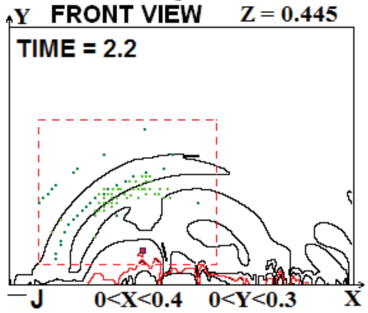
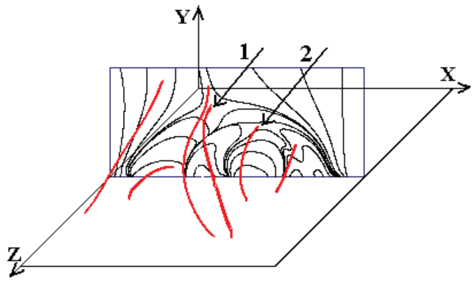
Thank you!

БЛАГОДАРЯ!

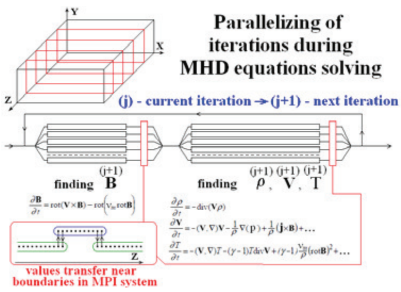
At the nearest future it is necessary:

to modernize the graphical system of current sheet search

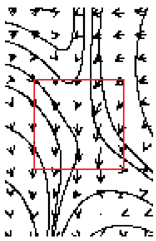


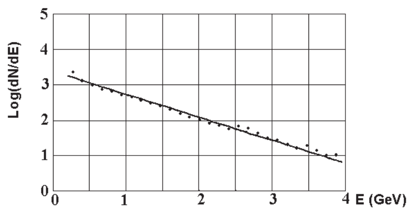


to parallelize calculations for numerical solving of MHD equations



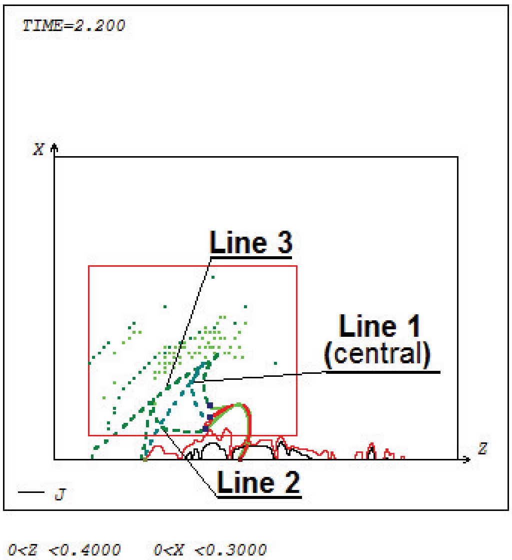
to have possibility to perform calculations for several active regions in real time scale for more detail grid and simulation of particles acceleration in appeared current sheets.





Further planes . . .

Coincidence of position of the current sheet obtained by MHD simulation with the observed position of the source of thermal X-ray emission during solar flare is the independent evidence that the mechanism of a solar flare is an explosive release of magnetic energy stored in the current sheet.



LINE 1 (CENTRAL):

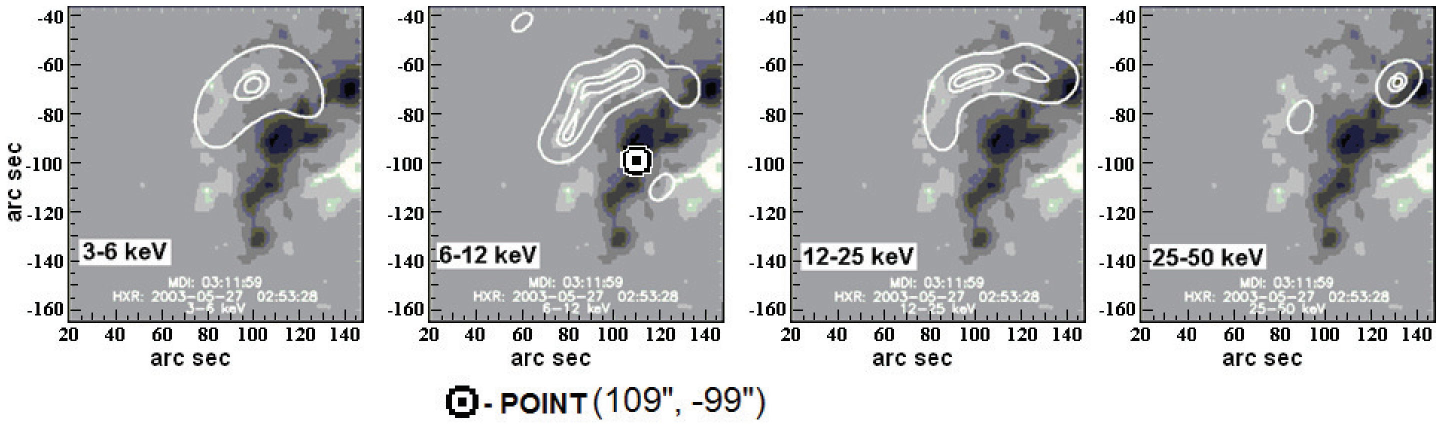
Top Point	95.94"	-55.57"
Direct End-Line Point	108.61"	-98.71"
Reverse End-Line Point	58.97"	6.78"

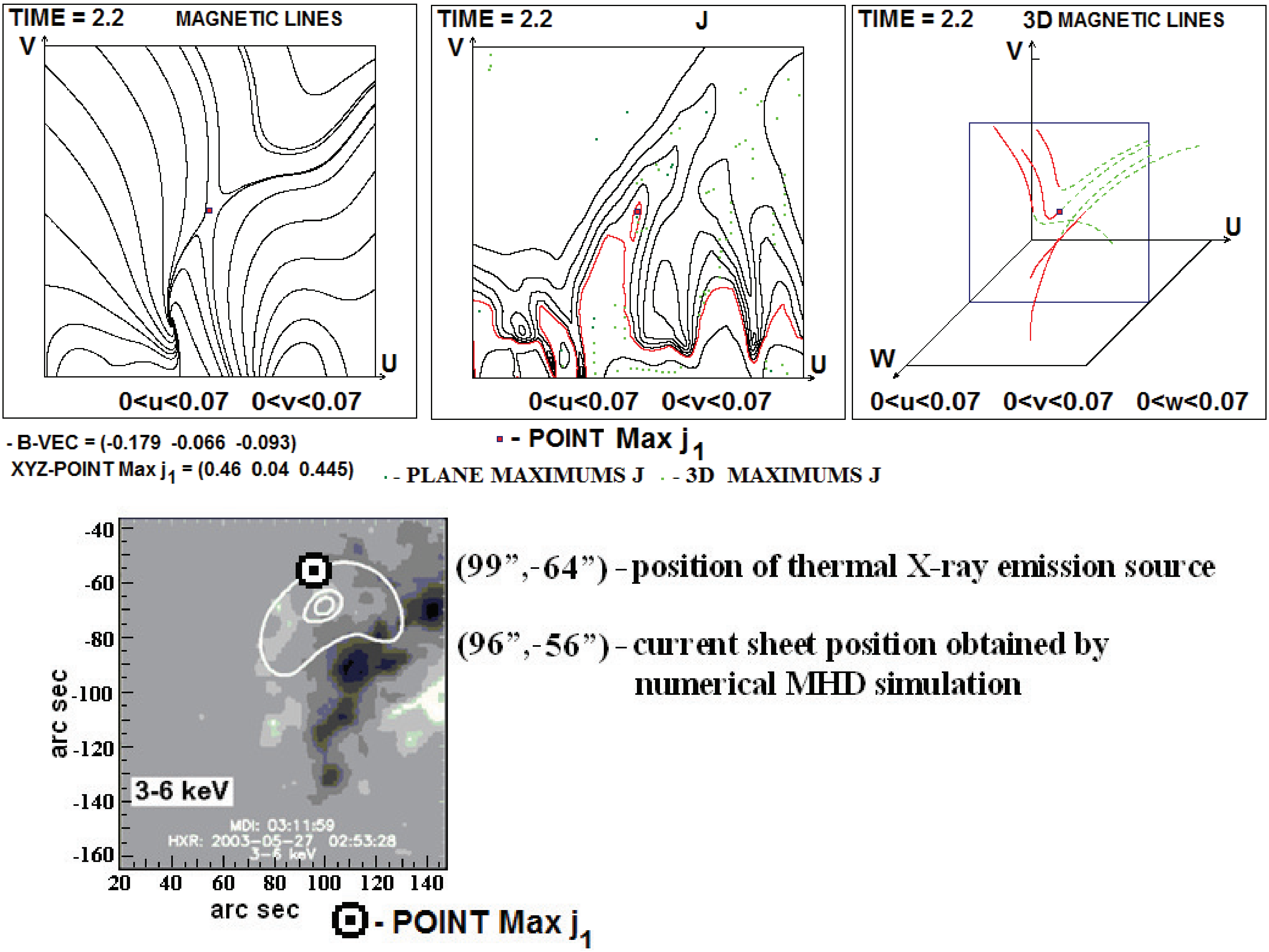
LINE 2

Top Point	93.62"	-55.05"
Direct End-Line Point	108.23"	-99.20"
Reverse End-Line Point	56.30"	-5.37"

