Formation and Dynamics of Current Sheets

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collaboration with
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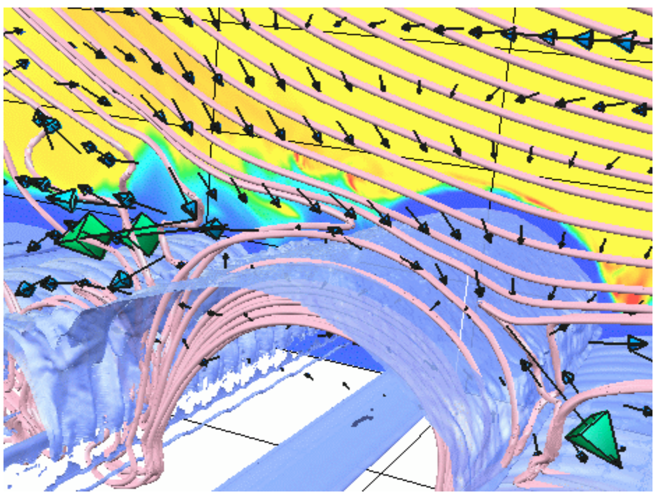
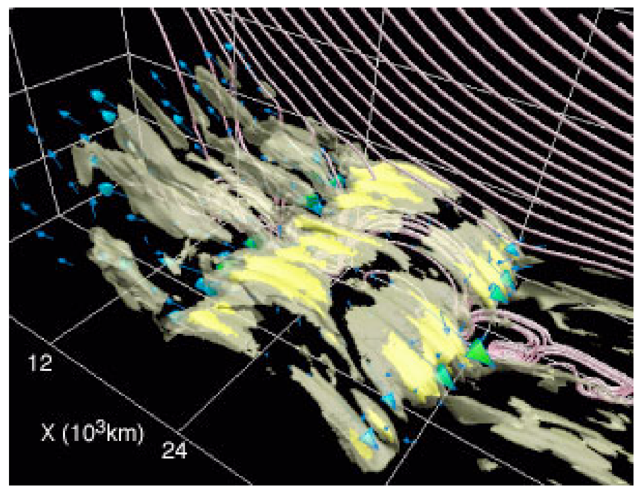




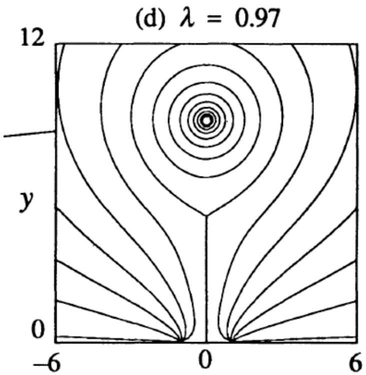
Outline

- Fundamental problems in the theories of magnetic reconnection
- Observation of dynamic phenomena in the current sheet and its implication for the dissipation mechanism
    - plasmoid ejections
    - turbulent fractal nature of current shee

- 3D MHD simulation of emerging flux and reconnection
    - small scale current formation by magnetic Rayleigh-Taylor instability
    - intermittent, patchy reconnection

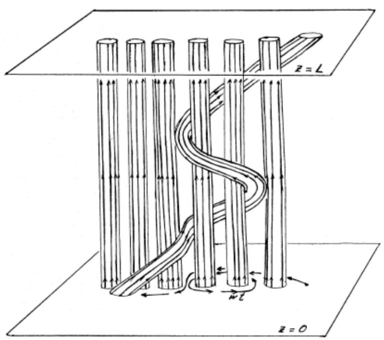
Locations and mechanism of current sheet formation

◇ Eruption of flux rope/arcade



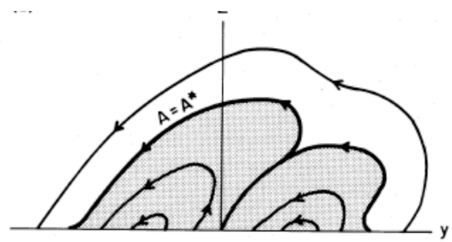
Forbes & Priest (1995)

◇ Brading by photospheric motions

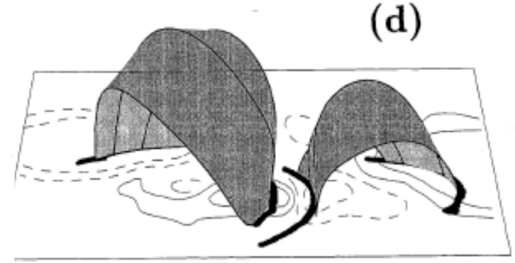


Parker (1983)

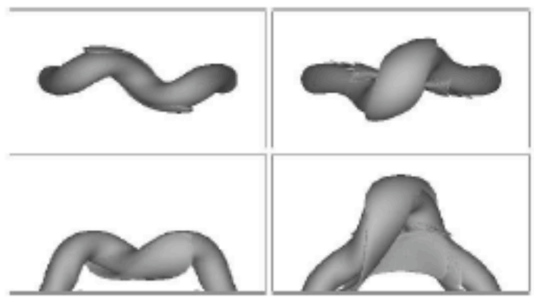
◇ (Quasi-) separatrix layers



Low & Wolfson (1988)



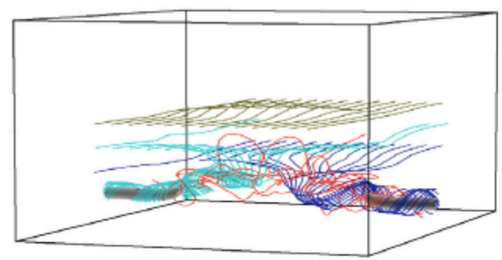
Démoulin et al. (1997)



Kliem, Titov & Török (2004)

◇ Kink instability

◇ Emerging flux



Archontis et al. (2004)

Introduction

- Current sheets play central role in explosive phenomena such as flares, jets, and CMEs, i.e., fast magnetic reconnection.

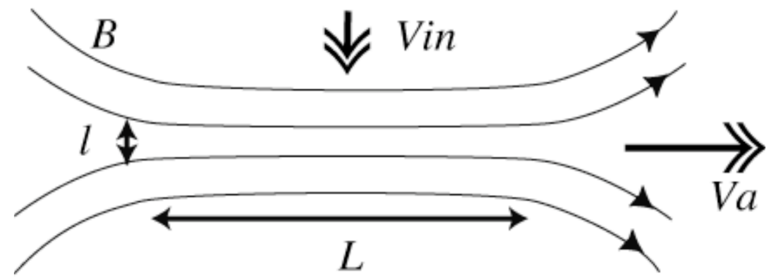
- Also likely to be important in the heating of quasi-static corona and less explosive events.

- Much evedence for reconnection in flares:
  - cusp-shaped post flare loop (Tsuneta et al. 1992),
  - loop top HXR source (Masuda et al. 1994),
  - downflows above post flare loop (McKenzie & Hudson 1999; Innes et al. 2003),
  - reconnection inflow (Yokoyama et al. 2001)

- Fundamental problems still remain in the dissipation mechanism
  - huge Reynolds number
  - coupling of micro- and MHD scales

Reconnection models

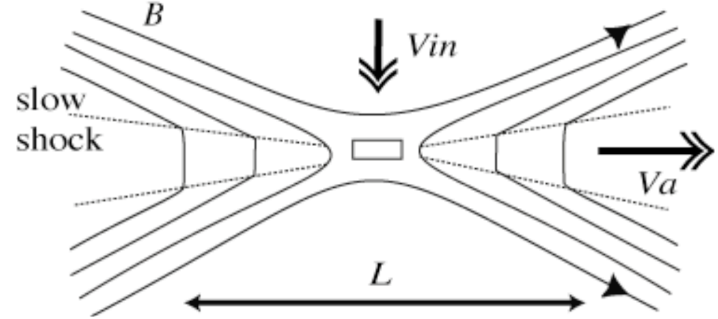
Sweet-Parker reconnection:



$$\frac{Vin}{Va} = \frac{l}{L} = Rm^{-1/2} \approx 10^{-7}$$ ... slow.

Rm: Lundquist number (magnetic Reynolds number defined by *Va*)

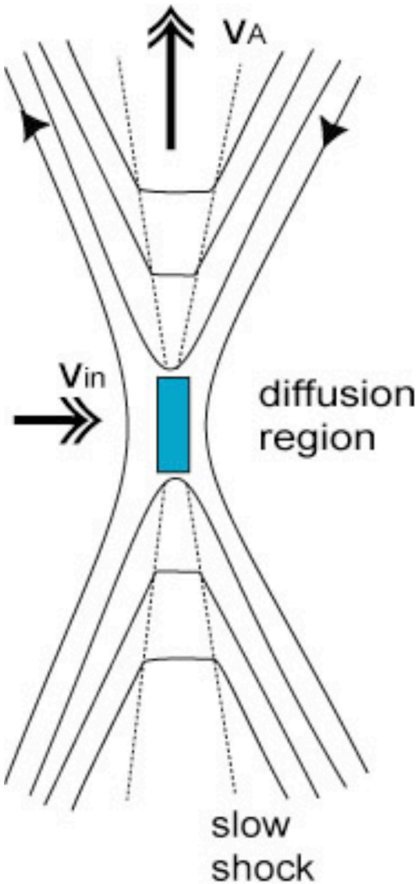
Petschek reconnection:



$$\frac{Vin}{Va} \propto \ln Rm \approx 0.01 - 0.1$$ ... fast.

