MECHANISM OF SOLAR FLARE BASED ON ENERGY STORAGE IN THE MAGNETIC FIELD OF THE CURRENT SHEET

I.M. Podgorny (INASAN), A.I. Podgorny (FIAN)

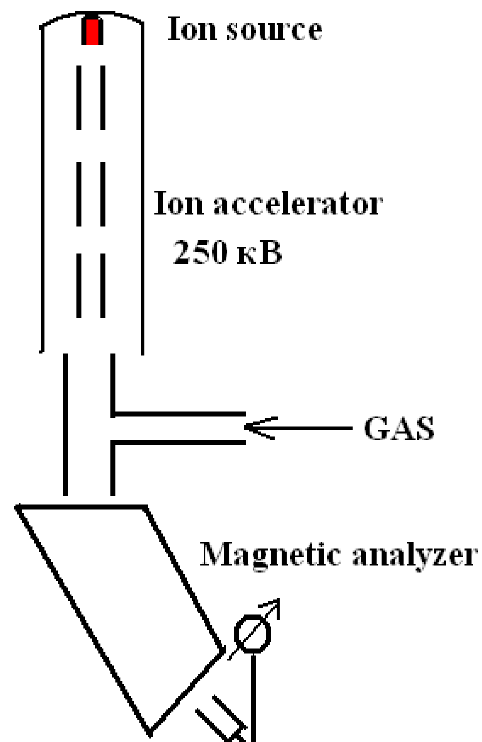
Understanding the solar flare mechanism, which makes it possible to establish a flare situation in the solar corona when using numerical MHD simulations and find a place for the accumulation of magnetic energy for a solar flare, can improve the forecast quality of solar flares, which have a significant impact on the Earth's space environment. The appearance of a flare in the corona at altitudes of 15 000 to 30 000 km is explained by the accumulation of energy in the magnetic field of the current sheet, which is created in the vicinity of X-type singular. Based on the mechanism of energy release in the current sheet, using the results of numerical simulation and observations, the electrodynamic model of a solar flare is proposed, explaining its main observable manifestations. The hard X-ray emission is caused by the electrons bremsstrahlung in the chromosphere, which are accelerated in field-aligned currents generated by the Hall electric field. To study the flare situation, numerical MHD simulation was performed in corona above the real active region. At setting the conditions of simulation, no assumptions were done about the flare mechanism. The simulation shows the appearance of a current sheet whose position coincides with the position of the observed source of thermal X-ray emission. For more accurate simulation in real scale of time, the parallelizing of calculations is currently underway on a supercomputer specially assembled for solving this task based on the Tesla M2050 multiprocessor GPU graphics card.

Igor Maximovich Podgorny (May 11, 1925 – October 4, 2018) is the Soviet and Russian physicist and astronomer. He is the participant of the Great Patriotic War. After graduating from Kharkov State University in 1951, he worked until 1967 at the Kurchatov Institute of Atomic Energy. He was the head of the laboratory. From 1967 to 1992, he worked at the Space Research Institute, first as a senior researcher, and then head of the department. Since 1992, he is leading researcher at the Institute of Astronomy, RAS. Doctor of Physical and Mathematical Sciences (1969), Professor (1990). He has lectured at the Moscow State University and the Moscow Institute of Physics and Technology. His students are famous scientists of Russia and many countries of the world. He is the author of more than three hundred works on laboratory and cosmic plasma physics, solar physics and cosmic rays. He has published four books, including Topics in plasma diagnostic (Plenum Press, 1967). He is winner of the Lenin Prize, he was awarded gold and two silver medals of the Exhibition of Achievements of National Economy. He was awarded the Order of Glory (Order of St. George the Victorious) and the Order of the Patriotic War of the first degree.

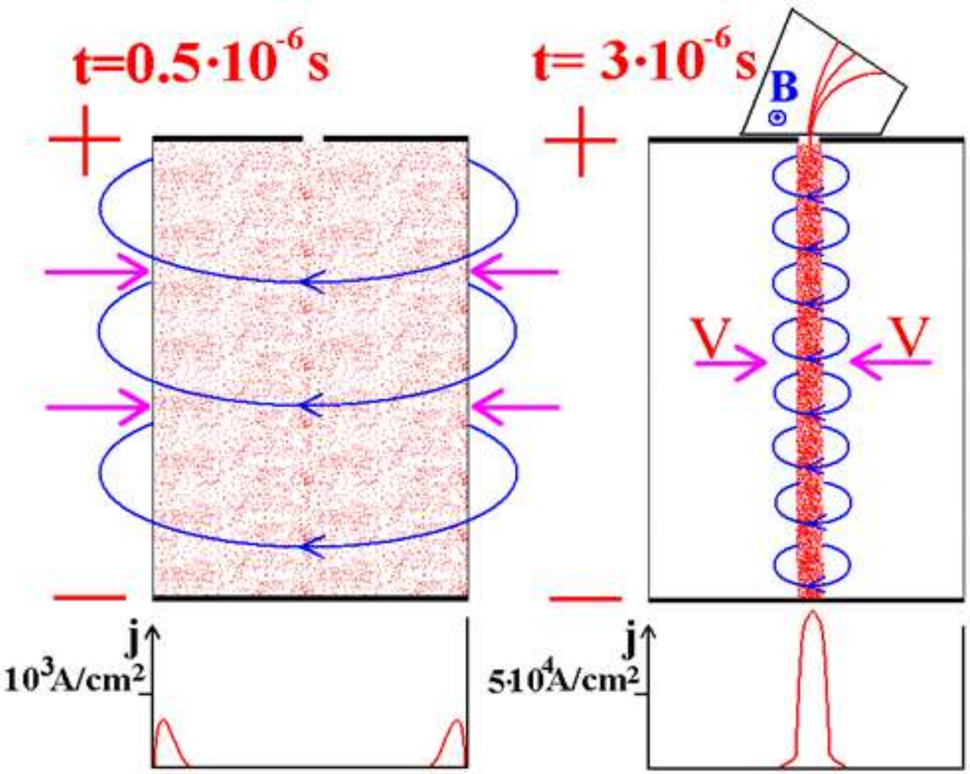
Igor Maximovich participated in Great Patriotic War as the gunner of the heavy machine gun on the 2nd Belorussian Front as part of the 102th Guards Division, 316th Regiment. After Torn (Poland) was taken, on 23 February 1945, it was necessary to break through the deeply echeloned German defense. Igor, without attracting attention, read the Lord's prayer. It was impossible to attack under the fire of machine guns knee-deep in the mud, and the asphalt road was defended by a German rapid-fire machine-gun, located in a concrete cap with a narrow horizontal slit. Igor, with his machine-gun group, crawled with a machine gun along the ditch and opened the direct fire on the embrasure, forcing the enemy's machine gun to silence. After the destruction of the enemy's firing point, our infantry was able, without obstacles, make an offensive on an asphalt road. For this feat, Igor was awarded the Order of Glory, this is the highest soldier's award, corresponding to the Order of St. George the Victorious established earlier in Russia.

Дипломная работа Игоря Максимовича Украинский физико-технический институт, Кафедра ядерной физики, Физико-математический факультет, Харьковский государственный университет.

Determination of effective sections loss of electrons due to charge exchange of Li and Na ions in the energy range 80 - 220 keV. Formation of multiply charged ions at singly charged ions passing through the gas is shown. For the first time the cross sections of multiply charged ions creation due to charge exchange is measured. At 250 keV $\sigma(Na^{+} \rightarrow Na^{+++++}) \sim 10^{-20}\ cm^{-2}$; $\sigma(Li^{+} \rightarrow Li^{++}) = 5.5\ 10^{-17}\ cm^{-2}$.



The compression of the gas discharge by its own magnetic field at the currents of 200 kA leads to generation of the Lorentz electric field, directed along the axis of discharge. The energy of accelerated particles ~300 KeV at an applied potential difference of ~15 KV.



$\varphi = 15$ kV

$dI/dt = 10^{11}$ A/s

$I_{max} = 200$ kA

$W > 300$ keV

$\mathbf{E = -V \times B / c}$

$V \sim 10^7$ cm/s

$B_{max} \sim 4 \cdot 10^4$ G

$E \sim 4 \cdot 10^3$ V/cm

Lab. № 2. 1954.
Atomnaja energija
№ 3. 1956.
Artsimovich et. al. P. 84.
Lukjanov, Podgorny. P. 93.

SINP MSU 1957.
Podgorny, Kovalsky,
Palchikov.
DAN SSSR. 123, 825 (1958).

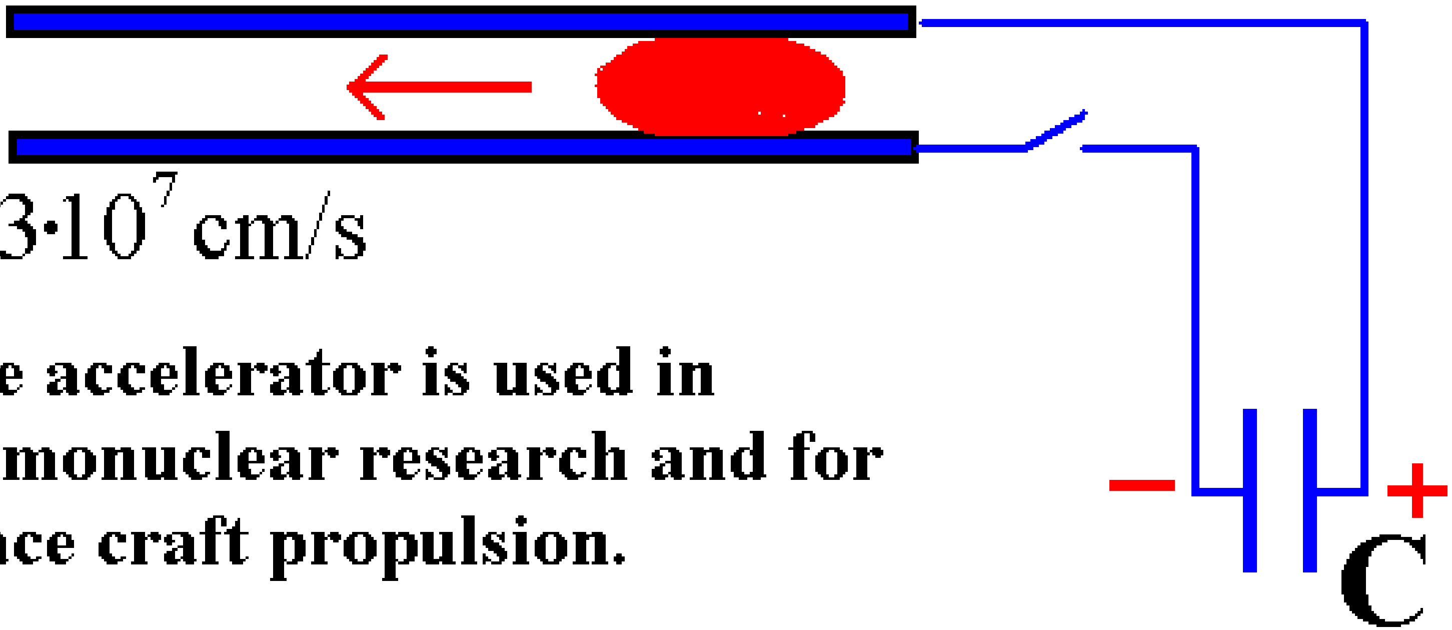
1957.
Severny, Toneman } Electric discharge in solar corona.

S. N. Vernov

As part of a team led by L. A. Artsimovich, Igor was the first to receive plasma in the laboratory with a temperature of 1,000,000 degrees and to detect neutron radiation in a deuterium discharge. The team of scientists who made this discovery was presented for awarding the Lenin Prize.

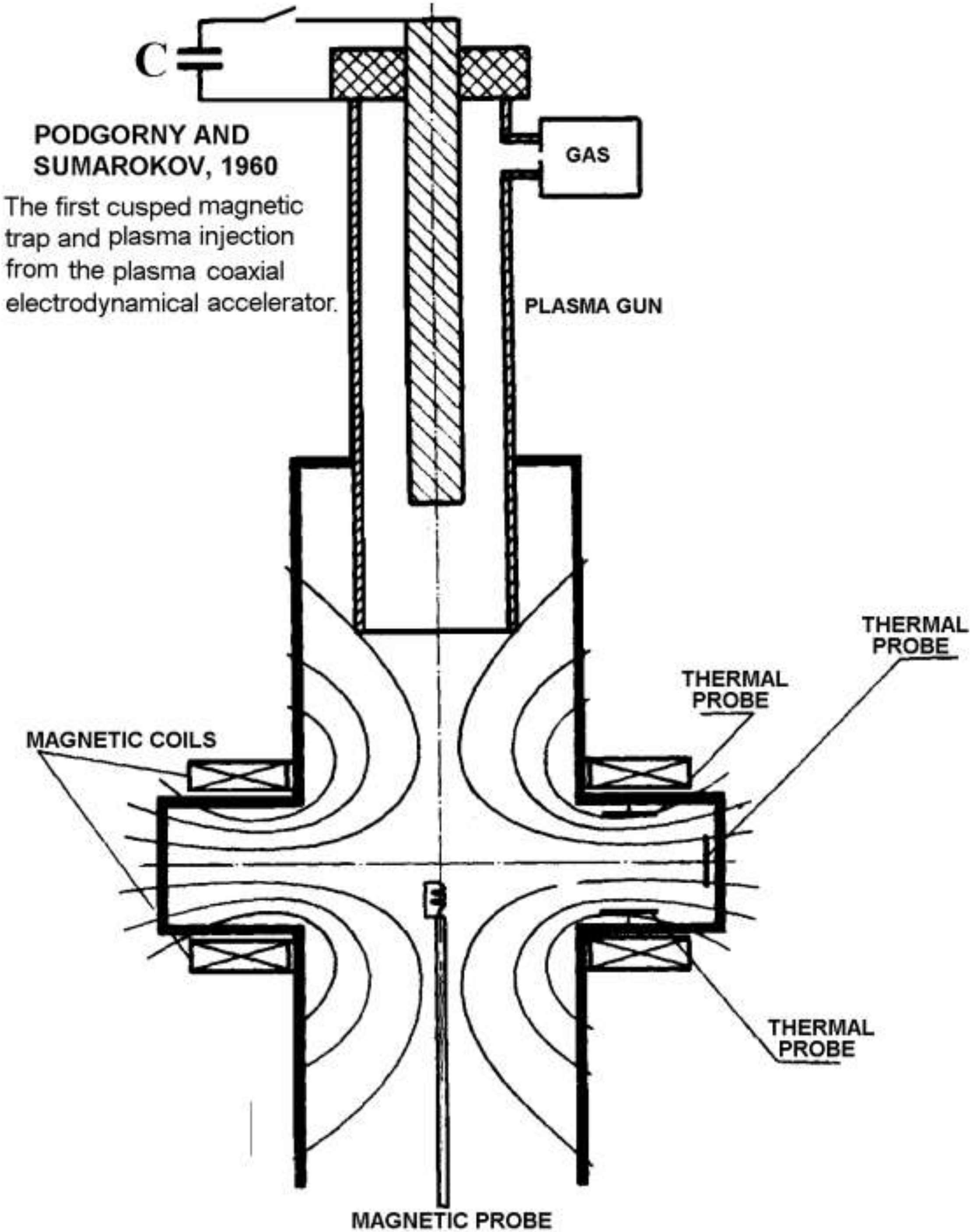
First plasma acclerator was developed.

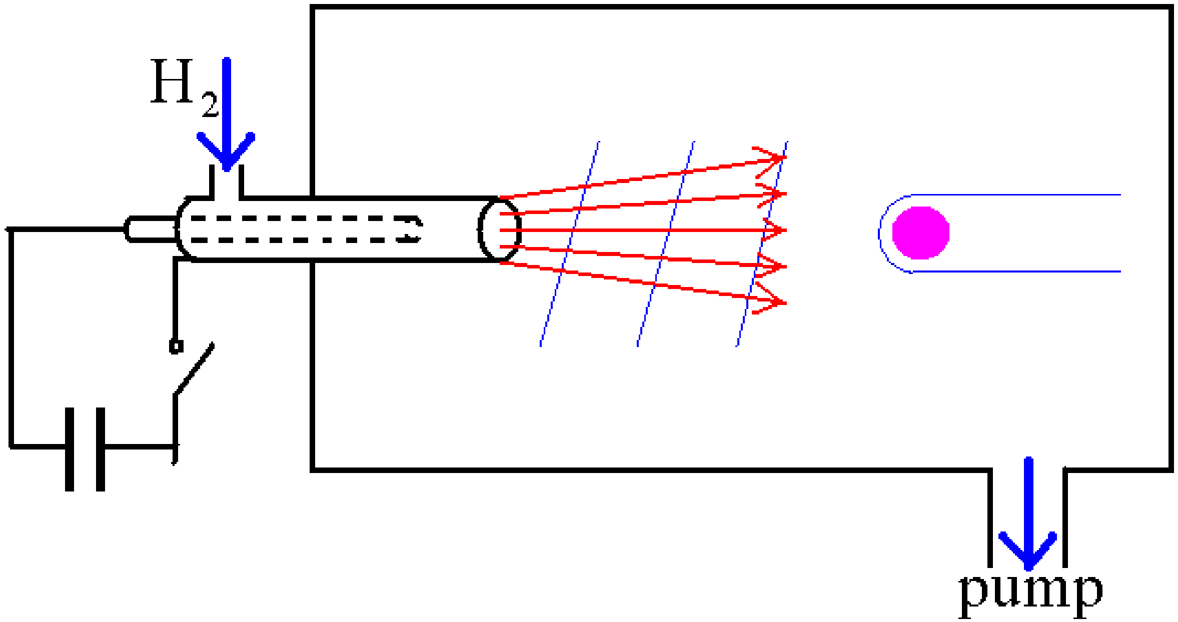
Artsimovich, Lukjanov, Podgorny, Chuvatin. **1956**



$V = 3 \cdot 10^7$ cm/s

The accelerator is used in themonuclear research and for space craft propulsion.


