Three dimensional simulation of solar emerging flux and magnetic reconnection using the Earth Simulator

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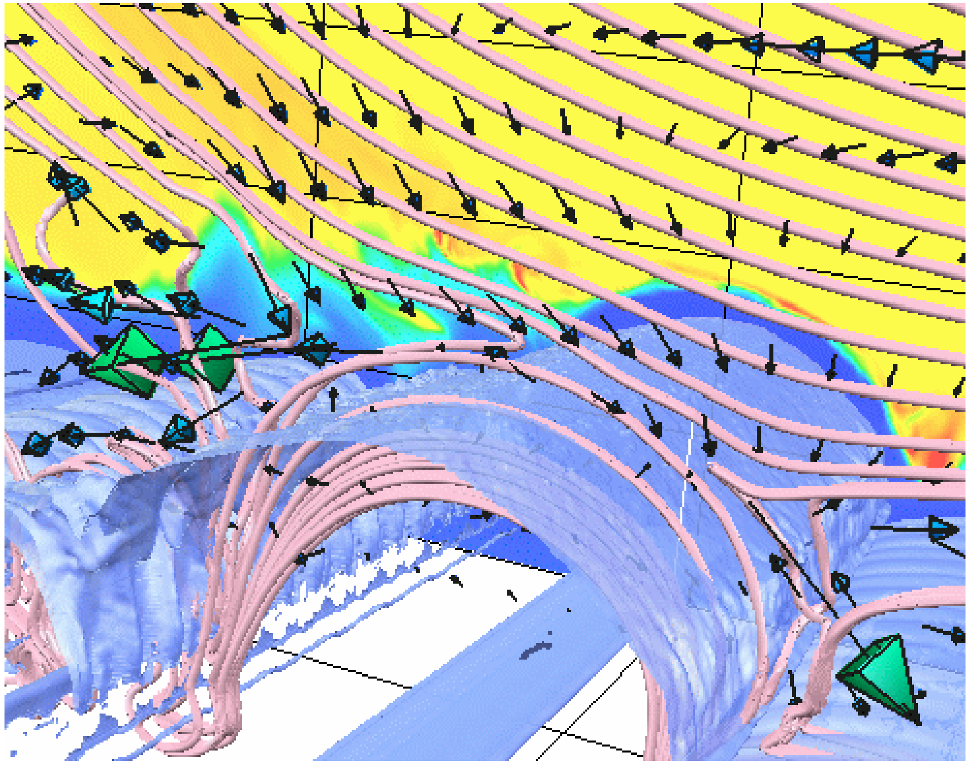


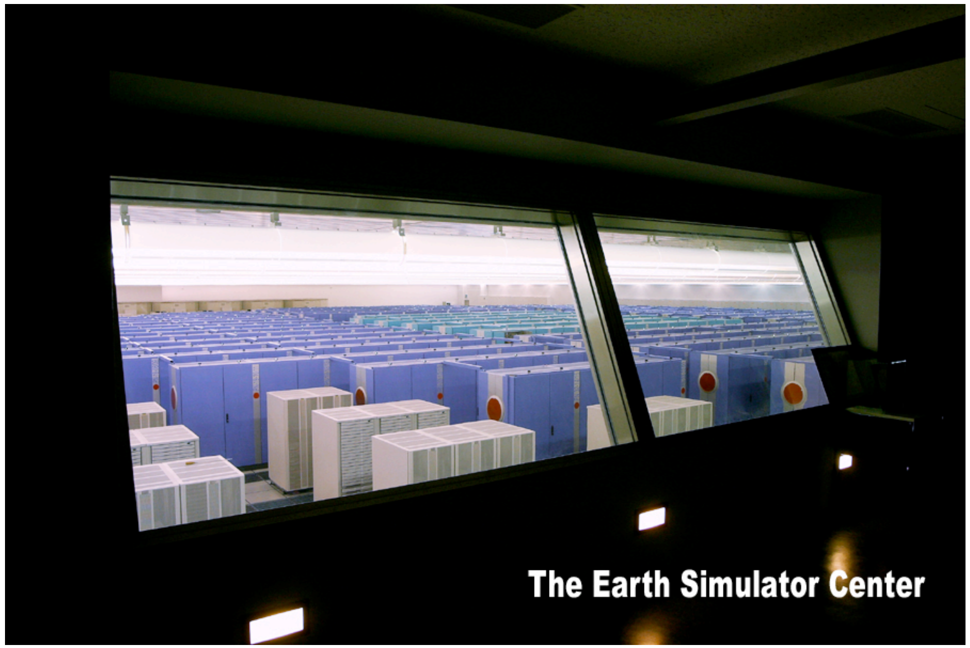
Outline

- The Earth Simulator: what it is and how it is operated.

- MHD simulation of solar emerging flux and its interaction with pre-existing coronal field.
  - Rayleigh-Taylor instability in the emerging flux as the origin of filamentary structures
  - Spatially intermittent magnetic reconnection

The Earth Simulator

- A parallel vector computer system installed at the Earth Simulator Centre, in Yokohama, Japan.
- It *had* been the fastest computer in the world since 2002 until last September. (Now, second).



The Earth Simulator: hardware and software

•640 Processor Nodes (PNs)
•One PN consists of 8 vector-type arithmetic processors (APs) and 16 GB shared memory..

