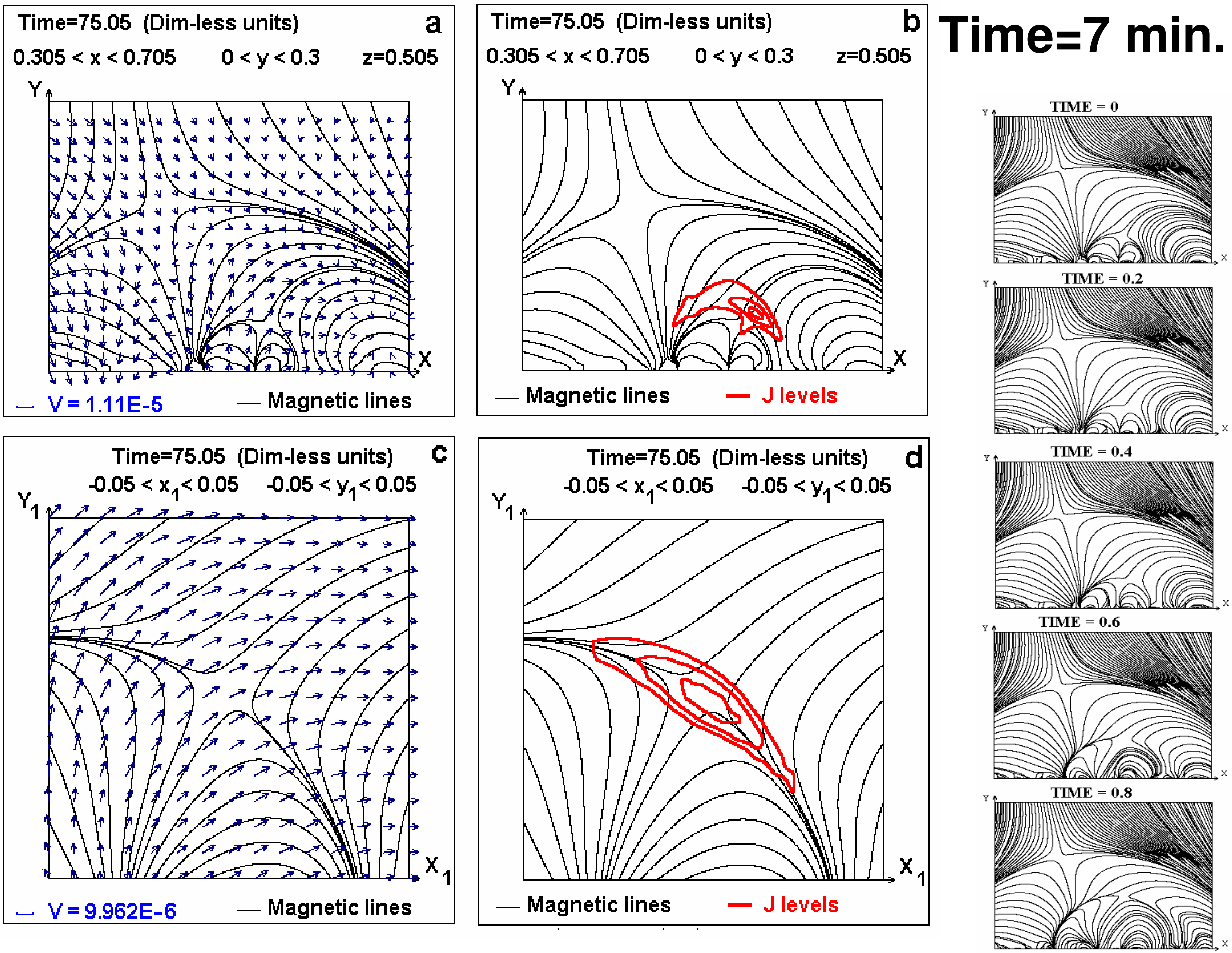
Previous MHD simulations performed in the strongly compressed time scale. To perform MHD simulations in real time scale it is necessary to accelerate calculations: The scheme should remain stable for a large time steps.

Last modernizations of numerical methods

Modernization of approximation of the dissipative term is proposed to $[\mathrm{div}\mathbf{B}] \rightarrow 0$ $((\partial \mathrm{div}\mathbf{B}/\partial t = \Delta(\mathrm{div}\mathbf{B}))$

To improve stability of the finite-difference scheme the method of boundary conditions setting on the photosphere is modernized.

