NUMERICAL SIMULATION OF THE SOLAR FLARE MECHANISM

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\[
\frac{\partial B}{\partial t} = \text{rot}(V \times B) - \frac{1}{\text{Re}_\infty} \text{rot} \left( \frac{\sigma_0}{\sigma} \text{rot} B \right)
\]

\[
\frac{\partial \rho}{\partial t} = -\text{div}(V \rho)
\]

\[
\frac{\partial V}{\partial t} = -(V, V)V - \frac{\beta}{2\rho} \nabla (\rho T) - \frac{1}{\rho} (B \times \text{rot} B) + \frac{1}{\text{Re}_\infty} \Delta V + \frac{G_d G}{1 - \gamma} 
\]

\[
\frac{\partial T}{\partial t} = -(V, V)T - (\gamma - 1) T \text{div} V + (\gamma - 1) \frac{2\sigma_0}{\text{Re}_\infty \sigma \beta \rho} (\text{rot} B)^2 - (\gamma - 1) G_d \rho L'(T) + \frac{\gamma - 1}{\rho} \text{div} (\kappa_{\parallel} (e_\parallel, VT) + e_{1,2} \kappa_{1,2} (e_{1,2}, VT)) + e_{1,2} \kappa_{1,2} (e_{1,2}, VT)
\]
SOLAR FLARE OCCURS IN THE SOLAR CORONA ON HEIGHTS 15 - 30 THOUSANDS KILOMETERS, WHICH IS 1/40 – 1/20 OF SOLAR RADIUS.
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
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

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.

B IN GAUSSES

\( B < -150 \)
\(-150 < B < -50 \)
\(-50 < B < 0 \)
\( 0 < B < 50 \)
\( 50 < B < 150 \)
\( 150 < B \)

COMPUTATIONAL DOMAIN IN CORONA ABOVE ACTIVE REGION

Y-axis directed from the Sun

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

--- REGION IN PICTURE PLANE

Cross-section \( Z = \text{const} \)

Nonphotospheric boundary:
\( B_{\perp} \) from \( \text{div} B = 0 \)
\( B_{\parallel} \) 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 \( \text{div} B = 0 \)
\( \rho = \text{const} \)
\( \partial V / \partial n = 0 \)
\( \partial T / \partial n = 0 \)

3D MHD equations are solved

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

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

\[
\frac{\partial \rho}{\partial t} = -\text{div}(\mathbf{V} \rho)
\]

\[
\frac{\partial \mathbf{V}}{\partial t} = -(\mathbf{V}, \nabla)\mathbf{V} - \frac{\beta}{2 \rho} \nabla (\rho T) - \frac{1}{\rho} (\mathbf{B} \times \text{rot} \mathbf{B}) + \frac{1}{\text{Re}_\rho} \Delta \mathbf{V} + \mathbf{G}_g \mathbf{G}
\]

\[
\frac{\partial T}{\partial t} = -(\mathbf{V}, \nabla)T - (\gamma - 1)T \text{div} \mathbf{V} + (\gamma - 1) \frac{2\sigma_0}{\text{Re}_m \sigma \beta \rho} (\text{rot} \mathbf{B})^2 - (\gamma - 1) G_g \rho L'(T) +
\]

\[
+ \frac{\gamma - 1}{\rho} \text{div} (\mathbf{e}_\parallel \kappa_{dl} (\mathbf{e}_\parallel, \nabla T) + \mathbf{e}_\perp \kappa_{dl} (\mathbf{e}_\perp, \nabla T) + \mathbf{e}_\perp \kappa_{dl} (\mathbf{e}_\perp, \nabla T))
\]

MAIN PUBLICATIONS:

A.I. Podgorny, I.M. Podgorny

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43, 608, 1999  46, 65, 2002  49, 837, 2005

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 $\Delta t$, 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.
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).
- The scheme is conservative relative to magnetic flux $[\text{div}B]=0$
  \[
  \mathbf{u}_i^{j+1} = \mathbf{u}_i^j - \mathbf{V} \frac{\Delta t}{\Delta x} \left( \mathbf{u}_i^j - \mathbf{u}_{i-1}^j \right)
  \]
- Nonsymmetrical (upwind) approximation $\mathbf{V}\times\mathbf{B}$.

Other methods:

- Explicit finite-difference schemes
- Often Godunov type (Riemann waves)
- 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 $[\text{div}B]=0$, but with symmetrical approximation $\mathbf{V}\times\mathbf{B}$.
  \[
  \mathbf{V}\times\mathbf{B} \text{ contains } \mathbf{V}(\mathbf{B}_{y,i+1,k+1} + \mathbf{B}_{y,i,k+1})/2
  \]
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:

\[ \frac{\partial \varphi_m}{\partial l_{\text{line-of-sight}}} = \mathbf{B}_{\text{line-of-sight}} \]

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 \( \frac{\partial \varphi_m}{\partial t} = \Delta \varphi_m \)
SET OF FLARES MAY 27, 2003

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L = 4×10^{10} CM = 400 000 KM
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 first 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)
FLARE
27 May 2003 02:40
S 6 W 7

\[ \text{line-of-sigt} = (-0.1241, 0.9882, -0.0899) \]
TIME = 2.2  MAGNETIC LINES

TIME = 2.2  J

TIME = 2.2  3D MAGNETIC LINES

- 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
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!