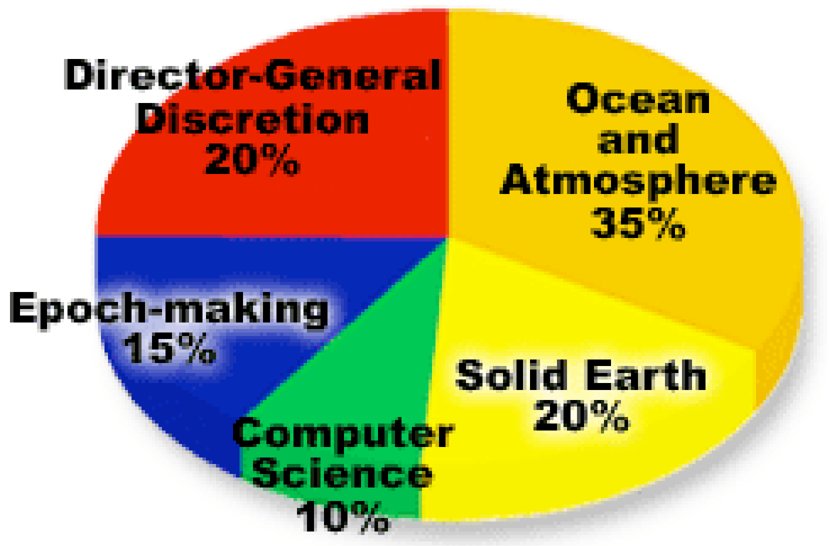
•In total, 5120 APs and 10TB memory (distributed).
•40Tflops at peak, 35.86Tflops for Linpack Benchmark

•Isolated from internet. No remote login

•Compiler: FORTRAN and C
•Parallelization: MPI, OpenMP, and High Performance Fortran
•System for visualization: IDL, AVS

The Earth Simulator: resource allocation

•The primary mission is the study and prediction of global climate and earthquakes.
•Practical, but no military.
•The "Director-General-Discretion" is mainly used for international collaborations, which is based on institute level.



•The astrophysical project is included in the "Epoch-making" .

Can astrophysicists use the Earth Simulator?

- You cannot apply at individual level.
- The astronomical society of Japan was required to organize a consortium and to propose a project under the consensus of the community.

- In 2004, 10,300 nodes×hours was allocated for "Cosmic Structure Formation and Dynamics", which includes:
  - -MHD modeling of the energy transport from convection zone into the corona of the Sun (Isobe, Shibata, Yokoyama, Miyagoshi, Tanuma)
  - -Global MHD simulation of accretion disk (Matsumoto)
  - -Hydrodynamic simulation of galaxy formation (Mori, Umemura)

Requirements for codes

- High efficiency of vectorization and parallelization is required to run your code.
- The number of Processor Nodes permitted to use depends on the efficiency of parallelization.
- Our code (CANS) now has passed the test up to 90 PNs (720 processors).

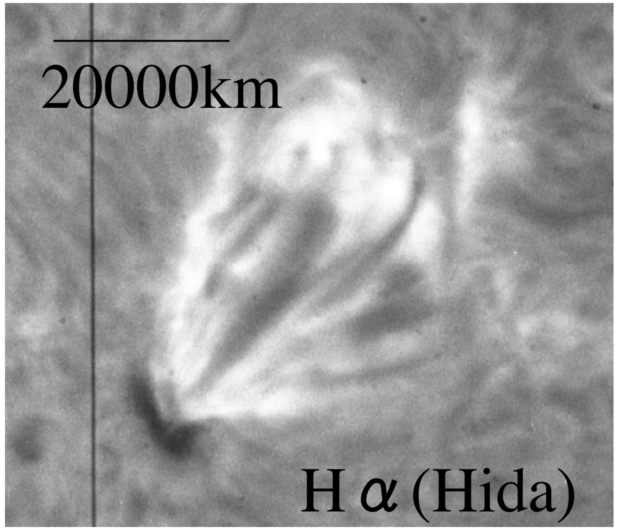
Numerical Code: CANS

- Package of HD/MHD solvers, samples of model problems (shock tube, Rayleigh-Taylor, reconnection etc...), and visualization programs (mainly based on IDL).
- Numerical scheme can be chosen from Lax-Wendroff, Roe-TVD, and CIP-MOC-CT.
- 1D and 2D versions are already open.

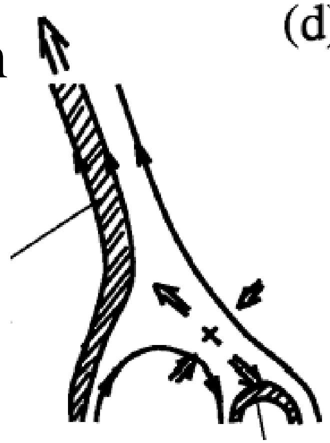
- We used Lax-Wendroff version.

Observations of emerging flux region

- H α
  - Arch Filament System =dark filaments connecting the sunspots with opposite polarities.



- EUV
  - Bright loops (10^6K) and dark loops (10^4K)
  - Jet: reconnection with preexisting field



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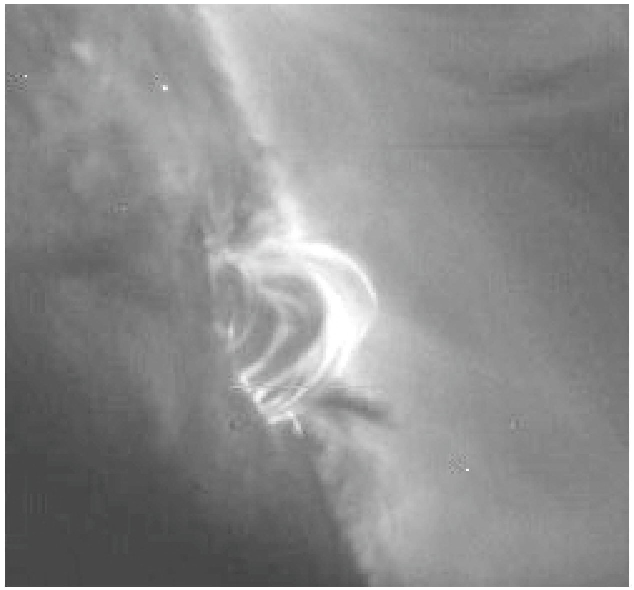