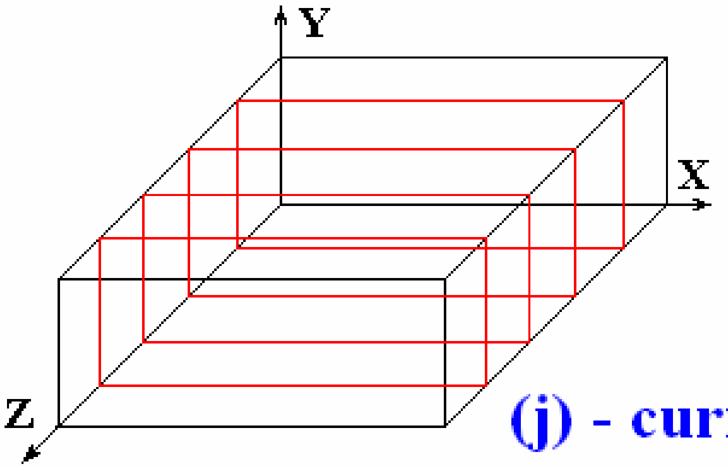
Two corrections of the initial potential field to decrease $\|[\mathrm{div}\,\mathbf{B}]\|$



Time=75.05 (Dim-less units)
a
0.305 < x < 0.705
0 < y < 0.3
z=0.505
Y
X
V = 1.11E-5
Magnetic lines
Time=75.05 (Dim-less units)
b
0.305 < x < 0.705
0 < y < 0.3
z=0.505
Y
X
Magnetic lines
J levels
Time=7 min.
TIME = 0
TIME = 0.2
TIME = 0.4
TIME = 0.6
TIME = 0.8
Time=75.05 (Dim-less units)
c
-0.05 < x1 < 0.05
-0.05 < y1 < 0.05
Y1
X1
V = 9.962E-6
Magnetic lines
Time=75.05 (Dim-less units)
d
-0.05 < x1 < 0.05
-0.05 < y1 < 0.05
Y1
X1
Magnetic lines
J levels

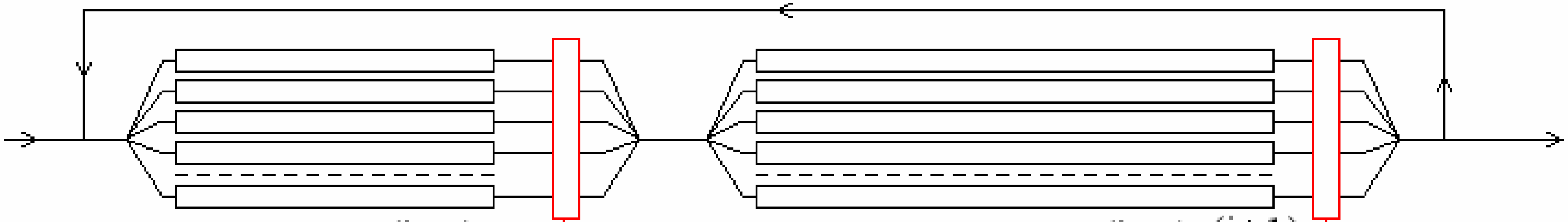
The firs results of real time simulation of active region after all modernizations of numerical methods show that to calculate during several days the active region evolution during one day it is necessary to have supercomputer which calculates 100 times faster than modern personal computer (double core processor 1.6 GHz).

To use the simulations for improving the solar flare prognosis the simulated evolution must be faster than real active region evolution, so it should be used supercomputer 10^4 times faster than personal computer.