C
PODGORNY AND SUMAROKOV, 1960
The first cusped magnetic trap and plasma injection from the plasma coaxial electrodynamical accelerator.
GAS
PLASMA GUN
THERMAL PROBE
THERMAL PROBE
MAGNETIC COILS
THERMAL PROBE
MAGNETIC PROBE



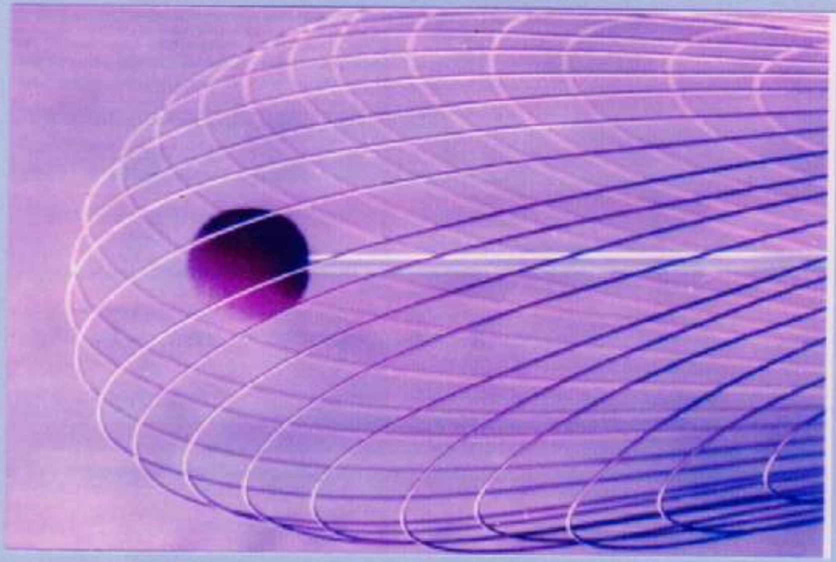
$$\frac{\partial \mathbf{B}}{\partial t} = \mathrm{rot}(\mathbf{V} \times \mathbf{B}) - \frac{c^2}{4\pi}\mathrm{rot}\left(\frac{1}{\sigma}\mathrm{rot}\mathbf{B}\right) \qquad L \ll \lambda$$

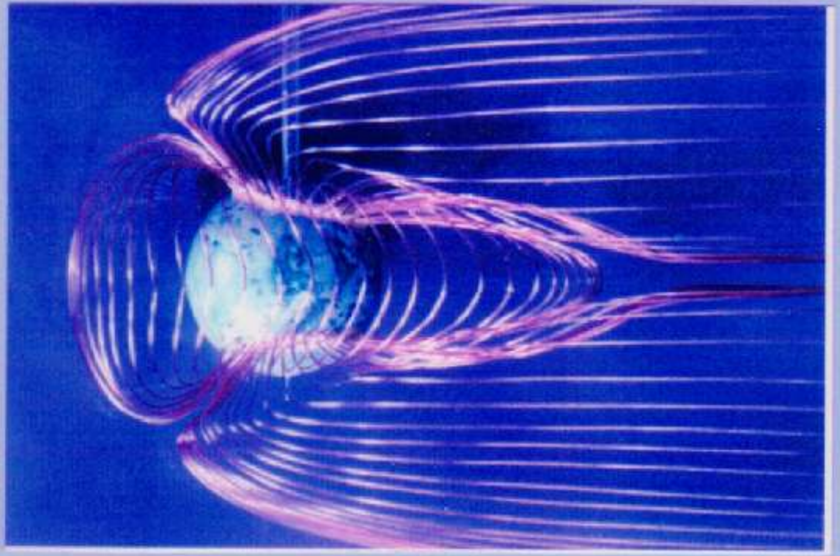
$$\frac{\partial \mathbf{V}}{\partial t} = -(\mathbf{V},\nabla)\mathbf{V} - \frac{1}{m_i\rho}\nabla(\rho T) - \frac{1}{4\pi\rho}\left(\mathbf{B}\times \mathrm{rot}\mathbf{B}\right) + \frac{\eta}{\rho}\Delta\mathbf{V}$$

$$V = inv; \quad M_S = \frac{C_S}{V}; \quad M_A = \frac{V_A}{V}; \quad \beta = \frac{4\pi n T}{B^2}; \quad Re_m = \frac{4\pi L V \sigma}{c^2}.$$

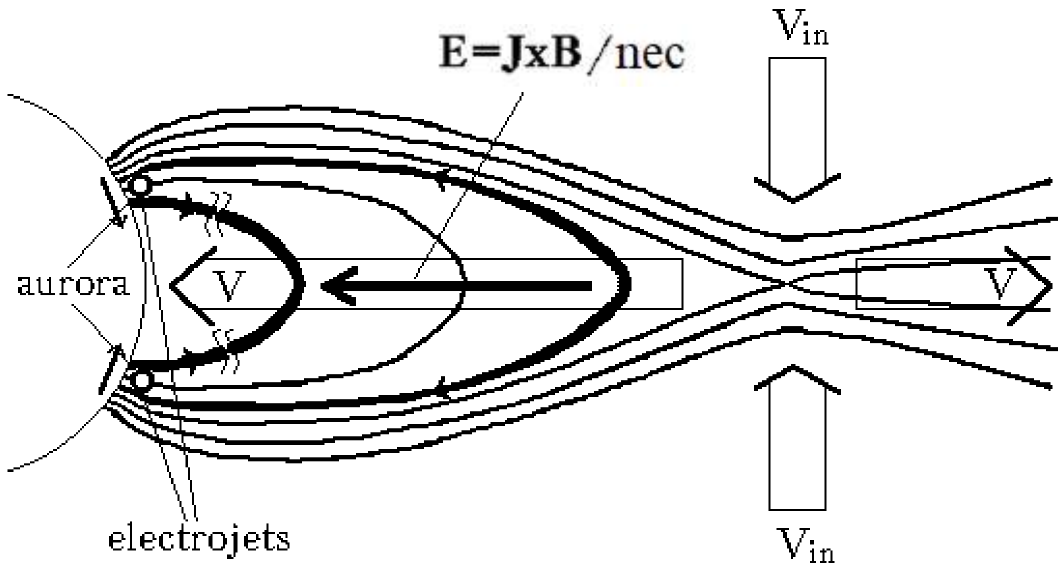
~ 5 $\qquad \sim 5$ $\qquad \sim 1$ $\qquad \sim 10^{13}$

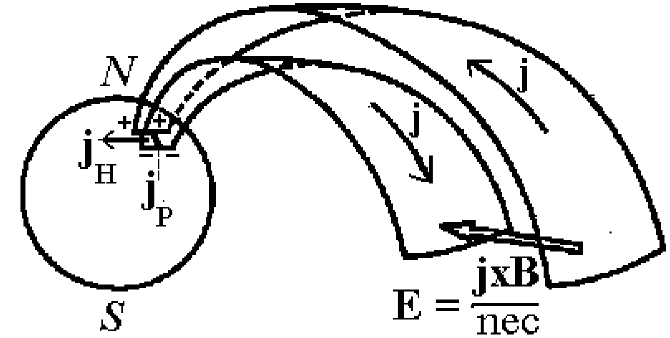
$(3–5)10^7$ cm/s $\quad n = 10^{13}\,cm^{-3}$ $\quad T = 15\,eV$ $\quad B = 40G$ $\quad Re_m = 100$

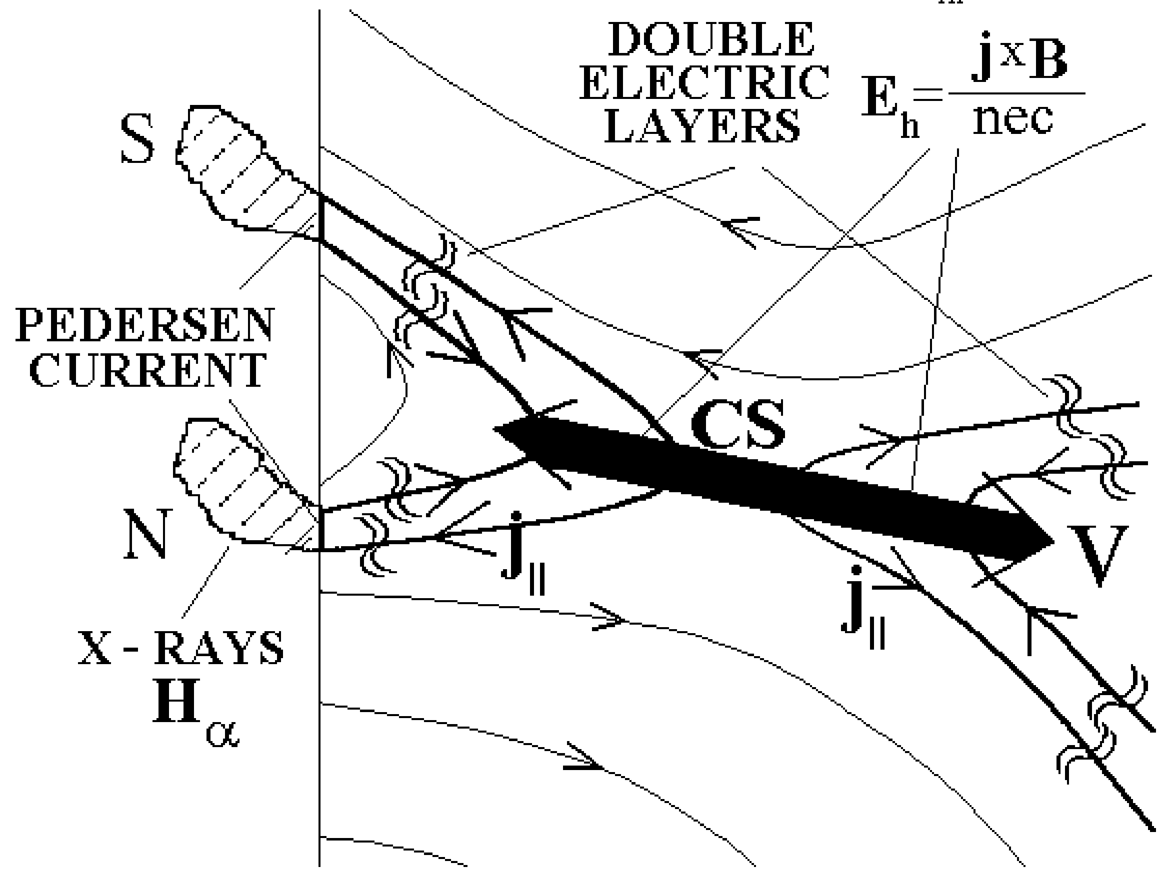


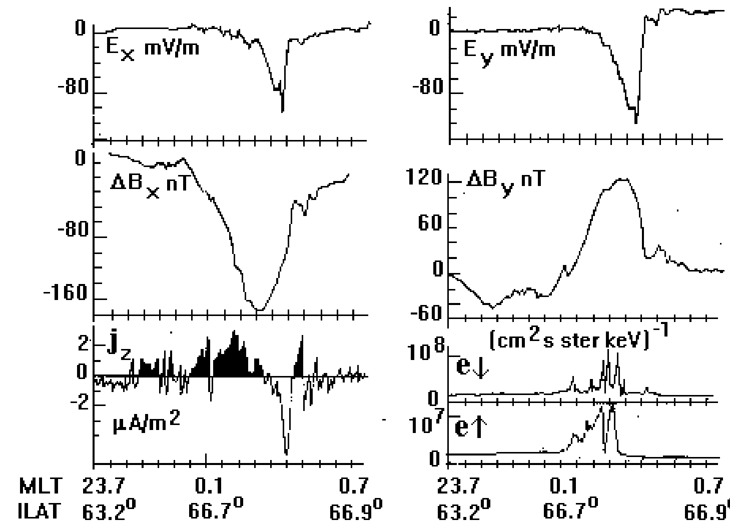


Igor Maximovich formulated the principle of limited simulation of cosmic phenomena, which was later used not only for laboratory simulation, but also for numerical simulation.



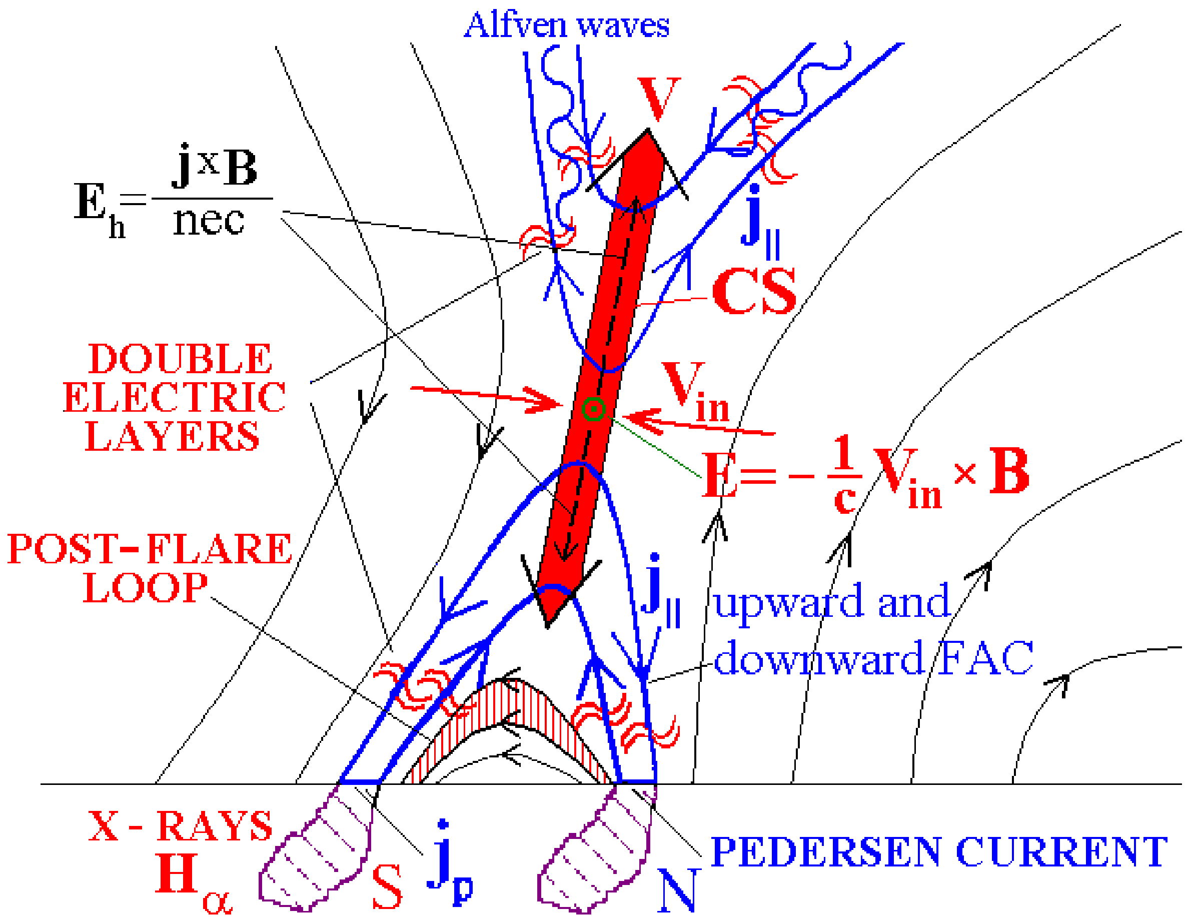




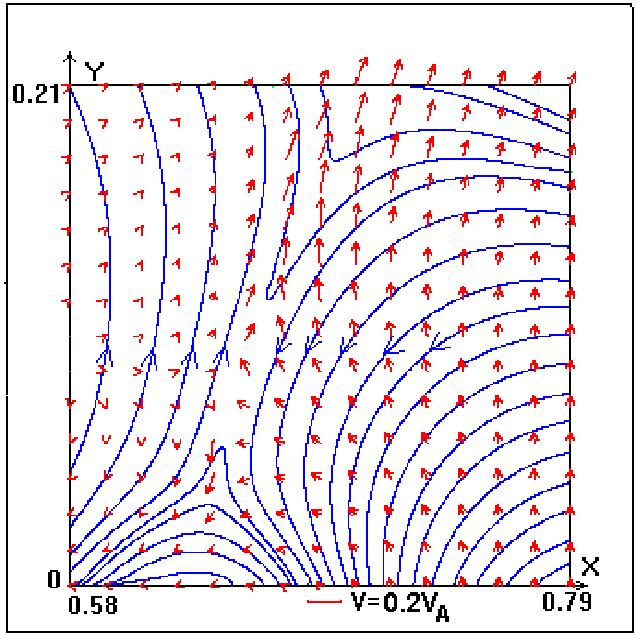


Based on measurements made on the Soviet-Bulgarian satellite Intercosmos Bulgaria-1300 spacecraft, Igor Maximovich suggested the electrodynamical model of a substorm.

Electrodynamical model of a solar flare is proposed by I.M. Podgorny by analogy with the electrodynamical model of a substorm on the basis of the results of MHD numerical simulation and observation.



Electrons accelerated in FAC produce hard X-ray.

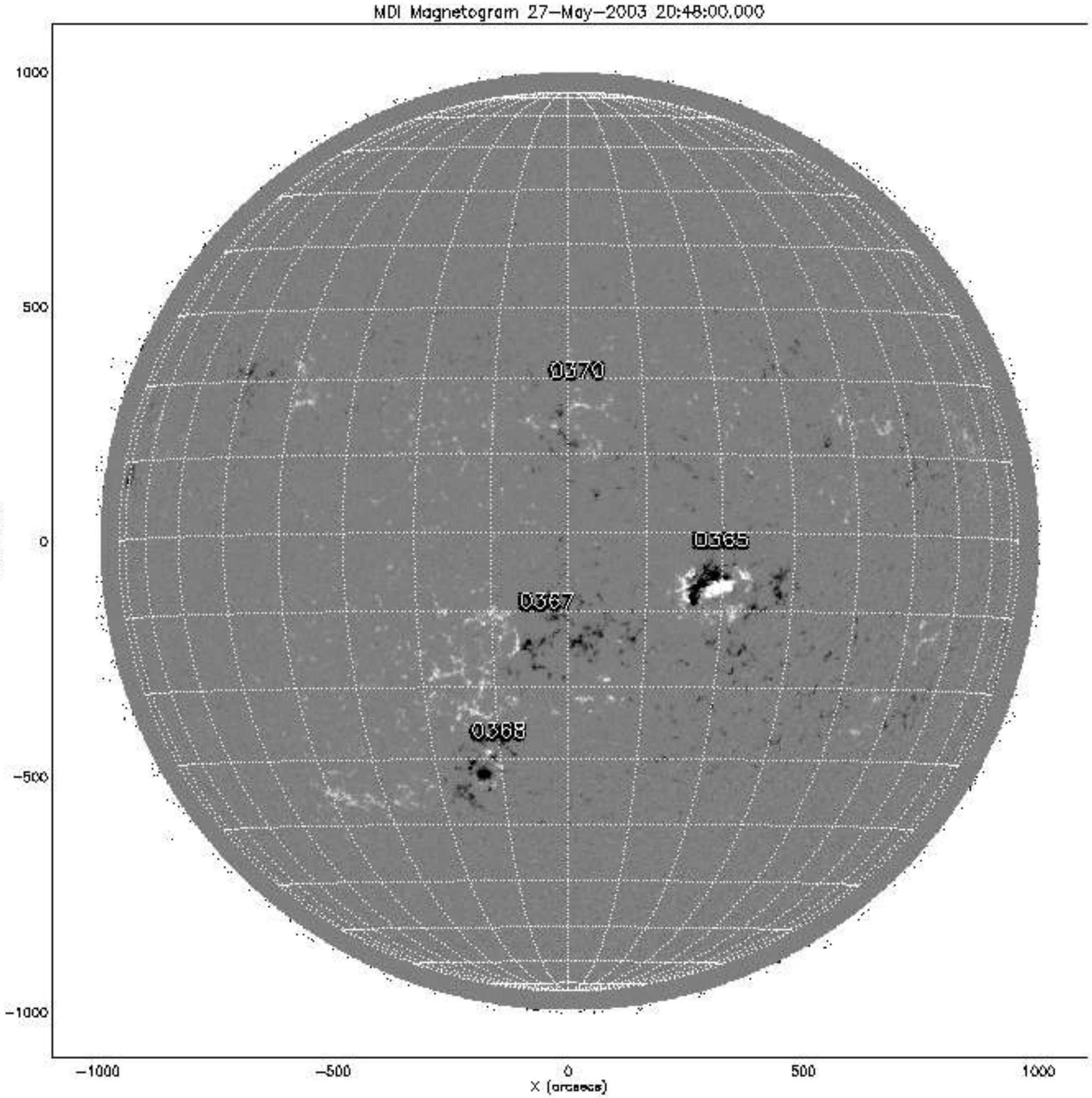


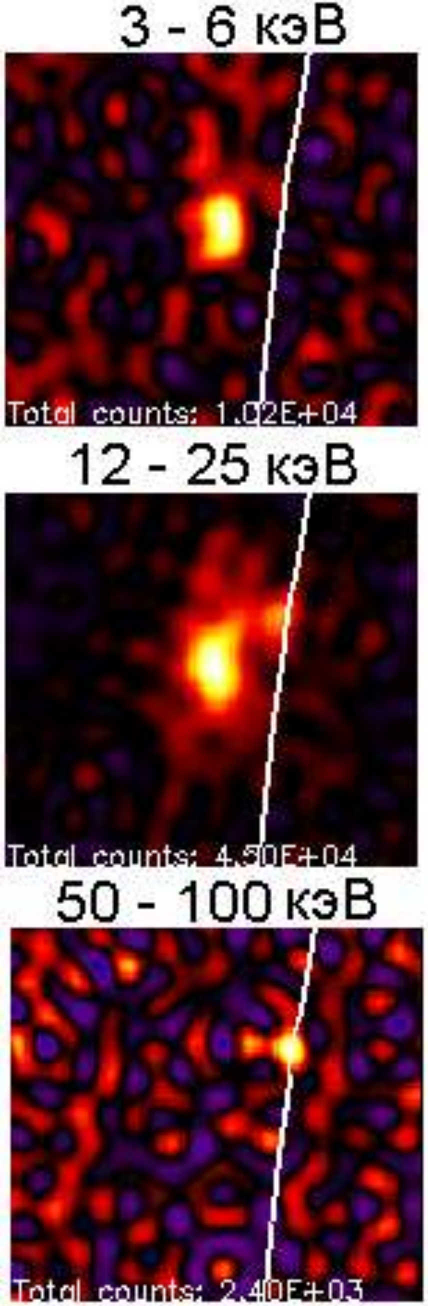
Results of current sheet creation in numerical MHD simulation. A sheet appears above an active region in the preflare state. Plasma inflows into a current sheet. Inside the sheet plasma acceleration takes place by **j**x**B** force producing CME.

