MHD SIMULATIONS OF SOLAR FLARE AND COMPARISON WITH X-RAY OBSERVATIONS

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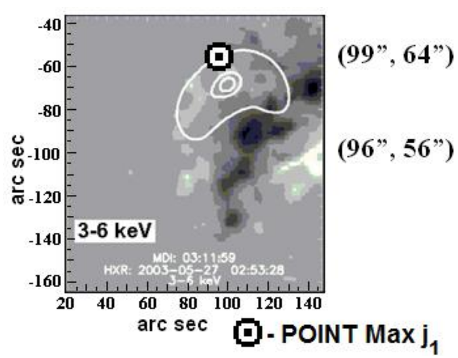
Bulgaria June 2016

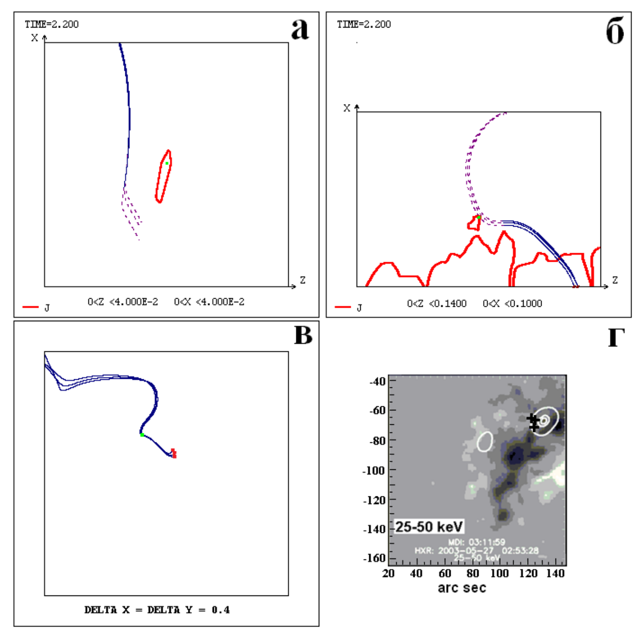
$$\frac{\partial \mathbf{B}}{\partial t} = \mathrm{rot}(\mathbf{V}\times\mathbf{B}) - \frac{1}{\mathrm{Re}_m}\mathrm{rot}\left(\frac{\sigma_0}{\sigma}\mathrm{rot}\mathbf{B}\right)$$

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

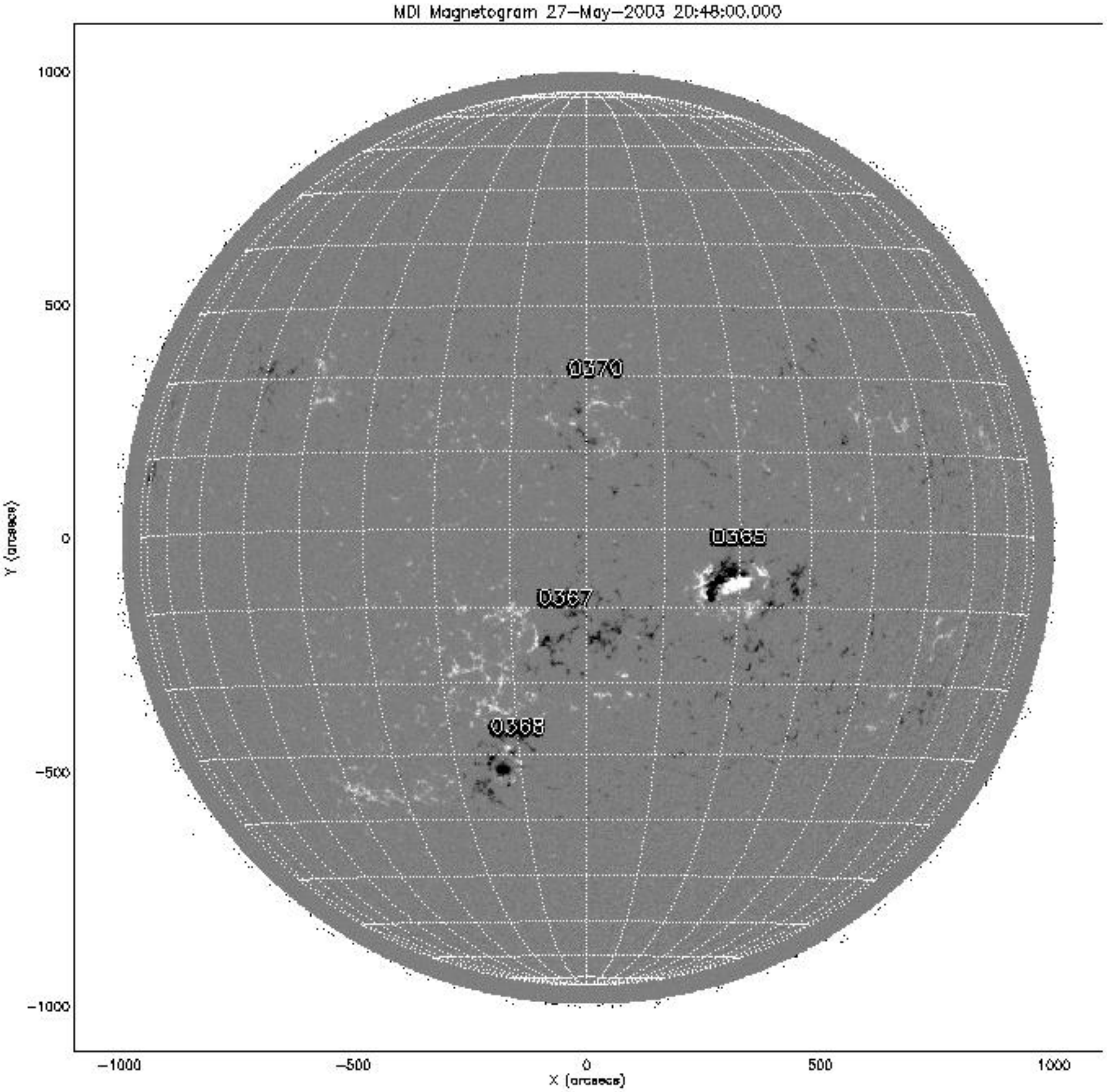
$$\frac{\partial \mathbf{V}}{\partial t} = -(\mathbf{V},\nabla)\mathbf{V} - \frac{\beta}{2\rho}\nabla(\rho T) - \frac{1}{\rho}(\mathbf{B}\times\mathrm{rot}\mathbf{B}) + \frac{1}{\mathrm{Re}\rho}\Delta\mathbf{V} + G_g\mathbf{G}$$

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

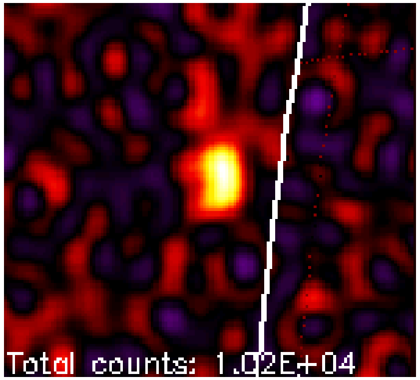




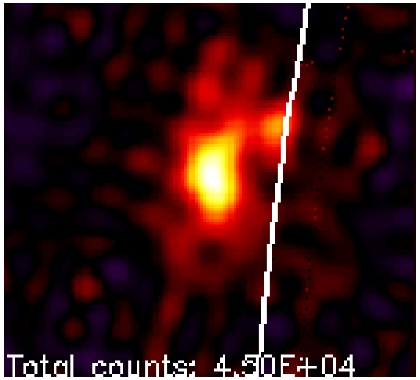
SOLAR FLARE OCCURS IN THE SOLAR CORONA ON HEIGHTS 15 - 30 THOUSANDS KILOMETERS, WHICH IS 1/40 – 1/20 OF SOLAR RADIUS.