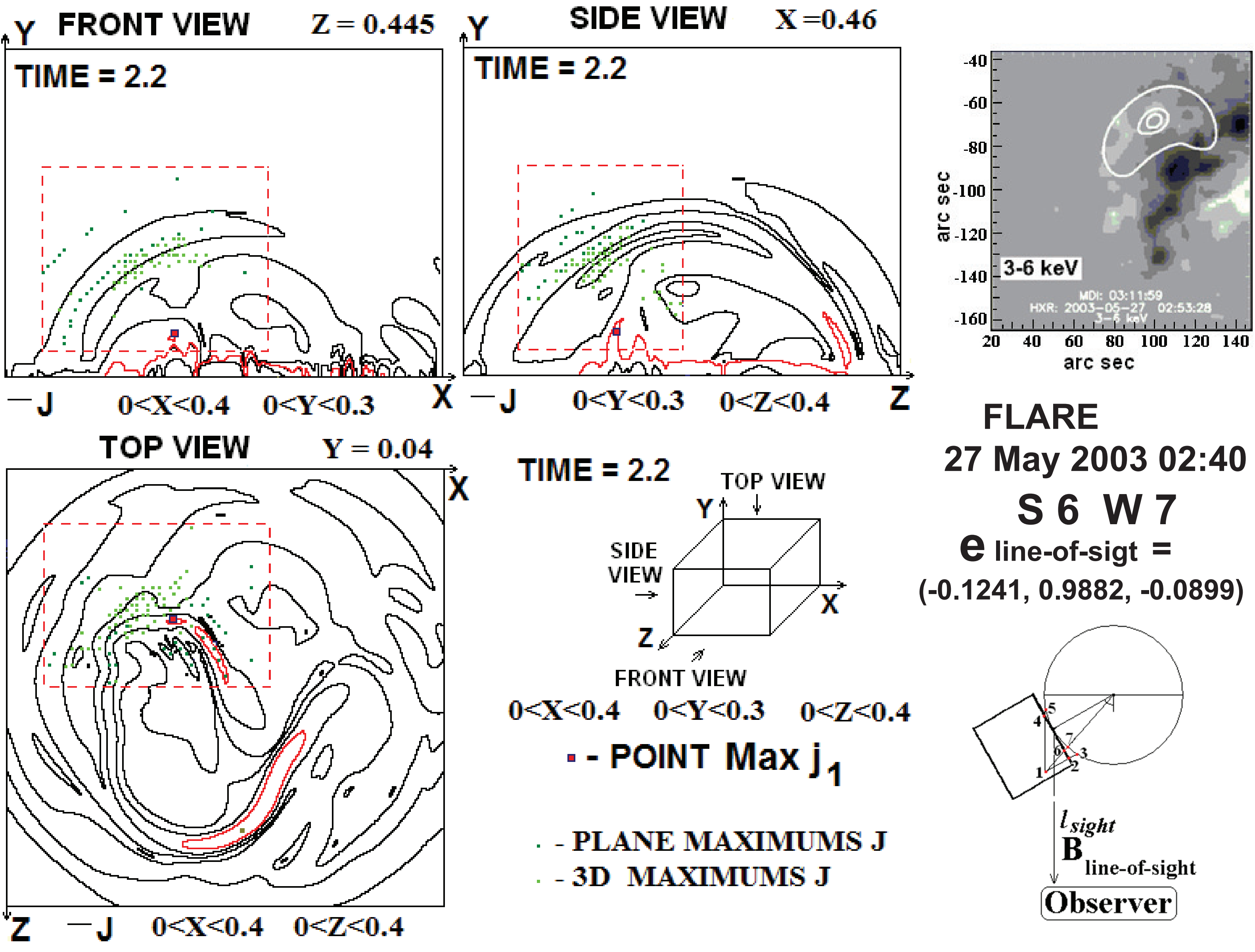
LINE 3

Top Point	97.41"	-56.06"
Direct End-Line Point	109.03"	-97.90"
Reverse End-Line Point	29.64"	-3.27"