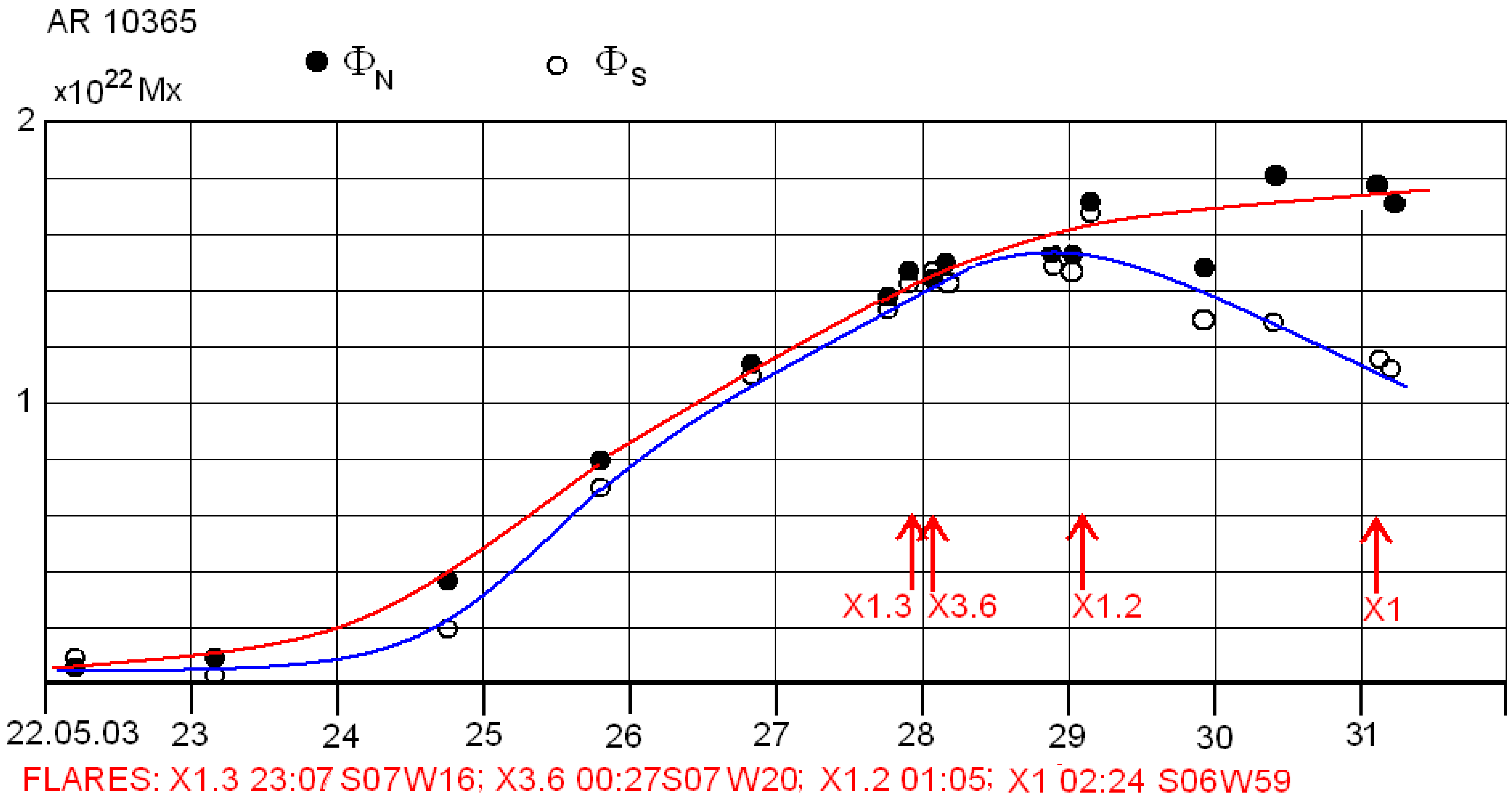
- Cosmic rays are studied for 100 years, but their origin is still not clear.
- Sun - is an astronomical observatory. Due to its proximity to the Earth, we can get information, which does not come to us from other stars.
- John N. Bahcal

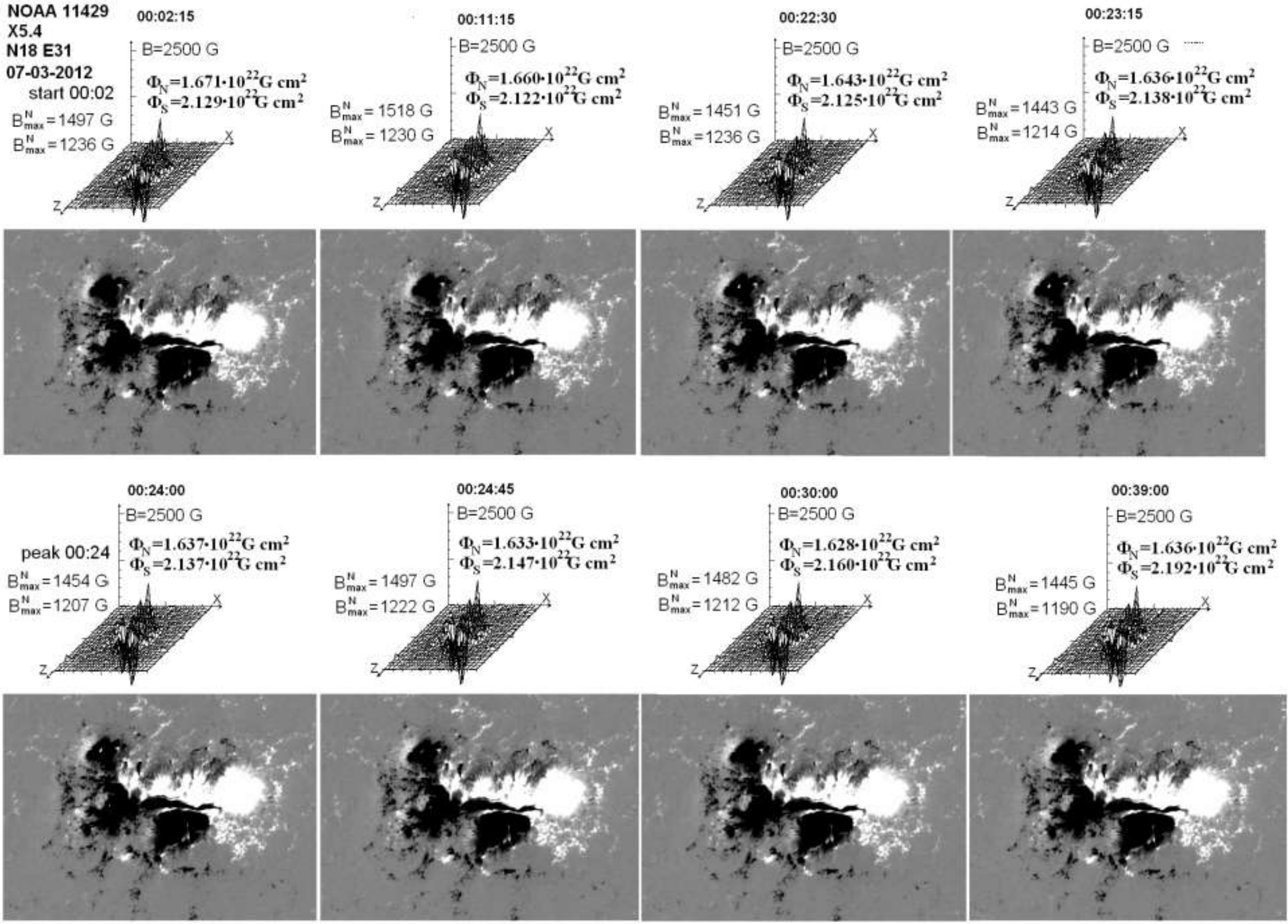
During a solar flare, a few tens of minutes release $\sim 10^{32}$ erg of magnetic energy, which is converted into thermal energy of a plasma heated to $\sim 10^{7}$ ^{o}K, the kinetic energy of coronal plasma emissions, the energy of accelerated charged particles (protons - up to 20 GeV) and radiation energy in a wide the range produced by accelerated and thermal particles — radio emission, optical radiation, ultraviolet radiation, x-rays (soft thermal 1–20 keV, and hard beam 20–200 and above keV), γ-radiation.

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

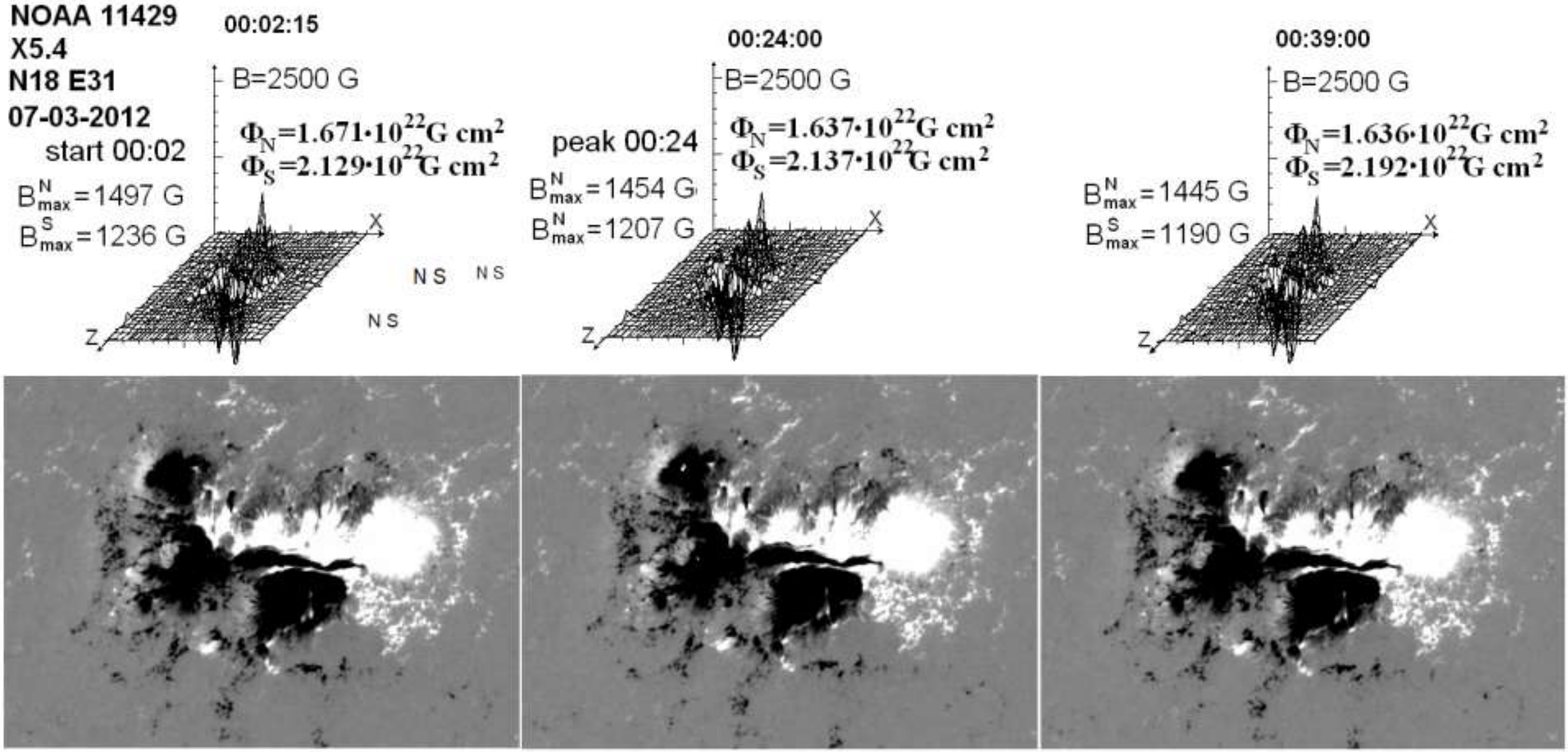




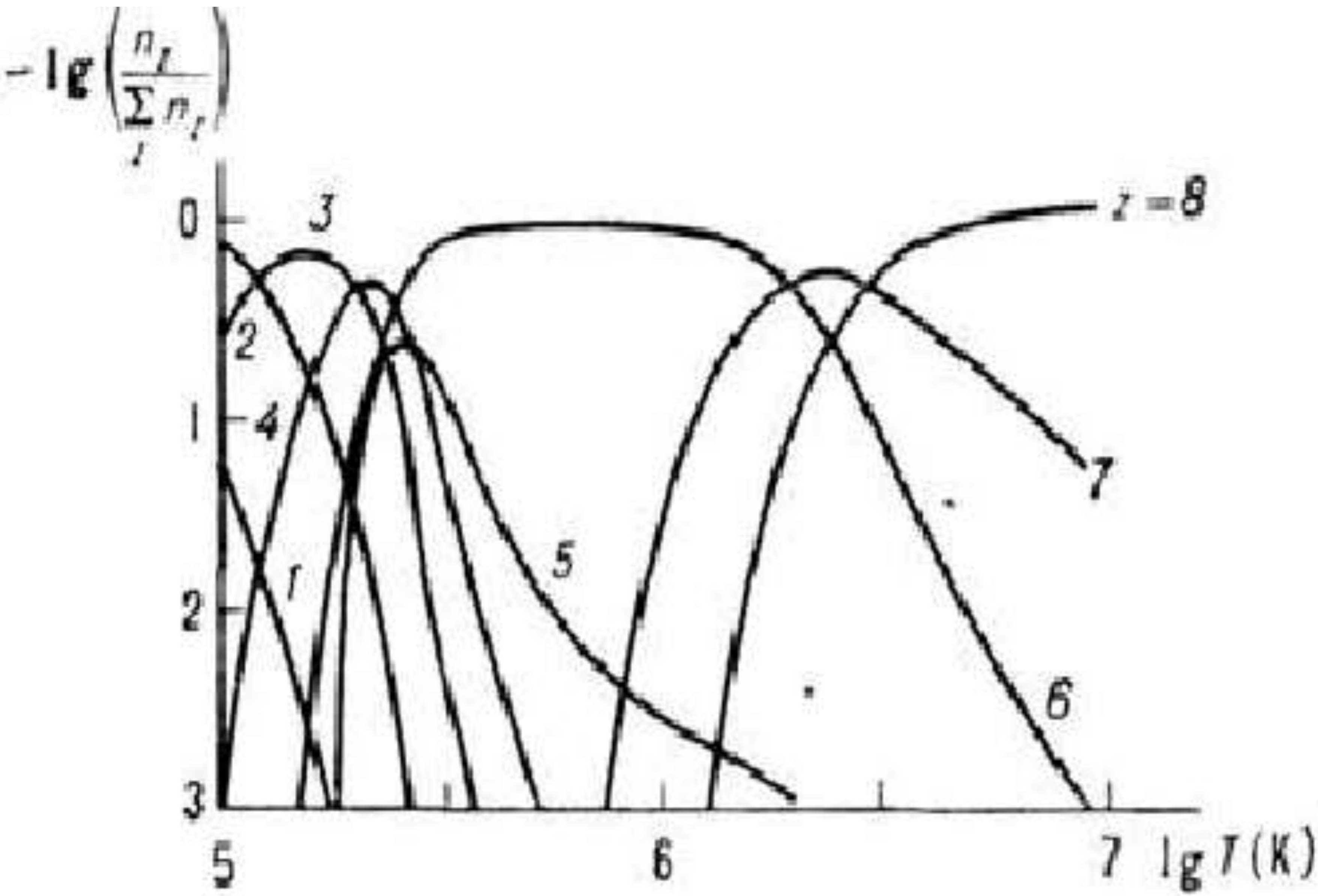

AR 10365
Φ_N
Φ_S
$x10^{22}$ Mx
2
1
X1.3
X3.6
X1.2
X1
22.05.03
23
24
25
26
27
28
29
30
31
FLARES: X1.3 23:07 S07W16; X3.6 00:27S07W20; X1.2 01:05; X1 02:24 S06W59



Подгорный, Подгорный, Мешалкина. АЖ. 92, 669, 2015.



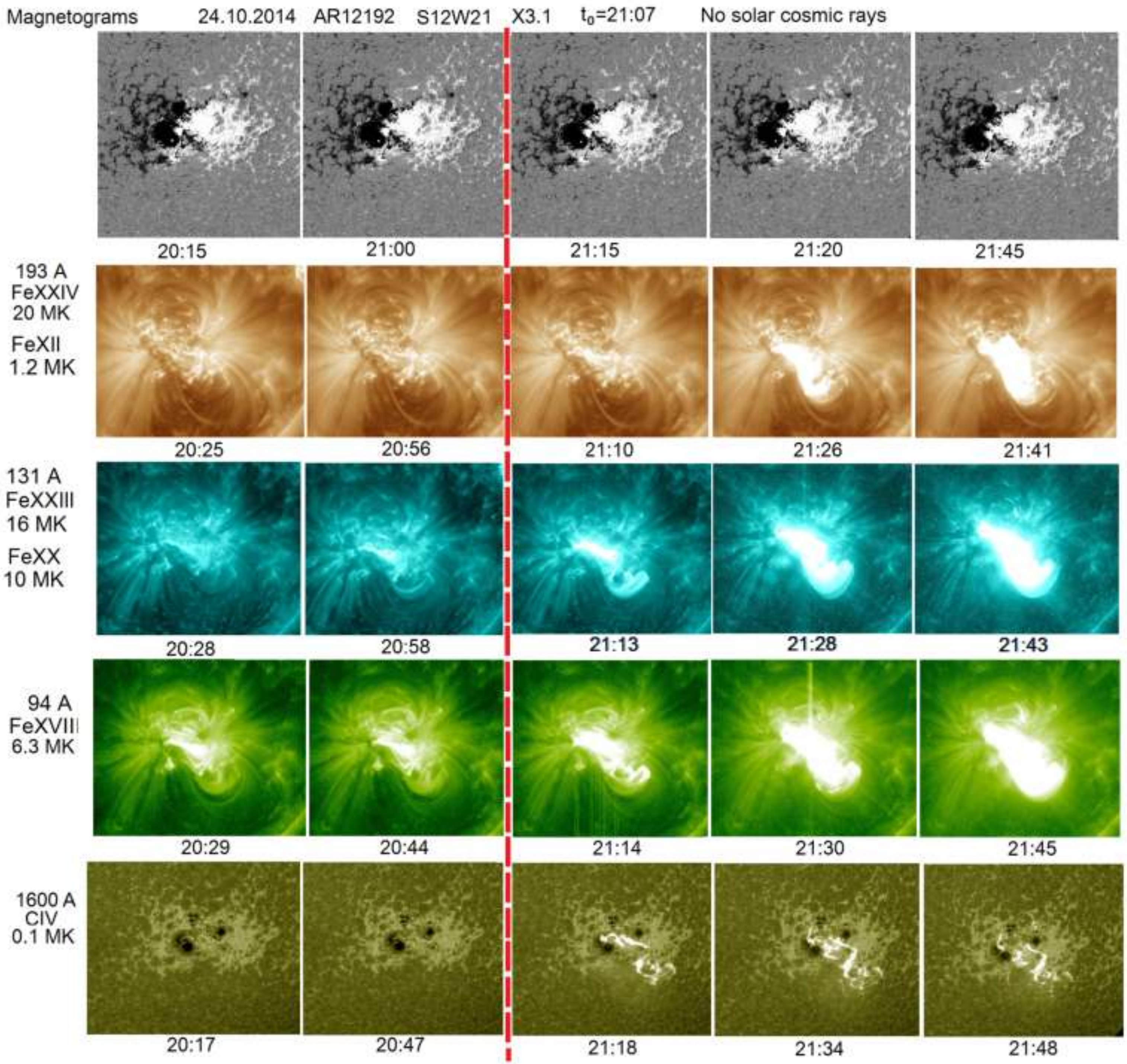
Podgorny, Podgorny, Meshalkina. Astr. Rep. 92, 669, 2015.