Parallelizing of iterations during MHD equations solving

(j) - current iteration → (j+1) - next iteration



finding $\mathbf{B}^{(j+1)}$

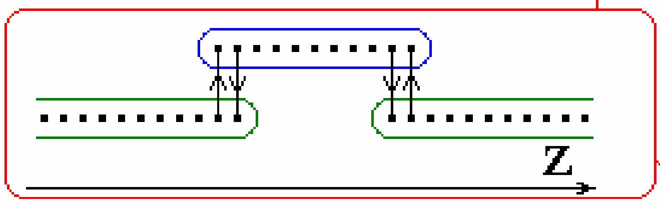
$$\frac{\partial \mathbf{B}}{\partial t} = \mathrm{rot}(\mathbf{V}\times\mathbf{B}) - \mathrm{rot}\left(\nu_m \,\mathrm{rot}\mathbf{B}\right)$$

finding $\rho^{(j+1)}, \mathbf{V}^{(j+1)}, \mathrm{T}^{(j+1)}$

$$\frac{\partial \rho}{\partial t} = -\mathrm{div}(\mathbf{V}\rho)$$

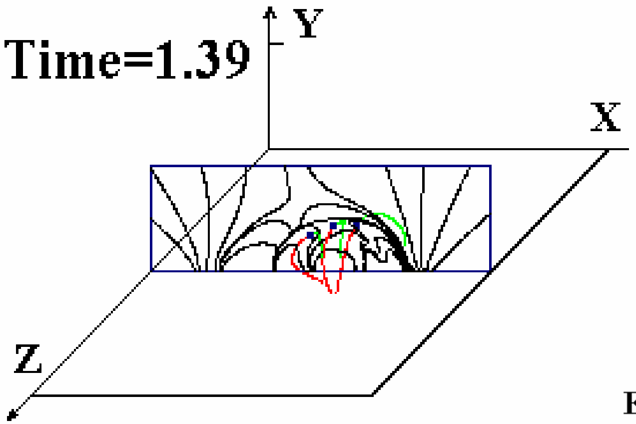
$$\frac{\partial \mathbf{V}}{\partial t} = -(\mathbf{V},\nabla)\mathbf{V} - \frac{1}{\rho}\nabla(\mathrm{p}) + \frac{1}{\rho}(\mathbf{j}\times\mathbf{B}) + \ldots$$

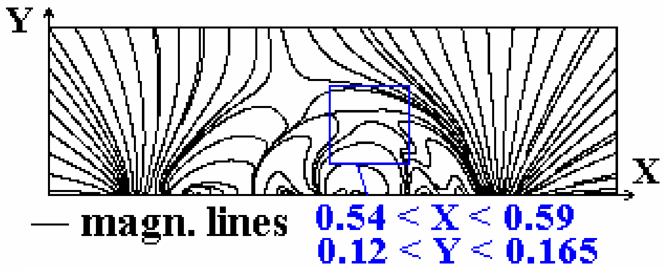
$$\frac{\partial T}{\partial t} = -(\mathbf{V},\nabla)T - (\gamma-1)T\mathrm{div}\mathbf{V} + (\gamma-1)\frac{\nu_m}{\rho}(\mathrm{rot}\mathbf{B})^2 + \ldots$$