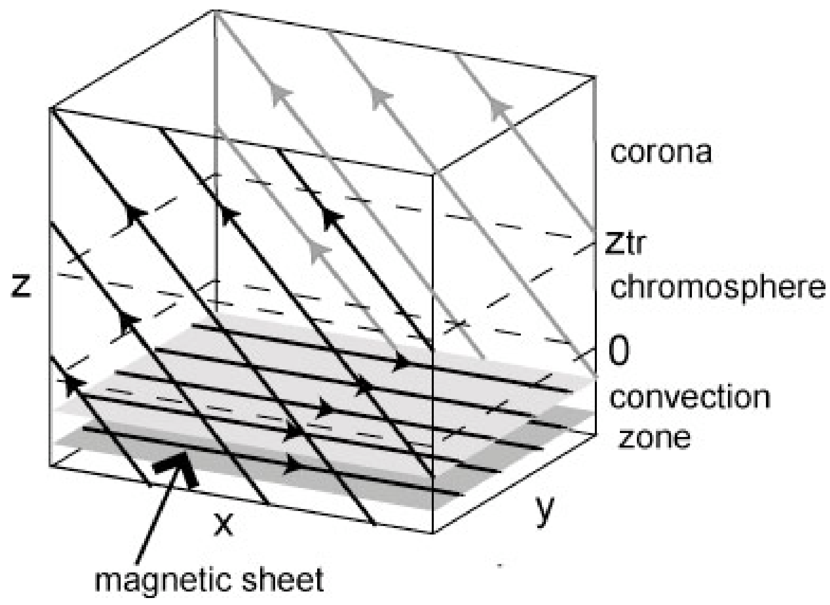
EUV(TRACE)

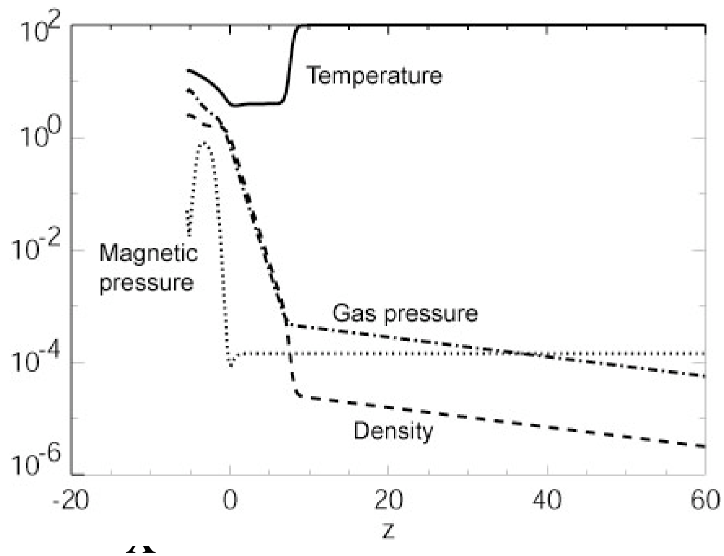
Model set up

•3D compressible MHD

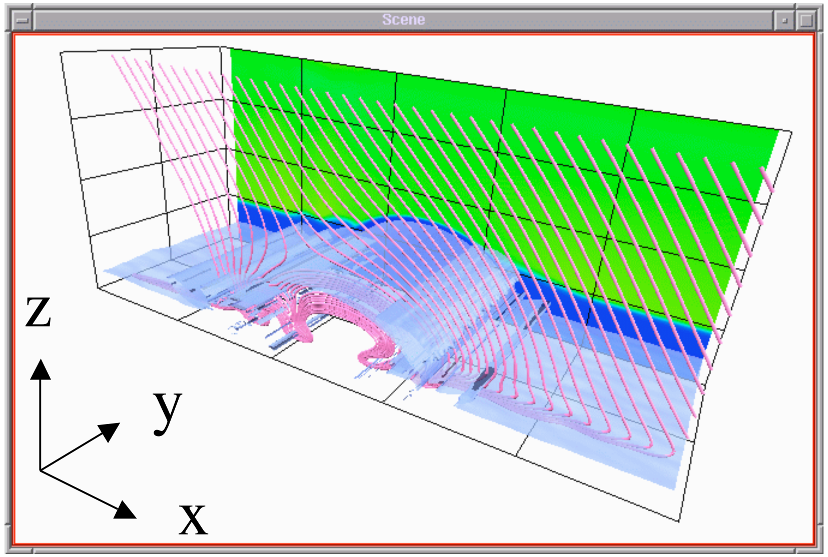
•Simulation domain includes upper convection zone (z～-1500 km), photosphere, chromosphere, and corona. Realistic stratification.

•Magnetic sheet in the convection zone + uniform oblique field. Plasma beta in the corona～0.1





Model set up



- Simulation domain:
  0<x<160, 0<y50<50, -5<z<65
  (unit: scale height at z=0)
- grid: 800x400x600
- Periodic in x and y, symmetric (mirror) at the bottom, free boundary at the top.
- Anomalous resitititivity
  => fast reconnection

$$\eta = \begin{cases} \eta_0 & \text{for } v_{\mathrm{d}} < v_{\mathrm{c}}, \\ \eta_0 + \eta_1 (v_{\mathrm{d}}/v_{\mathrm{c}} - 1)^2 & \text{for } v_{\mathrm{d}} \geq v_{\mathrm{c}}, \end{cases}$$

$v_d = J/\rho$

- Perturbation in 70<x<90

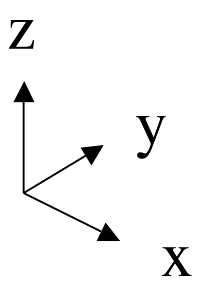
It took about 28,600 sec to calculate 50,000 steps (including I/O), using 20 PNs (160 processors).