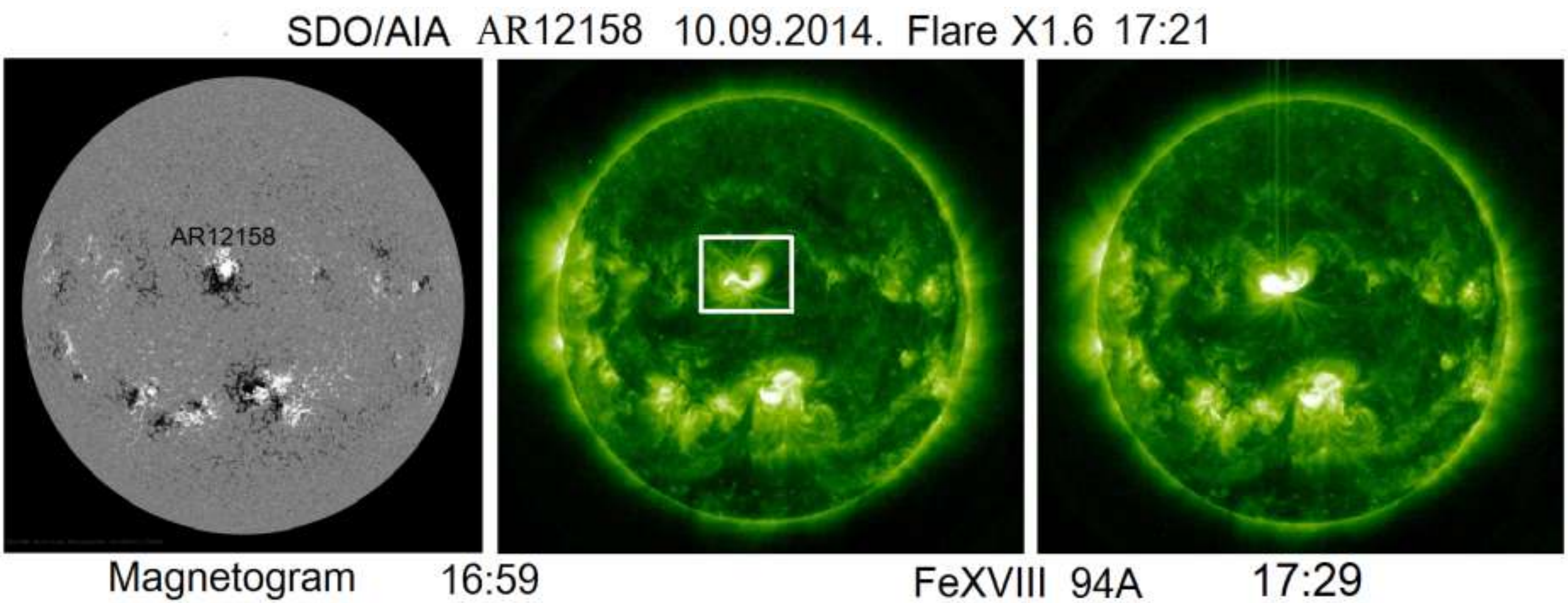
TOPICS ON PLASMA DIAGNOSTICS

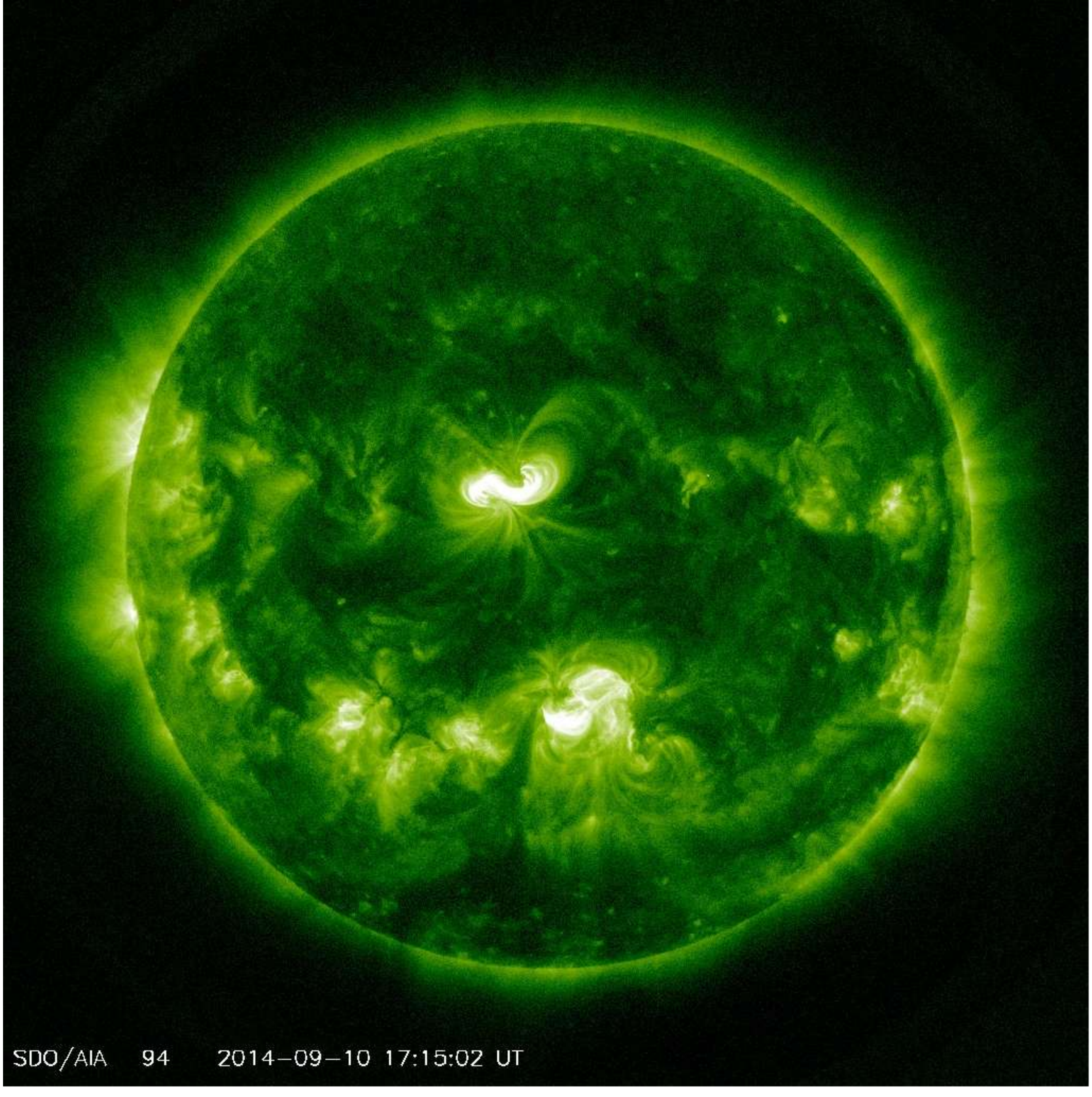
I. M. PODGORNY

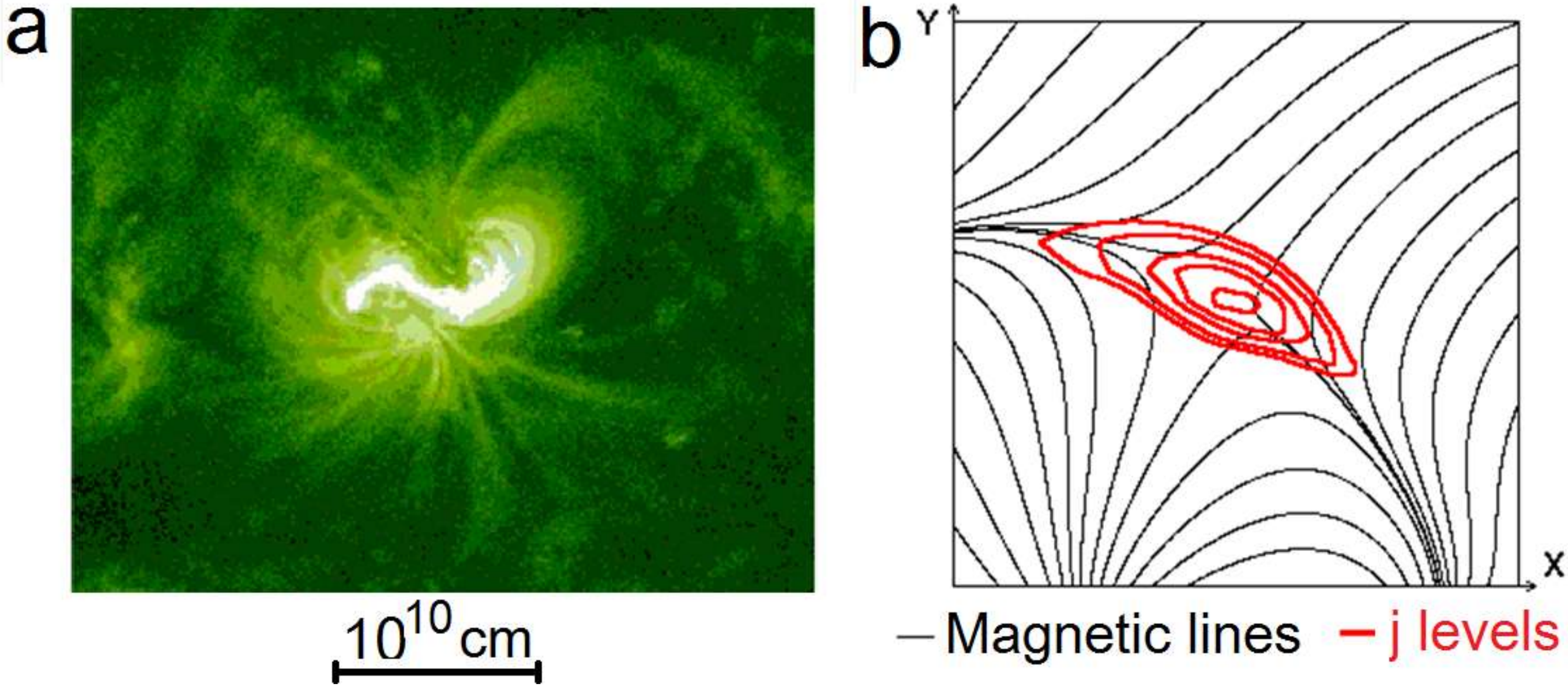
И. М. ПОДГОРНЫЙ   АТОМИЗДАТ 1968


Magnetograms
24.10.2014
AR12192
S12W21
X3.1
t_0=21:07
No solar cosmic rays
20:15
21:00
21:15
21:20
21:45
193 A
FeXXIV
20 MK
FeXII
1.2 MK
20:25
20:56
21:10
21:26
21:41
131 A
FeXXIII
16 MK
FeXX
10 MK
20:28
20:58
21:13
21:28
21:43
94 A
FeXVIII
6.3 MK
20:29
20:44
21:14
21:30
21:45
1600 A
CIV
0.1 MK
20:17
20:47
21:18
21:34
21:48

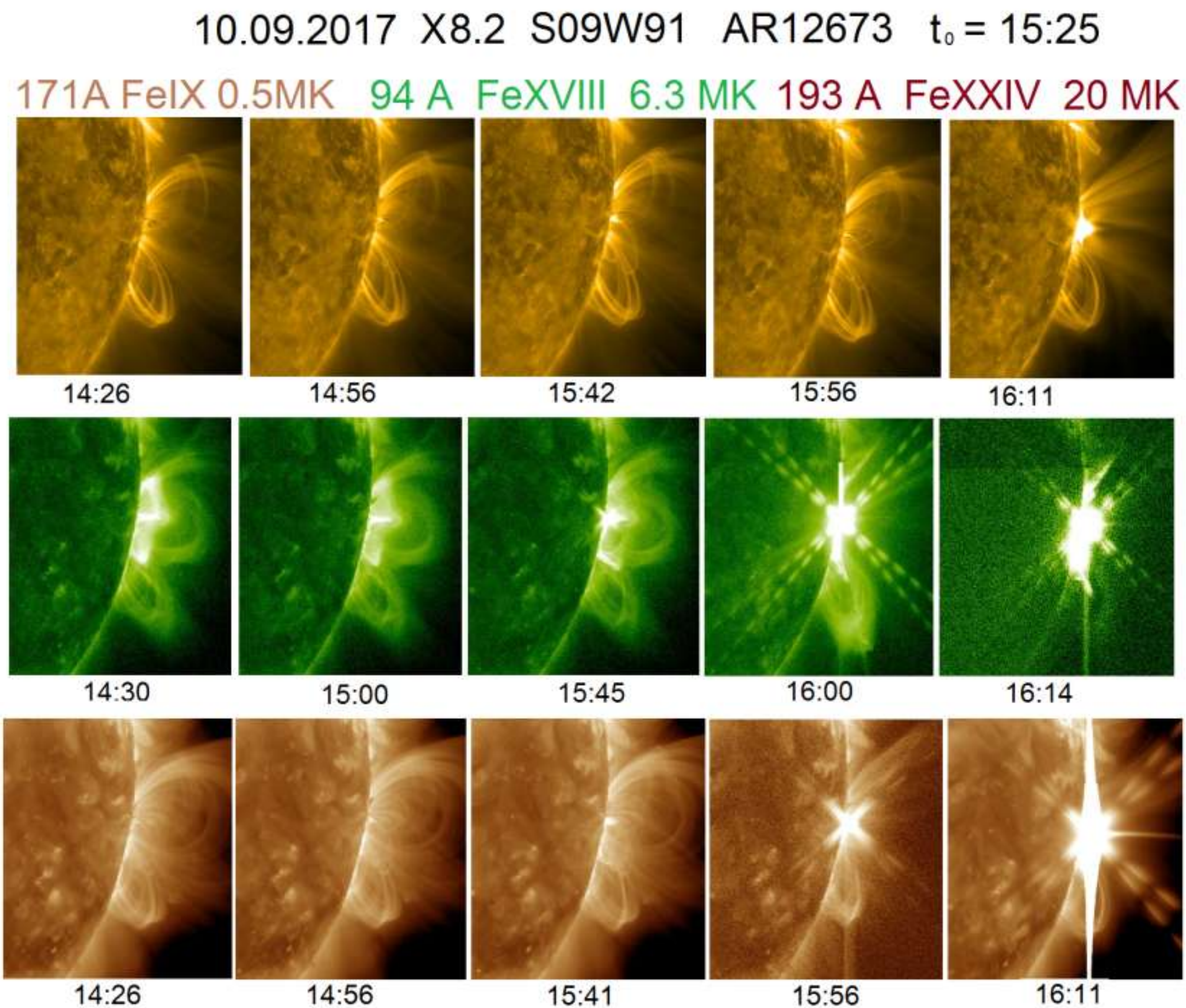
FLARE X1.6 17:21

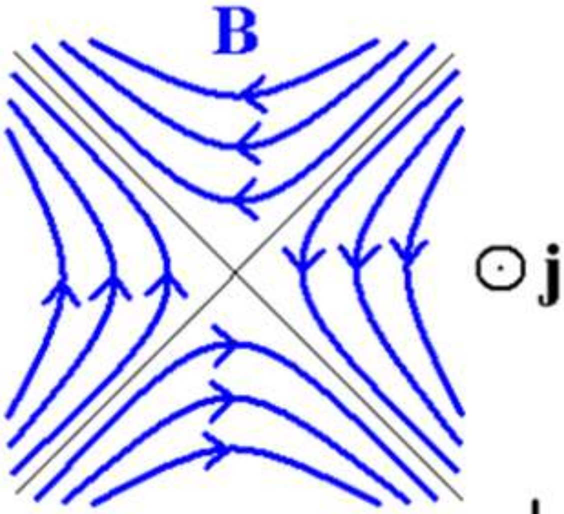



SDO/AIA 94 2014-09-10 17:15:02 UT

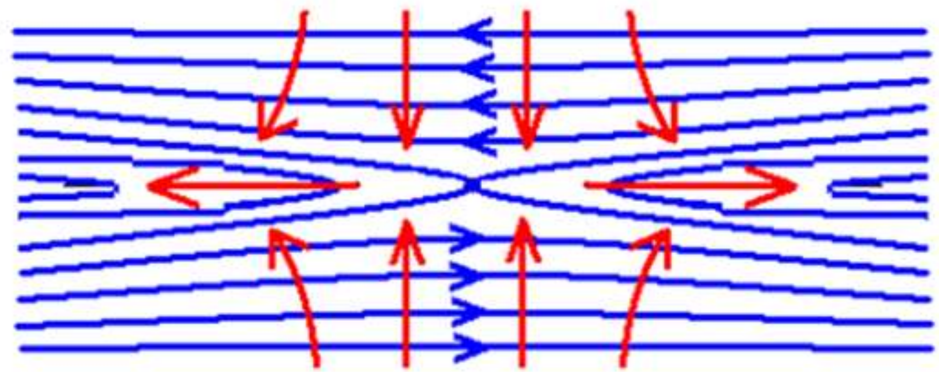


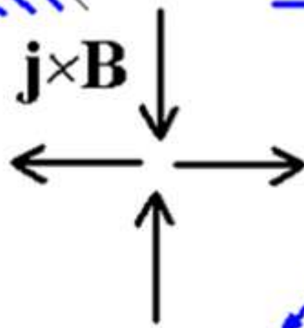
a) The photo of the preflare emission in the spectral line 94A. б) The lines of the magnetic field and current density according the numerical MHD simulation in the initial stage of current sheet creation in the solar corona.