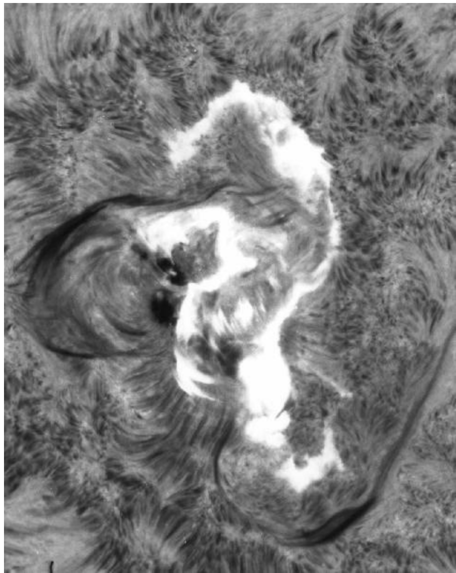


3 - 6 кэВ

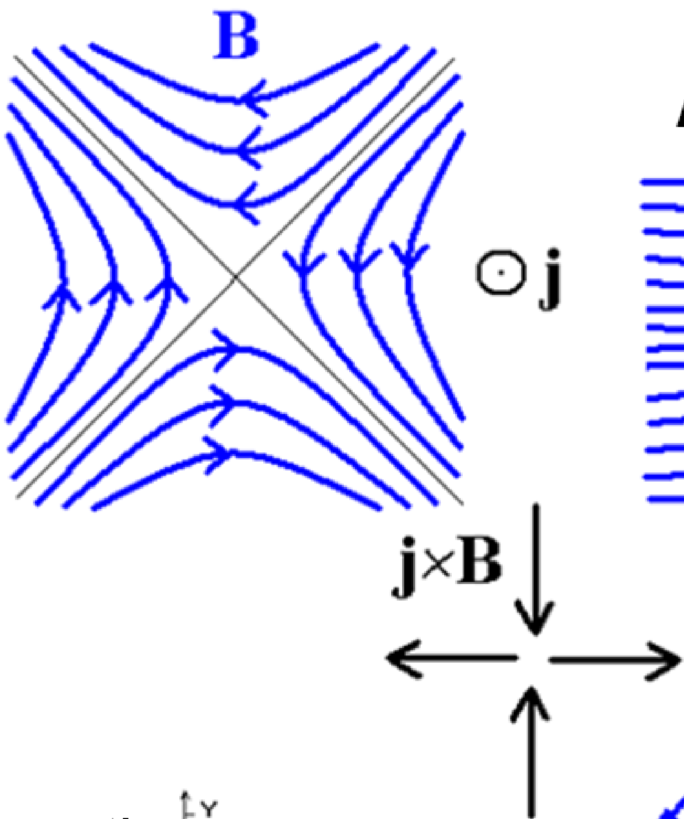


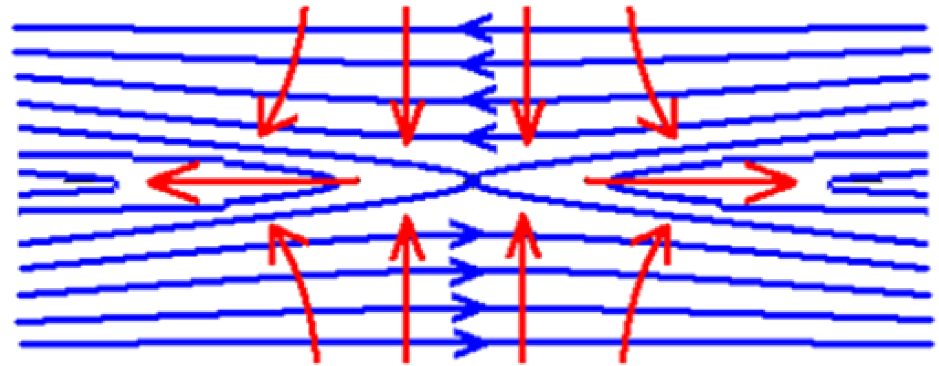
12 - 25 кэВ

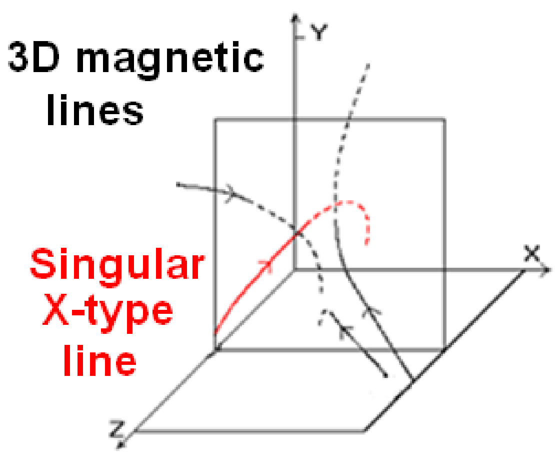


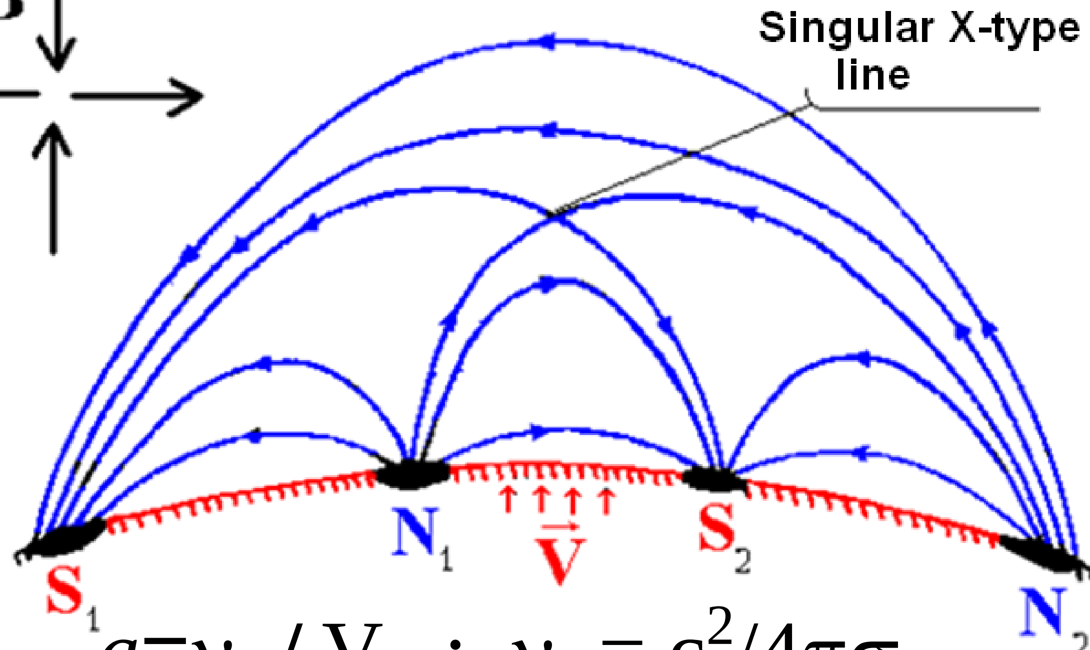


S. I. Syrovatskii 1966
A. Bratenahl, W. Hirsh 1966







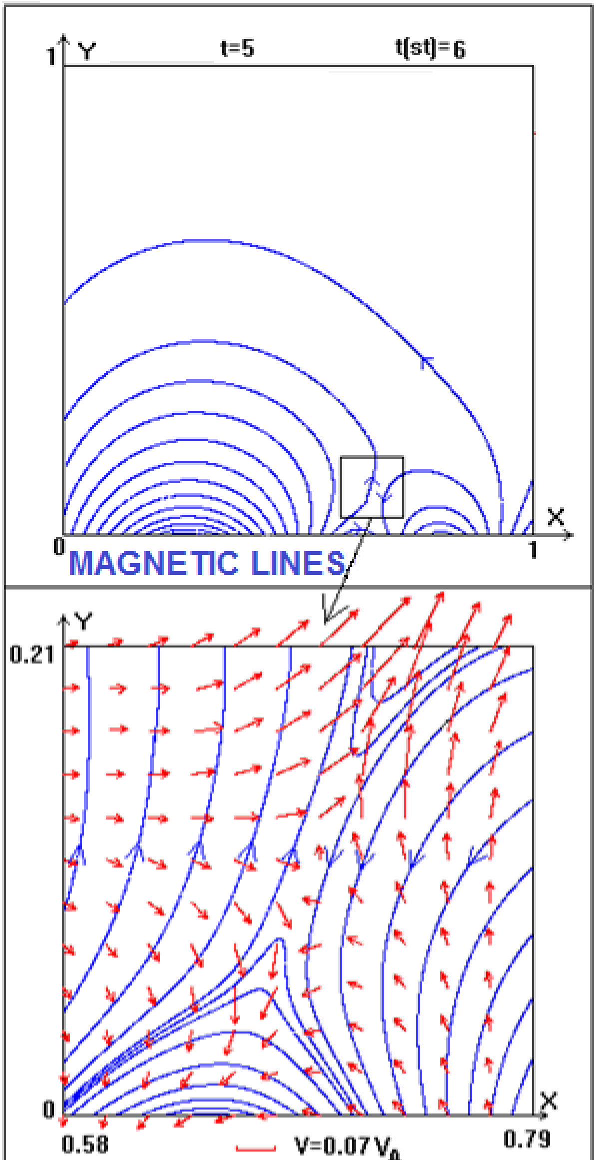


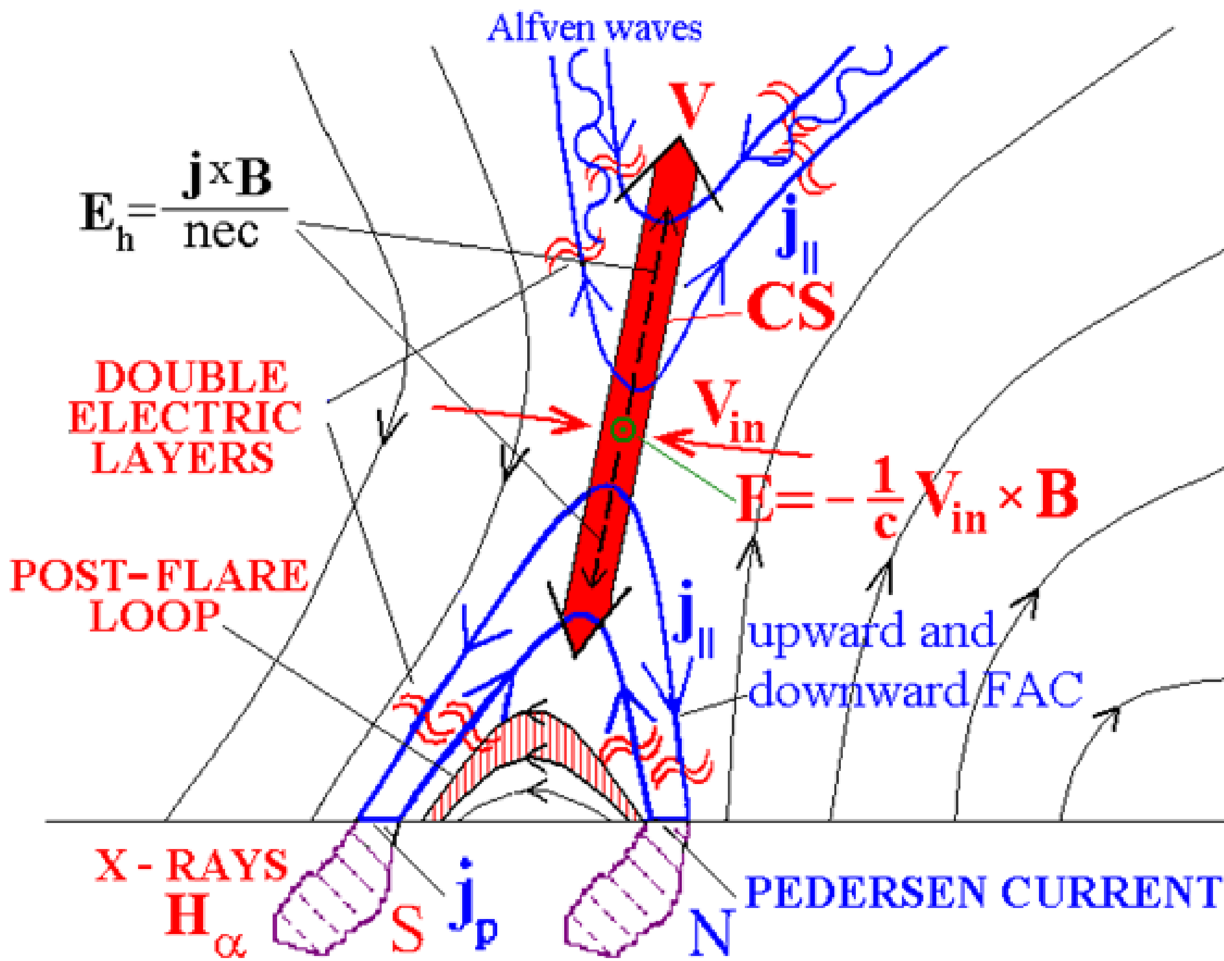
$$a = \nu_m / V_{in}\ ;\ \ \nu_m = c^2/4\pi\sigma$$