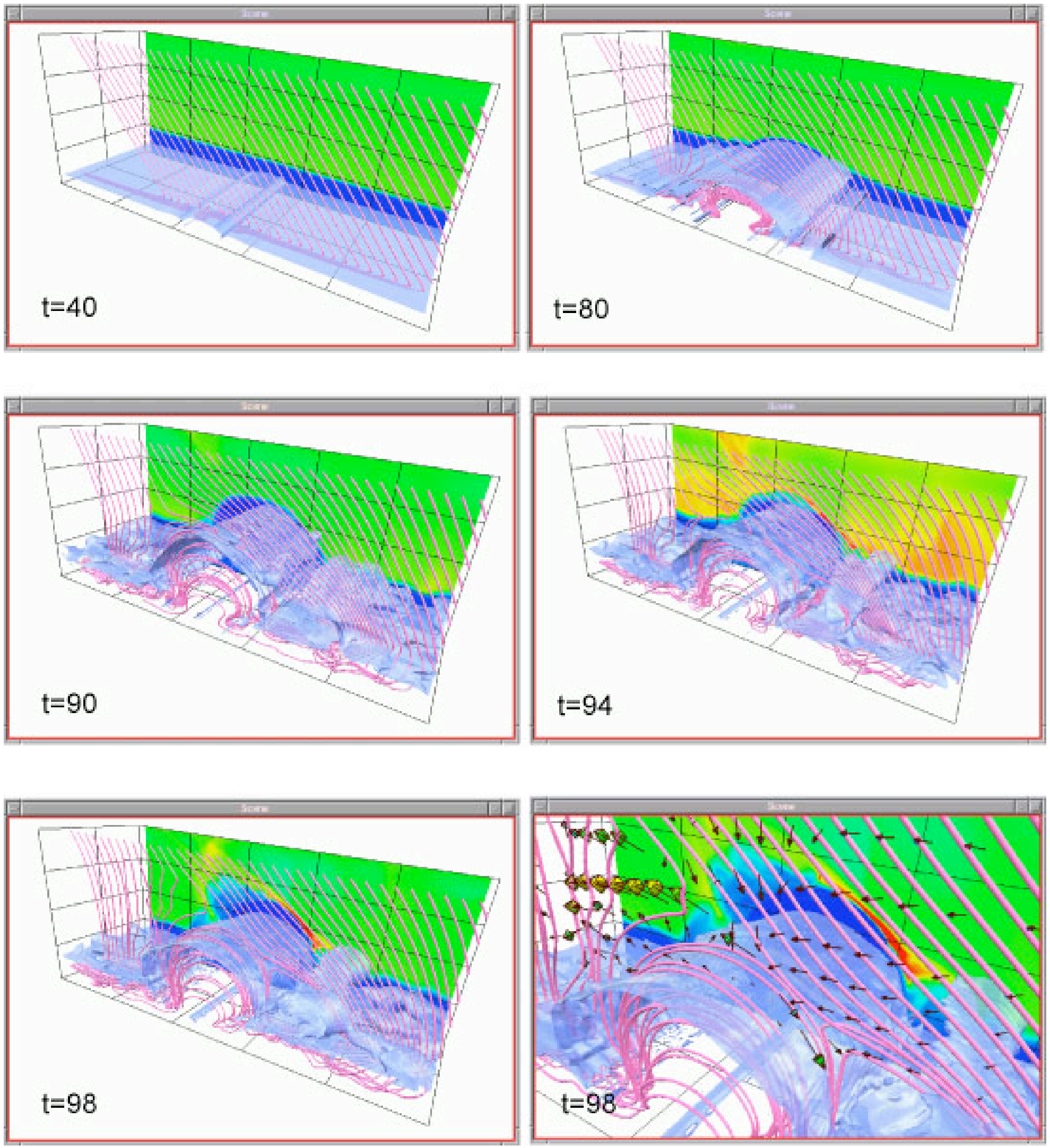
Results

Blue:
isosurface of |B|

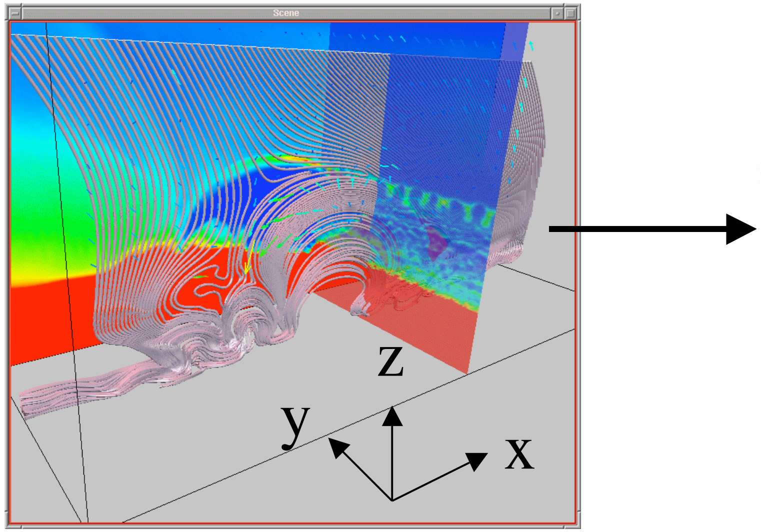
Side:
Temperature

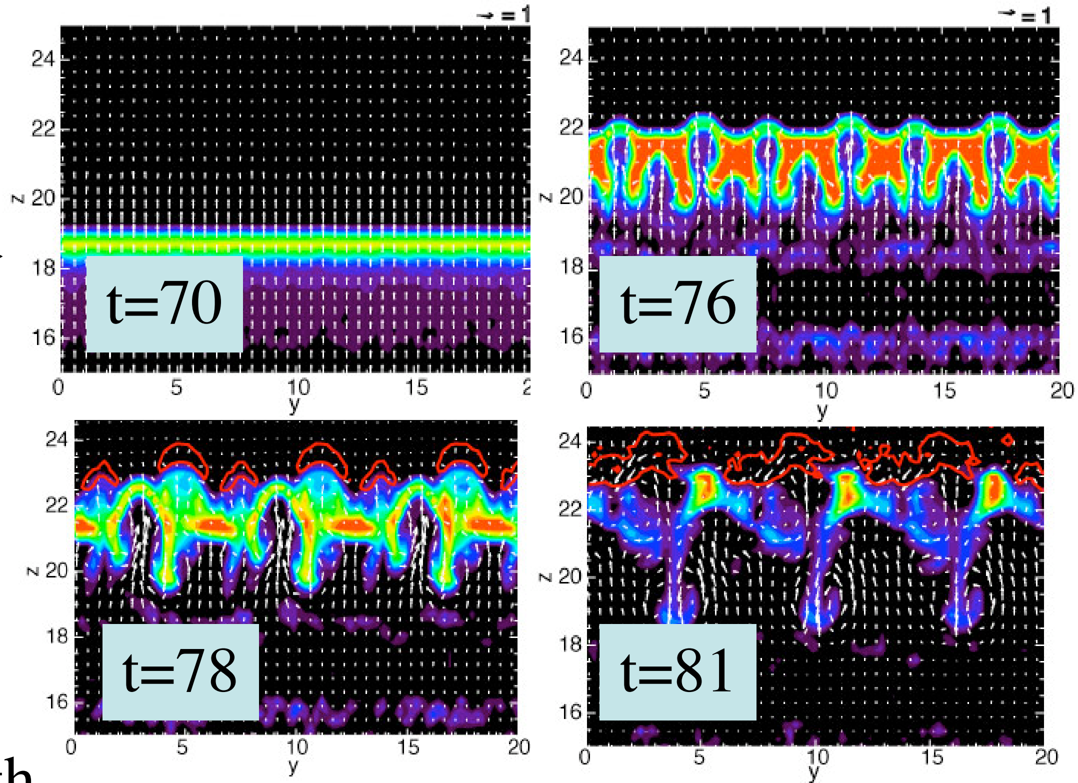
Pink:
magnetic fied lines





Rayleigh-Taylor instability

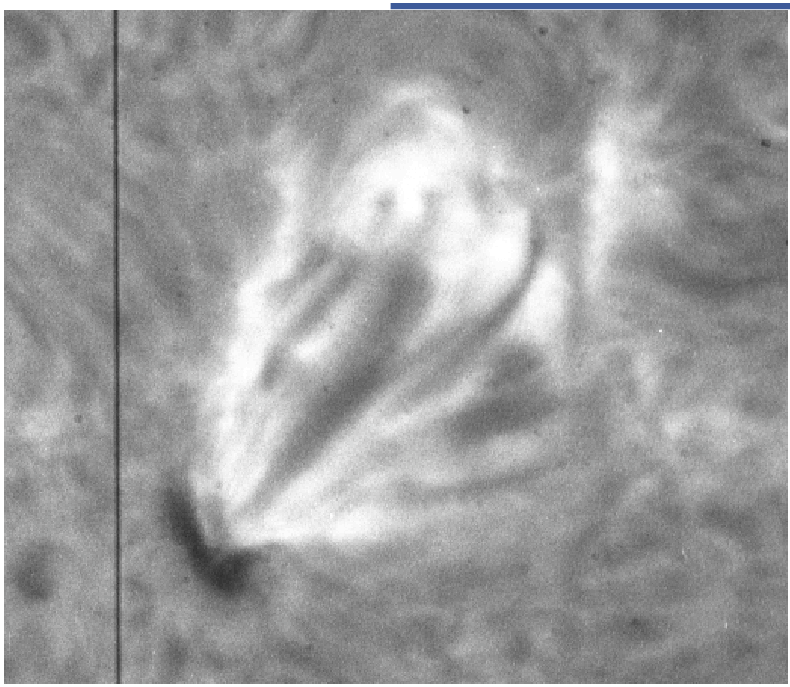




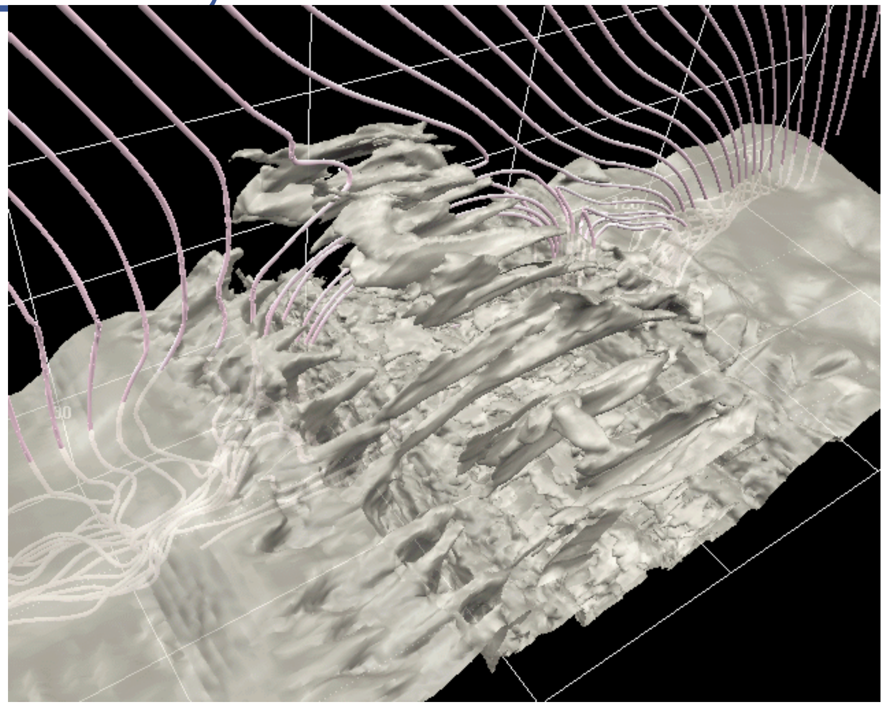
Temporal evolution of density at the mid point of EF.