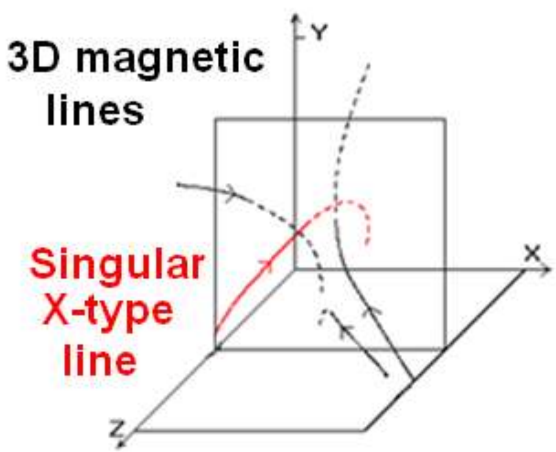

10.09.2017 X8.2 S09W91 AR12673 t_0 = 15:25
171A FeIX 0.5MK 94 A FeXVIII 6.3 MK 193 A FeXXIV 20 MK
14:26
14:56
15:42
15:56
16:11
14:30
15:00
15:45
16:00
16:14
14:26
14:56
15:41
15:56
16:11

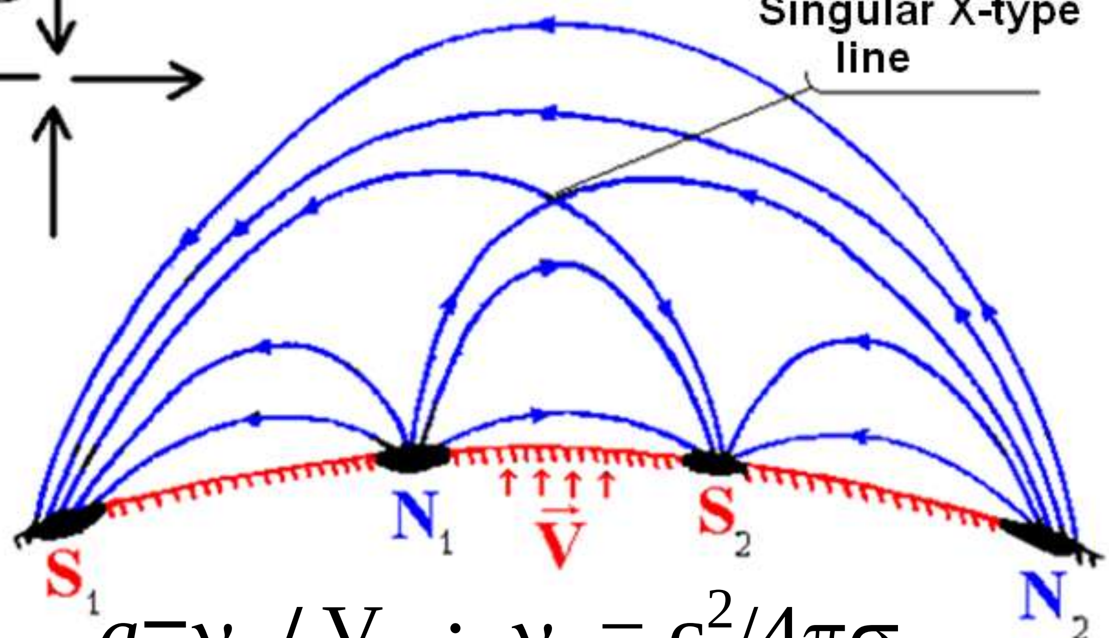


S. I. Syrovatskii 1966
A. Bratenahl, W. Hirsh 1966







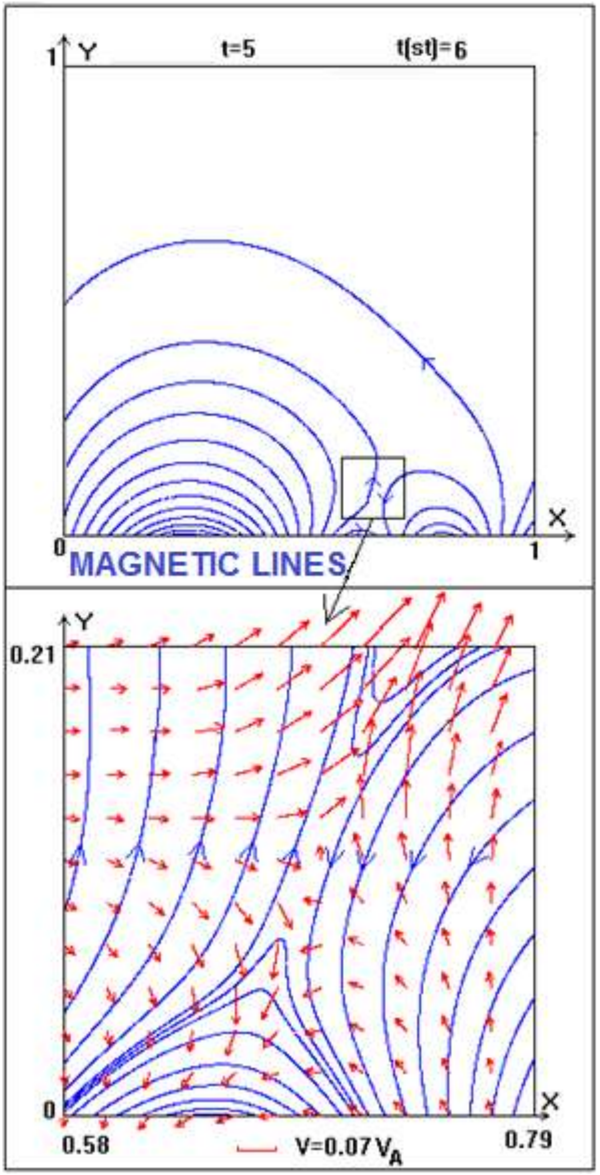


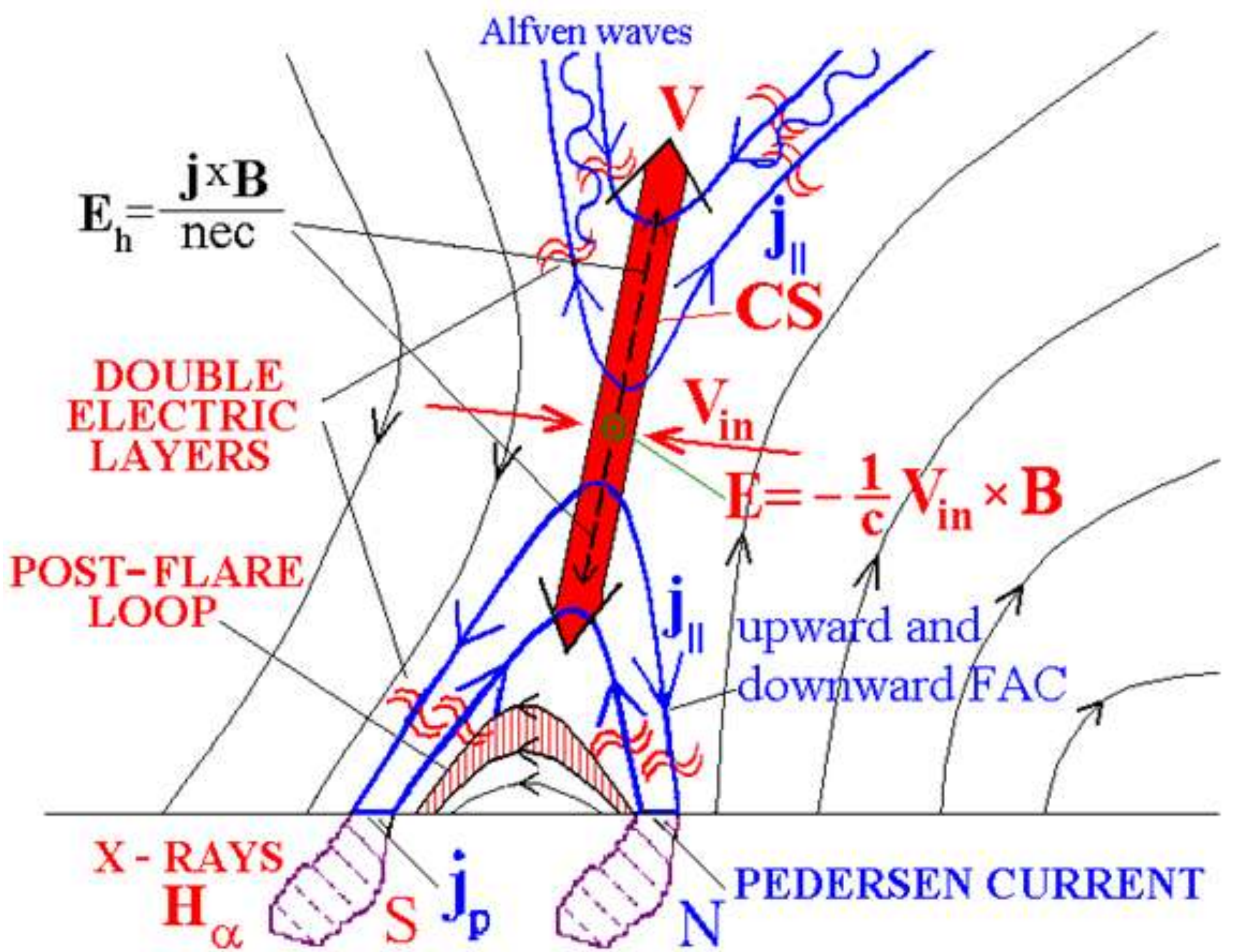
$$a = \nu_m / V_{in} \; ; \;\; \nu_m = c^2 / 4\pi\sigma$$

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.

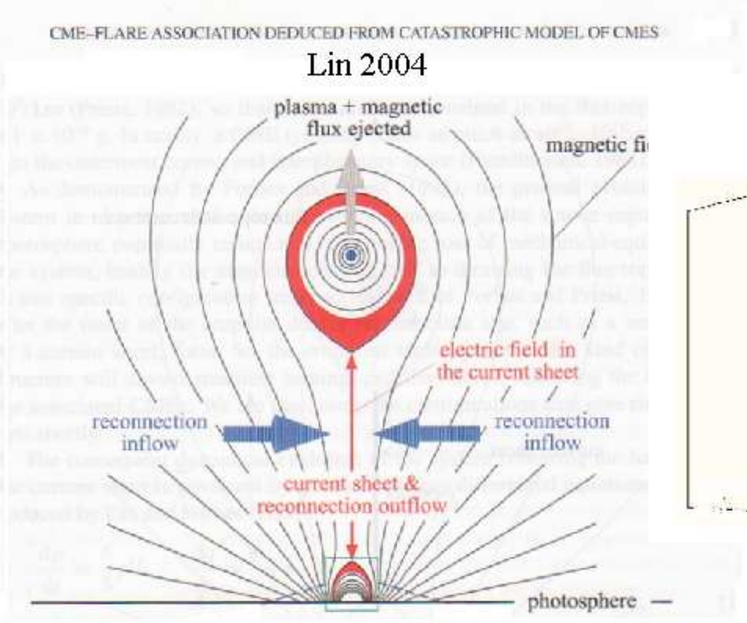
Electrodynamic model of solar flare

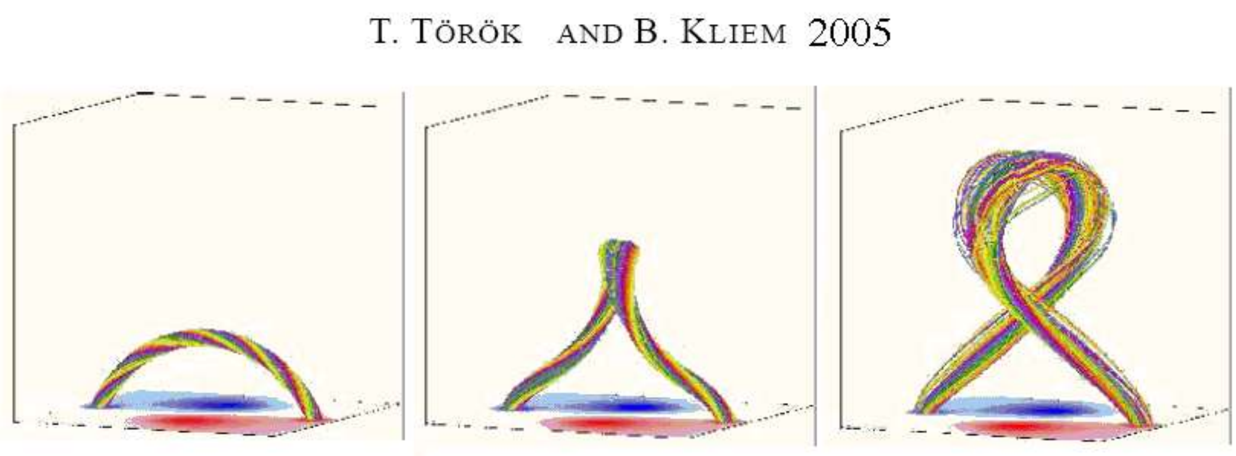
Igor M. Podgorny using results of measurements on the satellite Intercosmos-Bulgaria-1300





Examples of alternative models of the solar flare

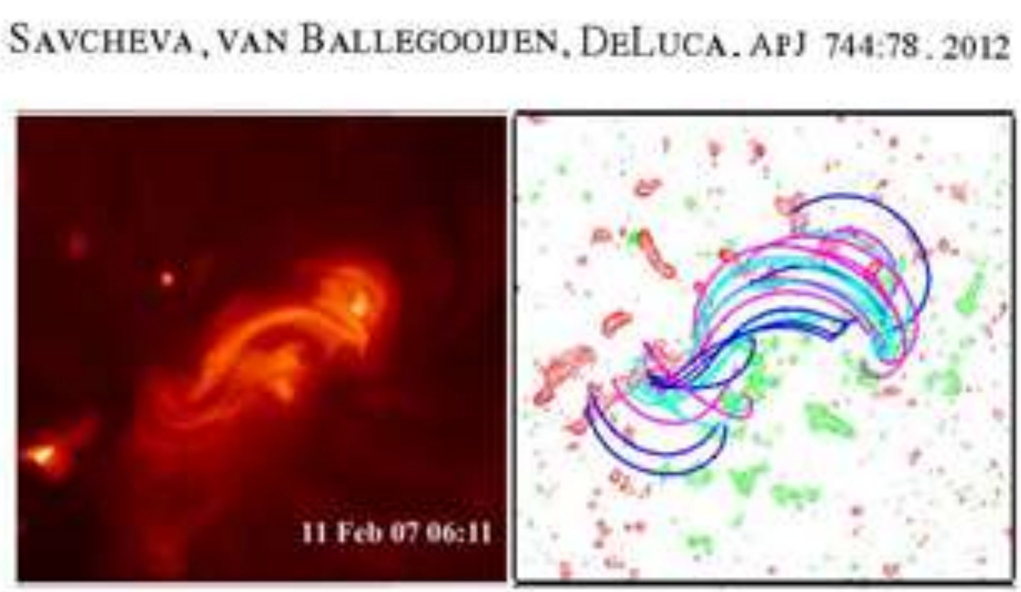


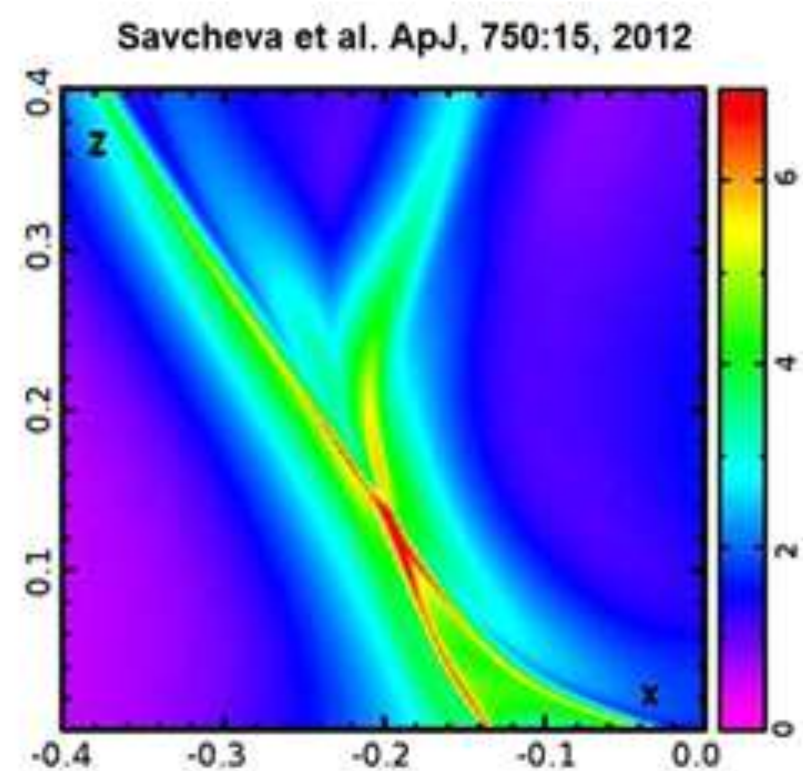


It is unclear how the rope can appear due to real disturbances on the photosphere.

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

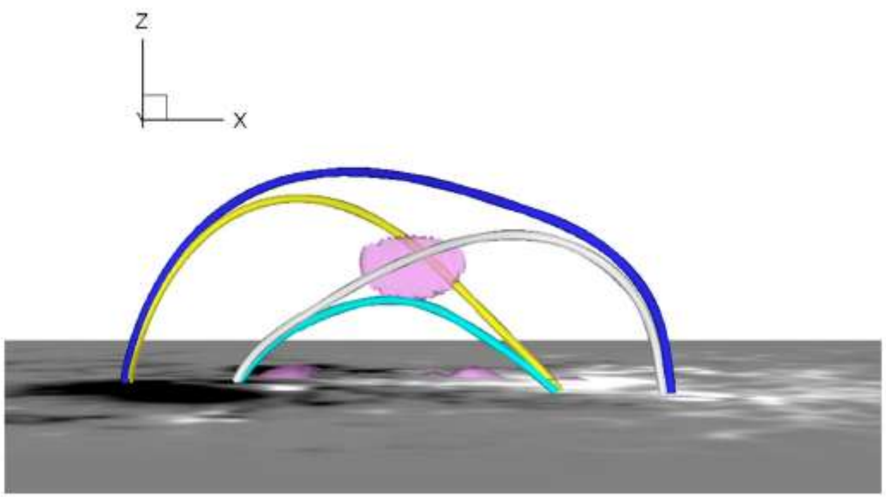
Calculations of magnetic fields in corona above the active region in **force-free** approximation (rot**B**=α**B**).

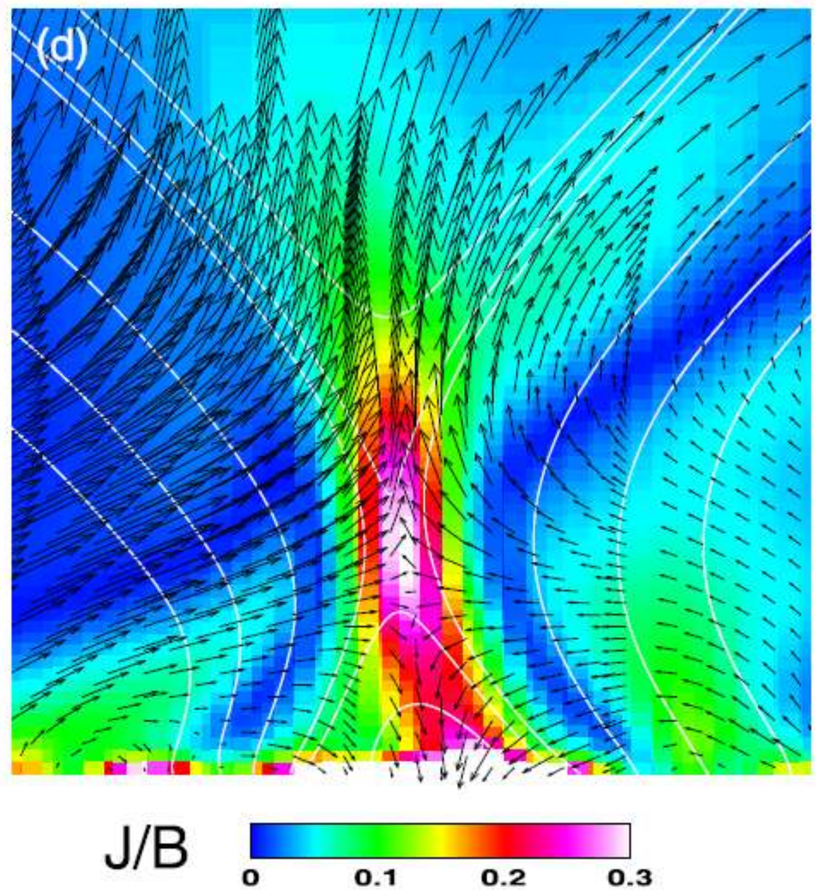




Jiang, C., Wu, S.T., Yurchyshyn, V., Wang, H., Feng, X., Hu, Q. 2016

2014 October 24 21:00 UT
AR 12192 X3.1

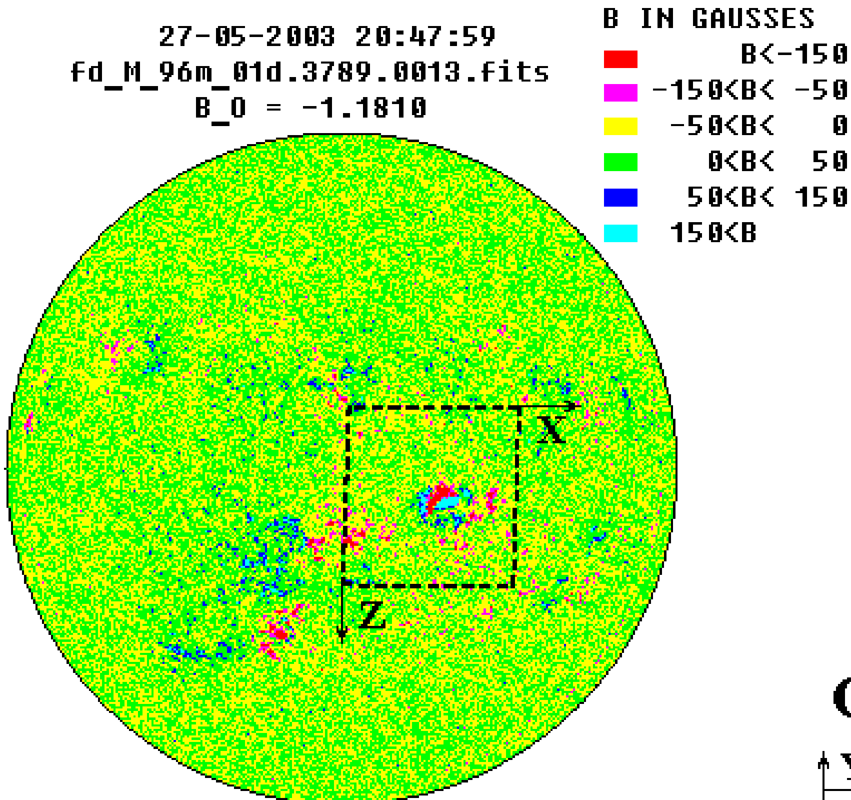




Our aim is:

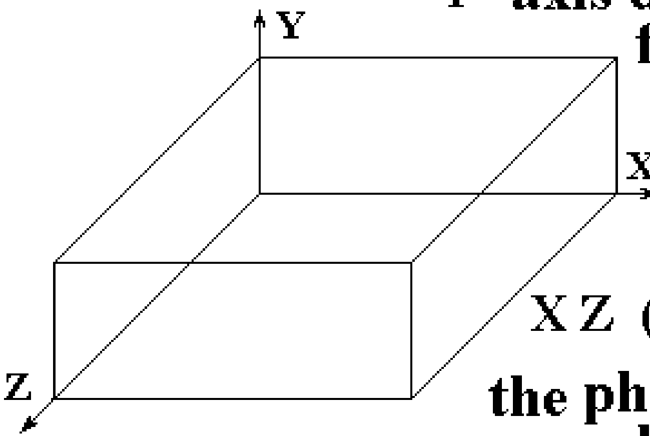
To find solar flare mechanism directly by MHD simulation in real active region.