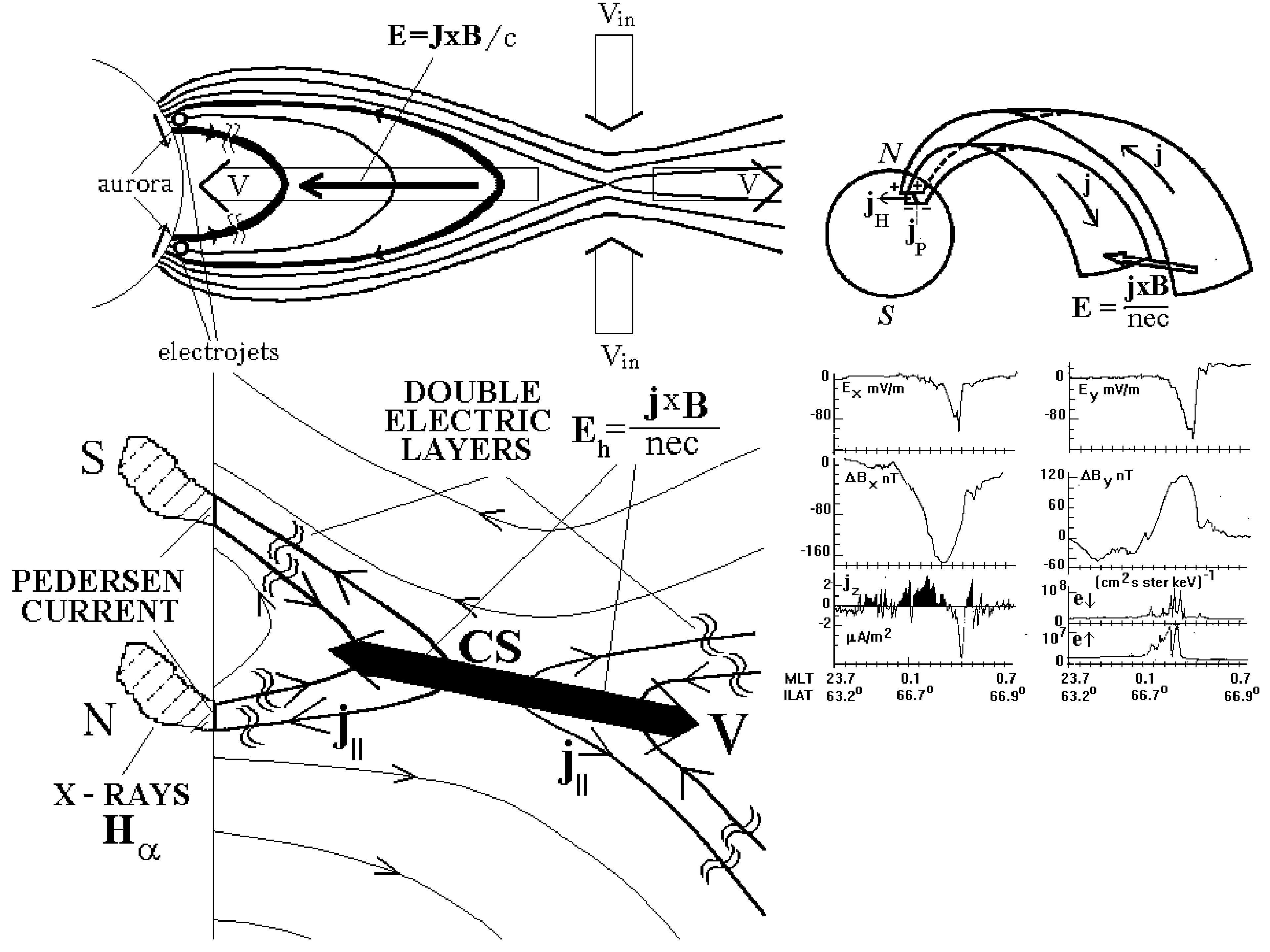
After the quasi-steady evolution the current sheet transfers into an unstable state. As a result, explosive instability develops, which cause the flare energy release.

Electrodynamic model of solar flare

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

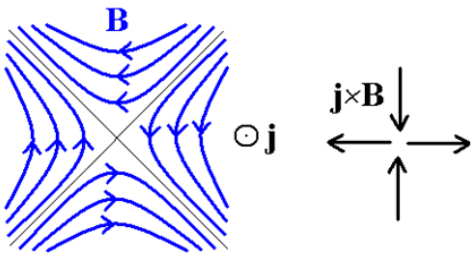


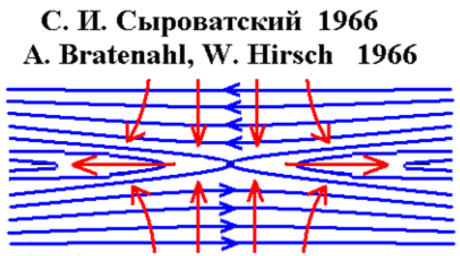


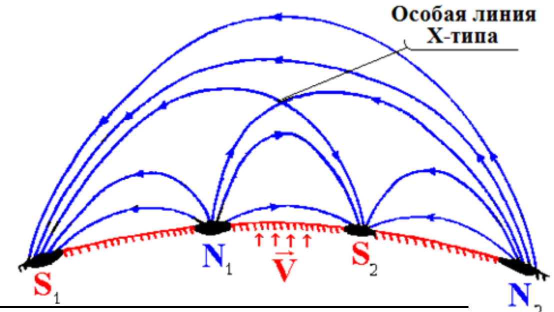


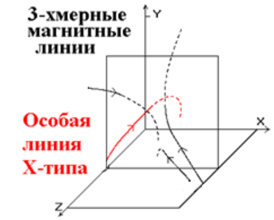
V_{in}
E=JxB/c
aurora
V
V
electrojets
V_{in}
N
j
j
j_H
j_P
S
$E = \frac{jxB}{nec}$
DOUBLE
ELECTRIC
LAYERS
$E_h = \frac{jxB}{nec}$
S
PEDERSEN
CURRENT
CS
N
$j_\parallel$
$j_\parallel$
V
X - RAYS
H_α
E_x mV/m
E_y mV/m
ΔB_x nT
ΔB_y nT
j_z
$\mu A/m^2$
$(cm^2 s\ ster\ keV)^{-1}$
e↓
e↑
MLT 23.7 0.1 0.7
ILAT 63.2° 66.7° 66.9°
23.7 0.1 0.7
63.2° 66.7° 66.9°

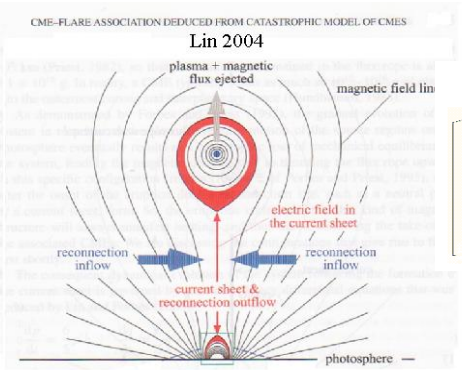
Flare meshanizms

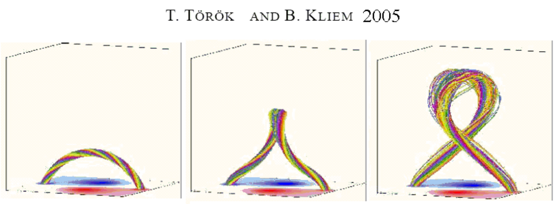


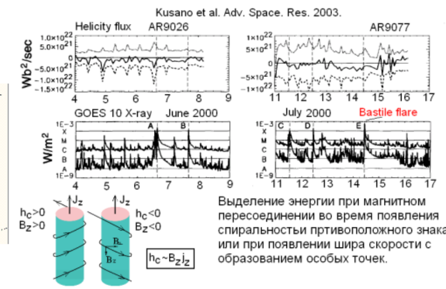


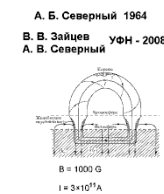


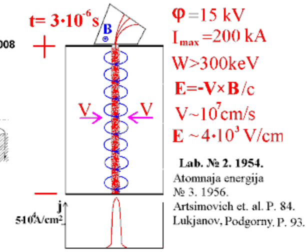




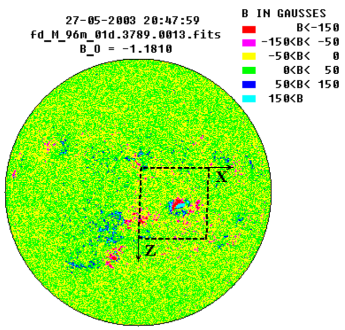


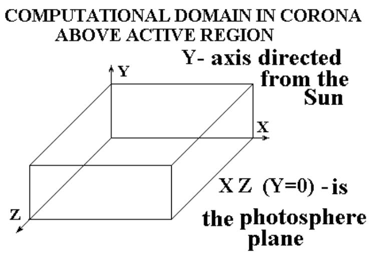






Now our aim is: To find solar flare mechanism directly by MHD simulation in real active region.