- Localization of resistivity leads to the Petschek type reconneciton (e.g., Ugai 1992, Yokoyama & Shibata 1994)
- Magnetosphere observations and collisionless plasma theory suggest that fast reconnection occurs when current sheet become as thin as ion Larmor radius or ion innertial length

Fundamental problem in fast reconnection: huge scale gap



Ion inertia length

$$l_{in,ion} = \frac{c}{\omega_{pi}} \approx 300\ cm \left(\frac{n}{10^{10}\,cm^{-3}} \right)^{-1/2}$$

Ion Larmour radius

$$r_{Li} = \frac{m_i vc}{eB} \approx 100\,cm \left(\frac{B}{10G} \right)^{-1} \left(\frac{T}{10^6\,K} \right)^{1/2}$$

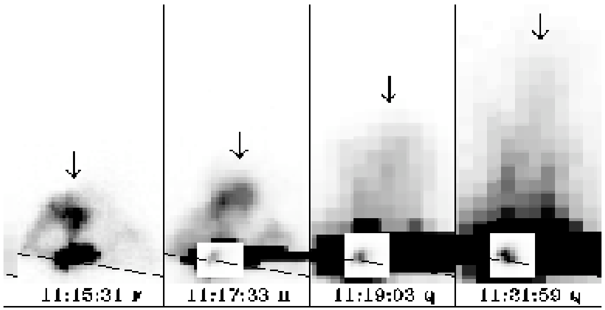
typical size of solar flare

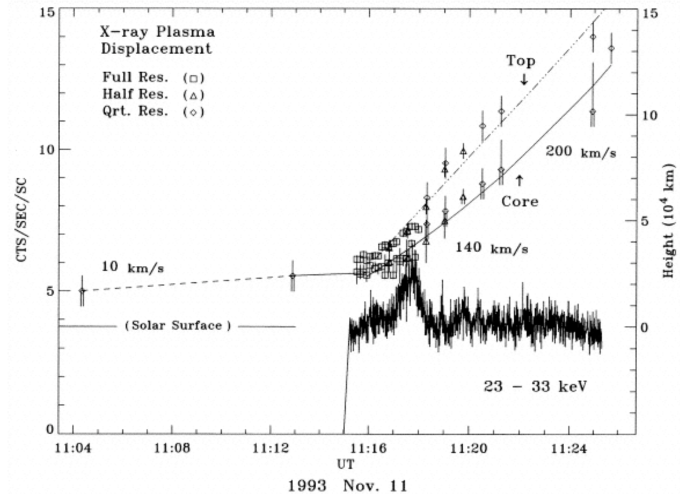
$$r_{flare} \approx 10^9\,cm$$

- Laminar and steady reconnection with extremely tiny diffusion region? Unlikely.
- Mesoscale (MHD) structure?

Key observation: plasmoid (flux rope) ejection

Ohyama & Shibata 1997





Zhang et al. 2001

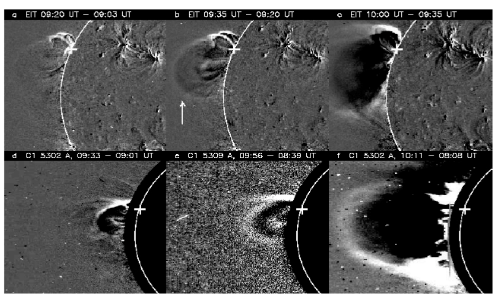
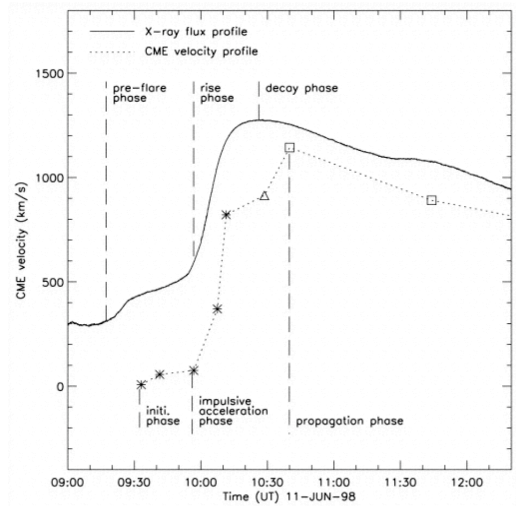


FIG. 1.—Running difference images of EIT λ195 (*upper three panels*) and LASCO/C1 (*lower three panels*), which show early evolution of the CME on 1998 June 11. Their timings are indicated at the top of each panel. The white circle in each panel indicates 1.0 $R_\odot$ solar limb. The plus sign in each panel indicates the position of the corresponding flare. The arrow in (*b*) points at the CME front.

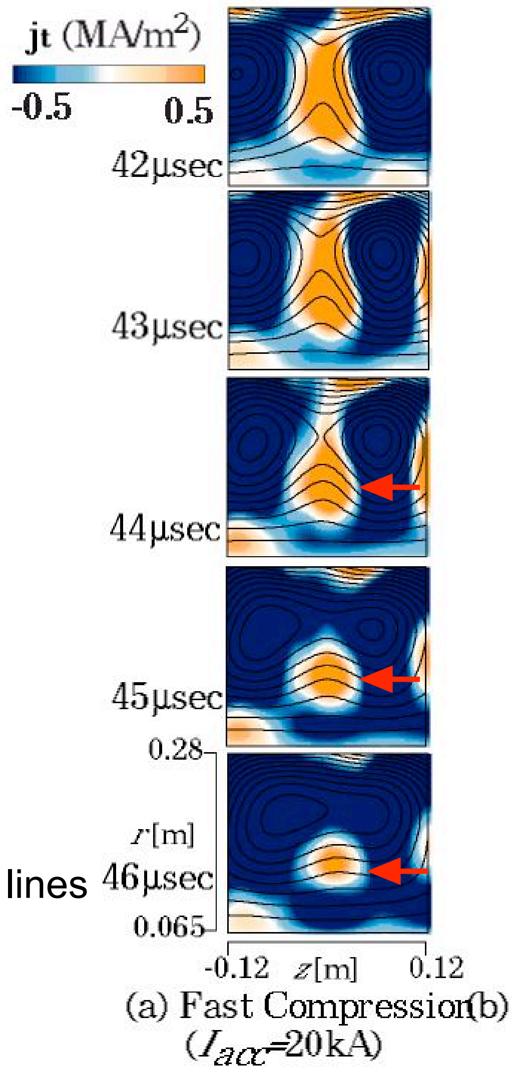


Acceleration of Plasmoid/CME and simultaneous energy release

Laboratory experiment

Fast compression of current sheet causes its mechanical ejection in high-Bx MHD regime.

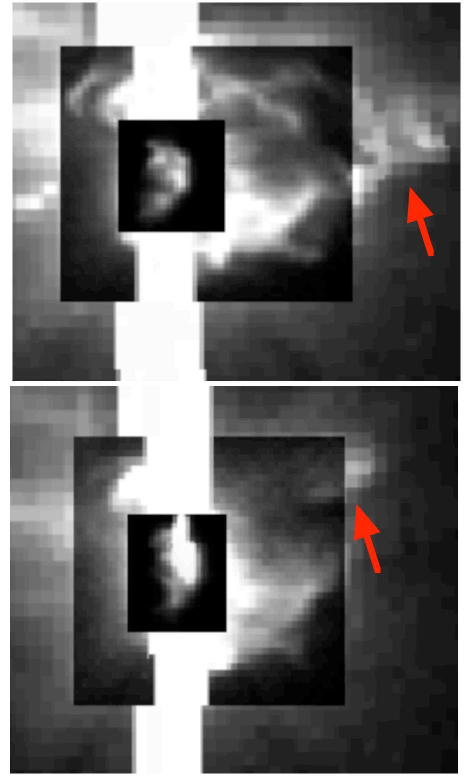
Reconnection rate is enhanced when current sheet (plasmoid) is ejected (Ono et al. 1997).



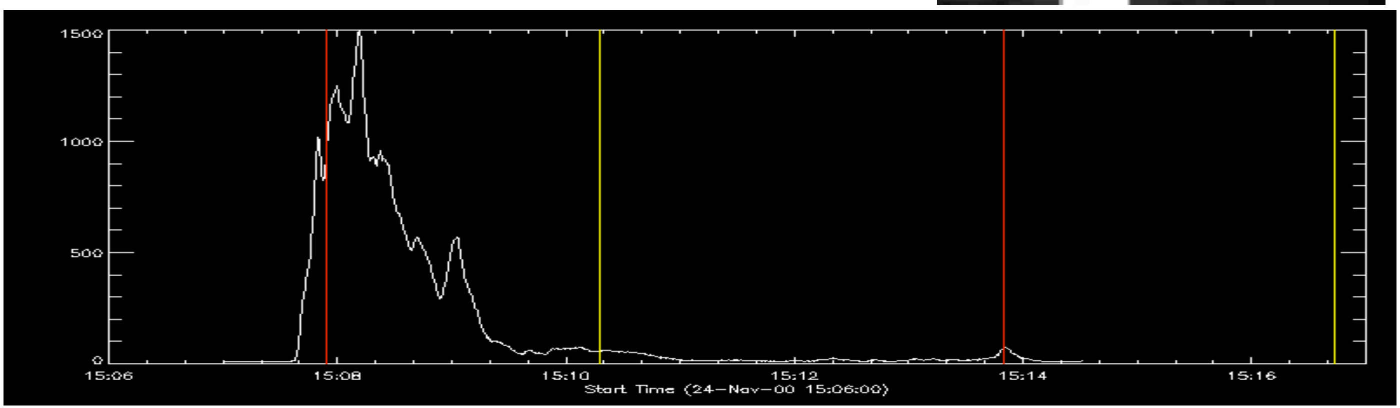
color: current density
solid lines: magnetic field lines

Multiple plasmoid ejections

Each plasmoid ejection corresponds to an elementary hard X-ray burst (Takasaki et al. in prep)