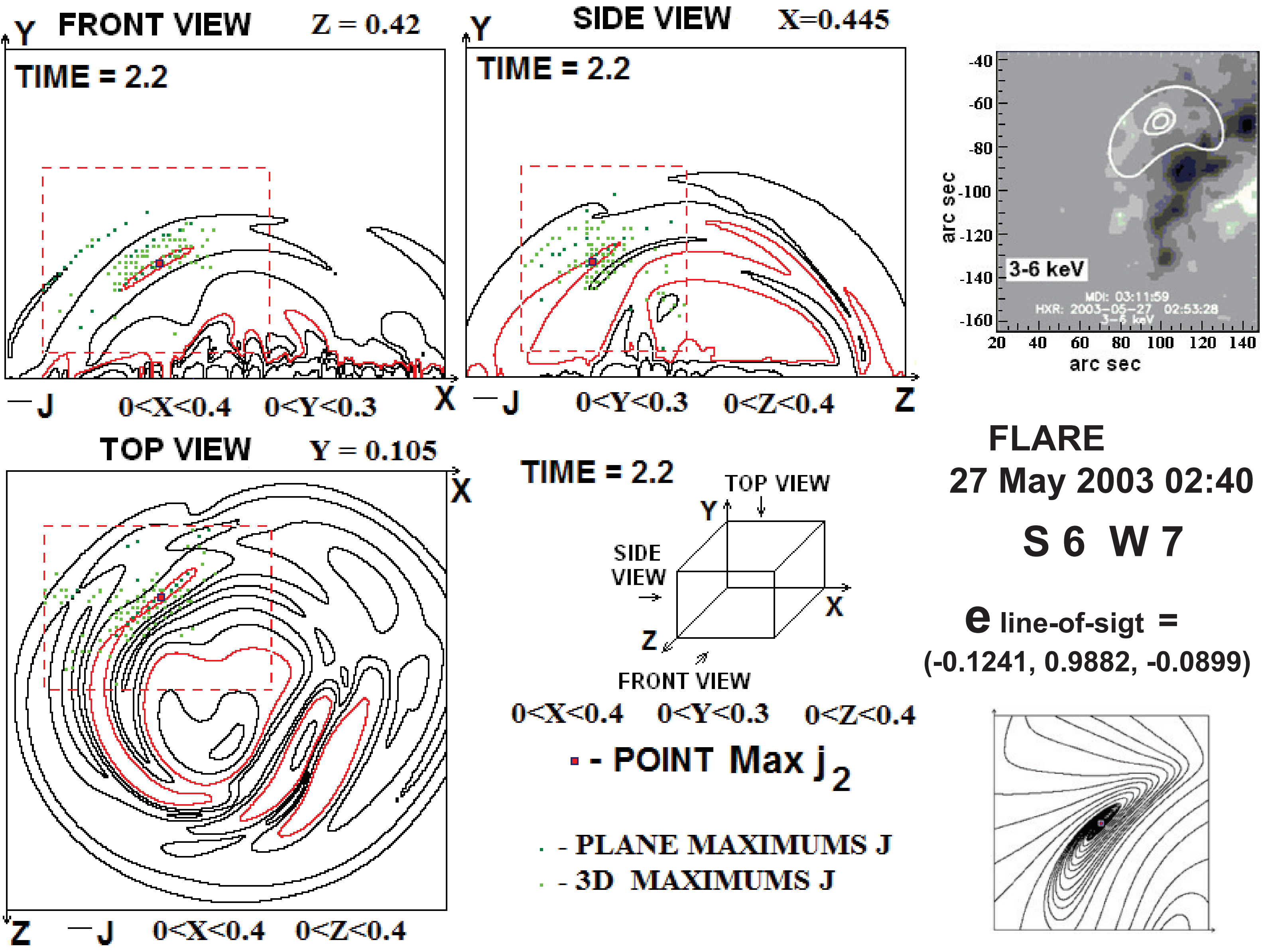


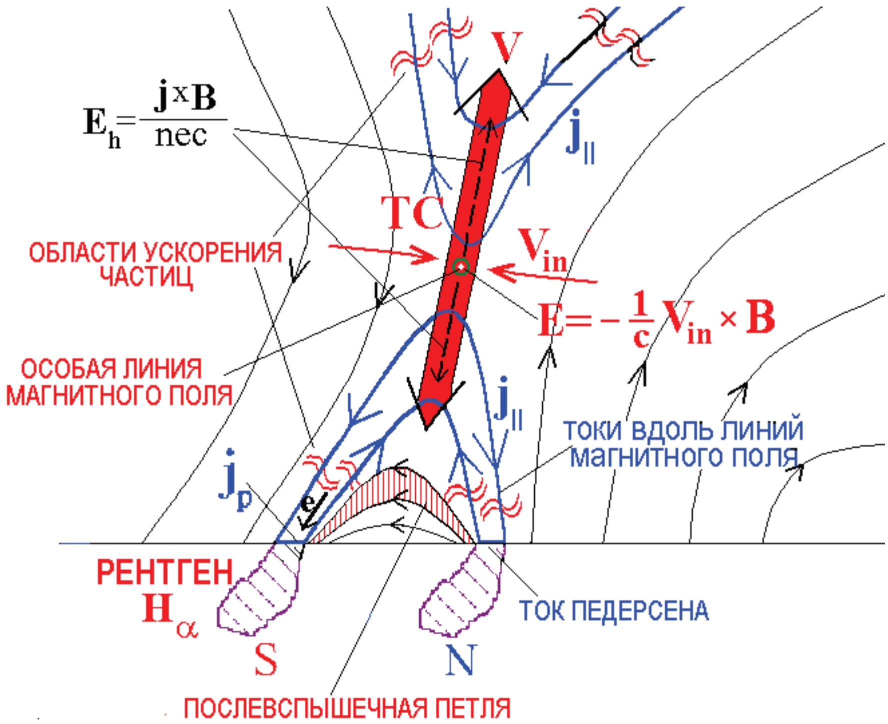


TIME = 2.2
MAGNETIC LINES
V
U
0<u<0.07 0<v<0.07
TIME = 2.2
J
V
U
0<u<0.07 0<v<0.07
TIME = 2.2
3D MAGNETIC LINES
V
U
W
0<u<0.07 0<v<0.07 0<w<0.07
- B-VEC = (-0.179 -0.066 -0.093)
XYZ-POINT Max j1 = (0.46 0.04 0.445)
- POINT Max j1
- PLANE MAXIMUMS J
- 3D MAXIMUMS J
-40
-60
-80
-100
-120
-140
-160
arc sec
3-6 keV
MDI: 03:11:59
HXR: 2003-05-27 02:53:28
3-6 keV
20
40
60
80
100
120
140
arc sec
- POINT Max j1
(99”,-64”) - position of thermal X-ray emission source
(96”,-56”) - current sheet position obtained by numerical MHD simulation

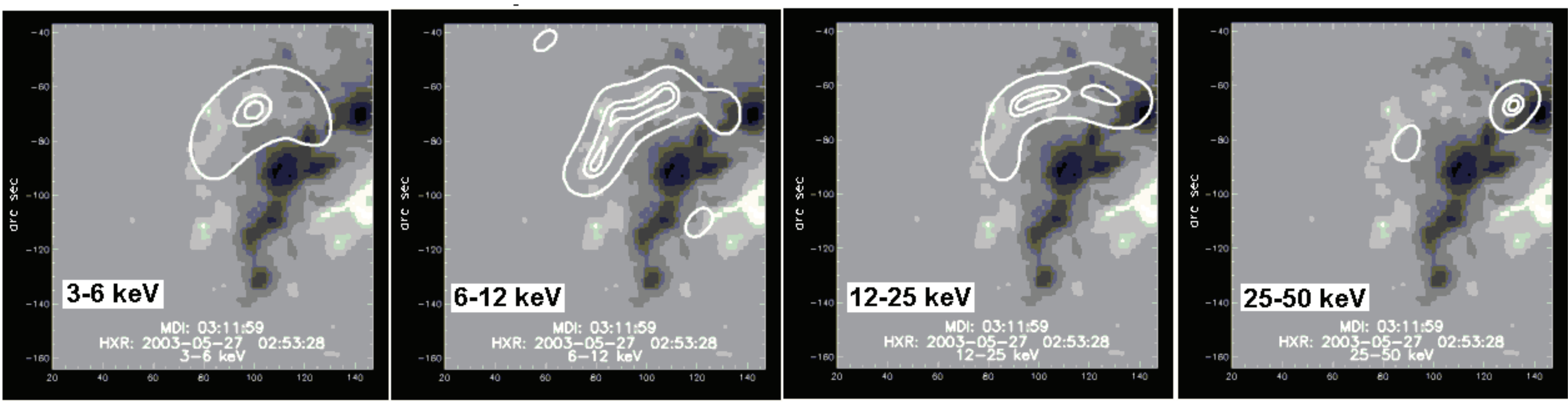


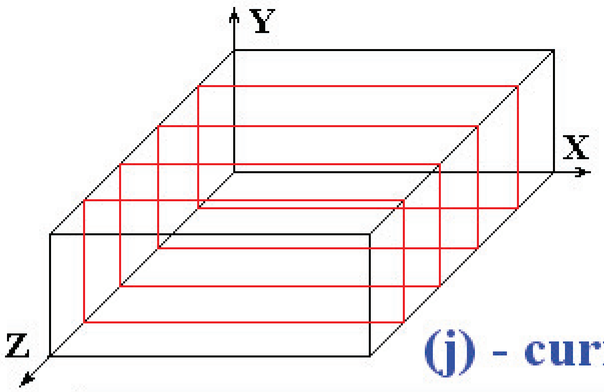
FRONT VIEW
Z = 0.445
TIME = 2.2
Y
X
J
0<X<0.4 0<Y<0.3
SIDE VIEW
X =0.46
TIME = 2.2
Y
Z
J
0<Y<0.3 0<Z<0.4
3-6 keV
arc sec
arc sec
MDI: 03:11:59
HXR: 2003-05-27 02:53:28
FLARE
27 May 2003 02:40
S 6 W 7
e line-of-sigt =
(-0.1241, 0.9882, -0.0899)
TOP VIEW
Y = 0.04
X
Z
J
0<X<0.4 0<Z<0.4
TIME = 2.2
TOP VIEW
SIDE VIEW
FRONT VIEW
0<X<0.4 0<Y<0.3 0<Z<0.4
- POINT Max j1
- PLANE MAXIMUMS J
- 3D MAXIMUMS J
l sight
B line-of-sight
Observer


FRONT VIEW Z = 0.42
TIME = 2.2
Y
X
J 0<X<0.4 0<Y<0.3
SIDE VIEW X=0.445
TIME = 2.2
Y
Z
J 0<Y<0.3 0<Z<0.4
TOP VIEW Y = 0.105
X
Z J 0<X<0.4 0<Z<0.4
3-6 keV
arc sec
arc sec
TIME = 2.2
TOP VIEW
SIDE VIEW
FRONT VIEW
0<X<0.4 0<Y<0.3 0<Z<0.4
- POINT Max j2
- PLANE MAXIMUMS J
- 3D MAXIMUMS J
FLARE
27 May 2003 02:40
S 6 W 7
e line-of-sigt =
(-0.1241, 0.9882, -0.0899)

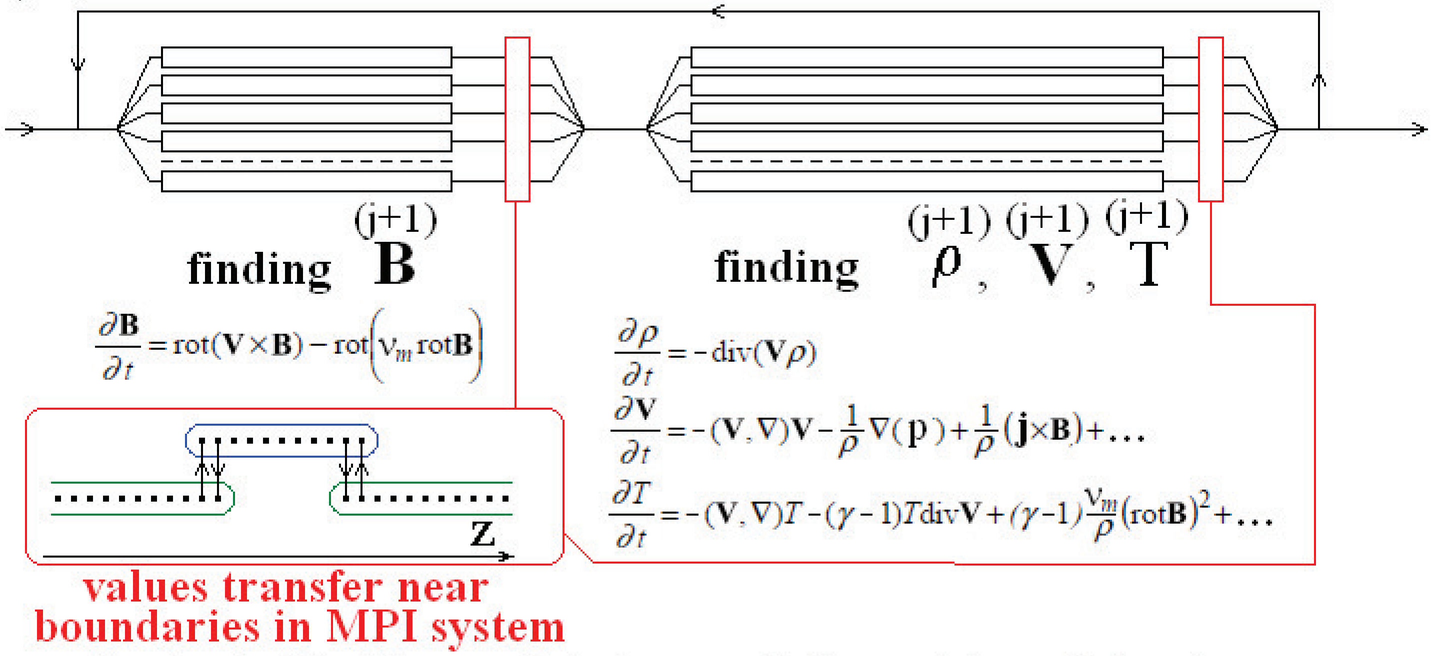


The graphical system of search of current sheet positions is created to compare with observed positions of thermal X-ray emission.