- Top of the EF becomes top-heavy => unstable to Rayleigh-Taylor instability
- Bending the field line (**k**=k**x**) is suppressed => formation of filaments along **B**

Density distribution similar to Hα arch filament system



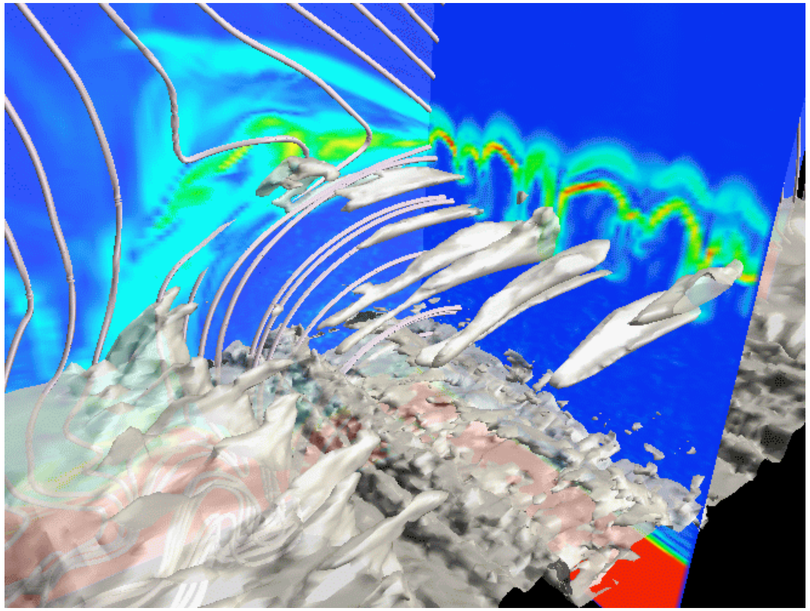
Hα AFS



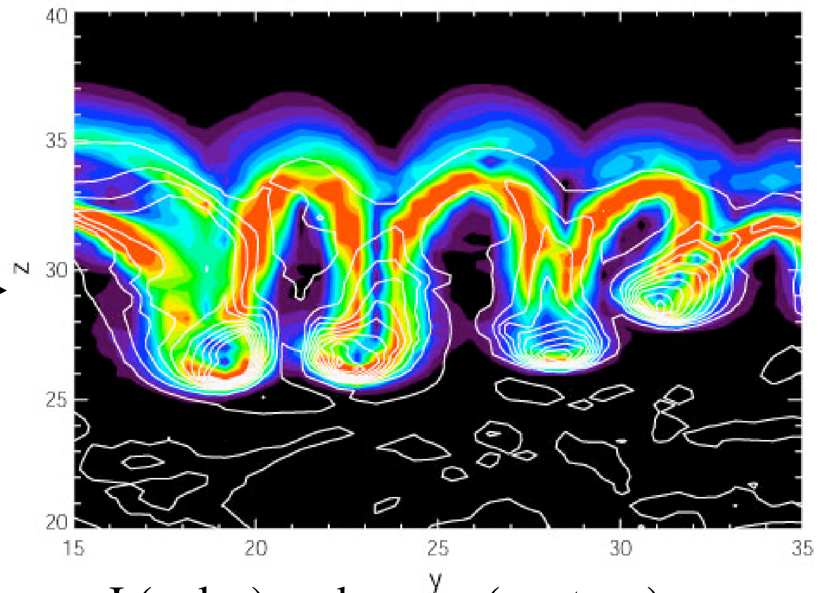
isosurface of ρ

Density～10^{12} cm^{-3}、Temperature～10000 K
Length ～10000km、Width～1000km

Filamentary current sheets in EF

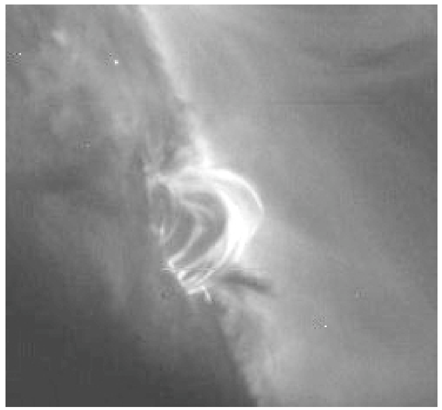


Isosurface of ρ and slices of J

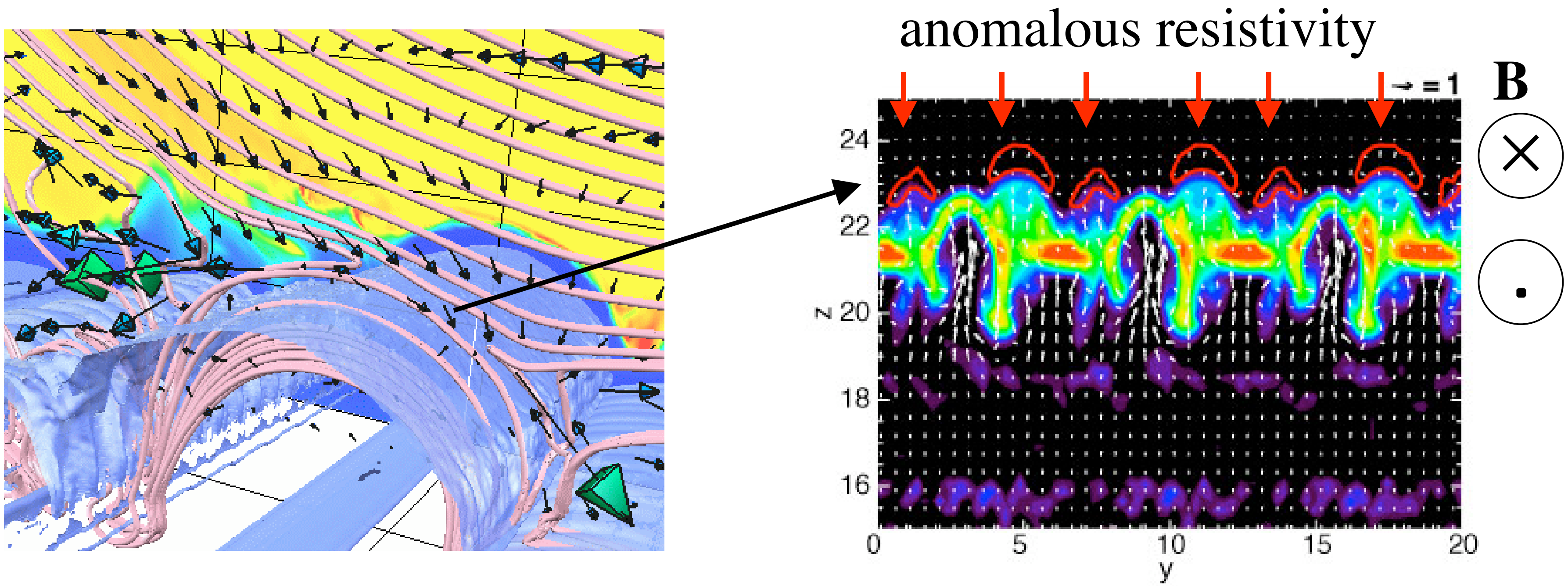


J (color) and gas ρ (contour)