At setting the conditions of simulation, no assumptions were done about the flare mechanism. All conditions are taken from observations.



--- REGION IN PICTURE PLANE

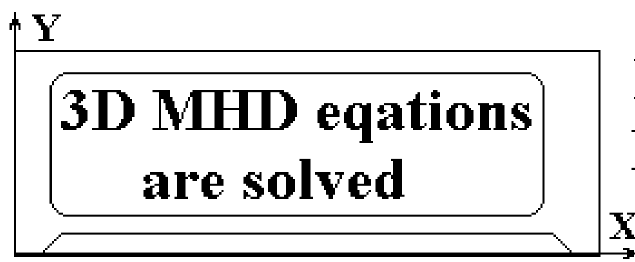
COMPUTATIONAL DOMAIN IN CORONA ABOVE ACTIVE REGION



Y- axis directed from the Sun

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

Cross-section Z=const



Nonphotospheric boundary:

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

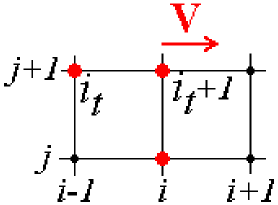
Cosmic Research 35, 35, 1997; 35, 235, 1997; 36, 492, 1998

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.

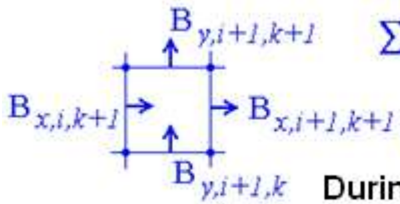
In the PERESVET program:



- 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



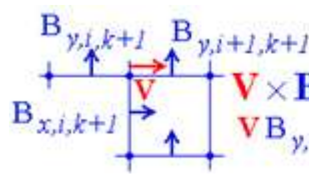
$$ \sum B_n \Delta S = 0 $$

Equivalency of equations

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

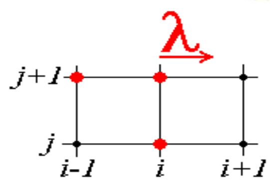
During dissipation relaxation of magnetic field, the current density $[\mathrm{rot}\,\mathbf{B}] \to 0$

- 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.

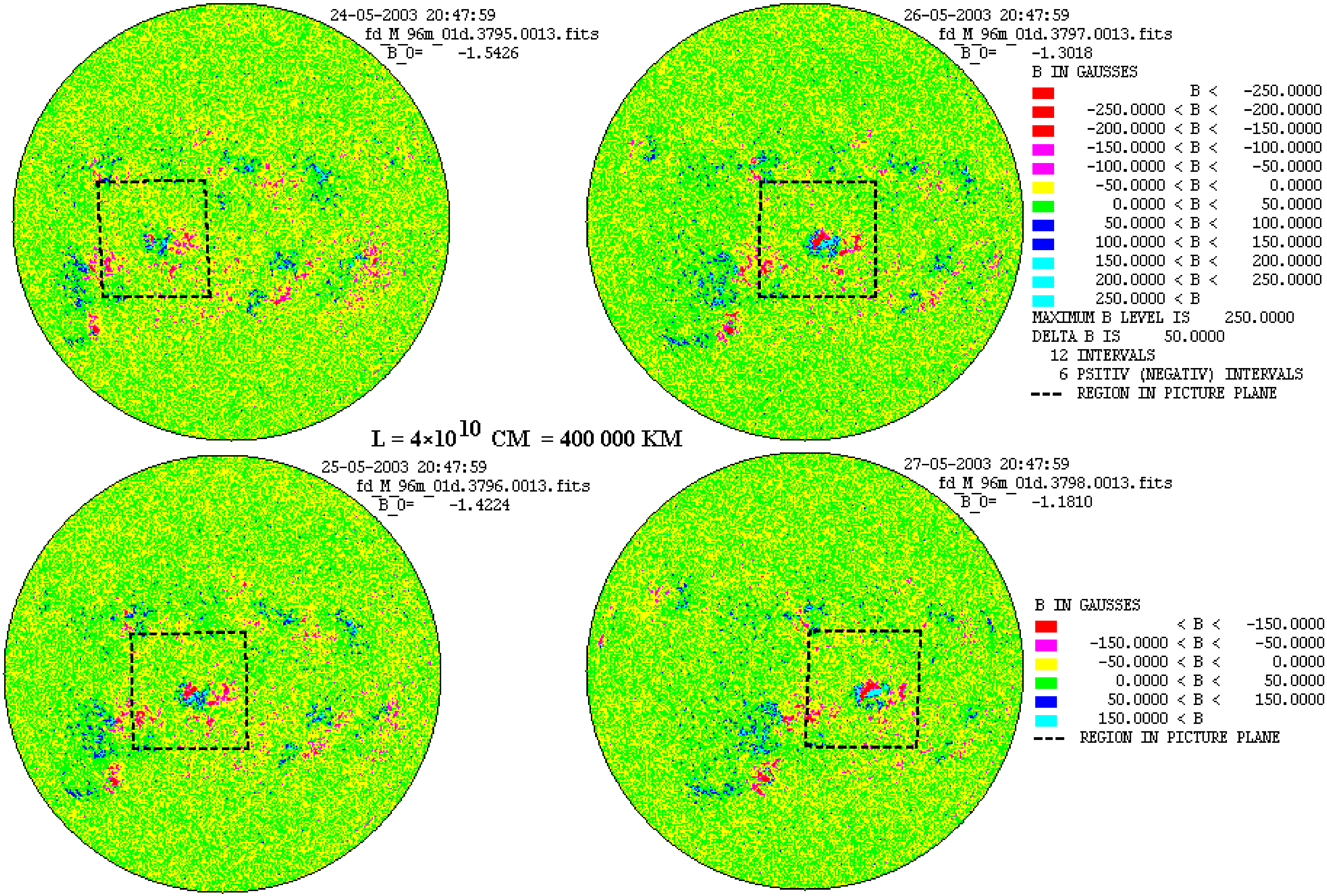
$\mathbf{V}\times\mathbf{B}$ contains $\mathbf{V}(B_{y,i+1,k+1} + B_{y,i,k+1})/2$

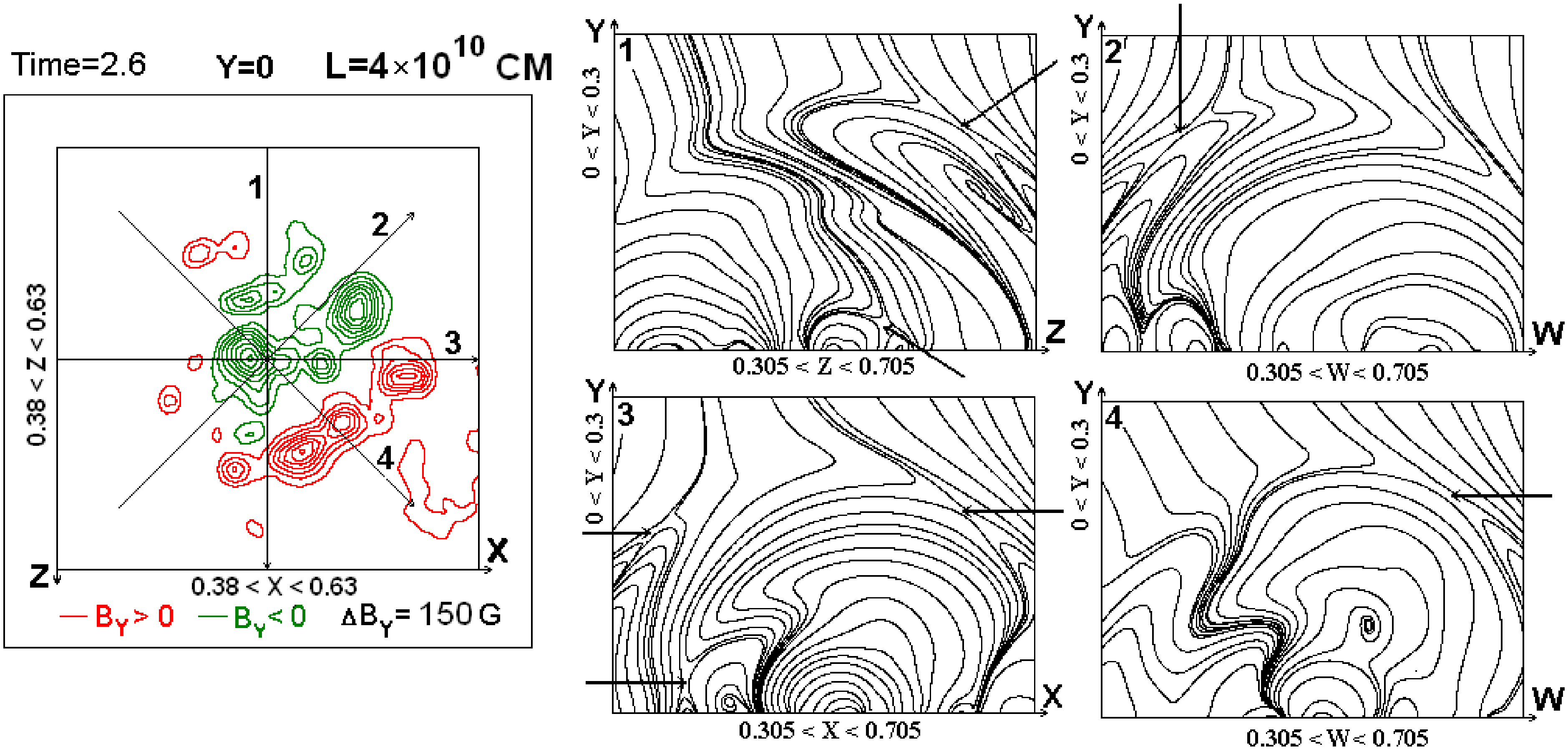
Despite the use of specially developed methods calculations are performed slowly. Therefore calculations on the personal computer (1.6 GHz dual core processor) are possible only in a strongly reduced time scale (10^4 times).

Unnaturally fast magnetic field change in time on the photosphere causes instability near the photospheric boundary. The developed numerical methods prevent the instability increase near the photospheric boundary to infinity and prevent propagation of the instability inside the region.

SET OF FLARES MAY 27-29, 2003

AR 10365





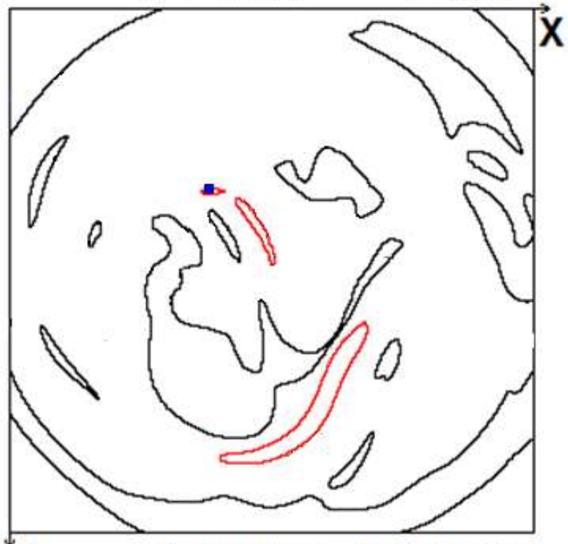
Time=2.6
Y=0
L=4×10^10 CM
1
2
3
4
0.38 < Z < 0.63
0.38 < X < 0.63
Z
X
B_Y > 0
B_Y < 0
ΔB_Y= 150 G
Y
0 < Y < 0.3
0.305 < Z < 0.705
0.305 < W < 0.705
0.305 < X < 0.705
W

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

To find the position of the current sheet, its property is used, according to which the local maximum of the absolute value of the current density is located in the center of a current sheet. All positions of local maxima of the current density are searched. Magnetic field configuration in the vicinity of each current density maximum is analysed.

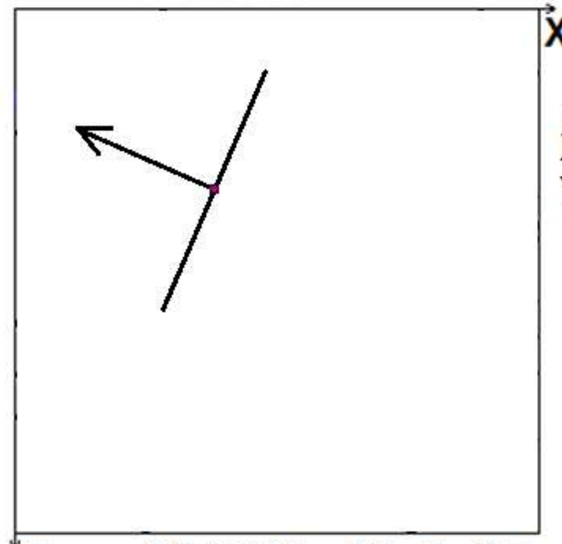
FLARE May 27, 2003 02:40 S6 W7

TOP VIEW Y=0.04



0.3<X<0.7 0.3 <Z <0.7

TOP VIEW Y=0.04

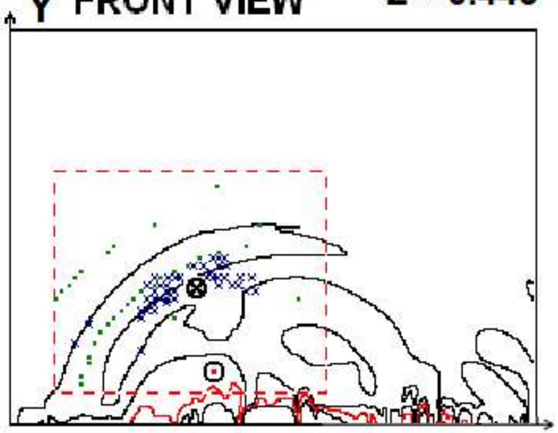


0.3<X<0.7 0.3 <Z <0.7

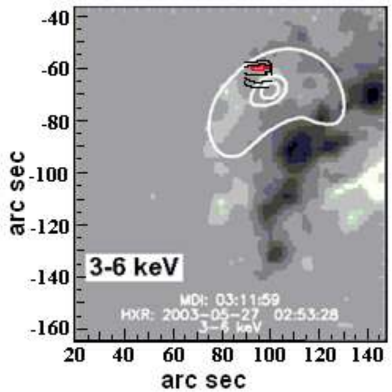
-B = (-0.179, -0.066, -0.093)
X-Y-Z POINT MAX J1 = (0.46, 0.04, 0.445)
Y=0.04

The plane of configuration of the magnetic field of the current sheet is inclined to the plane perpendicular to the photosphere at an angle of 18°

Y FRONT VIEW Z = 0.445



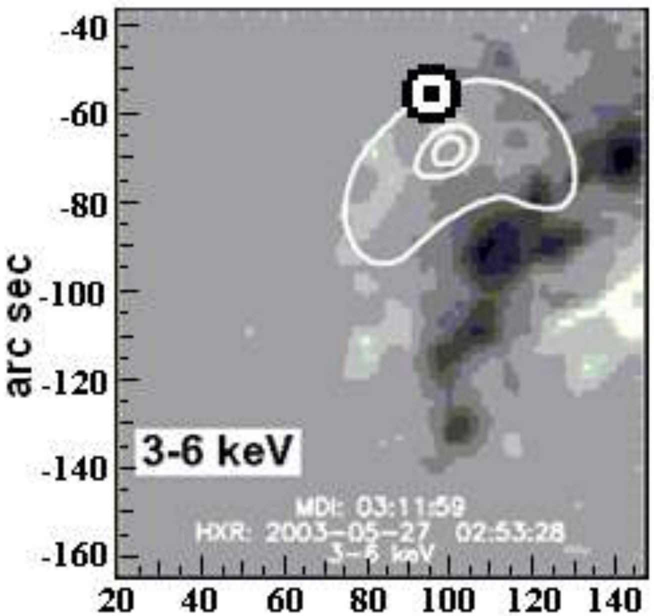
— J 0.3<X<0.7 0<Y<0.3 X



(99",-64") - OBSERVATIONS
(96",-56") - CALCULATIONS

Podgorny, Podgorny.
Sun and Geosphere. 8, 71, 2013

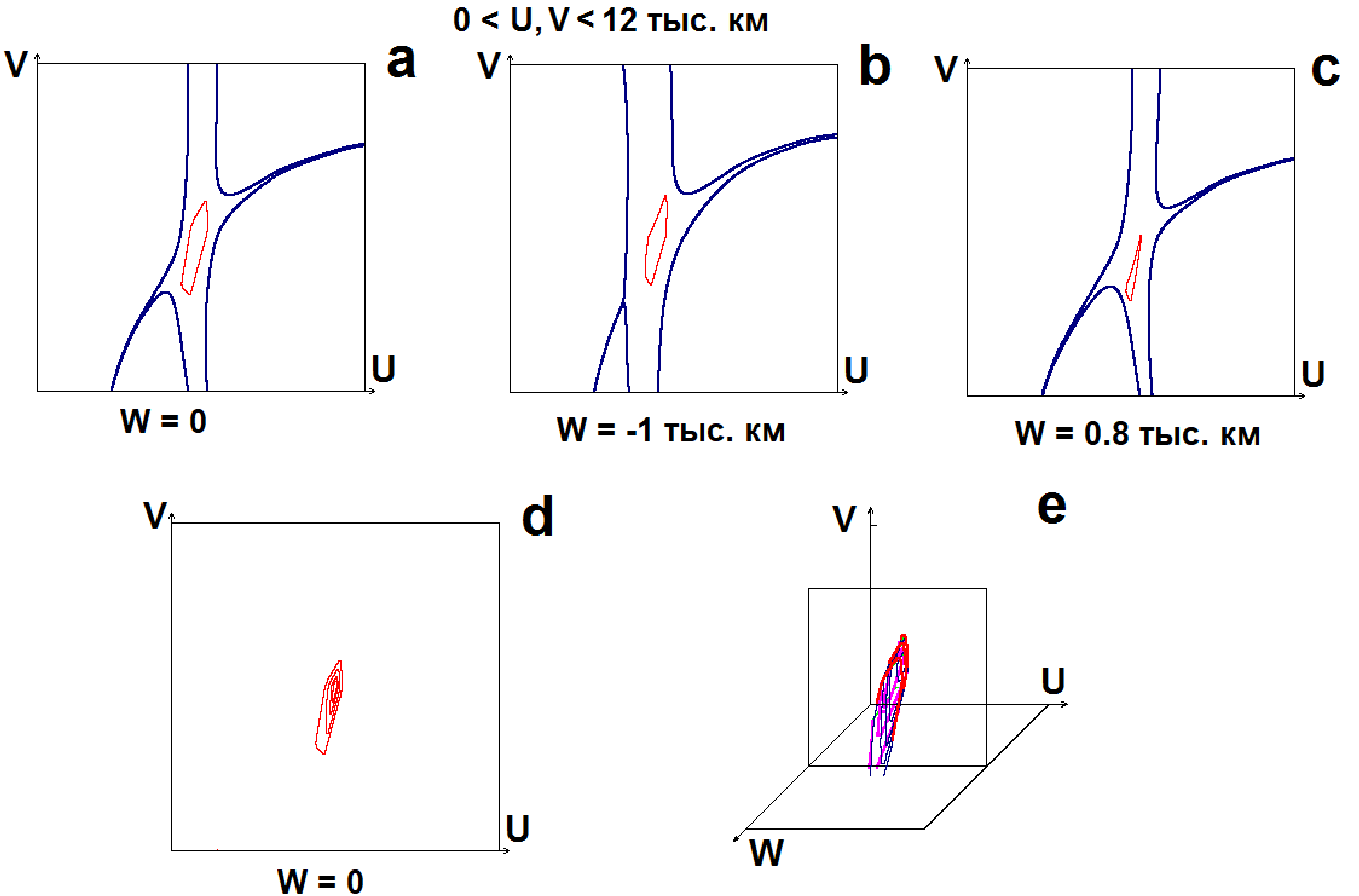
Podgorny, Podgorny, Meshalkina.
Sun and Geosphere. 12, 85, 2017