HXR count

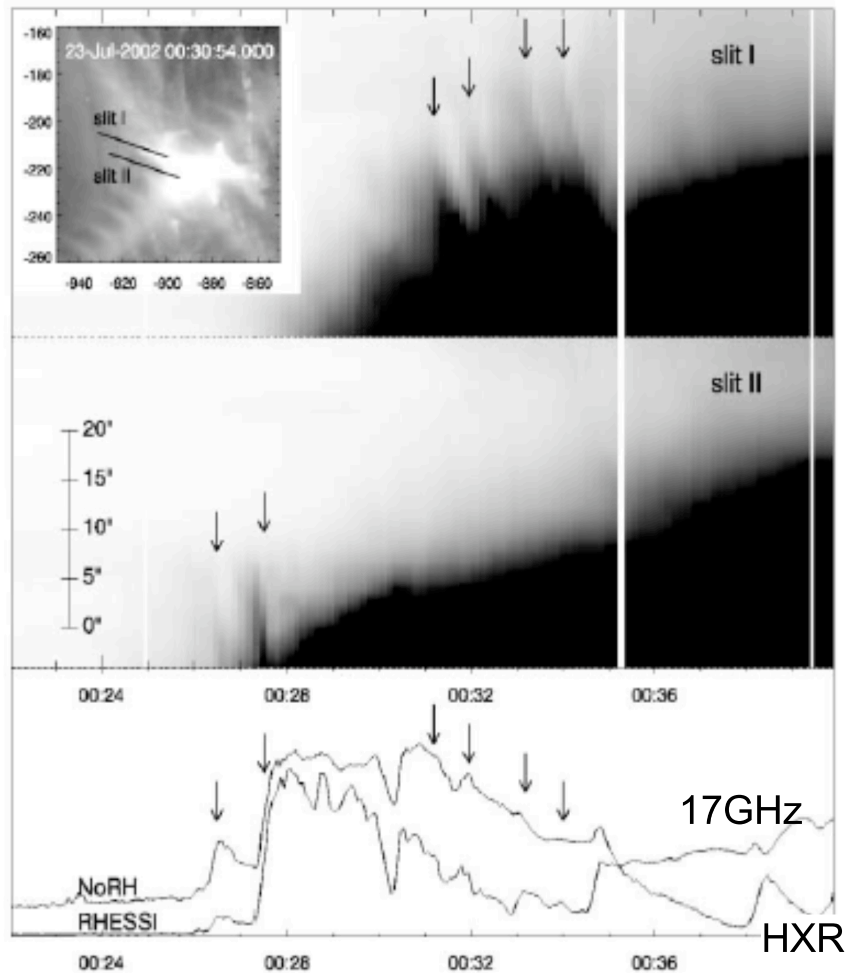


time

Supra-arcade downflows

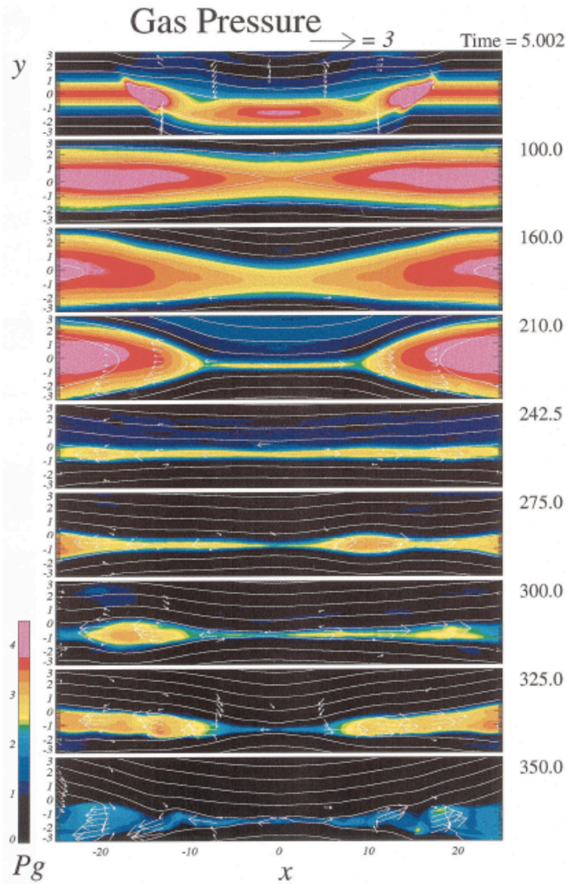
Again, each downflow (possibly reconnection outflow) cornresponds to an elementary burst of HXR and radio emissions.

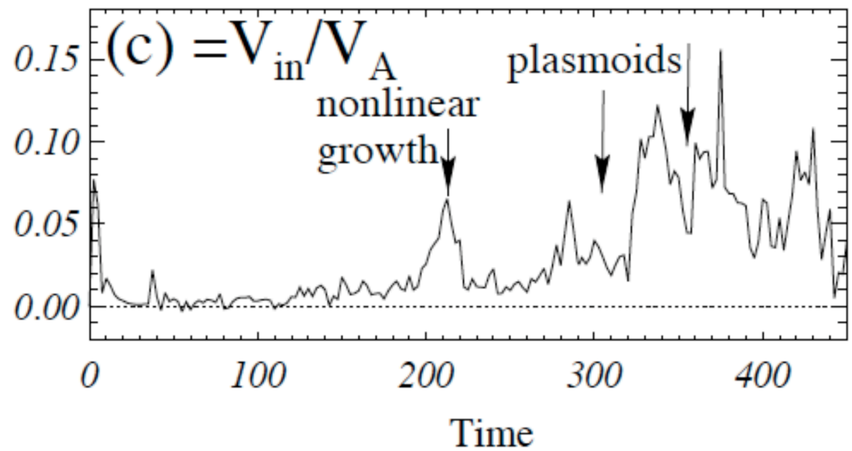
These observations strongly suggest that strong energy release (fast reconnection) in the current sheet is closely related to plasmoid ejection.



Asai et al. 2004

High-resolution MHD simulation of plasmoid ejection and magnetic reconnection (Tanuma et al. 2001)



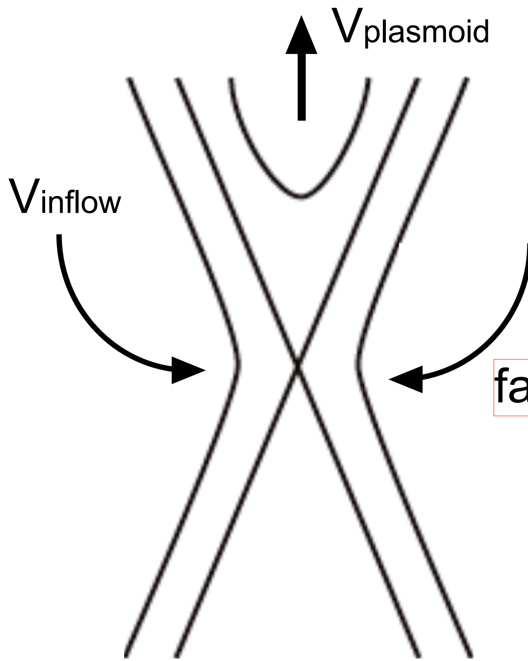


- Plasmoids (islands) formation and current thinning by tearing instability
- Explosive reconnection with Petschek-type slow shocks <u>after</u> plasmoid ejection
- Secondary tearing in the thin current sheet (=> further thinning)

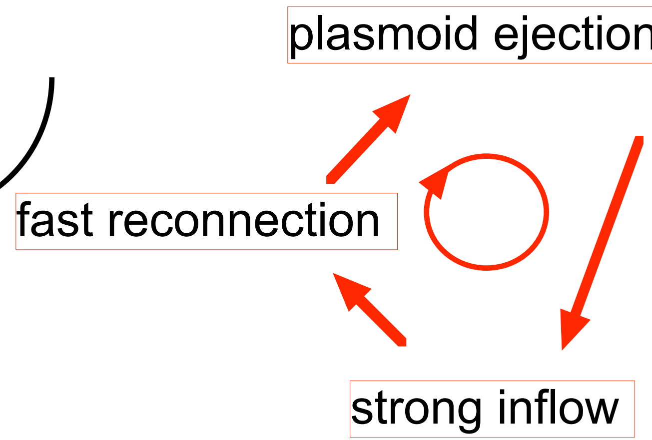
See also Kliem, Karlicky & Benz 2000

Plasmoid-induced-reconnection (Shibata & Tanuma 2001)

Existence of plasmoid inhibits the reconnection and store the energy



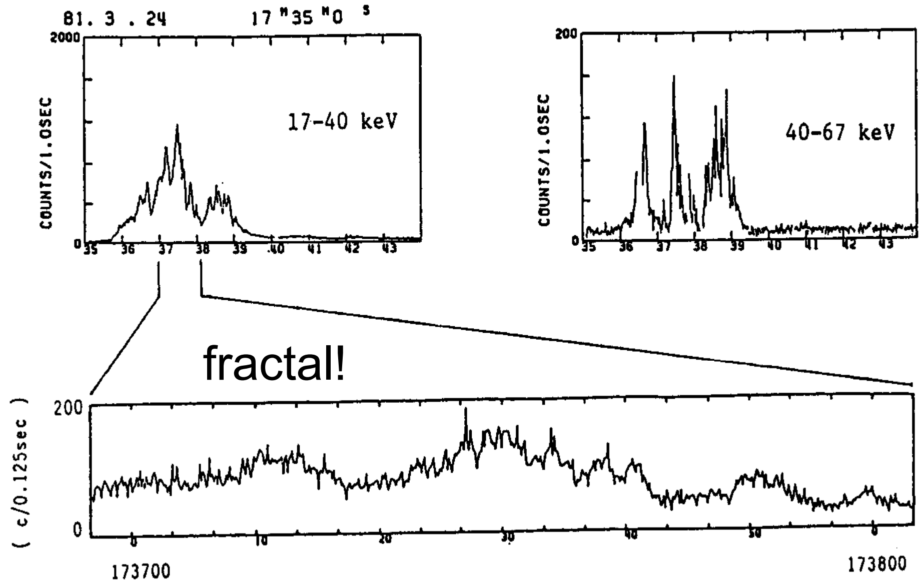
Ejection of plasmoid induces strong inflow, which then leads to the fast reconnection and further acceleration of plasmoid.