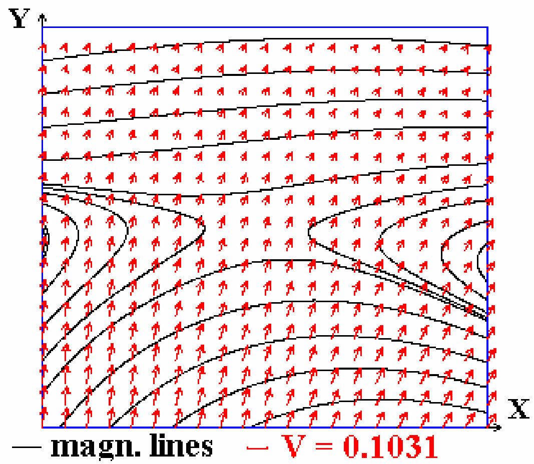


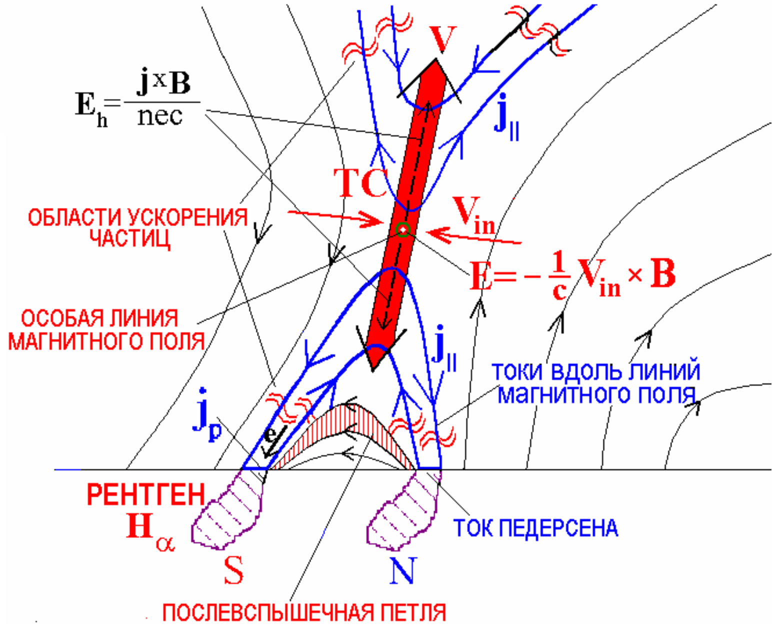
values transfer near boundaries in MPI system

Analogically it is possible to parallelize solving of Laplace equation $\Delta\varphi = 0$ to find of initial potential field and finding of boundary conditions of MHD equations