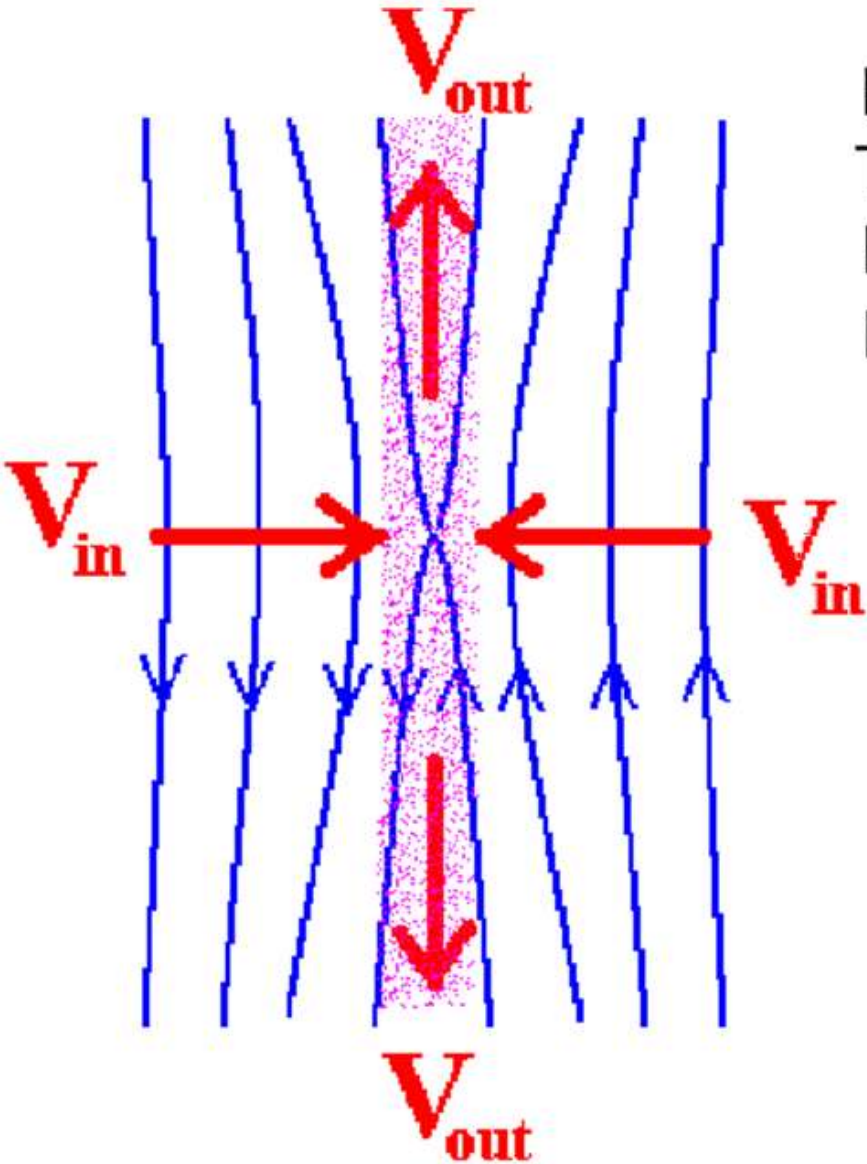


(99”,-64”) - position of thermal X-ray emission source

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

⊙ - POINT Max j_1


0 < U, V < 12 тыс. км
a
b
c
V
U
W = 0
W = -1 тыс. км
W = 0.8 тыс. км
d
e
W



From RHESSI: (ME)=$5\cdot10^{49}$ cm^{-3}.
T=3.1 keV n=10^{11} cm^{-3}.
$B^2/8\pi = nkT \rightarrow B = 110$G.
$M = Nm_p \sim 10^{15}$g --- CME.

At $V_{in} = 2\times10^7$ cm/s and L=10^9 cm.

E= V×B/c. E=20 V/cm.

W=2×10^{10}eV.

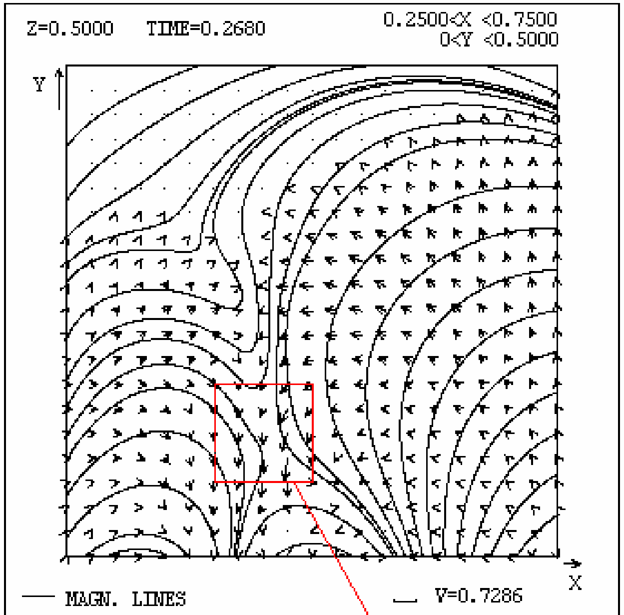
W_0=0.6 GeV

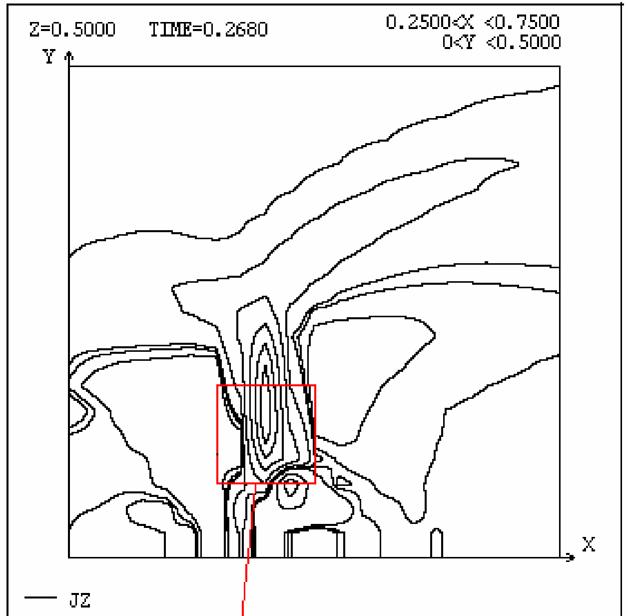
The rate of reconnection for W_0 ~ 0.6 GeV is order of 10^7 cm/s.

$E=V_{in} B/c$

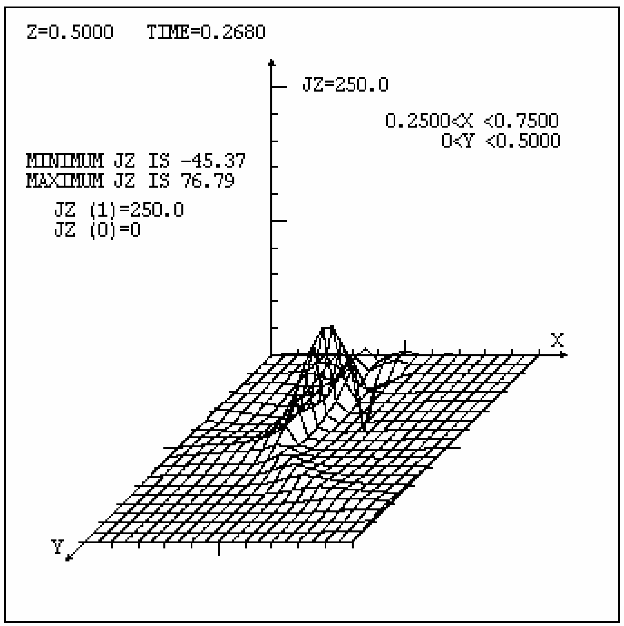
Подгорный, Балабин, Вашенюк, Подгорный Астр. Журн. Т. 87, С. 704 (2010)

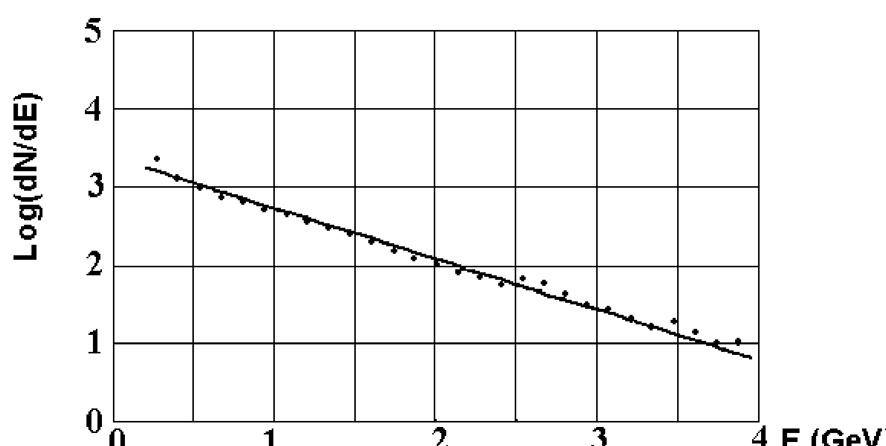
Podgorny, Balabin, Podgorny, Vashenyuk Journ. Atm. Solar-Ter. Phys. V. 72. P. 988 (2010)

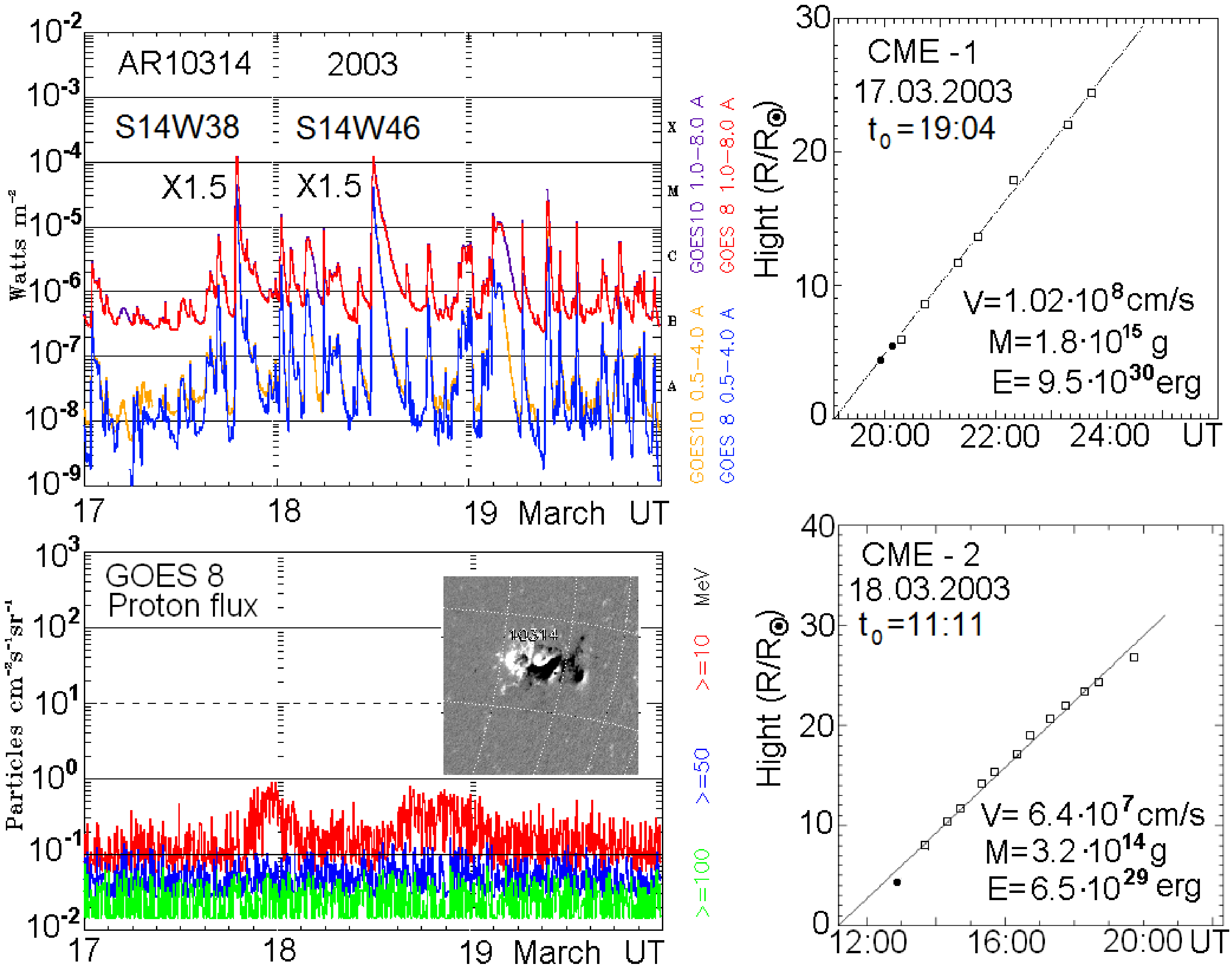


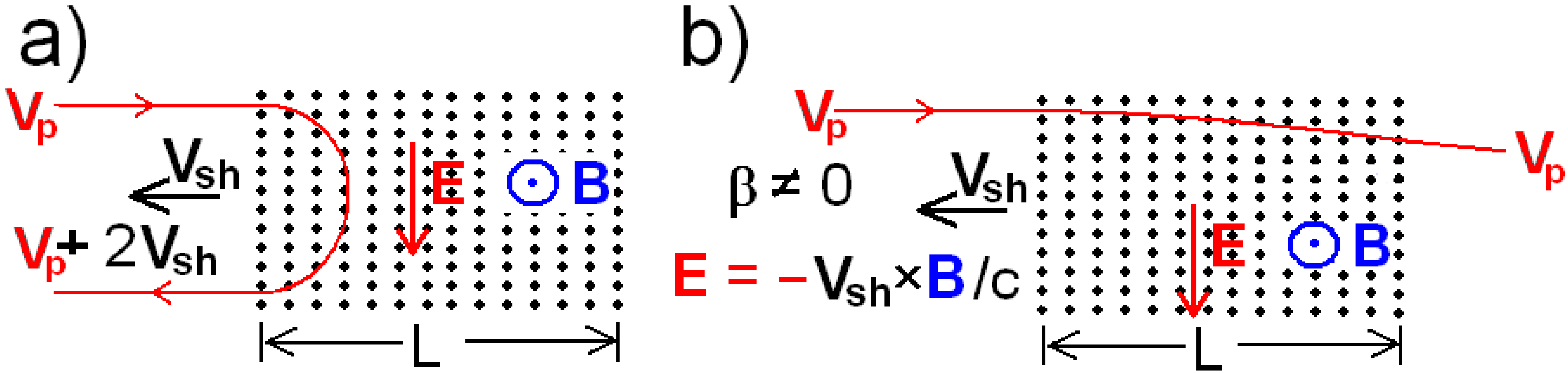


Plane region ($0.4<x<0.5$, $0.075<y<0.175$, $z=0.5$) i.e. intersection of the region ($0.4<x<0.5$, $0.075<y<0.175$, $0.45<z<0.5$), in which the calculation is performed, with the plane z=0.5.



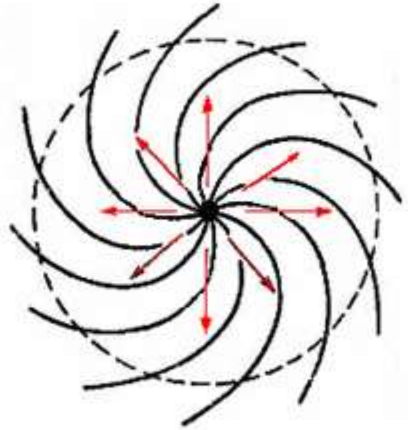



AR10314
2003
S14W38
S14W46
X1.5
X1.5
Watts m-2
X
M
C
B
A
GOES10 1.0–8.0 A
GOES 8 1.0–8.0 A
GOES10 0.5–4.0 A
GOES 8 0.5–4.0 A
17
18
19 March UT
CME -1
17.03.2003
t0=19:04
V=1.02·10^8 cm/s
M=1.8·10^15 g
E= 9.5·10^30 erg
Hight (R/R☉)
20:00
22:00
24:00
UT
GOES 8
Proton flux
Particles cm-2s-1sr-1
10314
MeV
>=10
>=50
>=100
17
18
19 March UT
CME - 2
18.03.2003
t0=11:11
V= 6.4·10^7 cm/s
M=3.2·10^14 g
E=6.5·10^29 erg
Hight (R/R☉)
12:00
16:00
20:00 UT