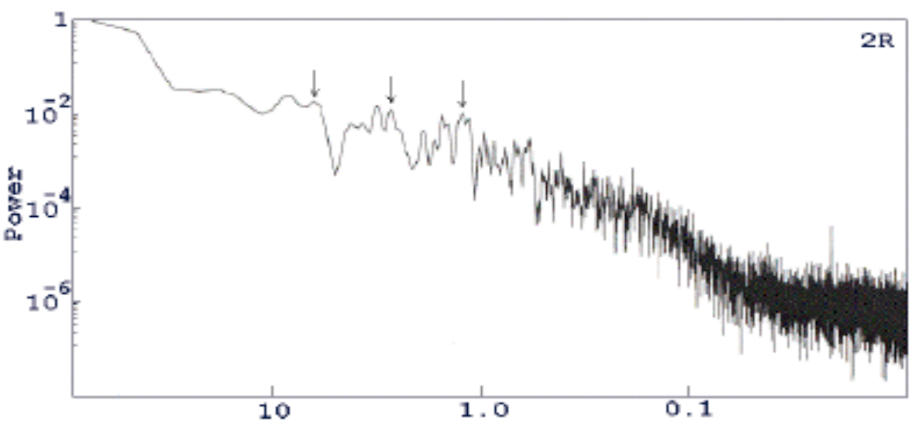


Nonlinear instability

Fractal nature of flare emissions

HXR light curve of a flare with high temporal resolution (Ohki 1992)

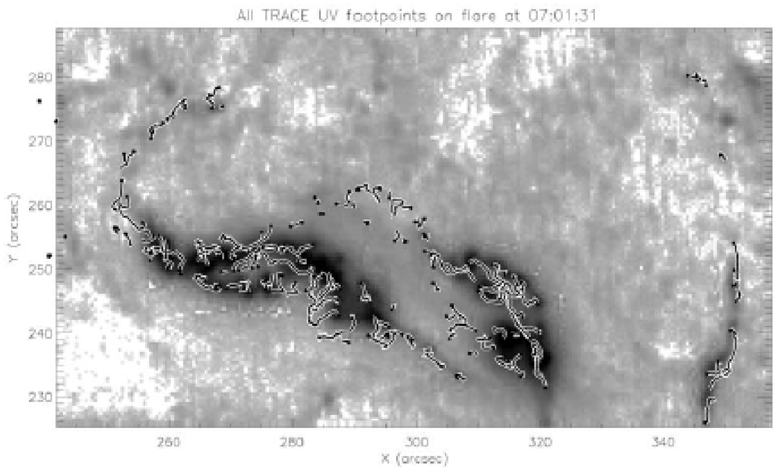




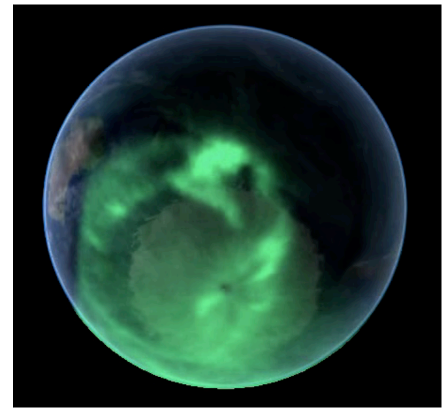
Period (s)

Power spectrum of radio (610MHz) emission (Karlicky et al. 2005)

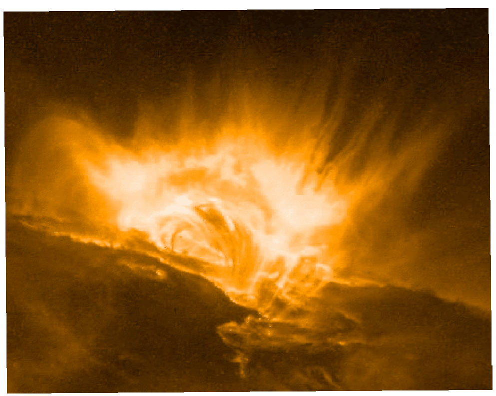
<u>Fine spatial structure in the Sun and aurora</u>



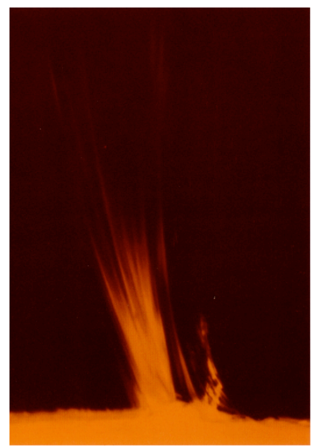
Bright kernels in flare ribbons
(Fletcher, Pollock & Potts 2004)



aurora

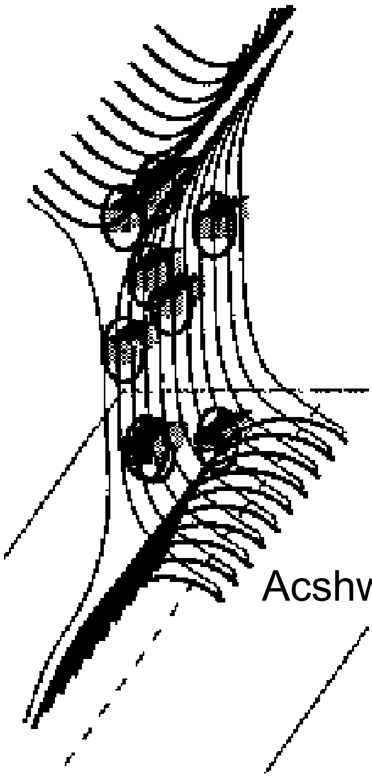


Supra arcade downflows
(McKenzie & Hudson 1999),
Innes, McKenzie & Wang (2003)

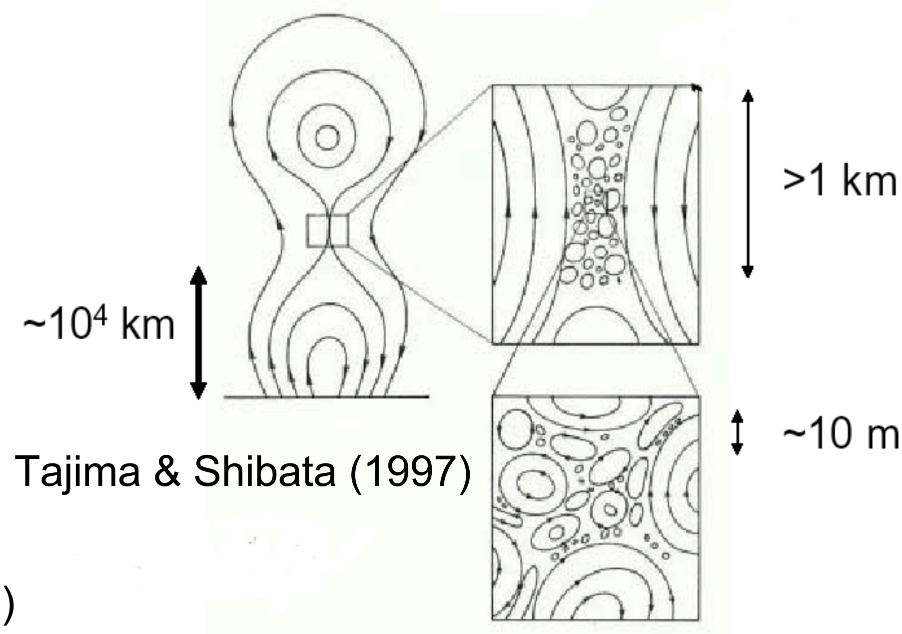


Jets/surges

Fractal current sheet with many plasmoids?



Acshwanden (2002)



Tajima & Shibata (1997)

- Consistent with the fractal nature of flare emission
- Natural connection between MHD and micro scales.

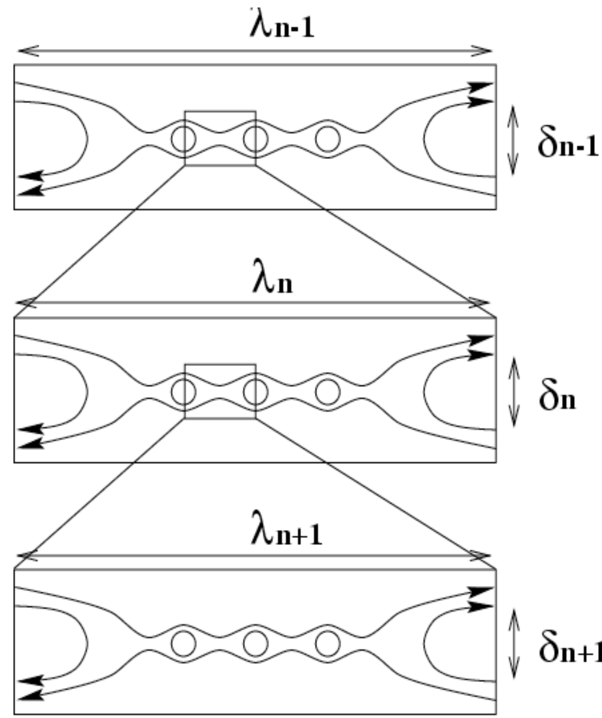
Excitation mechamisms of turbulence

Possible mechanisms for exciting MHD turbulence in the current sheet:

- □ **Tearing instability** (e.g., Furth et al. 1963, Shibata & Tanuma 2001...)
- □ Secondary kink of tearing-made flux rope (Duhlburg, Antiochos & Zang 1992)
- □ Kelvin-Helmholtz (Hirose et al. 2004)
- □ Non-linear coupling of microinstabilities to macroscale (e.g., Shinohara et al. 2001)

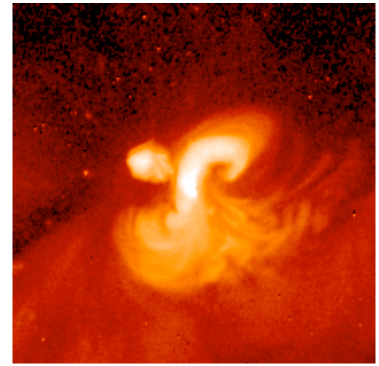
- ◇ Collision of reconnection jets (Watson & Craig 2003)
- ◇ Reconnection-driven filamentation (Karpen, Antiochos & DeVore 1997)

- **Rayleigh-Taylor type instability** (Isobe et al. 2005)



Shibata & Tanuma 2001

How about relatively moderate, quasi-steady heatings?