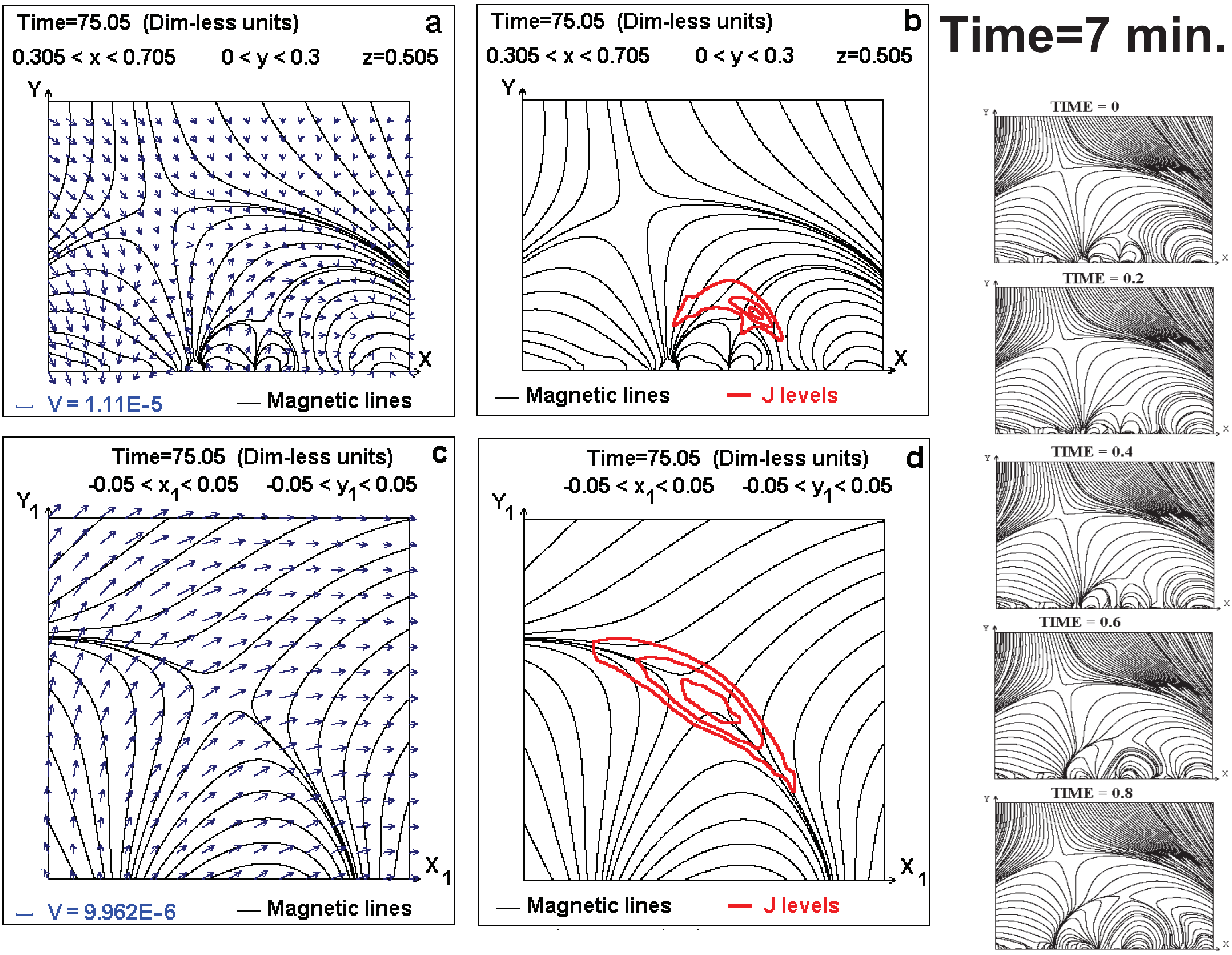
Parallelizing of iterations during MHD equations solving



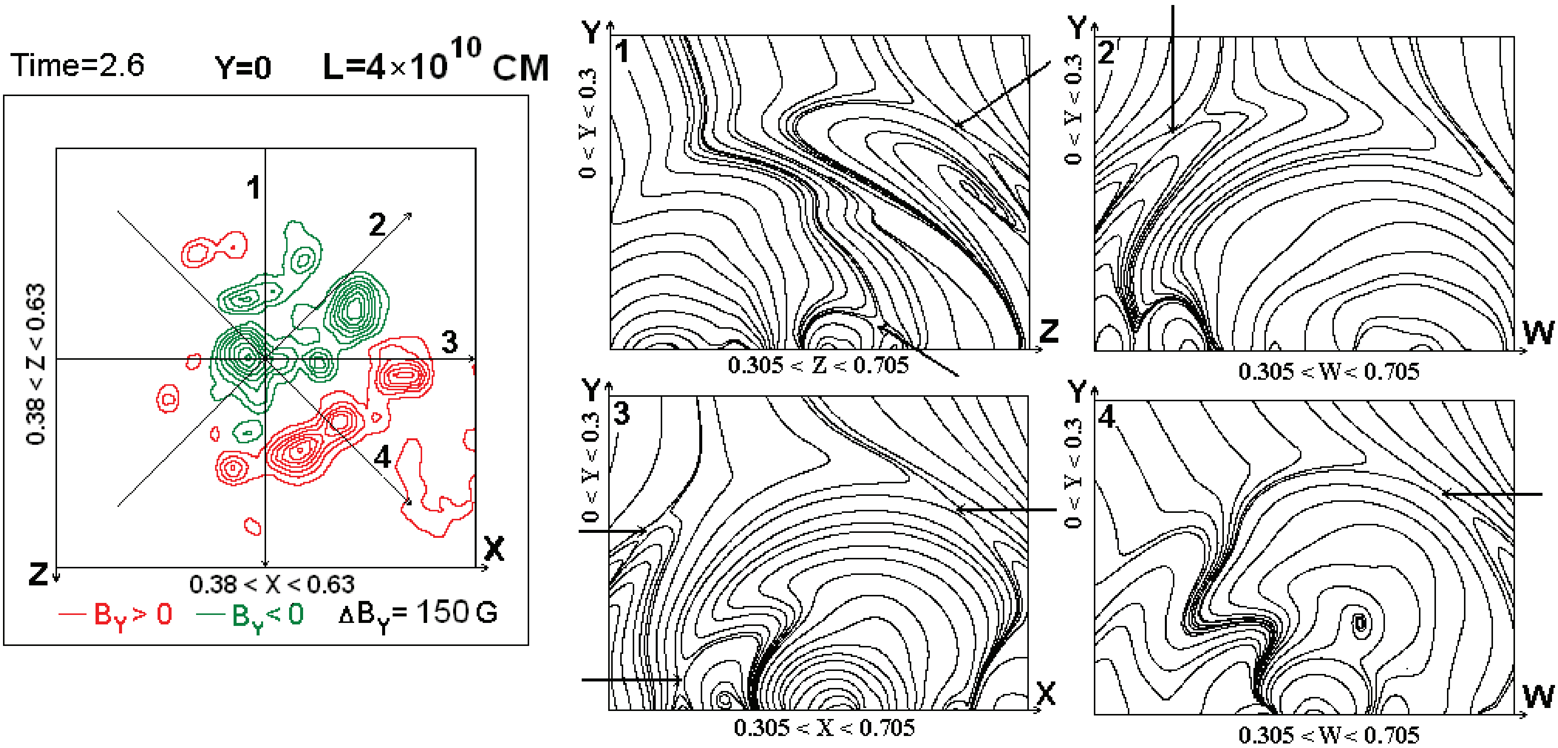
Analogically it is possible to parallelize solving of Laplace equation $\Delta\varphi=0$ to find of initial potential field and finding of boundary conditions of MHD equations

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).