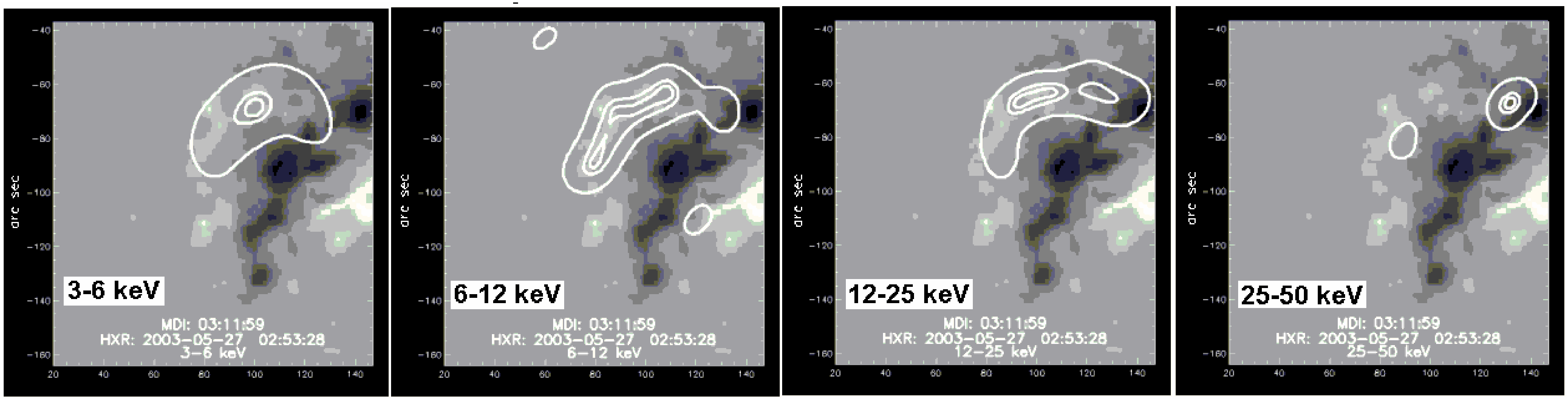


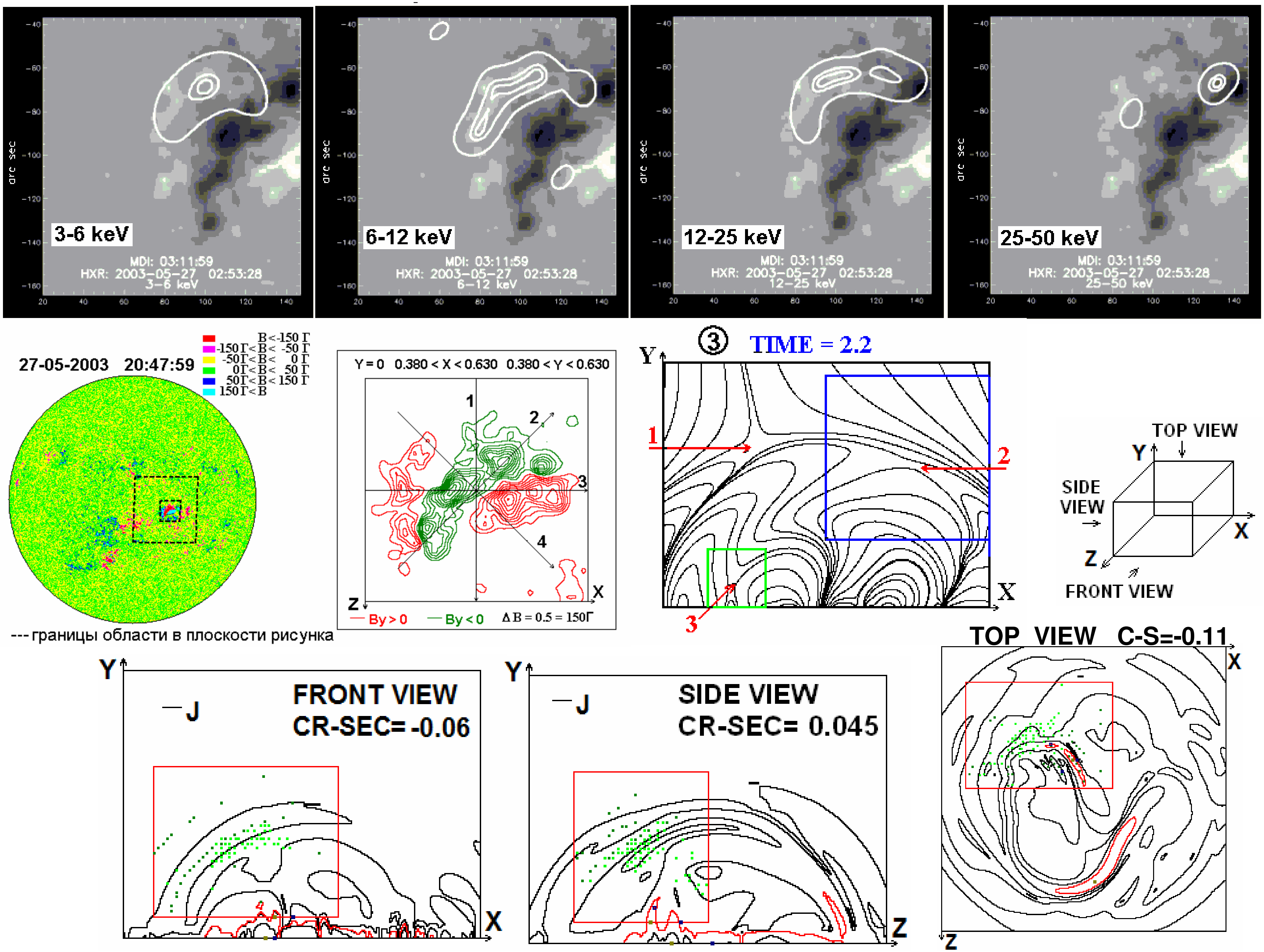


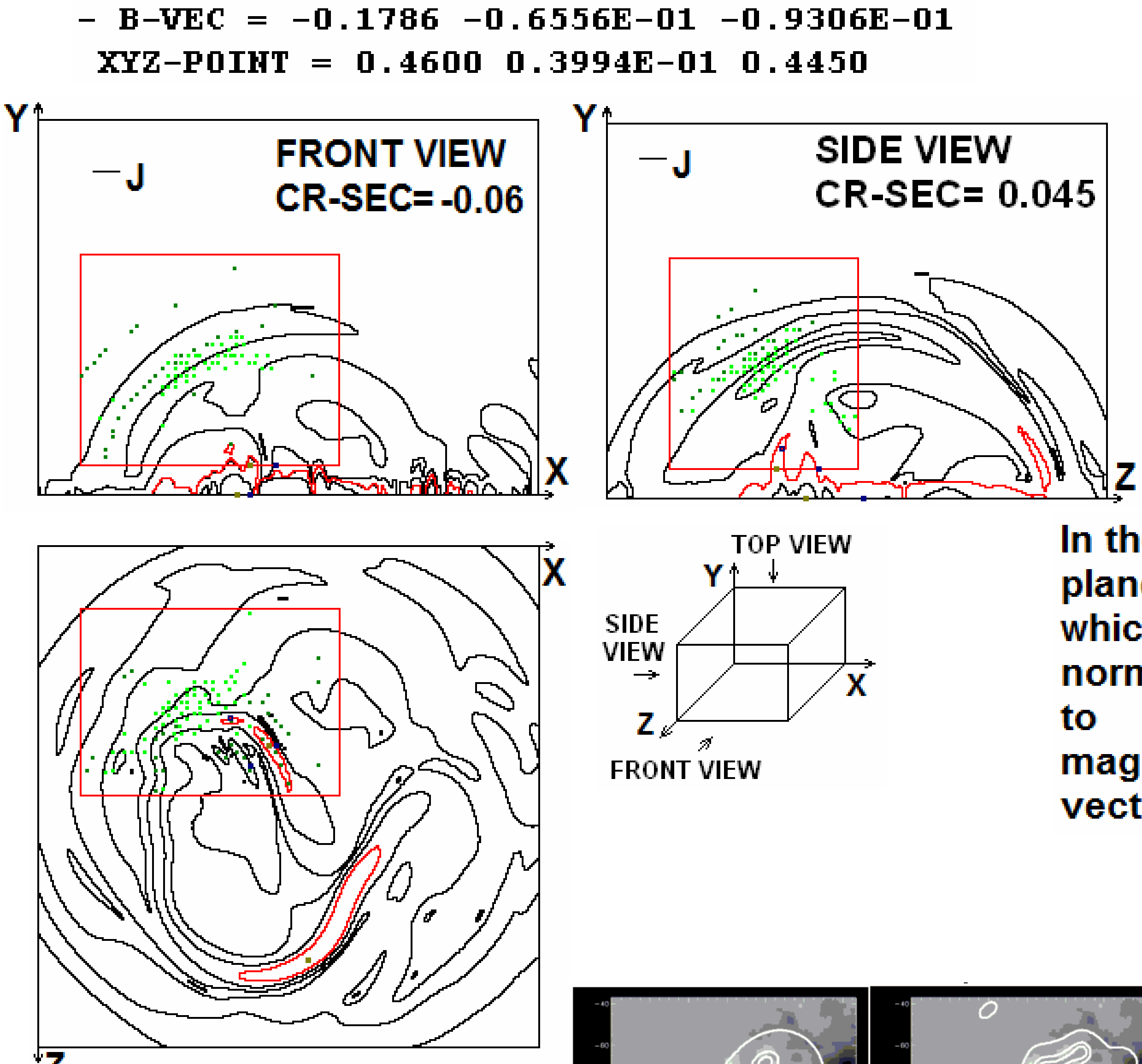




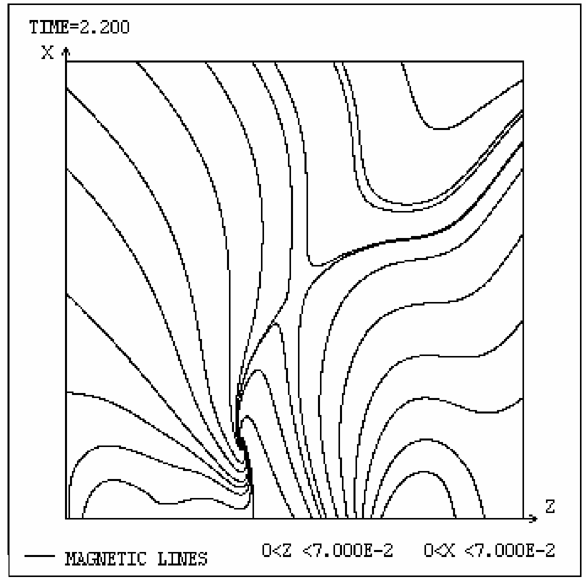
Modernization of graphical system permit to compare of supposed flare X-ray sources positions founded from MHD simulation with X-ray observations.