at the midpoint of the EF

•Deformation of magnetic field by R-T instability
=> formation of filamentary current sheet in the periphery of dense filaments.
•Nonuniform coronal heating?



Intermittent magnetic reconnection

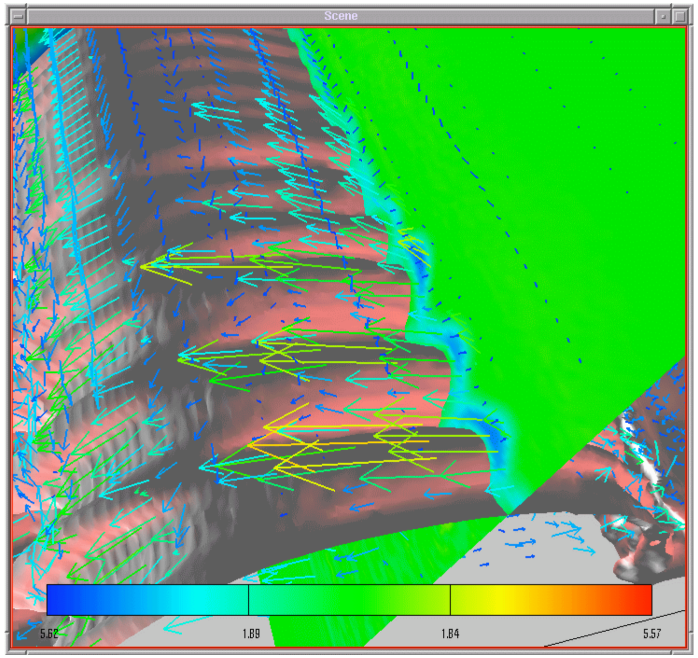


•The rising parts of R-T instability = increasing J and decreasing ρ
=> Anomalous resistivity locally sets in.

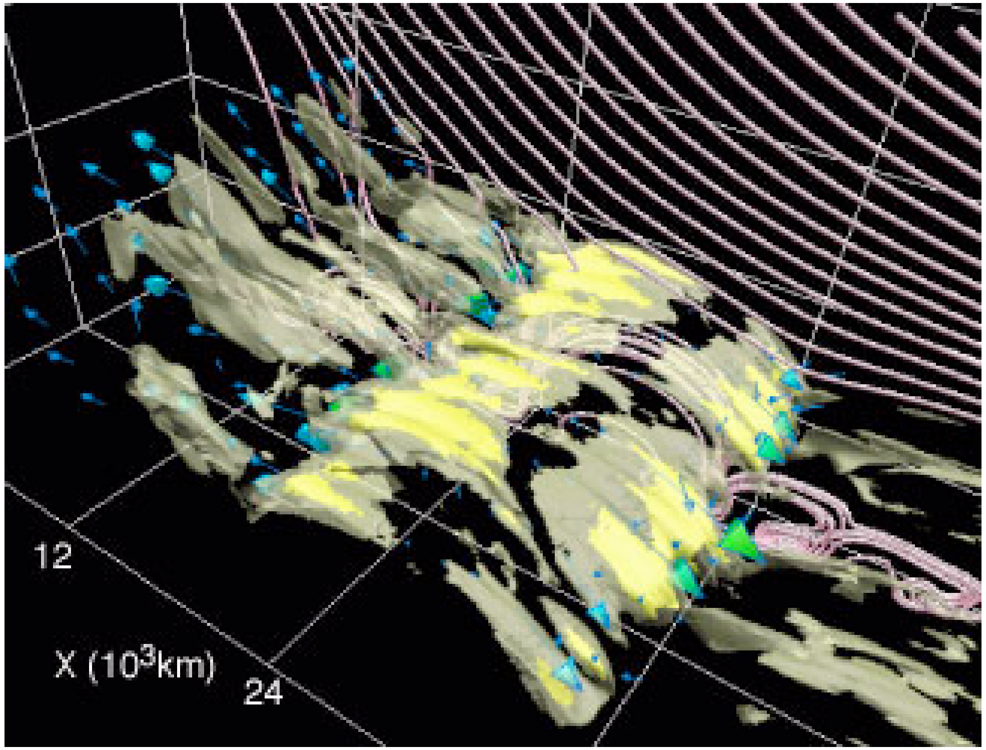
=>Fast reconnection starts in spatially intermittent way.

•Reconnection inflow enhances the evolution of RT ,which further enhances the reconnection rate => nonlinear instability.