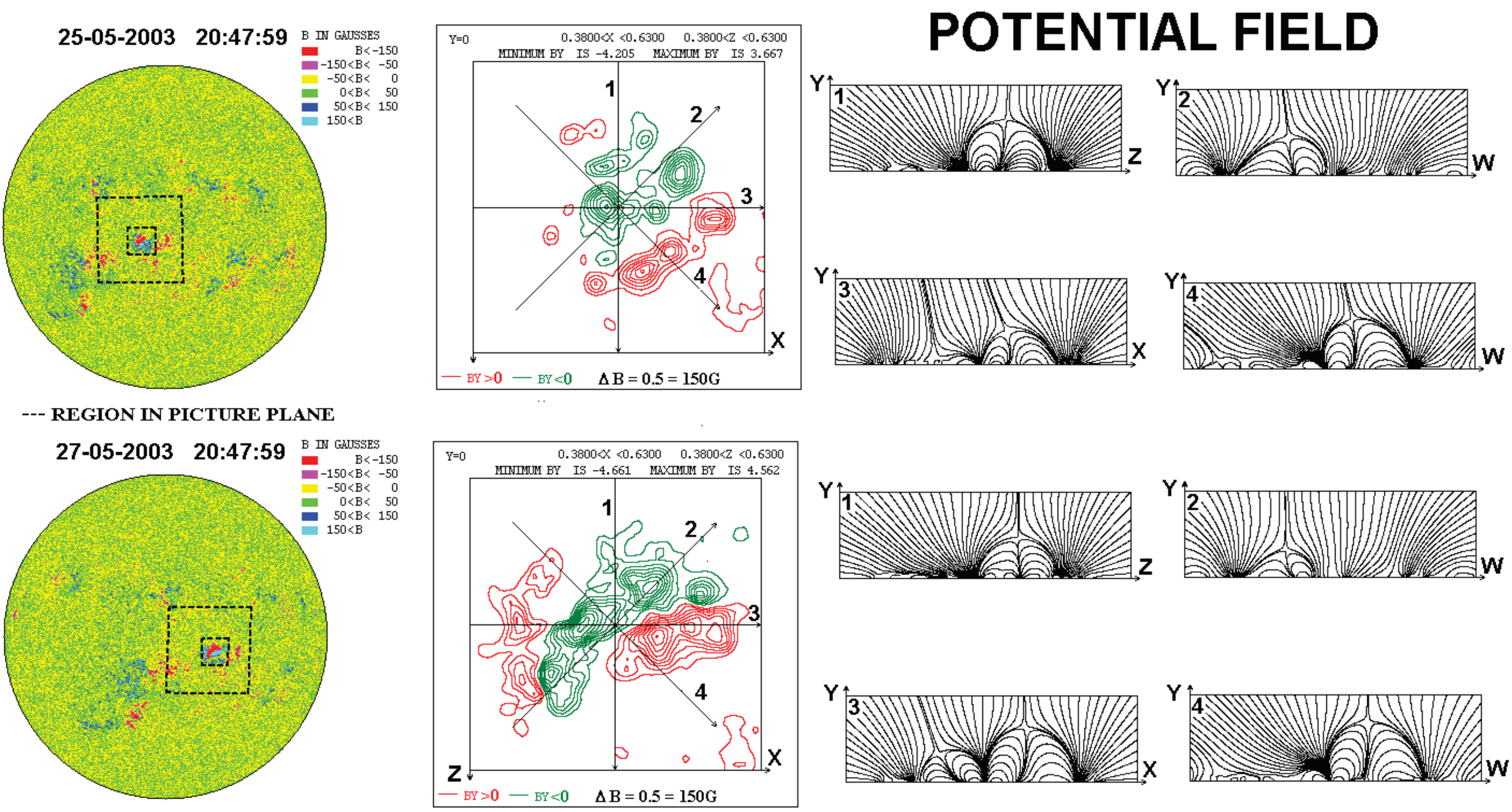
To use the simulations for improving the solar flare prognosis the simulated evolution must be faster than real active region evolution, so it should be used supercomputer 10^4 times faster than personal computer.



Time=75.05 (Dim-less units)
a
0.305 < x < 0.705 0 < y < 0.3 z=0.505
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
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
V = 9.962E-6
Magnetic lines
Time=75.05 (Dim-less units)
d
-0.05 < x1 < 0.05 -0.05 < y1 < 0.05
Magnetic lines
J levels



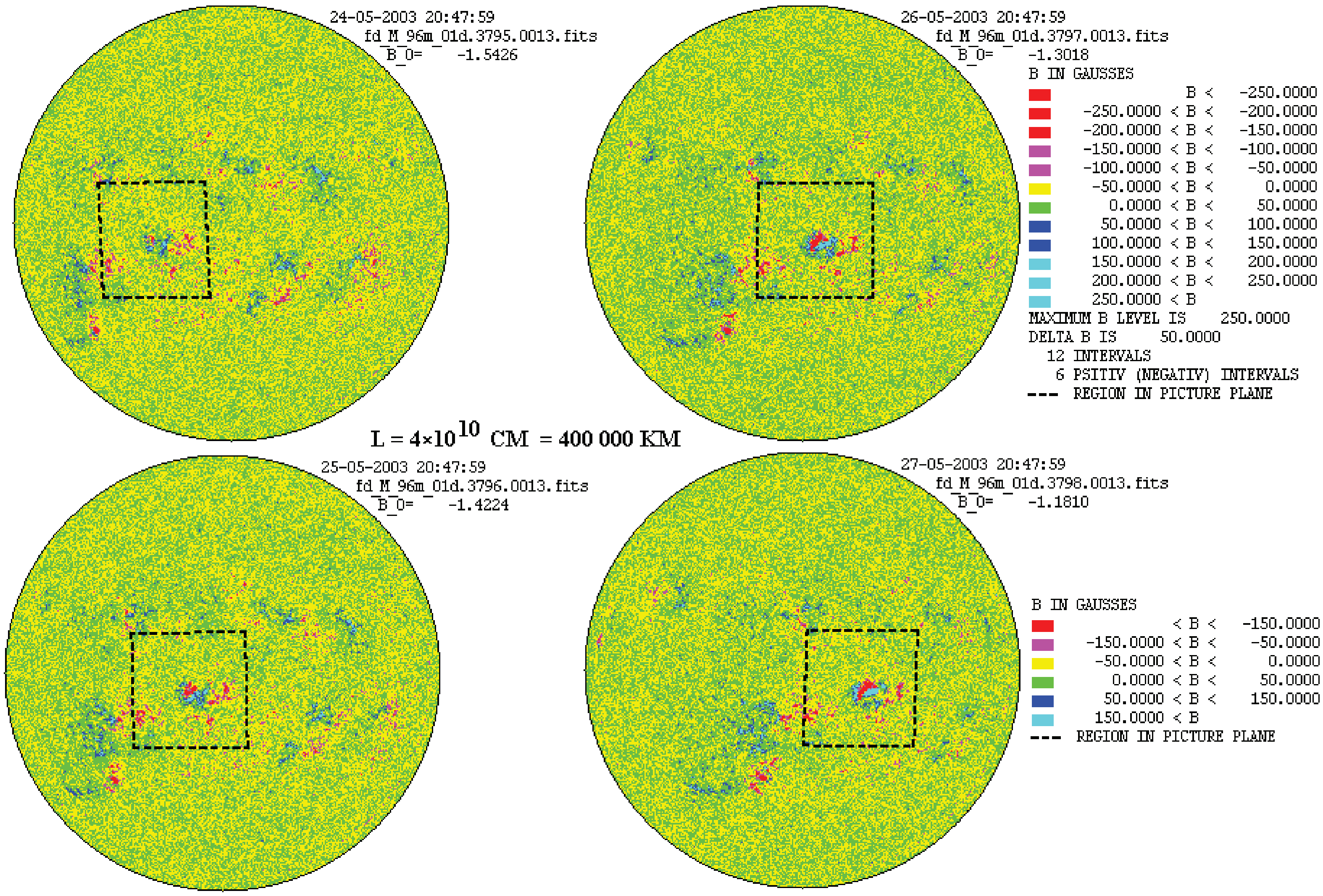
Time=2.6
Y=0
L=4×10^10 CM
0.38 < Z < 0.63
0.38 < X < 0.63
B_Y > 0
B_Y < 0
ΔB_Y = 150 G
0 < Y < 0.3
0.305 < Z < 0.705
0.305 < W < 0.705
0.305 < X < 0.705



POTENTIAL FIELD
25-05-2003 20:47:59
B IN GAUSSES
B< -150
-150<B< -50
-50<B< 0
0<B< 50
50<B< 150
150<B
--- REGION IN PICTURE PLANE
27-05-2003 20:47:59
Y=0
0.3800<X <0.6300 0.3800<Z <0.6300
MINIMUM BY IS -4.205 MAXIMUM BY IS 3.667
MINIMUM BY IS -4.661 MAXIMUM BY IS 4.562
BY >0
BY <0
ΔB = 0.5 = 150G

SET OF FLARES MAY 27, 2003

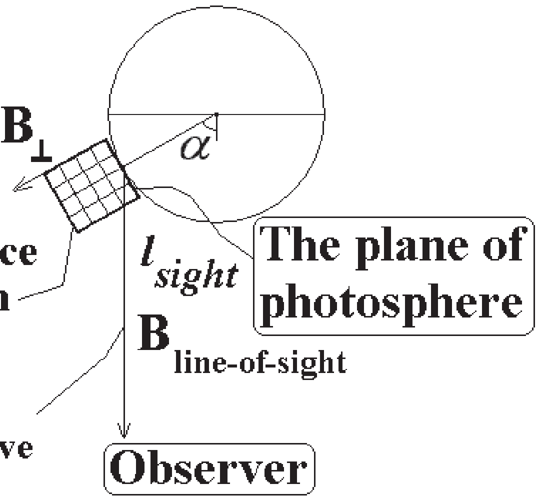
AR 0365



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: $\dfrac{\partial \varphi_m}{\partial l_{sight}} = B_{line-of-sight}$ - inclined derivative

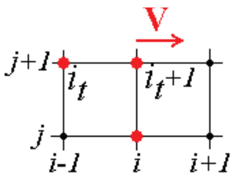
On the net corresponded to conservative relative to magnetic flux finite-difference scheme for solving MHD equations

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

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

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

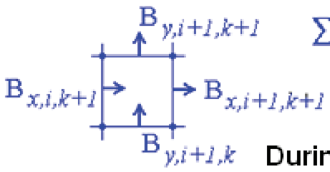
In the PERESVET program:



- 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).

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

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



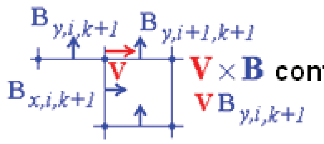
$$\Sigma \mathbf{B}_n \Delta \mathbf{S} = 0$$

Equivalency of equations

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

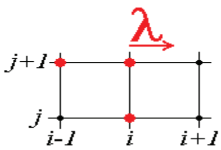
During dissipation relaxation of magnetic field, the current density $[\mathrm{rot}\ \mathbf{B}] \rightarrow 0$

- Nonsymmetrical (upwind) approximation V×B.