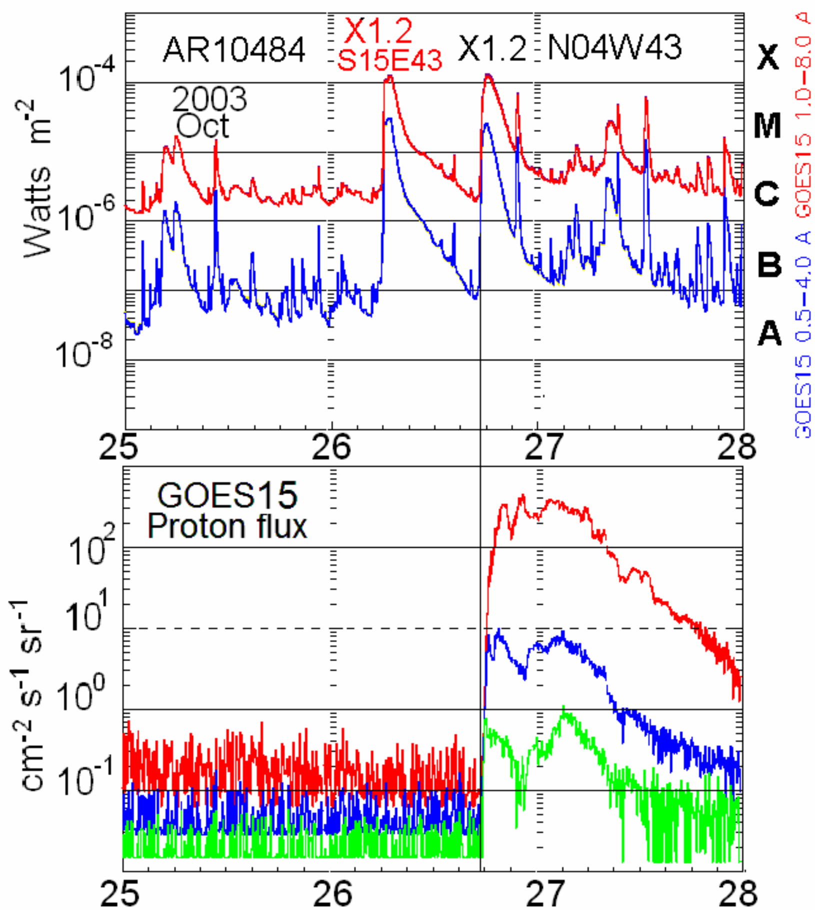


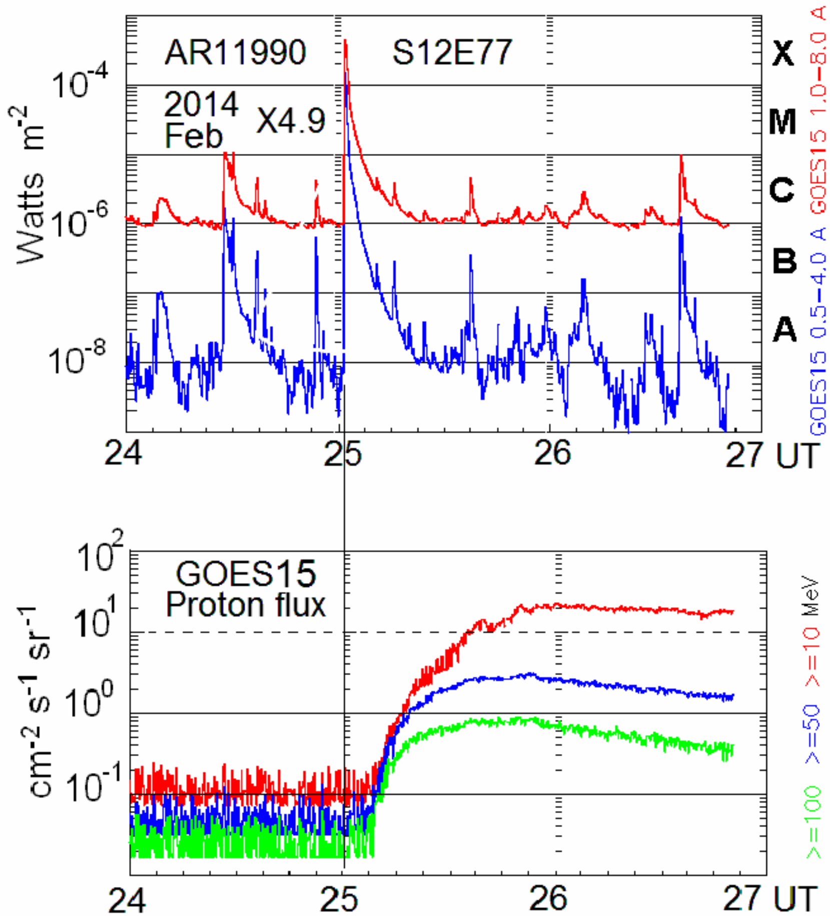
$$\delta W = 2\rho E e \qquad \rho = \frac{M V_p c}{e B} \qquad \delta W = 2 M V_p V_{sh} \qquad \delta V_p = 2 V_{sh}$$

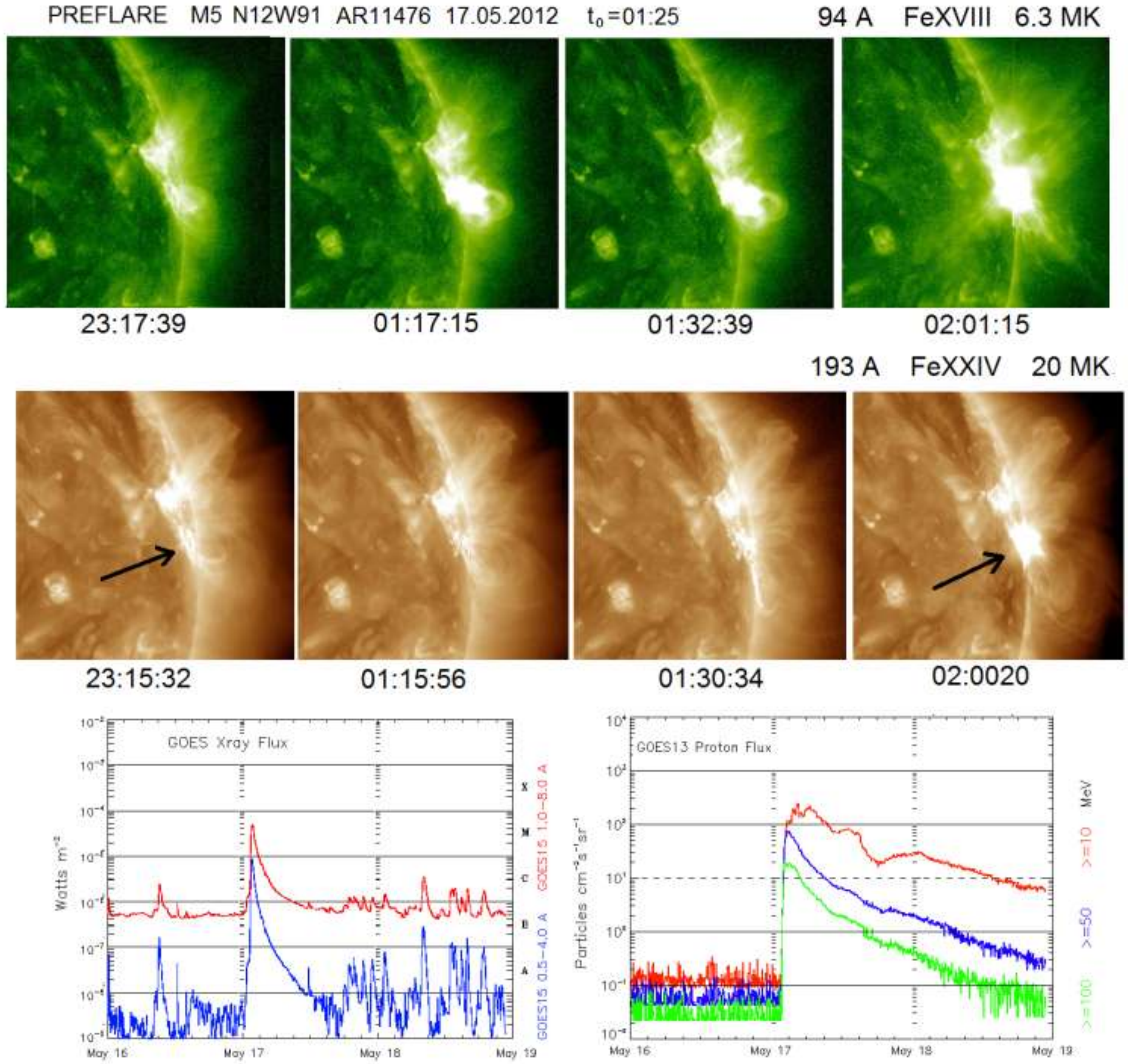
For Fermi particle acceleration, it is necessary that the size of the magnetic cloud (thickness of the shock wave) L be larger than the Larmor radius of the particle ρ. Otherwise, the particle passes through a magnetic cloud. The maximum achievable energy corresponds to the equality of the Larmor radius $\rho \sim W/300B$ to the size of the magnetic cloud. When the magnetic field in the shock wave is $B = 5\times10^{-4}$ G, for particle acceleration to 2×10^{9} eV, it is necessary the wave front width to be larger than $\sim10^{10}$ cm. The accumulation of such inhomogeneities in the solar wind has never been observed.

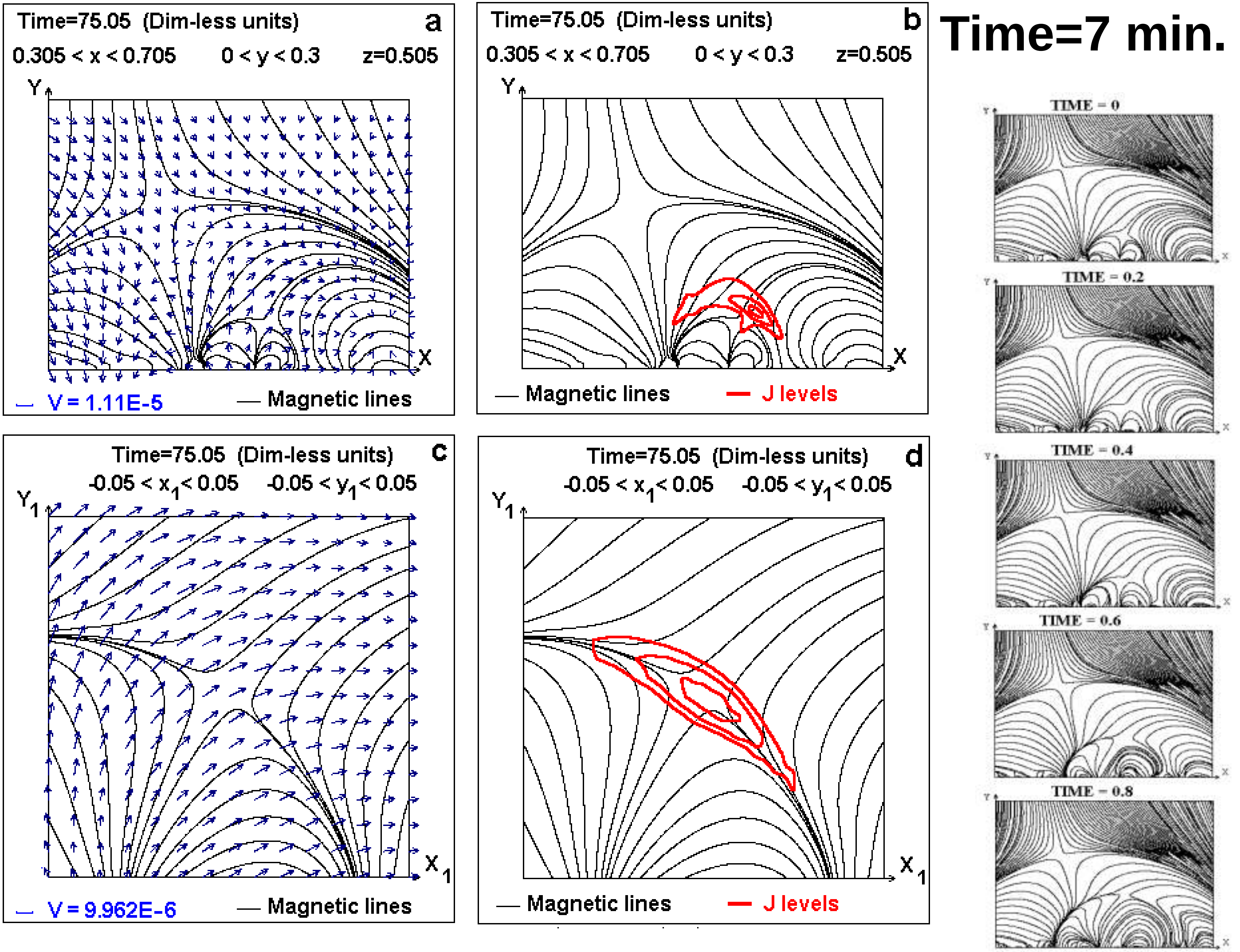


Solar wind -
plasma expansion
into vacuum at
$8\pi nW/B^2 > 1$.






PREFLARE M5 N12W91 AR11476 17.05.2012 t0=01:25
94 A FeXVIII 6.3 MK
23:17:39
01:17:15
01:32:39
02:01:15
193 A FeXXIV 20 MK
23:15:32
01:15:56
01:30:34
02:0020
GOES Xray Flux
Watts m⁻²
GOES15 1.0–8.0 A
GOES15 0.5–4.0 A
X
M
C
B
A
May 16
May 17
May 18
May 19
GOES13 Proton Flux
Particles cm⁻²s⁻¹sr⁻¹
MeV
>=10
>=50
>=100


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

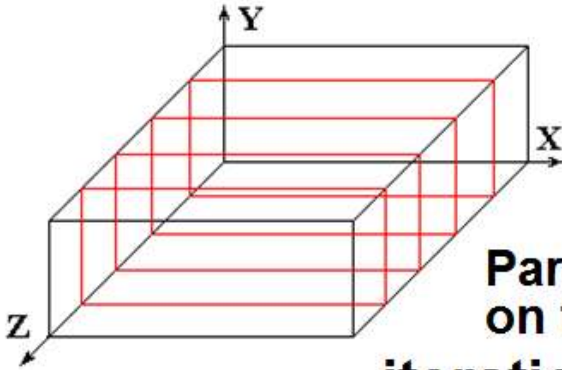
Simulation in the scale of real time during the first 7 minutes showed:

1. The absence of numerical instability near the photosphere boundary for simulation in the real time scale.

2. It is necessary calculation time ~3 years on the usual personal computer (1.6 GHz dual core processor) for MHD simulation in the real time scale of evolution above the active region during ~3 days.

3. For MHD simulation in the scale of real time above the active region, a supercomputer is needed, which performs calculations 100 times faster than a modern personal computer.

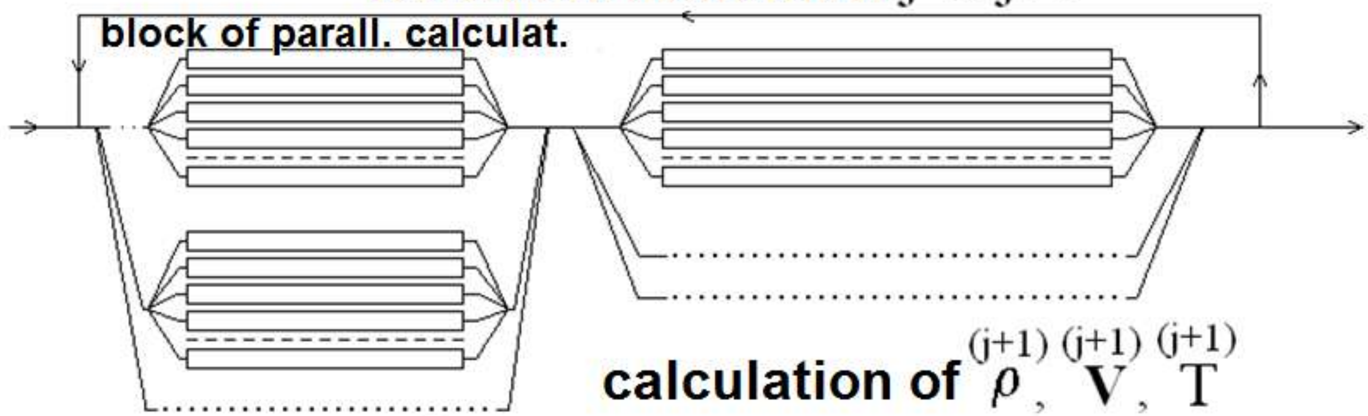
4. To improve the of solar flares prognosis, the MHD simulation should be carried out faster than the evolution of a real active region, i.e., the supercomputer is needed which calculate 10^4 times faster than a personal computer.



Parallelization of iterations when solving MHD equations

Parallelization of calculations on the base of CUDA technology

iteration transition $j \rightarrow j+1$



calculation of $\overset{(j+1)}{\rho}$, $\overset{(j+1)}{\mathbf{V}}$, $\overset{(j+1)}{T}$

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

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

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

calculation of $\overset{(j+1)}{\mathbf{B}}$

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

A.V. Borisenko configured software and hardware for the Tesla M2050 supercomputer card.

See Poster: Using CUDA for acceleration of calculations in study of solar flare mechanism for coronal MHD simulation

Borisenko A.V., Podgorny I.M., Podgorny A.I.

Preparation work on parallelization of calculations for the numerical solution of MHD equations has been carried out. Calculations of iterations are parallelized; these iterations are used for calculation of the values at the next time step. Parallelizing of calculations for the numerical solution of a simpler Poisson equation was carried out, which is solved by the method of iterations, similar to the method used to solve the MHD equations. The calculations showed the acceleration of parallel test calculations for the Poisson equation by 20–100 times, depending on the input conditions.

All the stages for preparing parallelizing subroutines planned for this year have been completed:

a) In the subroutines that will be parallelized, pointers have been removed, since the use of pointers is prohibited in subroutines executed simultaneously by several processors of the GPU board. These pointers permit for the convenience of drawing up the program to designate the same array components by different variables.

b) In the subroutines that will be parallelized, the subroutine calls are removed, since within the subroutines executed simultaneously by several processors of the GPU board, the use of subroutines is prohibited. Previously used chains of subroutines, which call each other, are replaced either by groups of operators, or by calculations of arrays whose elements are calculated in subroutines. Arrays are calculated in separate parallelized routines.

However, it turned out that for parallelizing the numerical solution of the work done is not enough. Two more changes are needed in the parallelizable subroutines, the first of which is done.

a) Due to the impossibility of transferring a large number of variables through formal parameters to the parallelized subroutine, it is necessary to transfer the existing ~ 40 parameters through arrays placed on the graphics card that are available for each processor (having the “DEVICE” attribute), as the arrays of variables of solved by MHD equations.

b) To make changes in the program, which permit not to use large-size parallelized subroutines. The analysis showed the possibility of an equivalent replacement of the existing two large parallelizable subroutines with several parallelizable subroutines of small volume. Translation and launching of the program containing small parallelizable subroutines shows that, apparently, parallelization as a result of replacing a large parallelizable subroutine with several parallelizable subroutines of a small volumes is possible, when all parallelizable subroutines are located in different modules.

Conclusions

1. Observations of ultraviolet radiation in the lines of highly ionized iron ions, which appear at temperatures much higher than the temperature of the corona, provide independent confirmation of the appearance of a flare in the corona.

2. The appearance of a luminous structure in the 94 Å Fe XVIII line, which emits at a temperature of 6.3 MK (above the corona temperature ~ 1 MK, but below the flare temperature 30-50 MK), several tens of hours before the flare, can be used for solar flare prognosis.

3. The coincidence of the position of the current sheet in a magnetic field obtained by MHD simulation in the corona above the active region with the position of the flare source of thermal X-ray emission is an independent proof of the solar flare mechanism, according to which the energy accumulated in the magnetic field of the current sheet is released.

4. Based on the results of MHD simulation and observations, an electrodynamic model of a solar flare is proposed, explaining its main observational manifestations.

5. Solar cosmic rays are accelerated by an electric field in the current sheet during the main flare process. The discovery on stars of dwarfs of class G "superflares", whose energy is 3-4 orders of magnitude higher than the energy of flares on the Sun, indicates the possibility of the same mechanism of generation of galactic and solar cosmic rays.

It is necessary, to parallelize the calculations and to perform MHD simulations in real time scale, which will allow us to more accurately determine the configuration of the magnetic field both near the current sheet and in the large-sized corona region, which will help solve the following problems:

1. More accurately determine the position of the current sheet for comparison with observations.
2. More accurately examine the configuration of the magnetic field in the vicinity of the current sheet and the shape of the region of high current density.
3. Accurately to determine the flare energy stored in the magnetic field of the current sheet.
4. Accurately determine the configuration of the magnetic field in a large region of the corona containing the current sheet, in particular, near the photospheric boundary, where the field in the calculation in a reduced time scale is determined roughly due to numerical instability. This will make it possible to determine the positions of the sources of beam X-rays at the intersections with the photosphere of magnetic lines going out the current sheet.
5. More accurately investigate the acceleration of protons in the current sheet by calculation of their trajectories in the electric and magnetic fields obtained by MHD simulation above the active region, and comparison of the calculated spectra with the spectra of cosmic rays measured on the world wide network of neutron monitors. May be it will appear possibility by calculating the proton trajectories to determine in which cases the protons accelerated in the current sheet can escape into the interplanetary space from the magnetic field above the active region, i.e., which flares will cause solar cosmic rays.

Thank you!

Благодаря за вниманието!