Reconnection jets



isosurface of |B| and **V** (arrows)

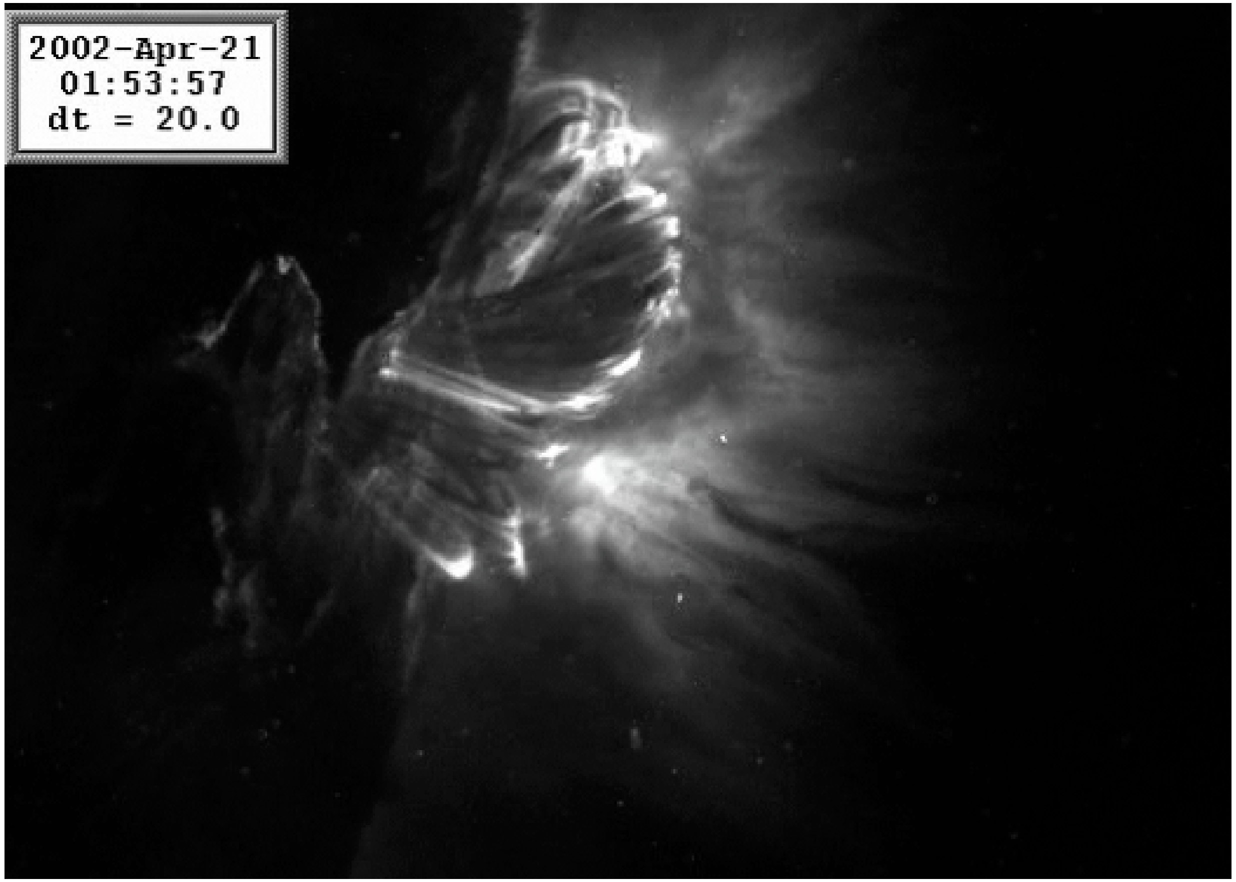


isosurfaces of |V|=6 and |V|=12

•Intermittent (patchy) reconnection

=> fine structure in jets and flares?

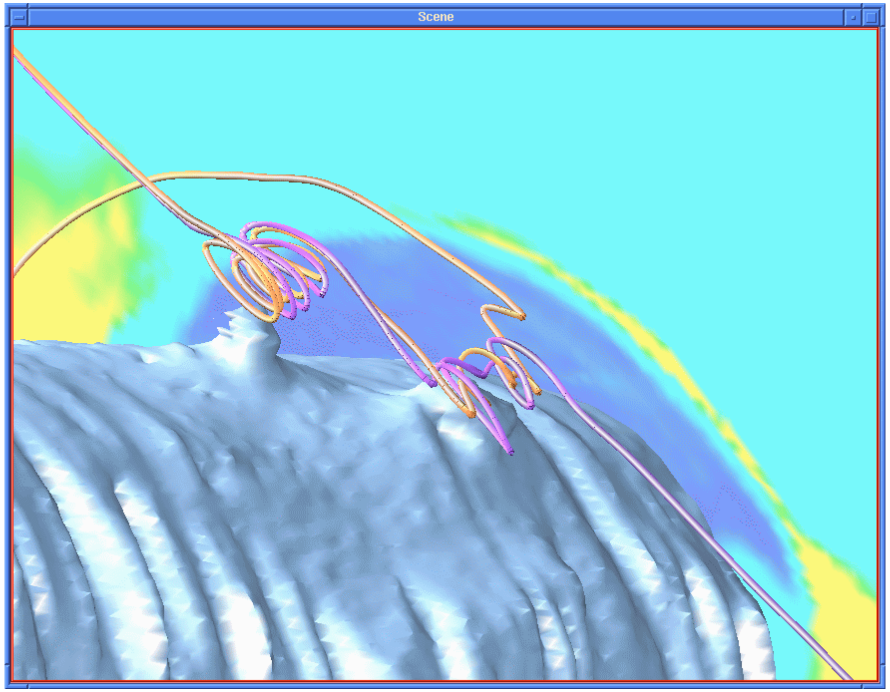
Evidence of “patchy” reconnection



TRACE
195A

•Small bright points (kernels) in the flare ribbons
•Down flows above post flare loops (reconnection outflows?)

Formation of helical flux rope (plasmoid)



- Tearing instability in the current sheet => formation of magnetic island (plasmoid)
- In the presense of guide field (By), the plasmoids form a helical flux rope.

Summary

- Using the Earth Simulator, we have carried out large scale 3D simulations of solar emerging flux and its interaction with pre-existing coronal field.
- Filamentary structure, which is very similar to H α arch filament system, is formed due to the Rayleigh-Taylor instability in the emerging flux.
- R-T instability causes the formation of many filamentary current sheet in EF, which may explain the nonuniform heating of the corona.
- Coupling of R-T instability and anomalous resistivity leads to spatially intermittent magnetic reconnection.