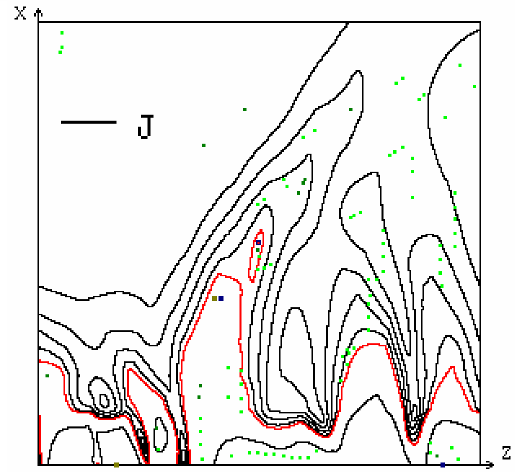

3-6 keV
6-12 keV
12-25 keV
25-50 keV
MDI: 03:11:59
HXR: 2003-05-27 02:53:28
arc sec
27-05-2003 20:47:59
B<-150 Г
-150 Г<B< -50 Г
-50 Г<B< 0 Г
0 Г<B< 50 Г
50 Г<B<150 Г
150 Г<B
---границы области в плоскости рисунка
Y = 0 0.380 < X < 0.630 0.380 < Y < 0.630
By > 0
By < 0
ΔB = 0.5 = 150Г
TIME = 2.2
TOP VIEW
SIDE VIEW
FRONT VIEW
FRONT VIEW CR-SEC= -0.06
SIDE VIEW CR-SEC= 0.045
TOP VIEW C-S=-0.11
J