Example: Sigmoids $\tau \approx$ a day

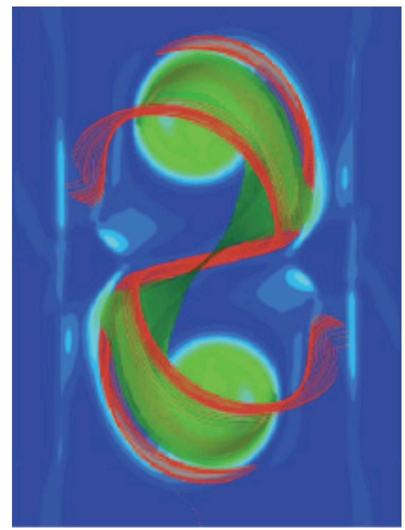
Sigmoids are possibly the current sheet formed in the vicinity of quasi-separatrix layers. (e.g., Fan & Gibson 2003).

Dissipation of current sheet by fast reconnection:

$$\tau \approx (1-10)\tau_A \approx 100-1000$$ sec ... too short.

By ohmic dissipation or Sweet-Parker reconnection of laminar current sheet:

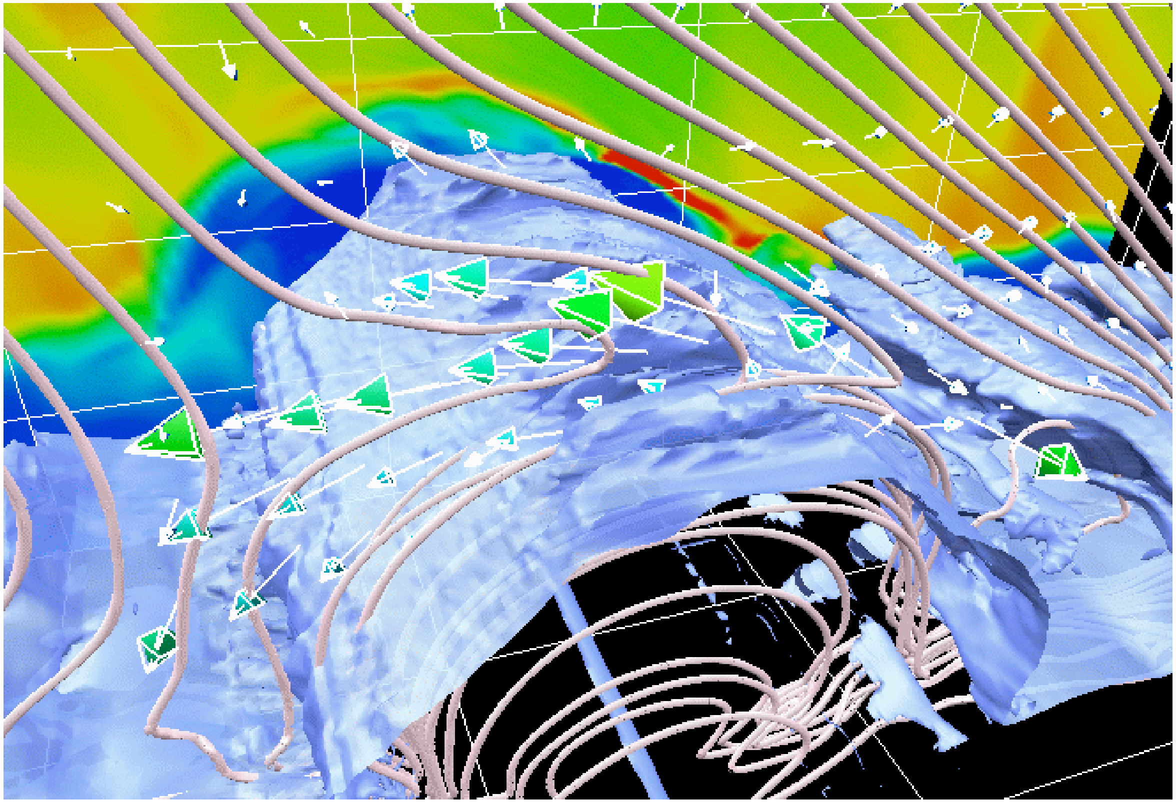
$$\tau > R_m^{1/2}\tau_A \approx 10^{8-10}$$ sec ... too long.



Gibson et al. 2004

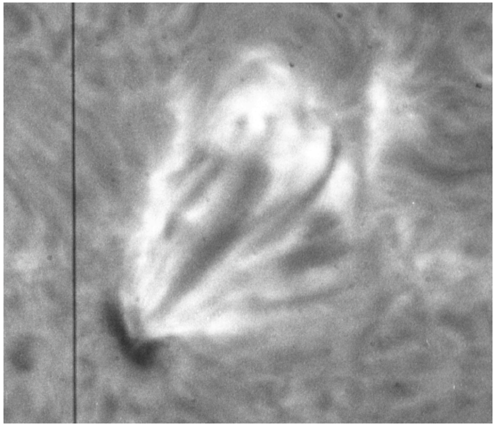
- □ Difference in global structure? (no large eruption?)
- □ Any difference in internal structure of current sheet?

Three-dimensional MHD simulation of emerging flux and its reconnection with overlying coronal field



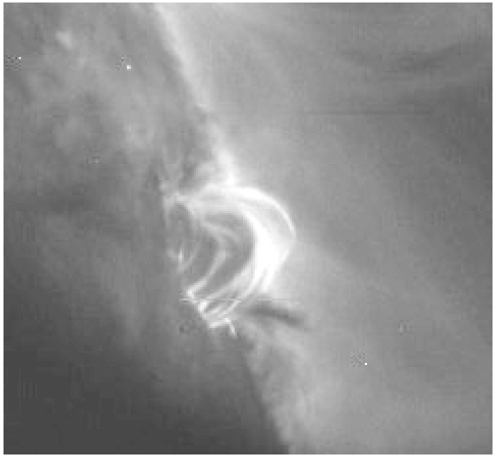
Isobe, Miyagoshi, Shibata & Yokoyama 2005, Nature, 434, 478

Observations of emerging flux



H-alpha (Hida observatory)

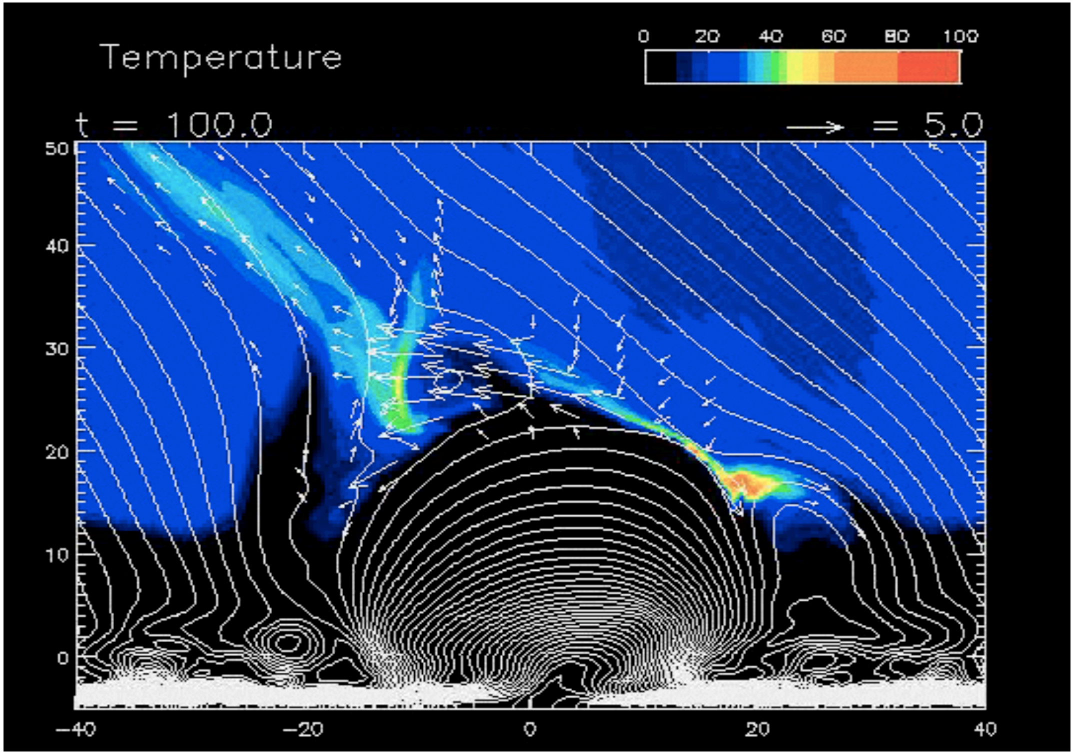
- Arch filaments connecting sunspots
- Finer structure in individual filament
- Why filament? Emerged magnetic field must fill the low-beta corona.