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

Other methods:



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

$$\mathbf{w}_i^{j+1} = \mathbf{w}_i^j - \lambda\frac{\Delta t}{\Delta x}\left(\mathbf{w}_i^j - \mathbf{w}_{i-1}^j\right)$$

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

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 ($\Delta t V_w / \Delta x < 1$) 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.

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.

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

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

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

$$\frac{\partial T}{\partial t} = -(\mathbf{V},\nabla)T - (\gamma-1)T\,\mathrm{div}\mathbf{V} + (\gamma-1)\frac{2\sigma_0}{\mathrm{Re}_m\sigma\beta\rho}(\mathrm{rot}\mathbf{B})^2 - (\gamma-1)\,G_q\rho L'(T) +$$
$$+\frac{\gamma-1}{\rho}\mathrm{div}\left(\mathbf{e}_\parallel\kappa_{dl}(\mathbf{e}_\parallel,\nabla T) + \mathbf{e}_{\perp1}\kappa_{\perp dl}(\mathbf{e}_{\perp1},\nabla T) + \mathbf{e}_{\perp2}\kappa_{\perp dl}(\mathbf{e}_{\perp2},\nabla T)\right)$$

The PERESVET program was developed

MAIN PUBLICATIONS:

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

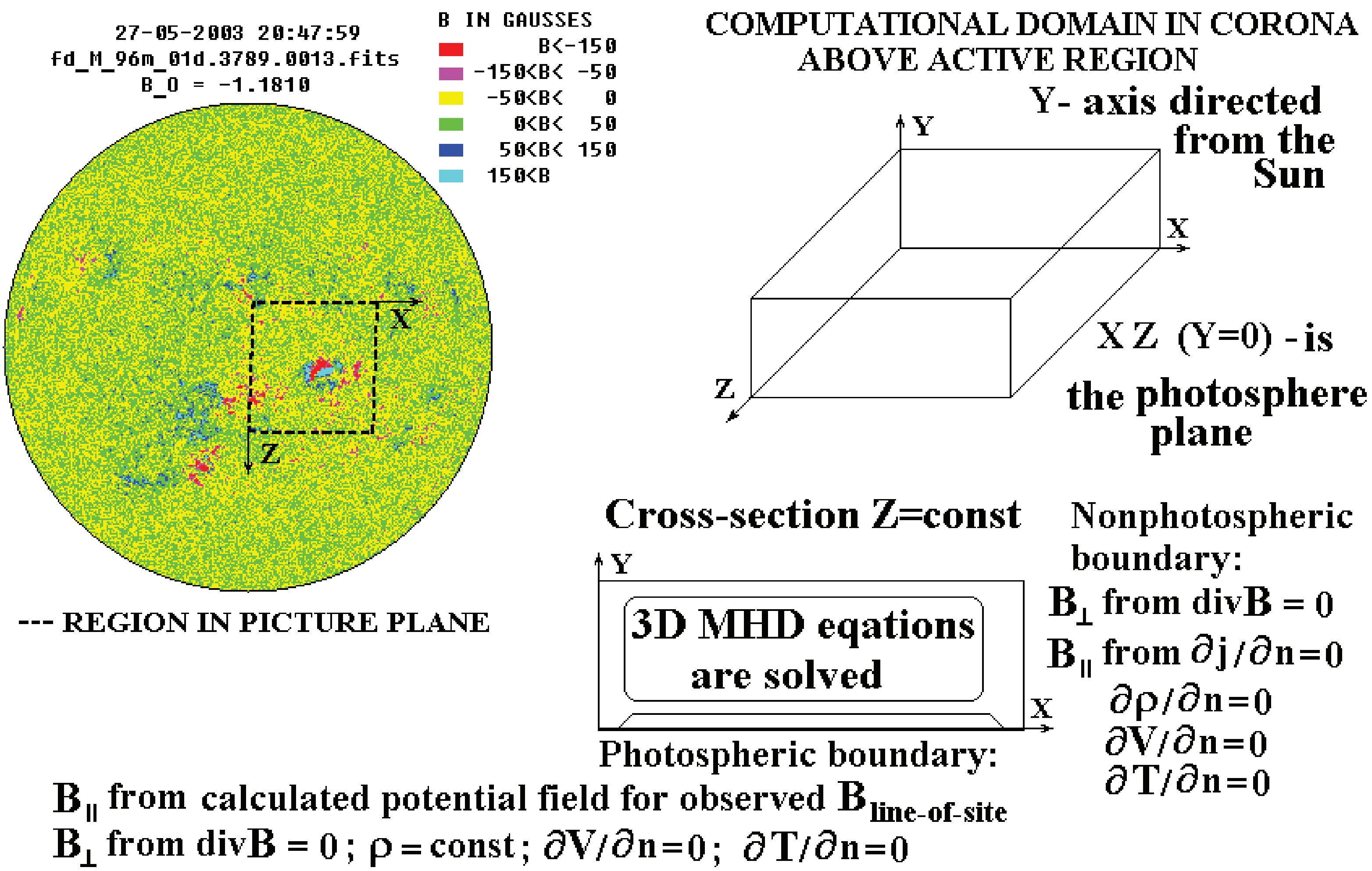
A.I. Podgorny, I.M. Podgorny

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



27-05-2003 20:47:59
fd_M_96m_01d.3789.0013.fits
B_0 = -1.1810
B IN GAUSSES
B<-150
-150<B< -50
-50<B< 0
0<B< 50
50<B< 150
150<B
X
Z
--- REGION IN PICTURE PLANE
COMPUTATIONAL DOMAIN IN CORONA
ABOVE ACTIVE REGION
Y- axis directed from the Sun
Y
X
Z
X Z (Y=0) - is the photosphere plane
Cross-section Z=const
Y
3D MHD eqations are solved
X
Photospheric boundary:
$B_\parallel$ from calculated potential field for observed $B_{\text{line-of-site}}$
$B_\perp$ from div$\mathbf{B} = 0$; $\rho = \text{const}$; $\partial V/\partial n = 0$; $\partial T/\partial n = 0$
Nonphotospheric boundary:
$B_\perp$ from div$\mathbf{B} = 0$
$B_\parallel$ from $\partial j/\partial n = 0$
$\partial \rho/\partial n = 0$
$\partial V/\partial n = 0$
$\partial T/\partial n = 0$

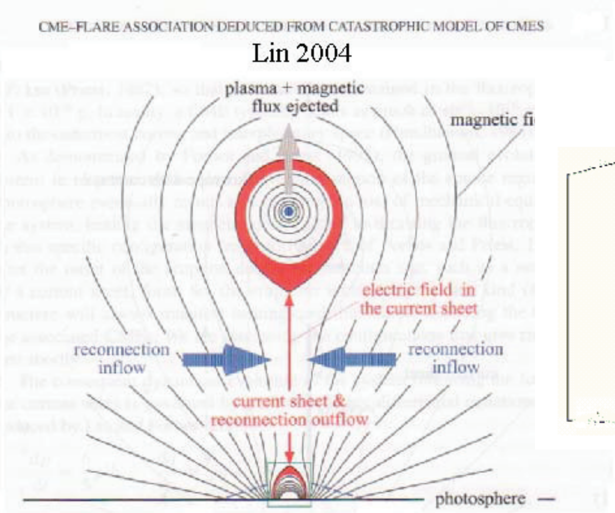
Now our aim is:

To find solar flare mechanism directly by MHD simulation in real active region.

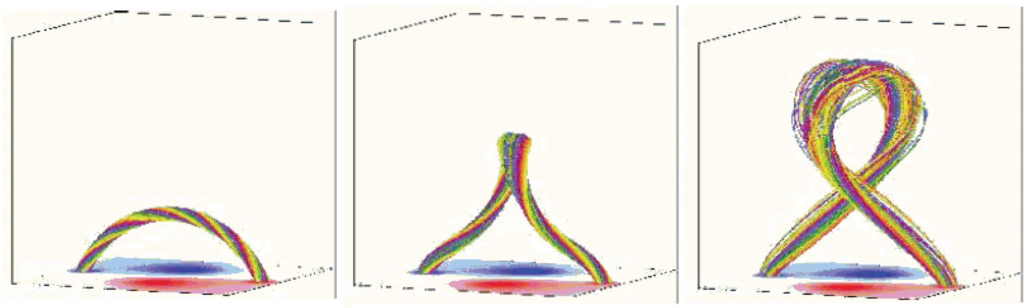
Earlier:

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

Examples of alternative models of the solar flare



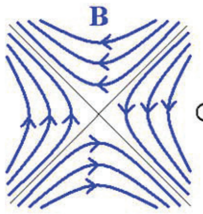
T. TÖRÖK AND B. KLIEM 2005

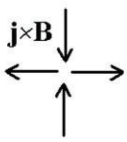


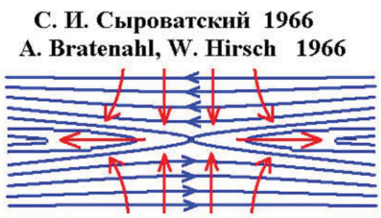
To our mind it is difficult to explain appearing of the rope.