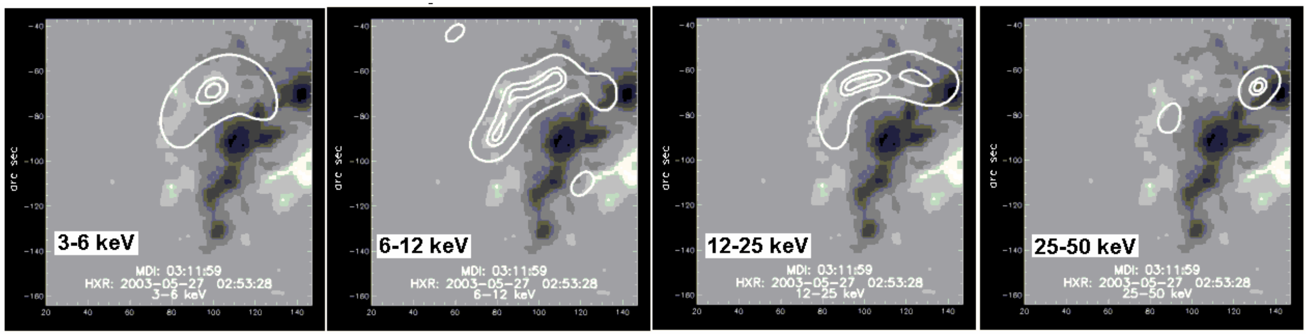


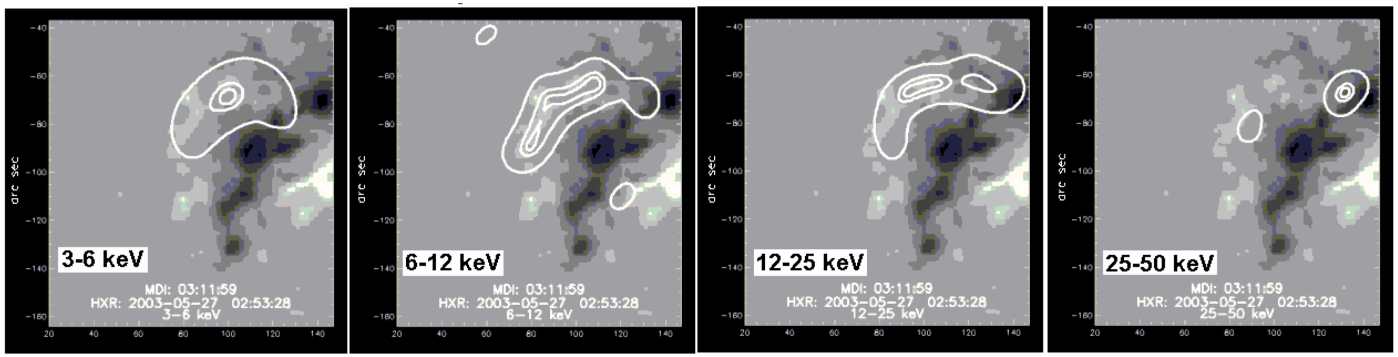
TOP VIEW CR-SEC=-0.11

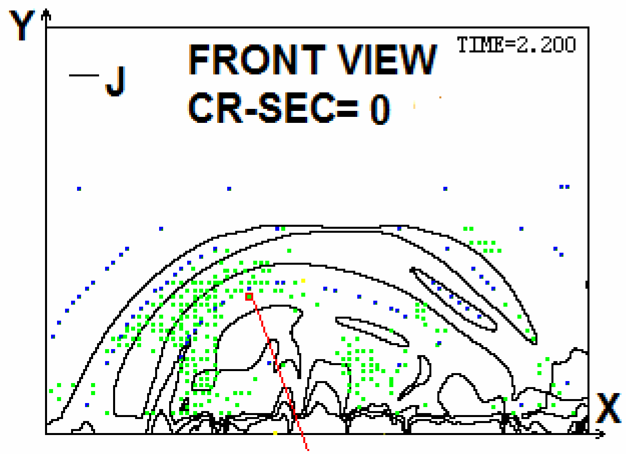


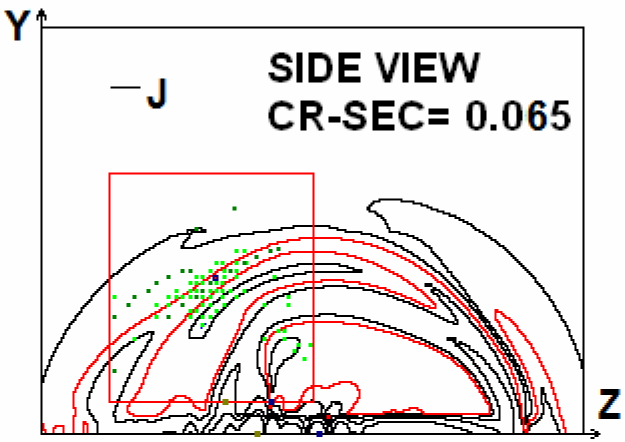
In the plane which is normal to magnetic vector:

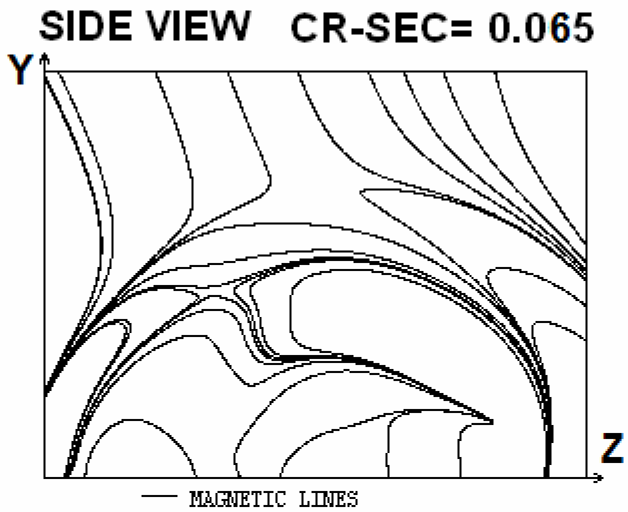




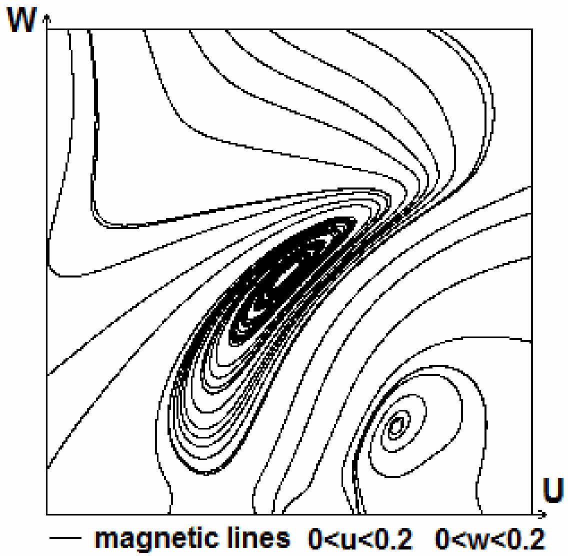








In the plane which is normal to magnetic vector:



To study the physical processes during solar flares and for improving of solar flare prognosis on the basis of understanding its physical mechanism, it is necessary to solve further problems:

1. **Real-time** MHD simulation of flare situation in active region – application of supercomputer, parallelizing.
2. Modernizing of graphical system, which permits **to find fast** possible positions of flare emission sources from MHD simulation results.

Thank you!

Благодаря за вниманието!