EUV (TRACE)

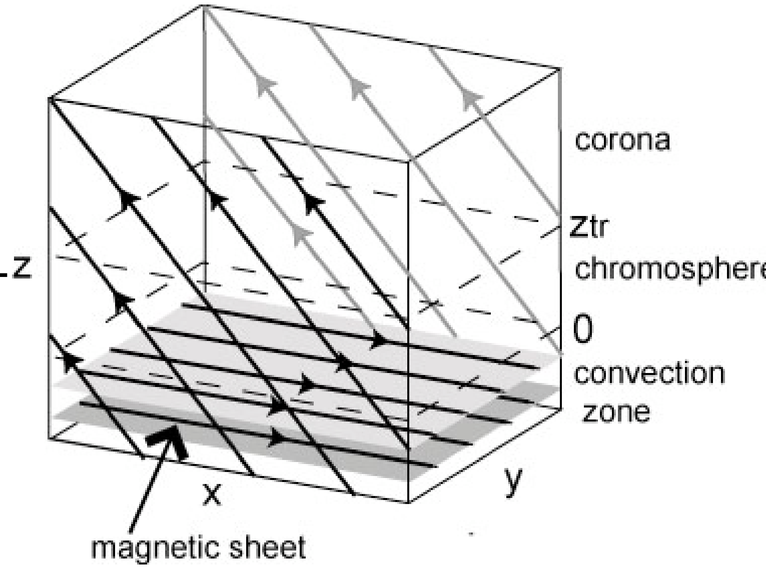
- Hot (10^6K) and cold (10^4K) loops exist alternatively. Intermittent heating?
- Jets and surges, indicating reconnection.

2D MHD simulation (Yokoyama & Shibata 1995)



Parker instability => expansion in the corona => fast reconnection with coronal field => heating and acceleration of plasma

Simulation model



3D extension of Yokoyama & Shibata (1995)

Convectively unstable convection zone + isothermal photoshepre/chromosphere + hot corona

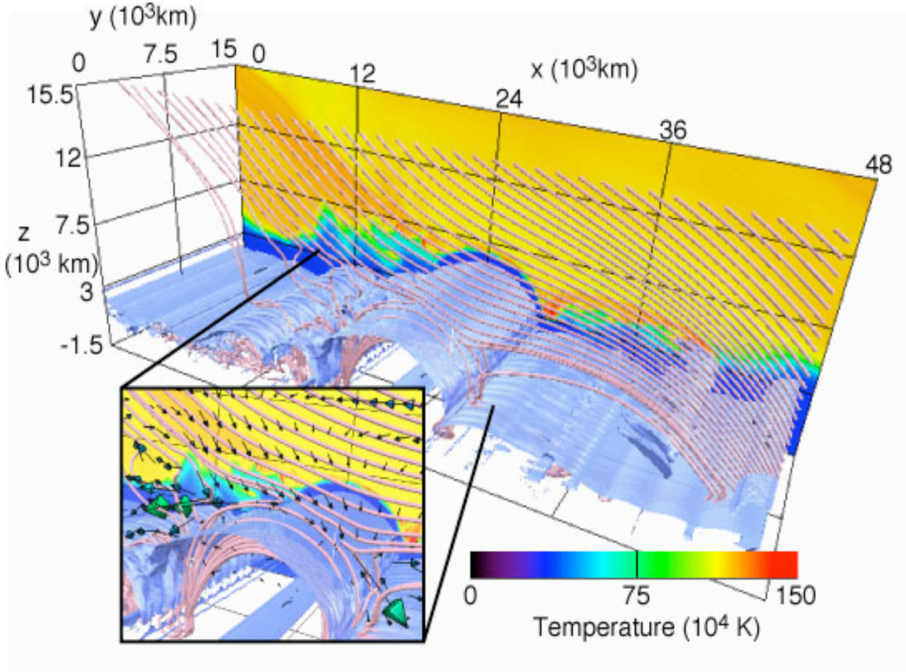
Horizontal flux sheet in the convection zone

Perturbation at the centre of the sheet
$Vz = \cos(2\pi x / \lambda)$ (ky=0) => Parker instability

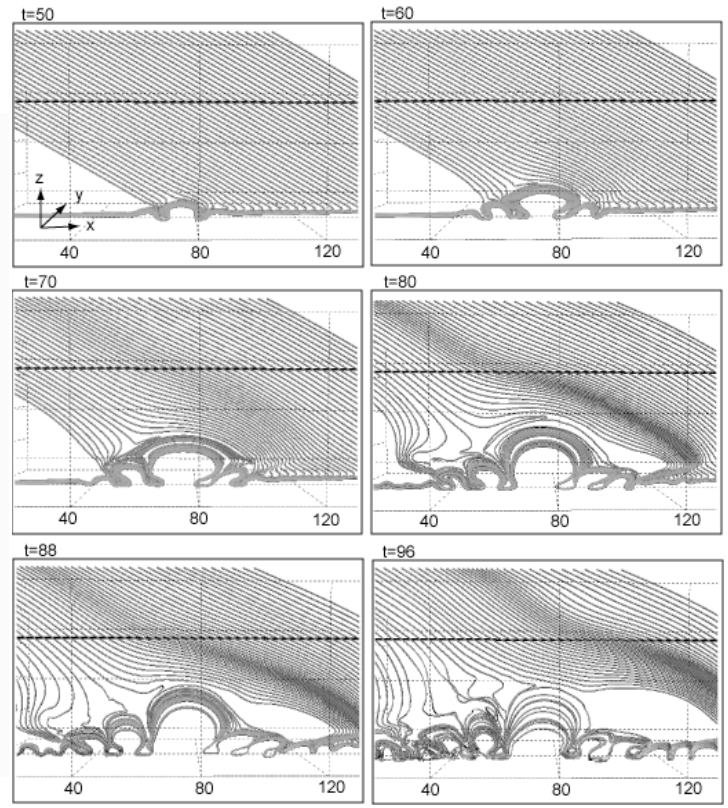
Anomalous resistivity model $$\eta = \begin{cases} \eta_0 & \text{for } v_{\mathrm{d}} < v_{\mathrm{c}}, \\ \eta_0 + \eta_1 (v_{\mathrm{d}}/v_{\mathrm{c}} - 1)^2 & \text{for } v_{\mathrm{d}} \geq v_{\mathrm{c}}, \end{cases}$$

In the highest resolution run, grid is 800x400x620. Culculation was carried out on the Earth Simulator (160 processors, 8 hours).

Overview of the result



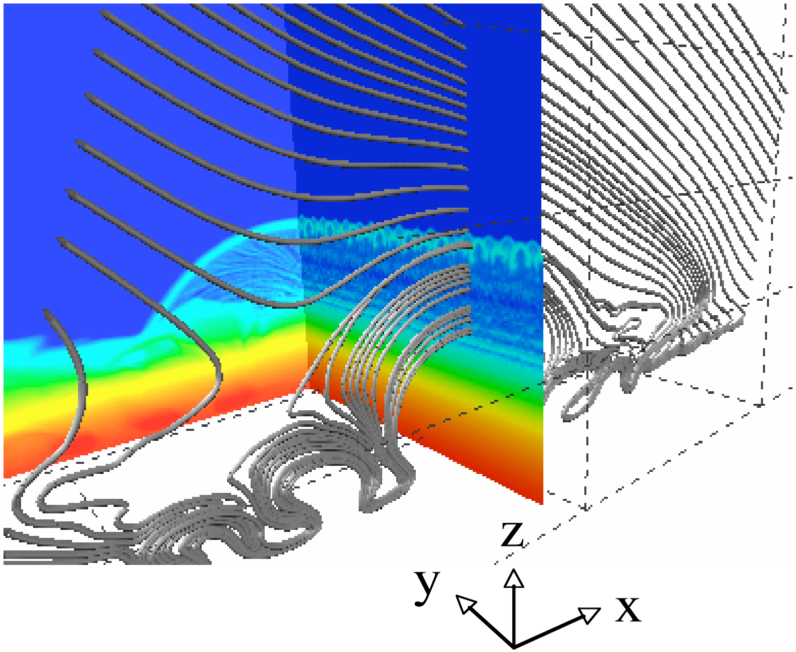
Magnetic field lines, isosurface of |B| (blue surface), temperature



Evolution of field lines

Basically similar to 2D case.

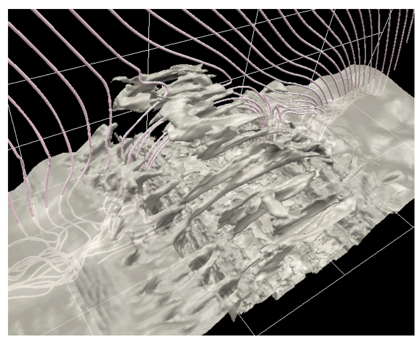
Filamentary strucututre due to magnetic Rayleigh-Taylor instability

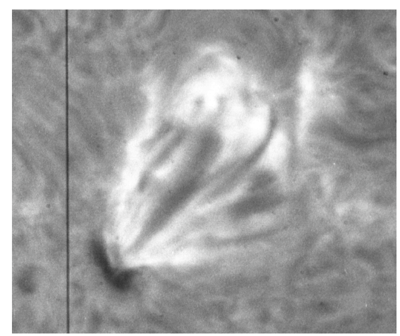


- Top of the emerging flux becomes top-heavy = unstable for Rayleigh-Taylor type instability
- Bending the magnetic field (**k**=kx) is stabilized by magnetic tension => formation of filamentary strucutre along magnetic field.

Up: mass density (color) and field lines.

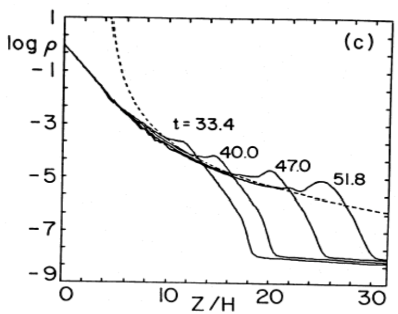
Right: isosurface of the density and H-alpha image of an EFR.