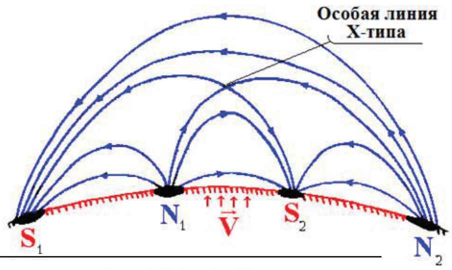
In any case to verify the validity of these models it is necessary to perform presented here MHD simulations for real active region.

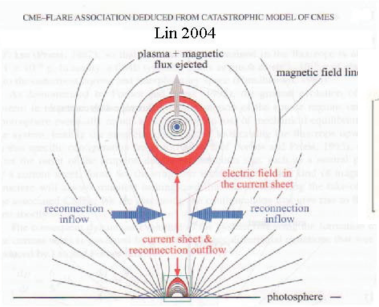
Flare meshanizms

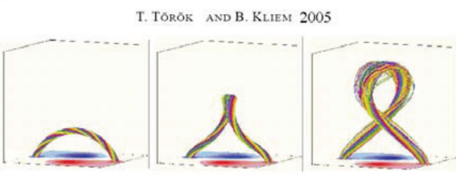


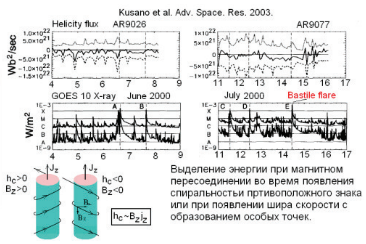


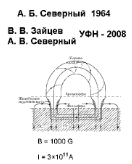


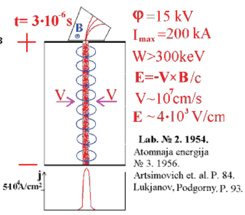




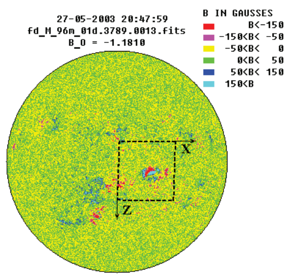


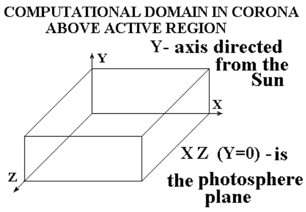






Now our aim is: To find solar flare mechanism directly by MHD simulation in real active region.



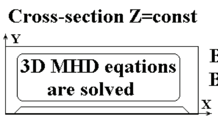


Photospheric boundary:

$B_{||}$ from calculated potential field for observed $B_{line-of-site}$

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

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



Nonphotospheric boundary:

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

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

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

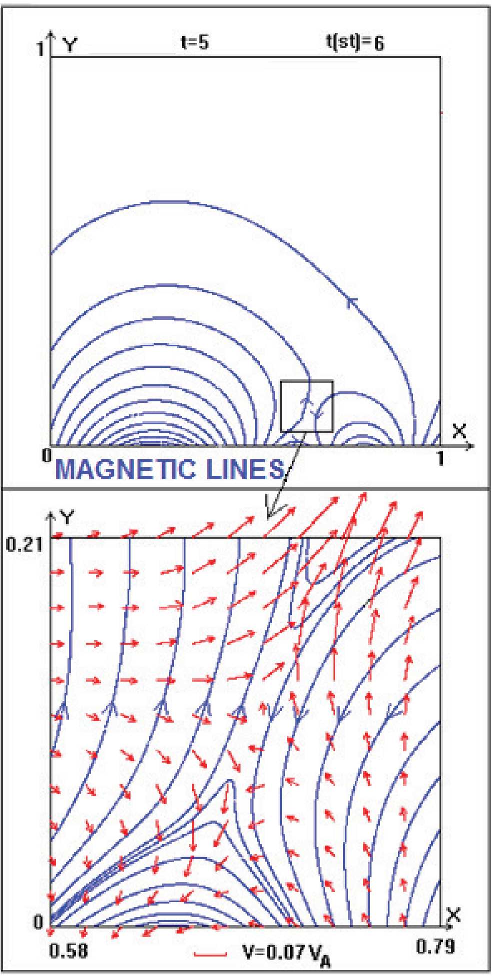
$\partial V/\partial n = 0$

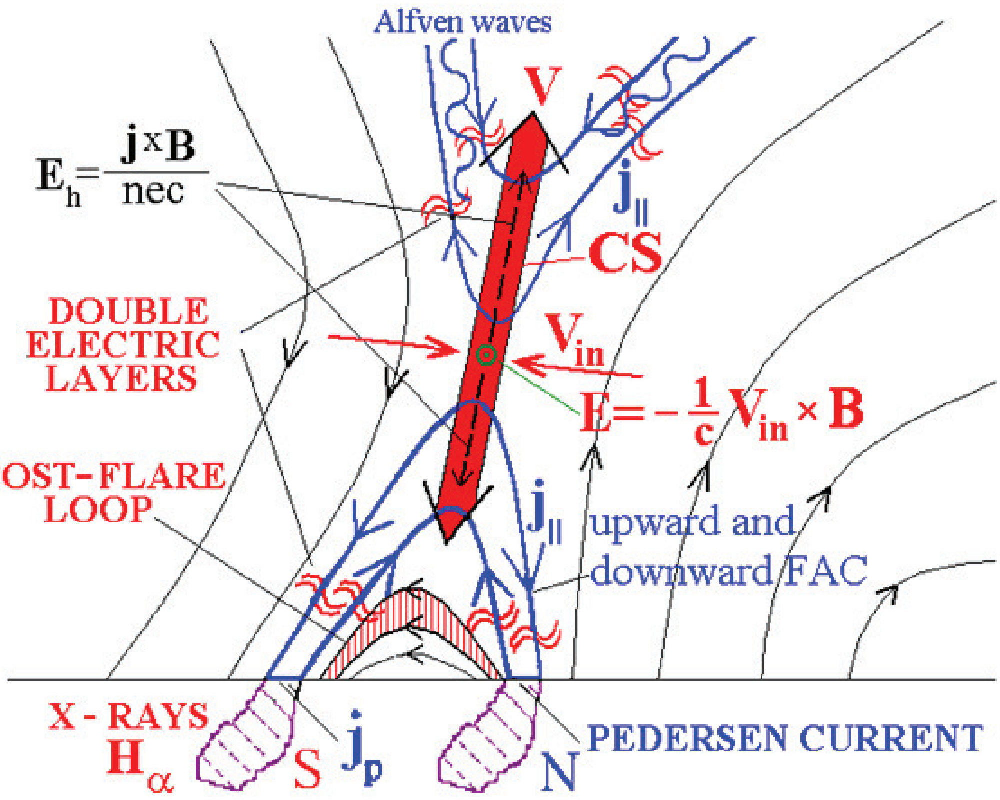
$\partial T/\partial n = 0$

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

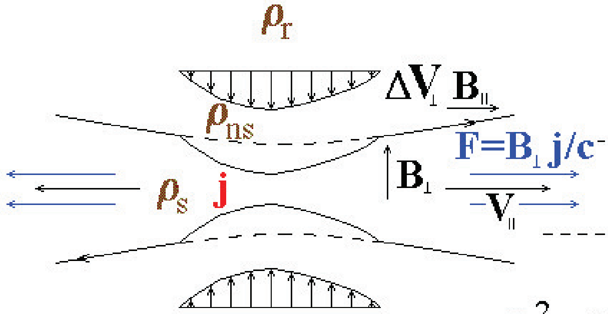
Electrodynamic model of solar flare

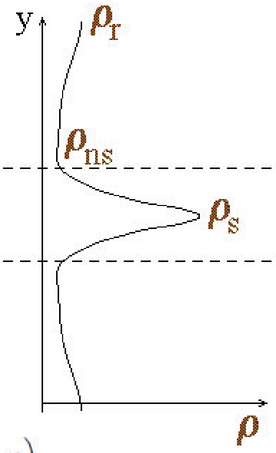
Igor M. Podgorny using results of measurements on the satellite Intercosmos-Bulgaria-1300