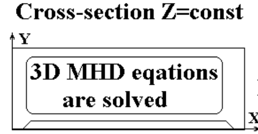
Photospheric boundary:

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

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

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

Cross-section Z=const



Nonphotospheric boundary:

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

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

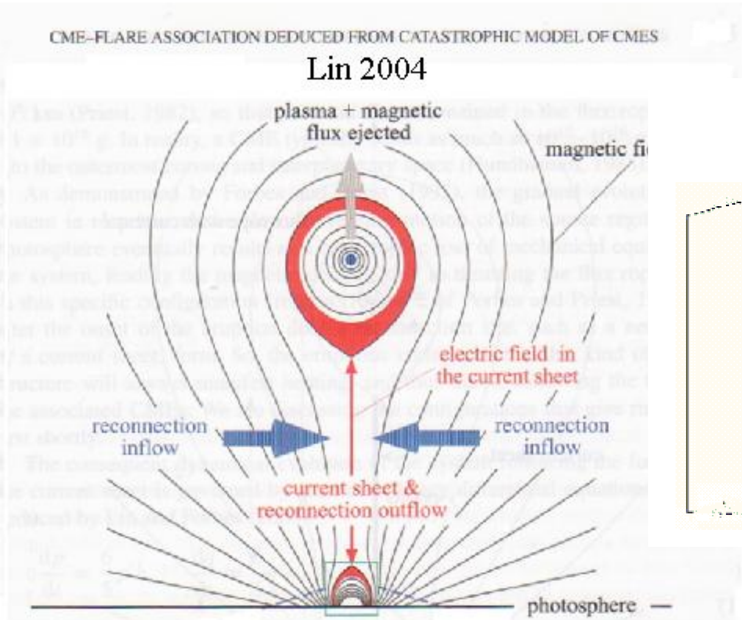
$\partial\rho/\partial n = 0$

$\partial V/\partial n = 0$

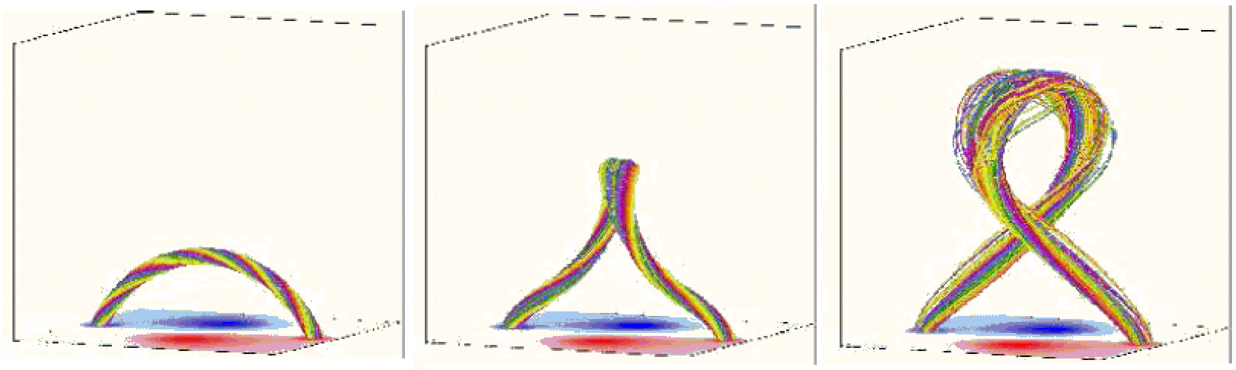
$\partial T/\partial n = 0$

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

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.

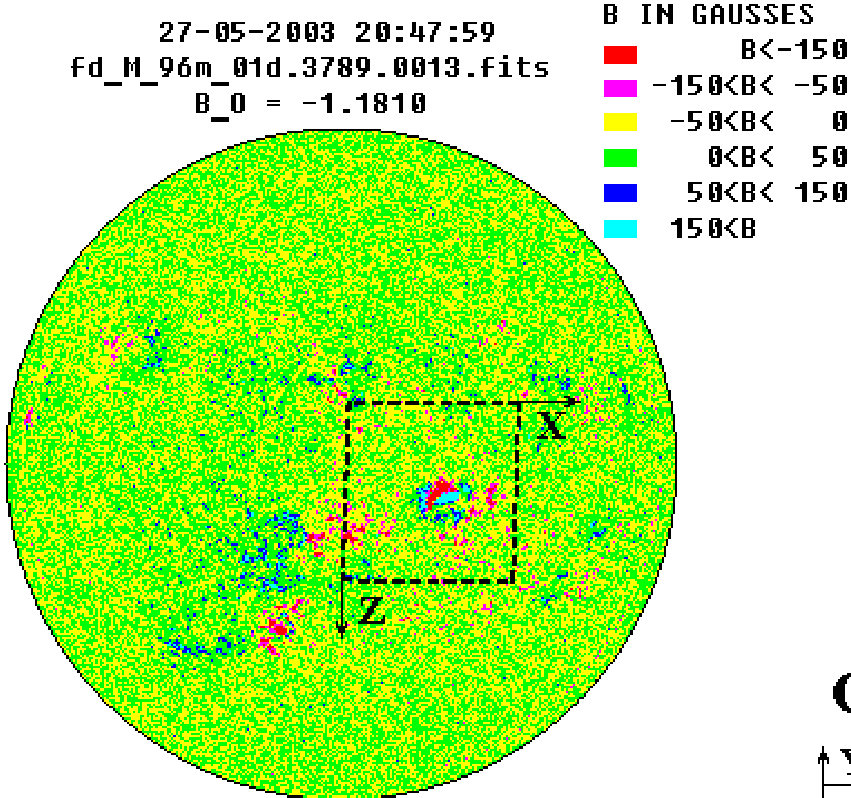
In any case to verify the validity of these models it is necessary to perform presented here MHD simulations for real active region.

Now our aim is:

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

Earlier:

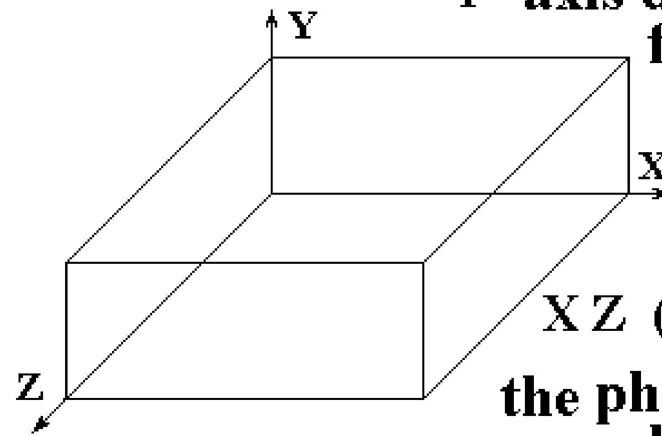
Hypothesized the mechanism of the solar flare, which is then tested.



--- REGION IN PICTURE PLANE

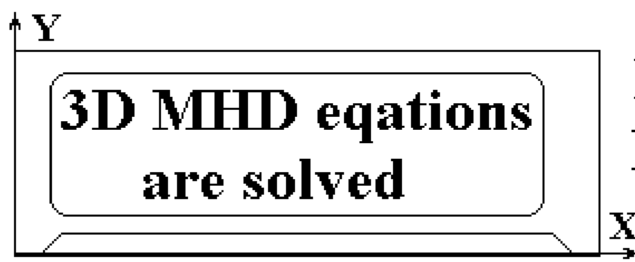
COMPUTATIONAL DOMAIN IN CORONA ABOVE ACTIVE REGION

Y- axis directed from the Sun



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

Cross-section Z=const



Nonphotospheric boundary:

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

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

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

$\partial V/\partial n = 0$

$\partial T/\partial n = 0$

Photospheric boundary:

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

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

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

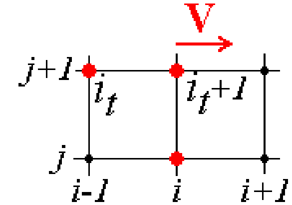
Cosmic Research 35, 35, 1997; 35, 235, 1997; 36, 492, 1998

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.

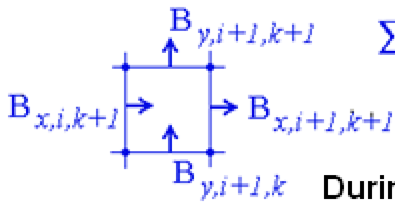
In the PERESVET program:



- 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).

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

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



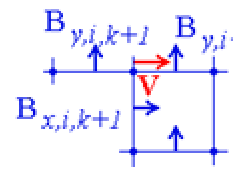
$$\Sigma B_n \Delta S = 0$$

Equivalency of equations

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

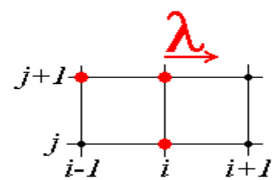
During dissipation relaxation of magnetic field, the current density $[\mathrm{rot}\,\mathbf{B}] \rightarrow 0$

- Nonsymmetrical (upwind) approximation V×B.