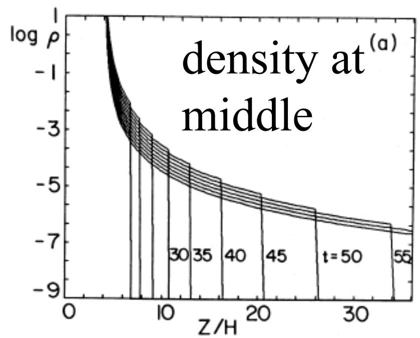


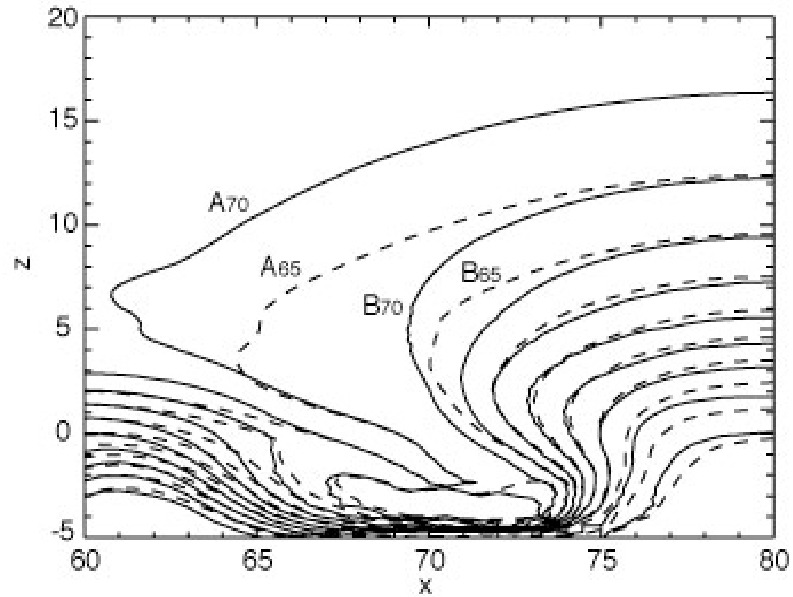


Why top-heavy?

Nonlinear evolution of Parer instability is approximately self-similar (Shibata et al. 1990)

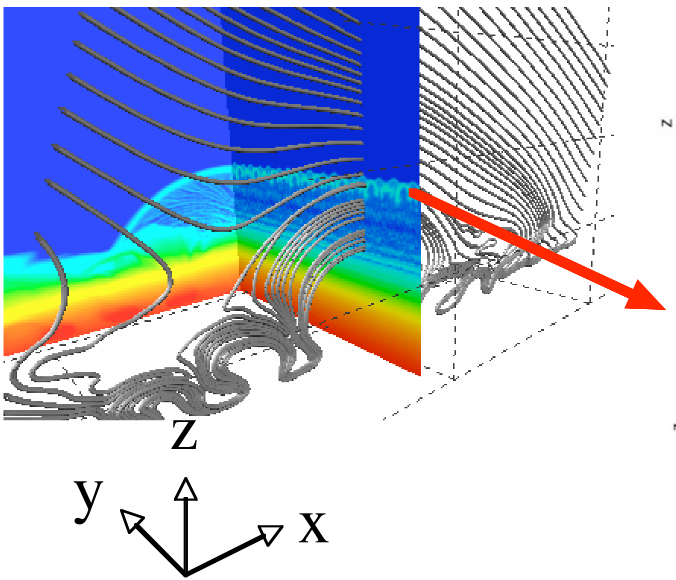




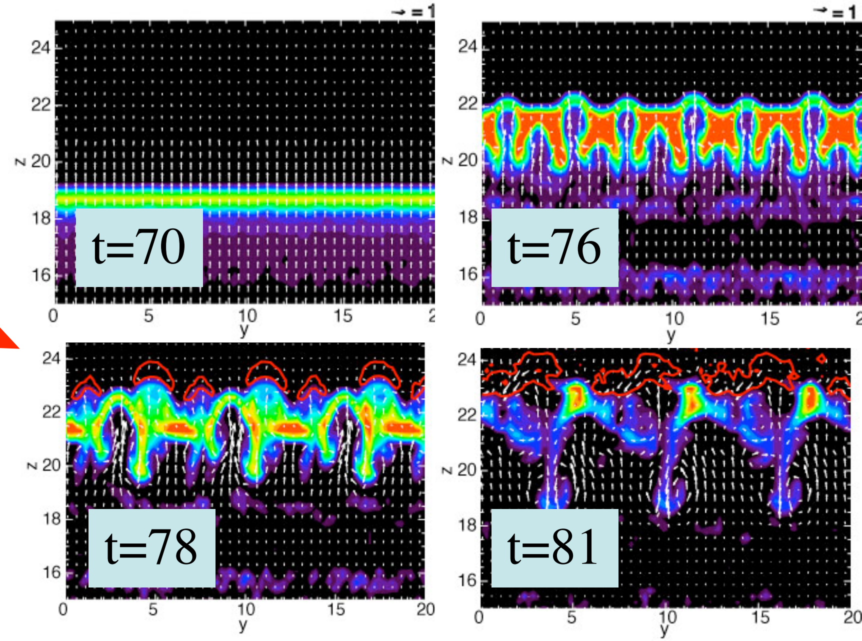


- The outermost part deviates from self-similar solution (naturally).
- Two reasons for the formation of top-heavy part:
  - compression between coronal pressure above and magnetic pressure below.
  - larger curvature radius => smaller gravity along ***B*** => less evacuation.

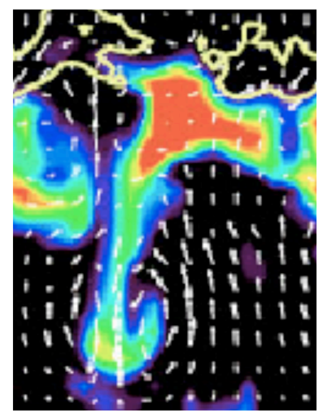
Nonlinear development of Rayleigh-Taylor instability



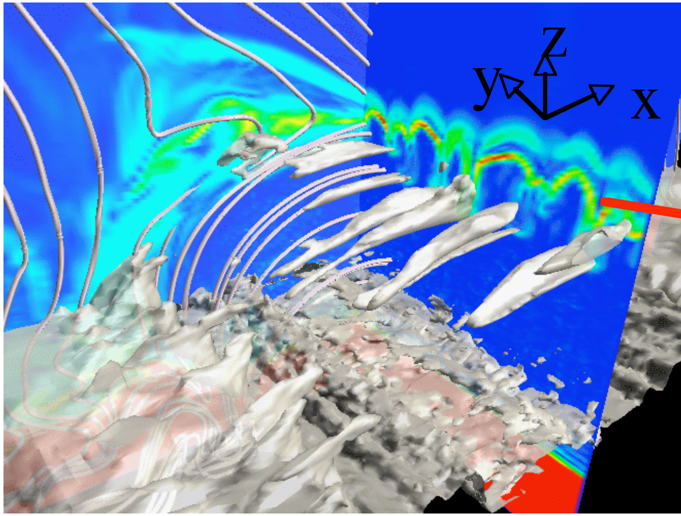
Density at the center of emerging flux

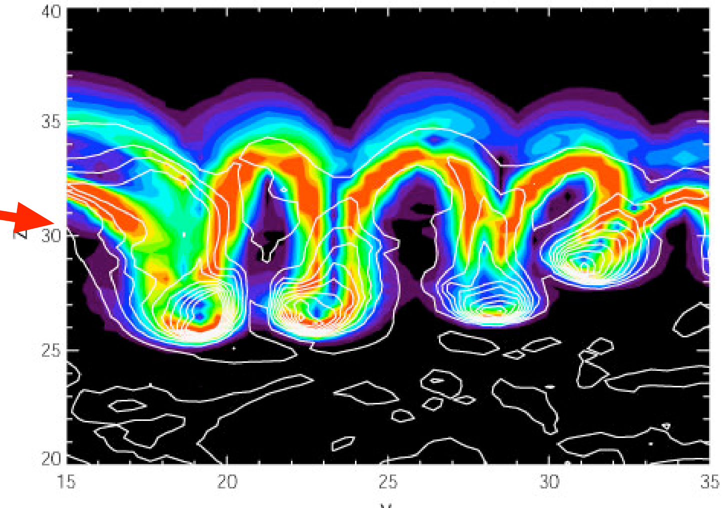


- Small structure grows first (larger linear growth rate)
- Larger structure grows later by nonlinear inverse cascade
- Vortecies by secondary KH instability => excitation of torsional Alfven wave small scale twist in arch filaments?



Fomation of small scale current sheet

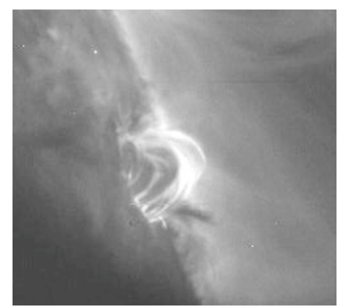




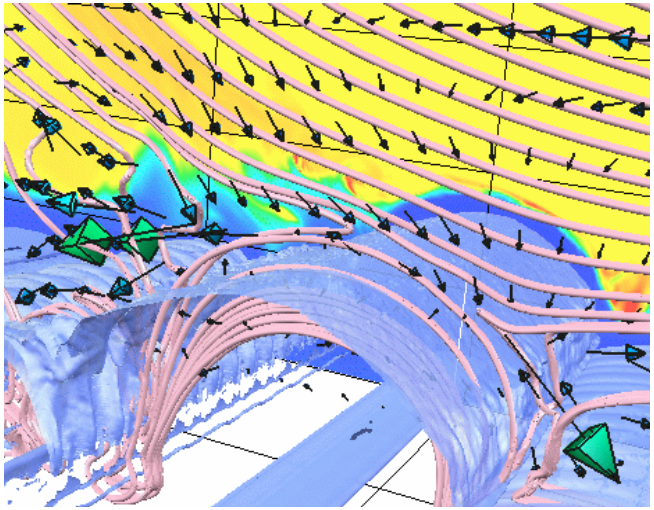
mass density isosurface (gray)
current density distribution (color)

Mass density contour and current density distribution (color) on y-z plane

- Deformation of magnetic field by R-T instability => formation of current sheet in the periphery of arch filaments.
- Dissipation of these filament may results in the spatially intermittent heating, leading to the formation of hot/cold loops system.