CURRENT SHEET INSTABILITY





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

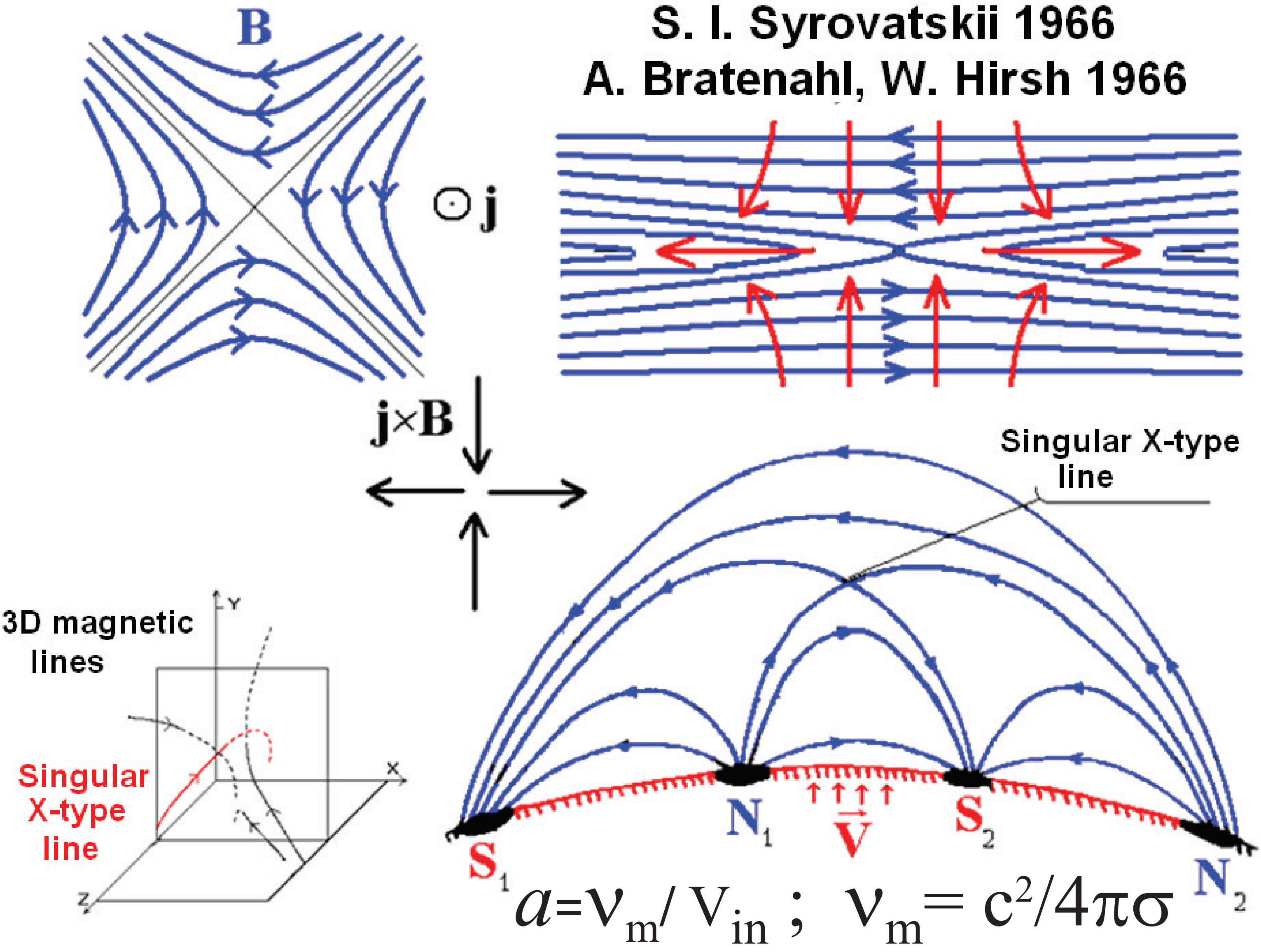
$$\begin{aligned}
\rho_s \frac{dD_V}{dt} &= -D_V A \rho_s + D_B \frac{B_s}{4\pi a} + V_{in1} K_I \frac{B_s h}{4\pi \nu_m} + \rho_1 \left(\frac{T_s}{b_1^2} - A^2 \right) \\
\rho_{ns} \frac{dV_{in1}}{dt} &= V_{in1} K_V \frac{\rho_{ns} V_{in0}}{a} - \rho_1 K_p \frac{T_s}{a} - D_B \frac{B_s}{4\pi} \\
\frac{d\rho_1}{dt}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

MAXIMAL INCREMENT OF CURRENT SHEET INSTABILITY:

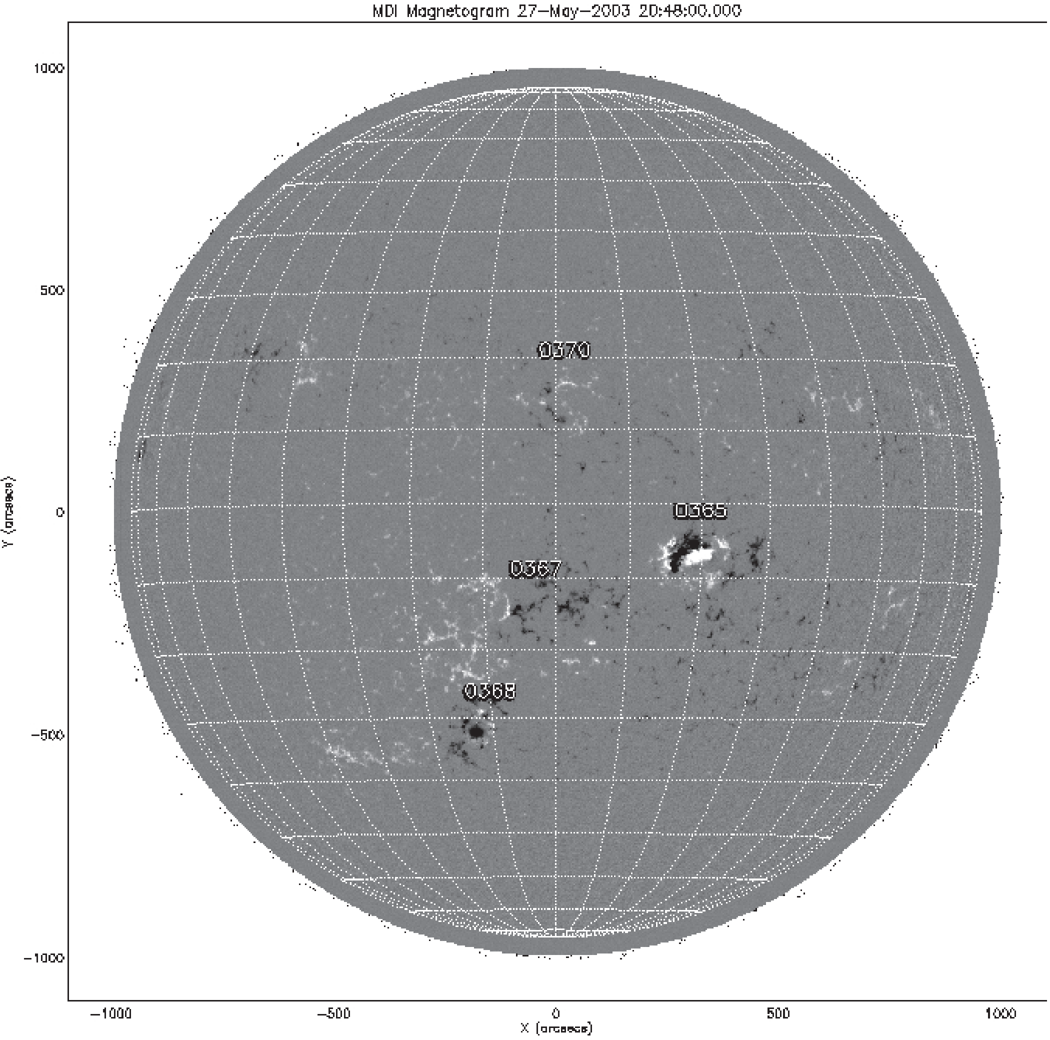
$$\gamma_{max} = \frac{1}{2} \mathrm{Re}_m{}^{-1} \varepsilon_v^{-2} + \sqrt{\left(\frac{1}{2} \mathrm{Re}_m{}^{-1} \varepsilon_v^{-2} \frac{\rho_r}{\rho_{ns}} \right)^2 + K_B \mathrm{Re}_m{}^{-1} \varepsilon_v^{-2} \left(\frac{\rho_r}{\rho_s} \right)^{1/2} - 2 \frac{\rho_r}{\rho_s}} - \sqrt{\frac{\rho_r}{\rho_s}}$$

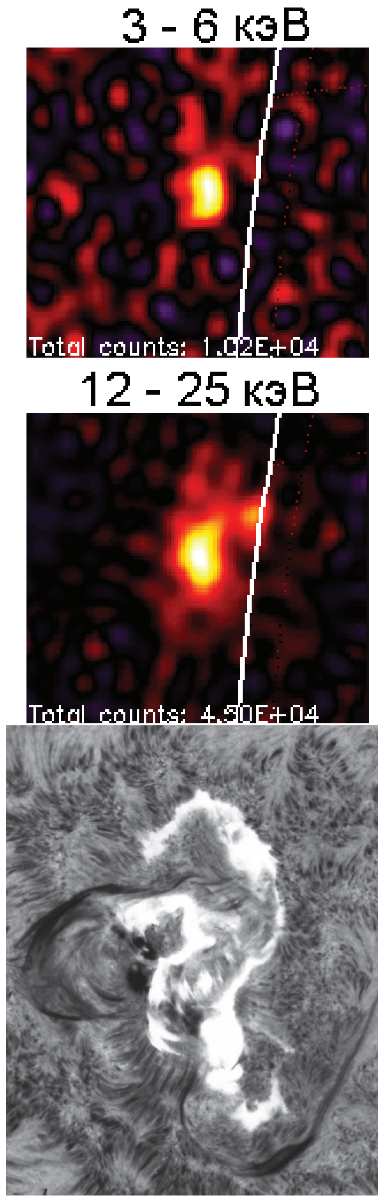
CONDITION OF CURRENT SHEET INSTABILITY $\gamma_{max} > 0$ **HAVE A FORM:**

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


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

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





SOLAR FLARE MODEL, MHD SIMULATIONS AND COMPARISON WITH OBSERVATIONS

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

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

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

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