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

Other methods:



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

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

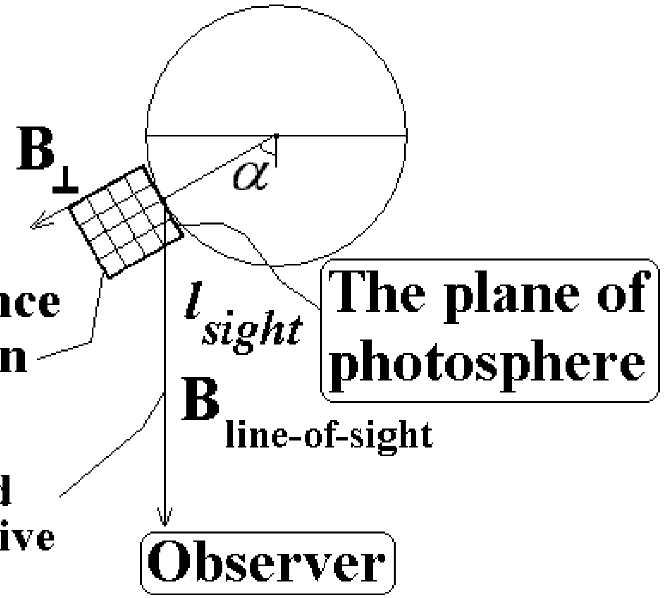
- The special methods are used to obtain high order approximation (FCT, TVD)
- Also Lagrangian schemes with further recalculation by interpolation on each step.
- Some schemes are also conservative relative to magnetic flux [divB]=0, but with symmetrical approximation V×B.

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

Initial potential magnetic field

$$\mathbf{B} = \nabla \varphi_{\mathrm{m}}$$

$$\Delta \varphi_{\mathrm{m}} = 0$$ is solved using finite-difference scheme in the region



Boundary condition on the plane of photosphere:

$$\frac{\partial \varphi_{\mathrm{m}}}{\partial l_{sight}} = B_{\text{line-of-sight}}$$ - inclined derivative

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

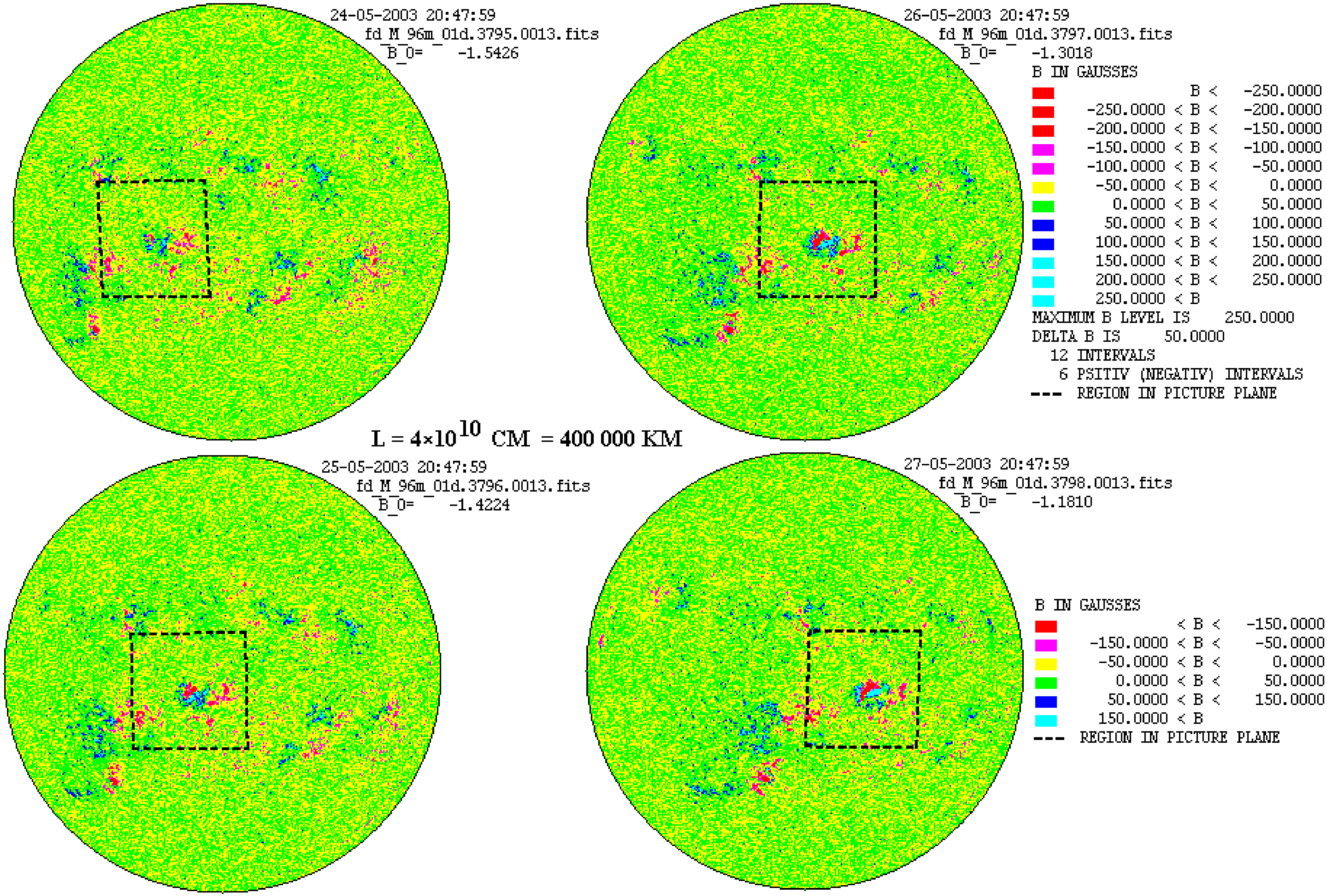
$$[\mathrm{rot}]\mathbf{B}=0 \quad [\mathrm{div}]\mathbf{B}=0$$

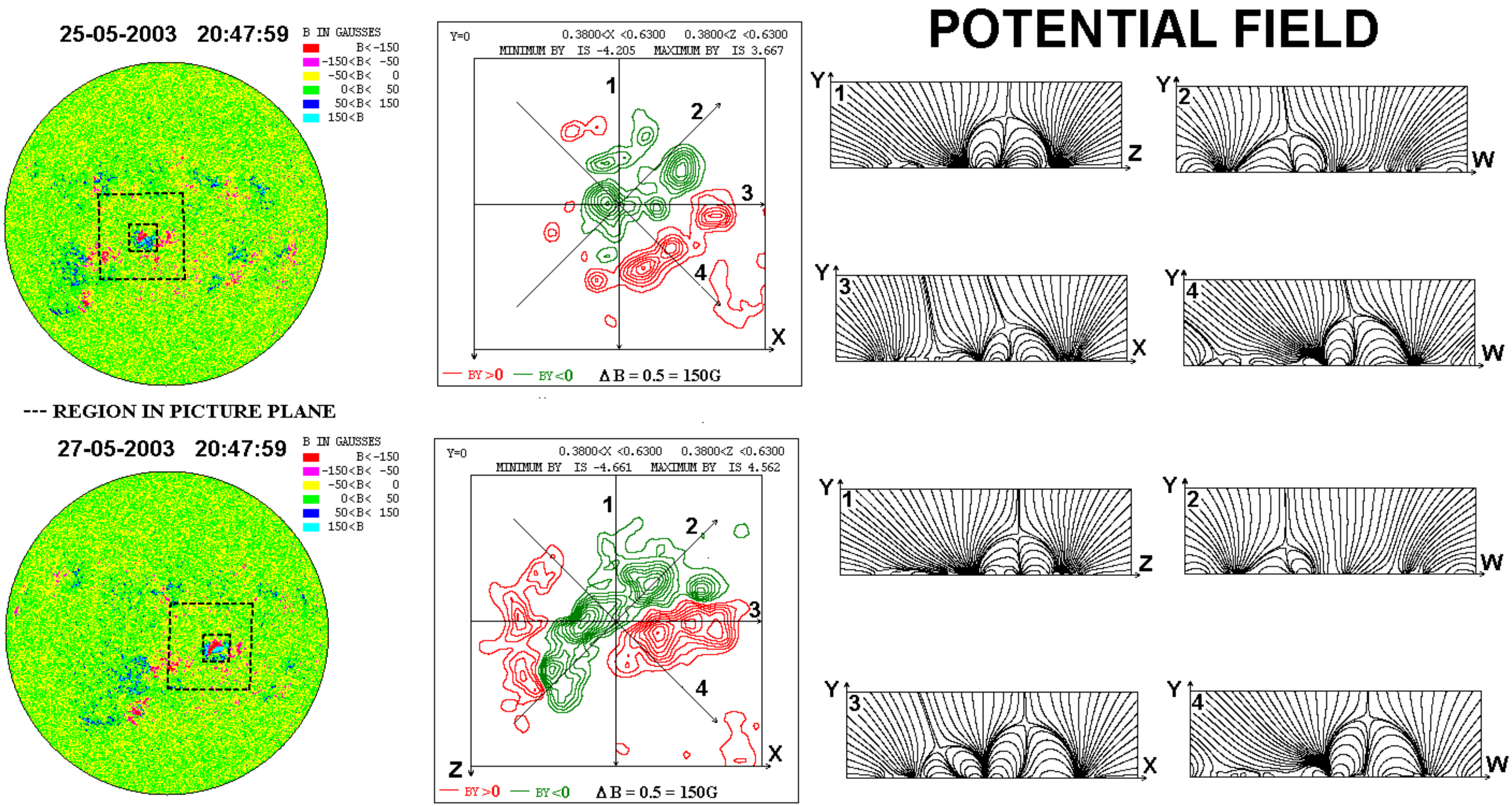
2 methods of $\Delta \varphi_{\mathrm{m}}=0$ solution:

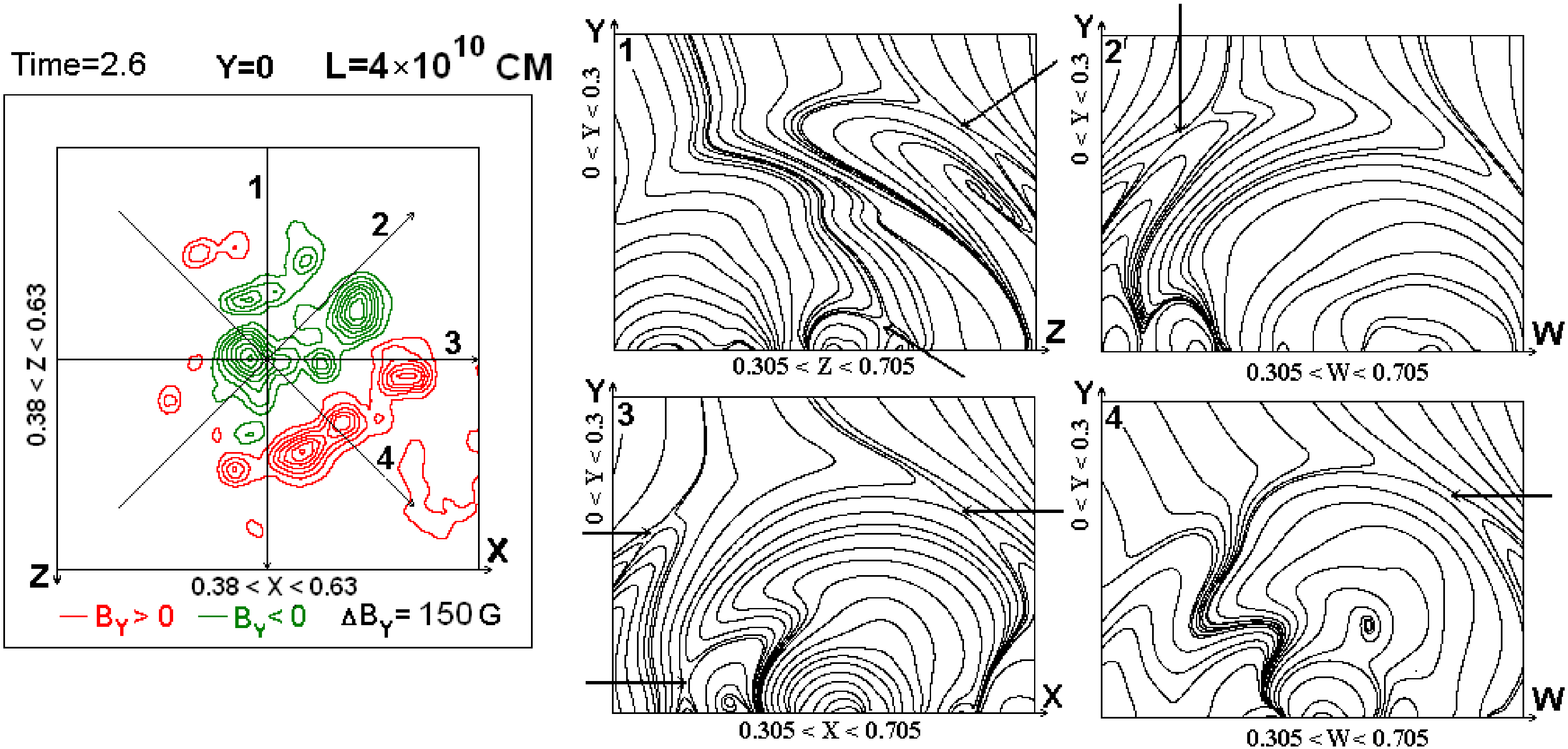
1. $\Delta \varphi_{\mathrm{m}}=0$ **directly by iterations**
2. **By relaxation of diffusion equation** $\frac{\partial \varphi_{\mathrm{m}}}{\partial t} = \Delta \varphi_{\mathrm{m}}$

SET OF FLARES MAY 27, 2003

AR 0365




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

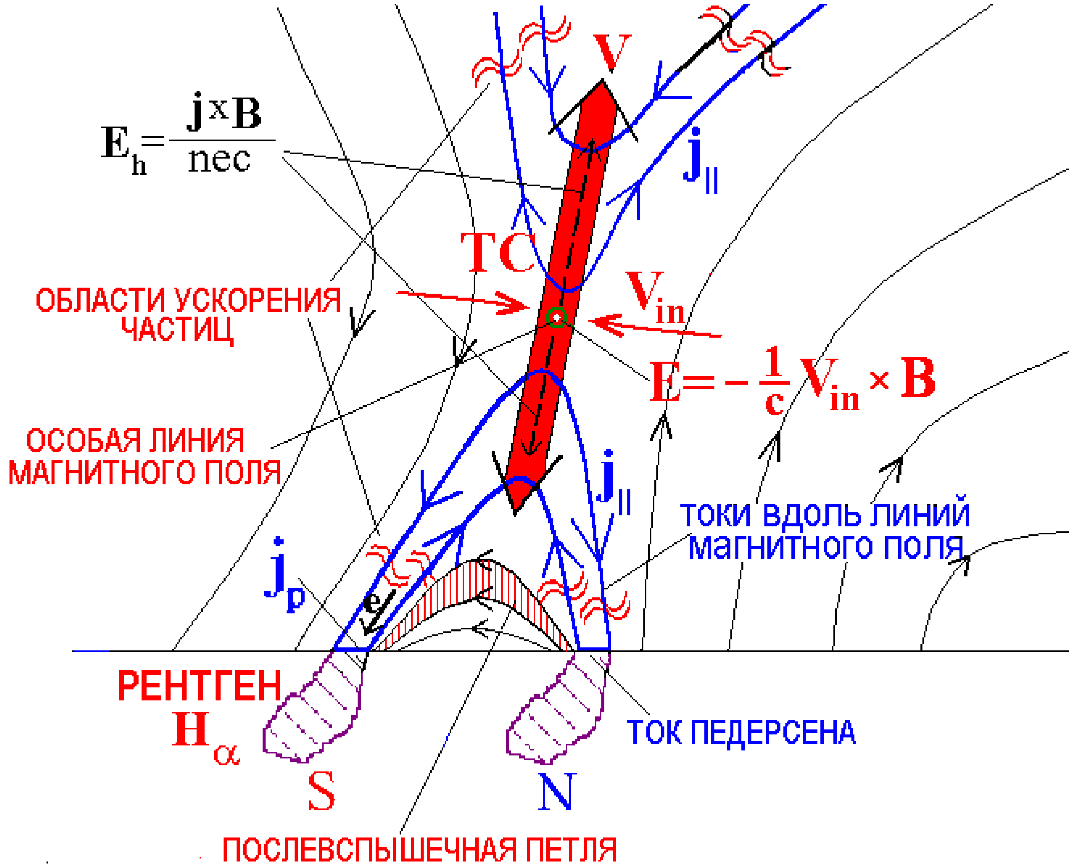


Time=2.6
Y=0
L=4×10^10 CM
0.38 < Z < 0.63
0.38 < X < 0.63
B_Y > 0
B_Y < 0
ΔB_Y = 150 G
1
2
3
4
X
Z
Y
W
0 < Y < 0.3
0.305 < Z < 0.705
0.305 < W < 0.705
0.305 < X < 0.705

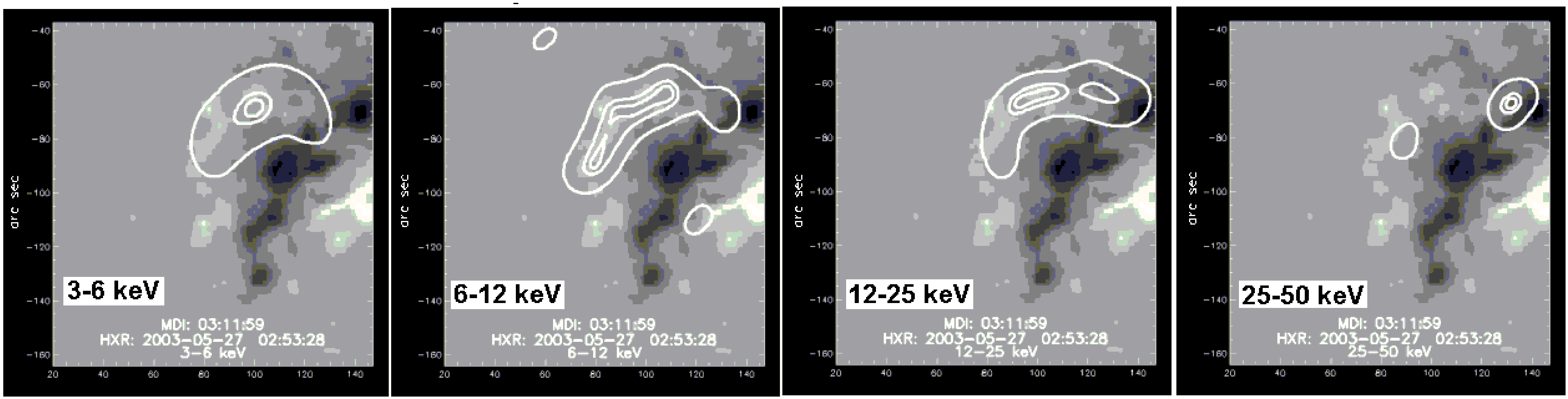
In spite of using specially developed numerical methods, the calculations are fulfilled rather slowly. So, to perform simulation on the personal computer (double core processor 1.6 GHz), the time scale must be strongly reduced.

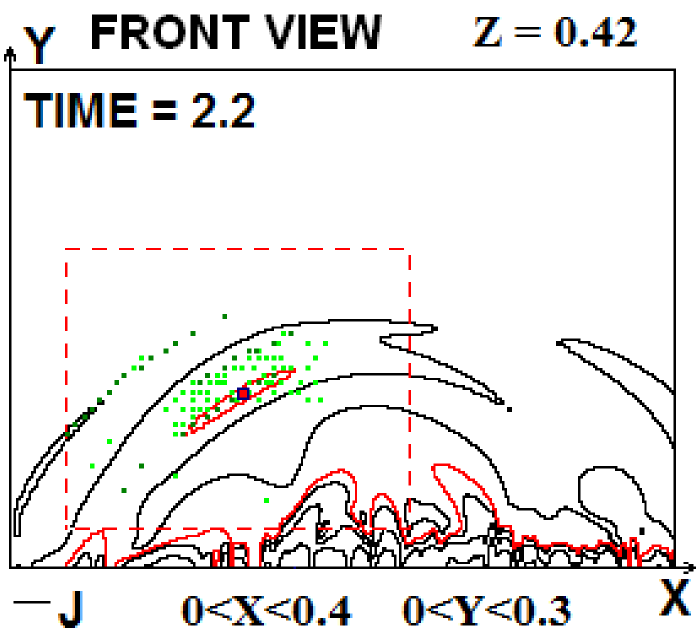
The firs results of real time simulation during several minutes evolution above the real active region after all modernizations of numerical methods show that to calculate during several days the active region evolution during one day it is necessary to have supercomputer which calculates 100 times faster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

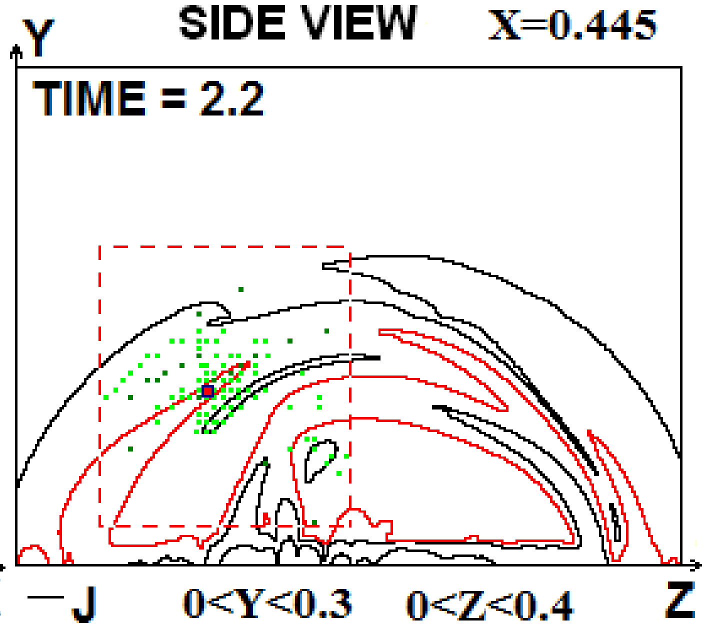
To use the simulations for improving the solar flare prognosis the simulated evolution must be faster than real active region evolution, so it should be used supercomputer 10^4 times faster than personal computer.

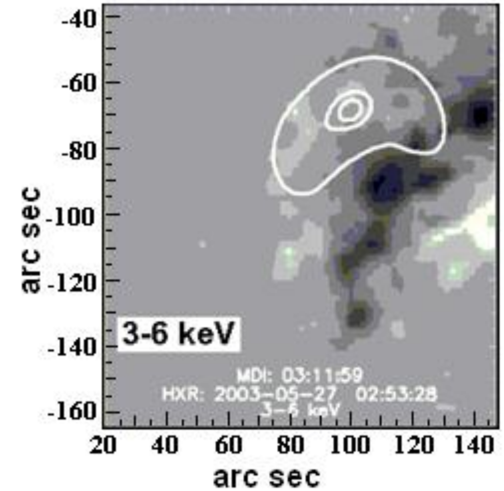


The graphical system of search of current sheet positions is created to compare with observed positions of thermal X-ray emission.





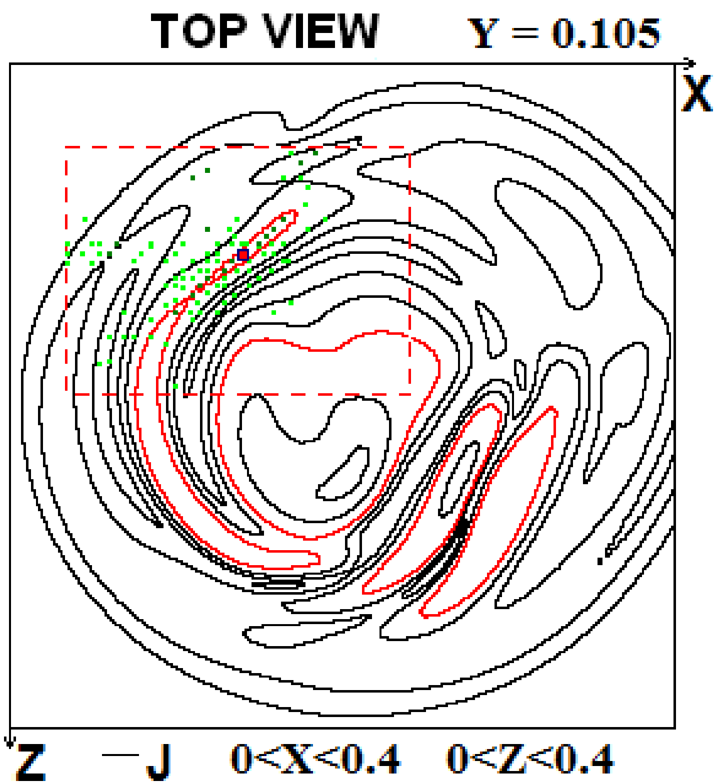


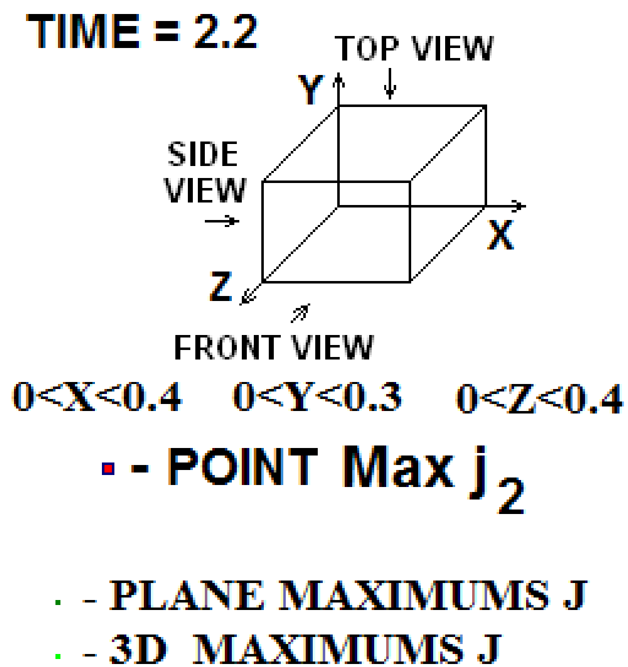


FLARE

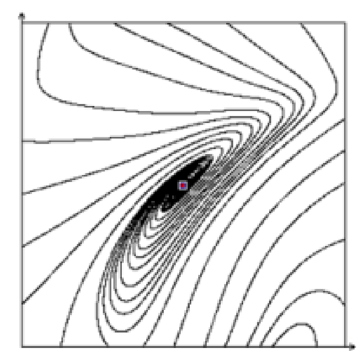
27 May 2003 02:40

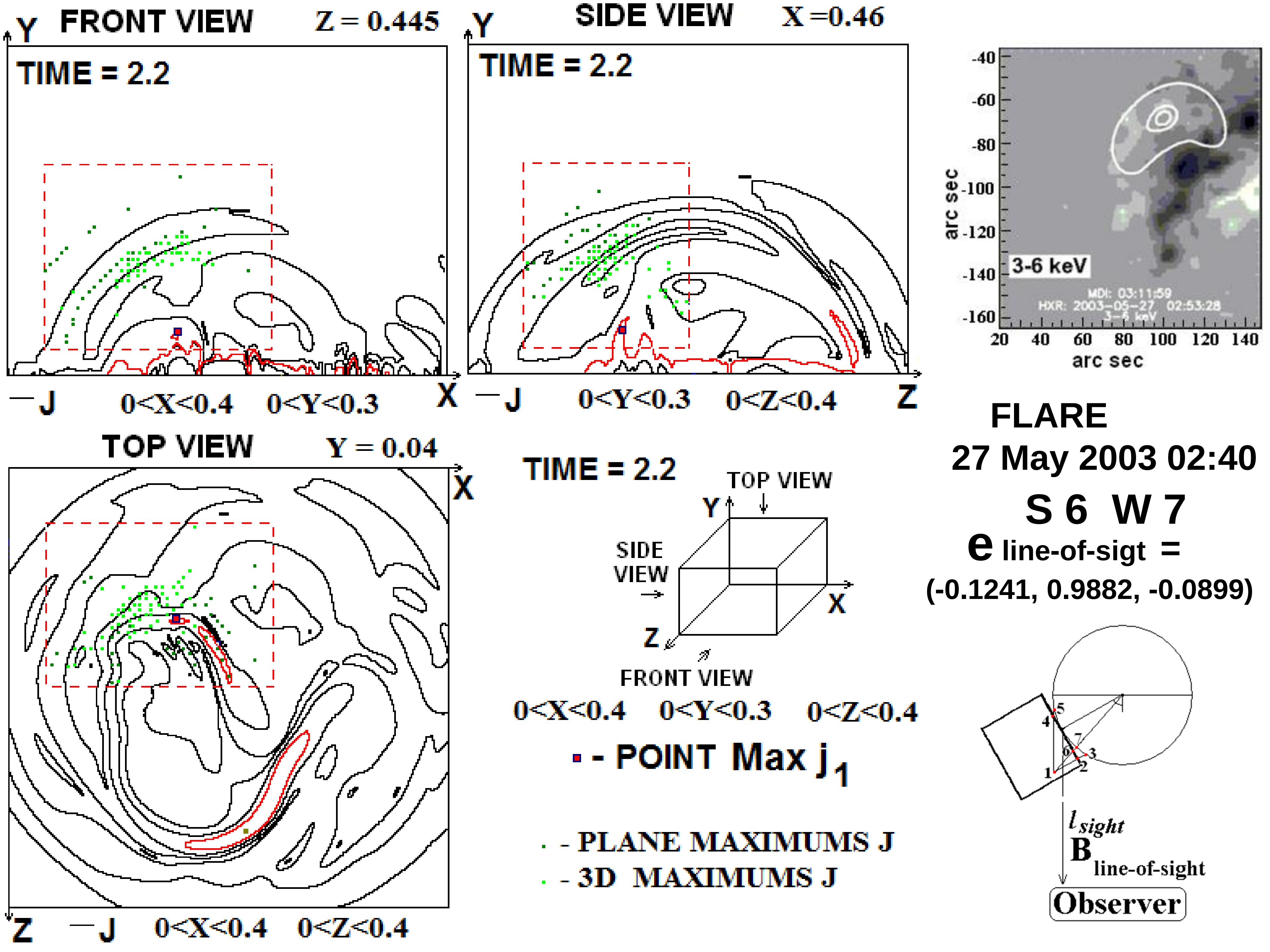
S 6 W 7

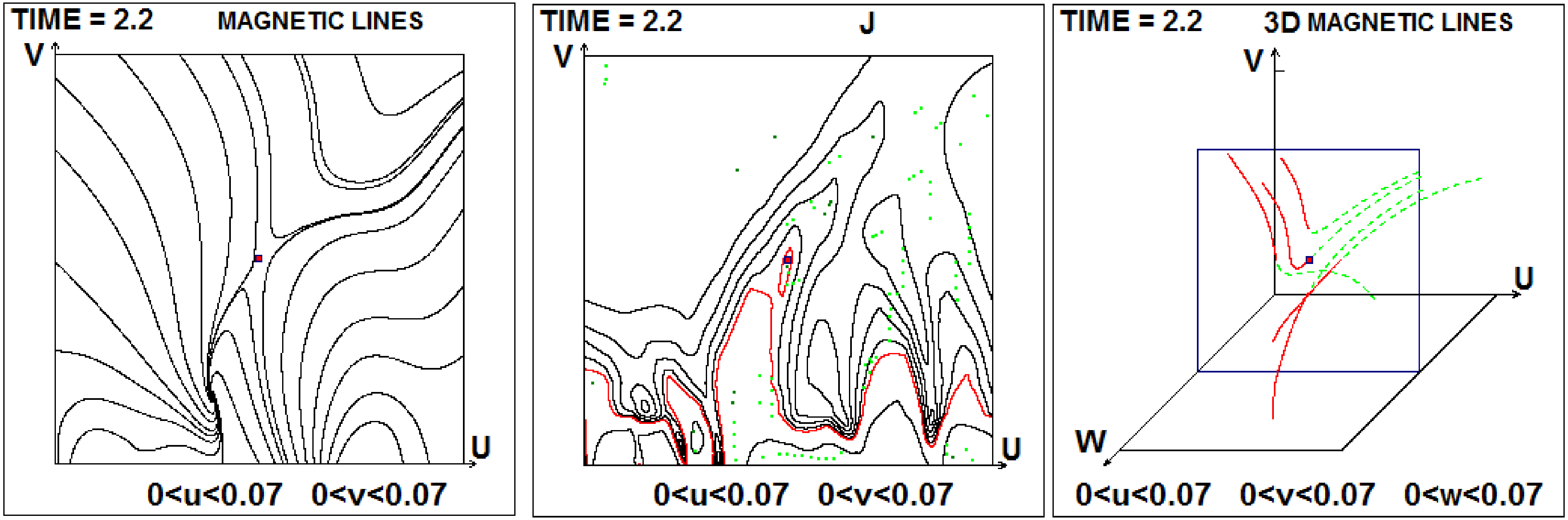




e line-of-sigt = (-0.1241, 0.9882, -0.0899)



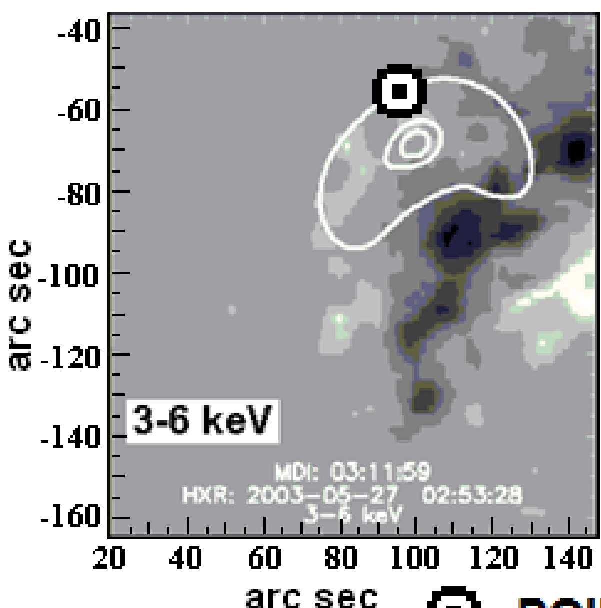

FRONT VIEW
Z = 0.445
TIME = 2.2
— J
0<X<0.4
0<Y<0.3
SIDE VIEW
X =0.46
TIME = 2.2
— J
0<Y<0.3
0<Z<0.4
3-6 keV
MDI: 03:11:59
HXR: 2003-05-27 02:53:28
3-6 keV
arc sec
arc sec
TOP VIEW
Y = 0.04
— J
0<X<0.4
0<Z<0.4
TIME = 2.2
TOP VIEW
SIDE VIEW
FRONT VIEW
0<X<0.4 0<Y<0.3 0<Z<0.4
- POINT Max j1
- PLANE MAXIMUMS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



- B-VEC = (-0.179 -0.066 -0.093)
XYZ-POINT Max j_1 = (0.46 0.04 0.445)

▪ - POINT Max j_1

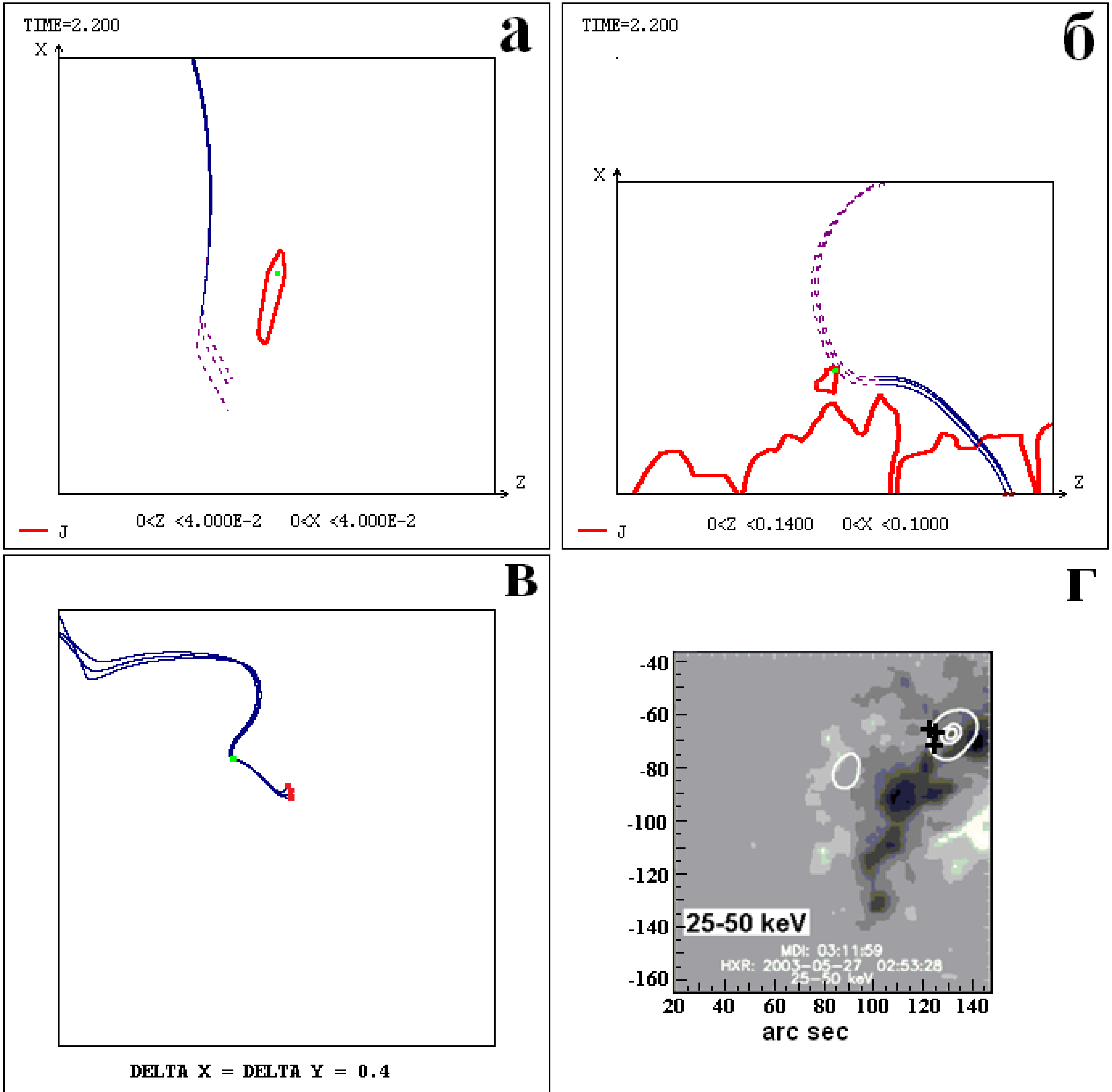
. - PLANE MAXIMUMS J . - 3D MAXIMUMS J



(99”,-64”) – position of thermal X-ray emission source

(96”,-56”) – current sheet position obtained by numerical MHD simulation

⊙ - POINT Max j_1



The points on the magnetic lines are situated at 0.007 dimensionless units (~ 3000 km) from the center of the current sheet.

The coordinates of the points of intersection of these magnetic lines with the photosphere on the picture plane are (124.0 "-70.79"), (124.1 "-68.40") and (123.1, "-65.88"); and the coordinates of the most powerful X-ray source is ("131 , -67 ").

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.

To study the physical processes during solar flares and for development 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!