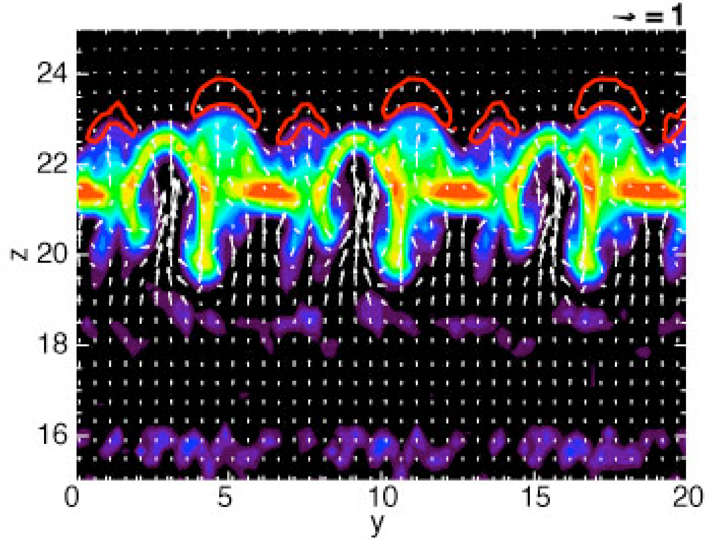


Patchy reconnection



color: mass density

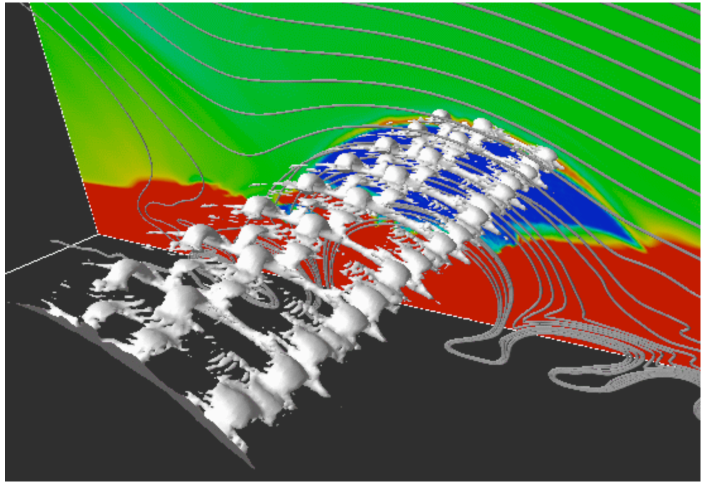
red contour: anomalous resistivity

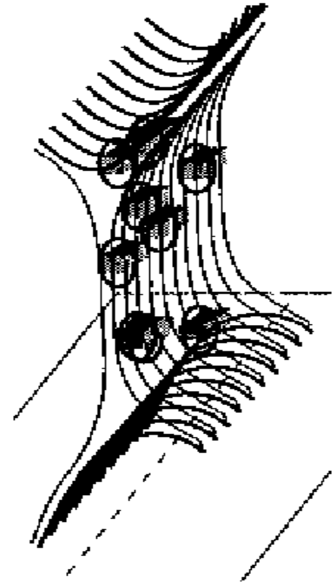


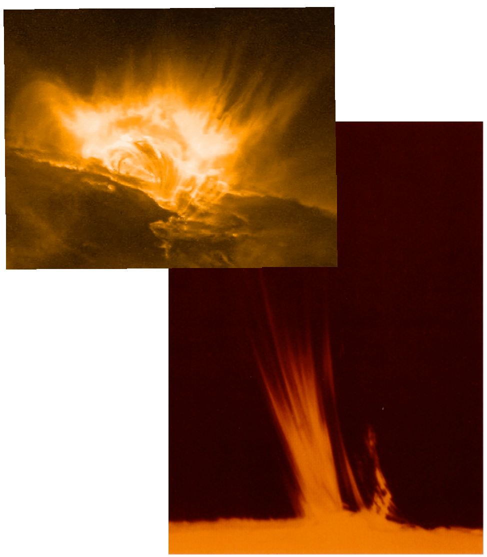
- Larger current density and smaller mass density in the rising part of the R-T instability => anomalous resistivity sets in locally.
- Fast reconnection occurs intermittently, both in space and time.
- Reconnection inflow enhance the nonlinear evolution of the R-T instability => nonlinear instability

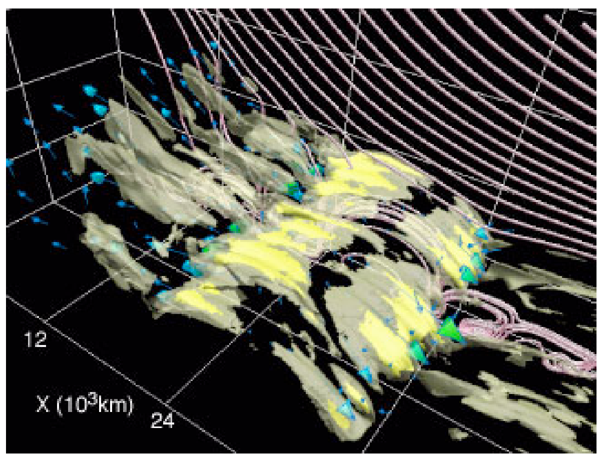
Plasmoids and reconnection jets

Isosurfaces of gas pressure.
Many plasmoids!



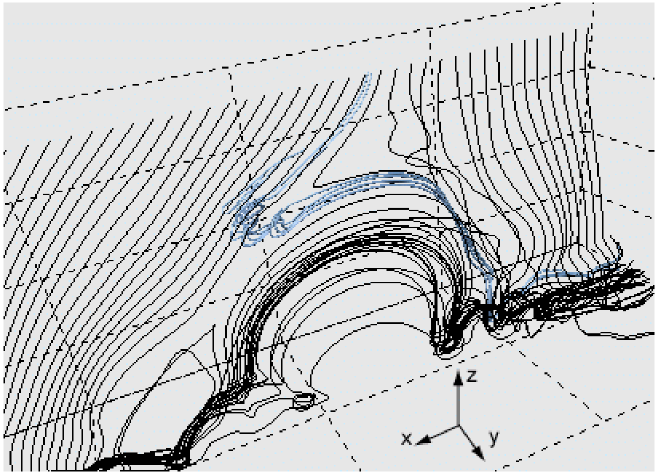


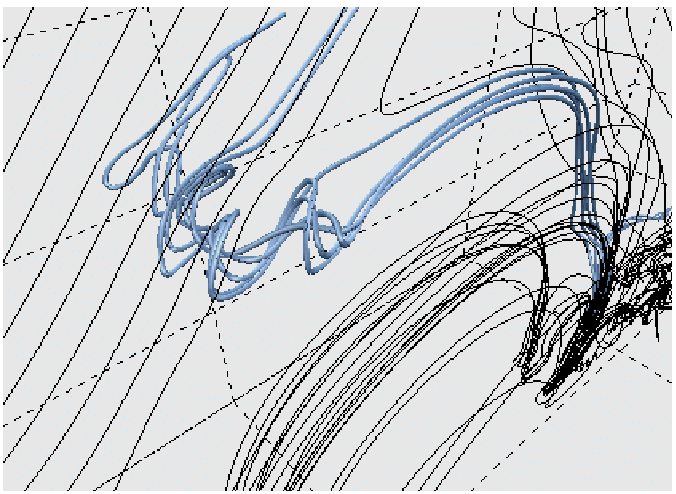




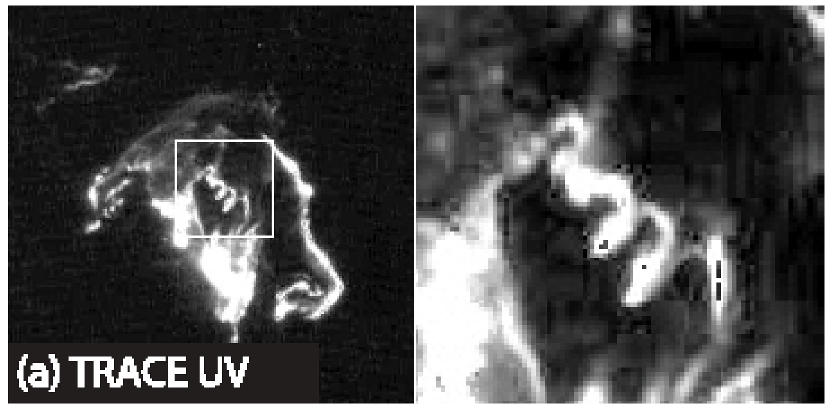
Isosurfaces of velocity.
Many narrow jets!

Heilcal fulx rope





- With the presense of guide field (By), helical flux ropes are formed and ejected.
- (Still preliminary, with lower resolution.)



Observation of erupting helical flux rope (Liu and Kurokawa 2004)

Conjecture:

- Rayleigh-Taylor type instability can occur if there is a density jump across the current sheet and effective acceleration (in suitable direction).
- Effective acceleration is likely to exist in dynamically evolving system (like eruptive flares and CMEs) and in driven reconnections.

- R-T is ideal instability, hence no restriction from small resistivity.
- Smaller scales grow faster. Bottom-up process? (magnetotail observation by Hoshino et al. 1994)

- Possible scenario may be...
  - Small scale turbulence grows by R-T or other instabilities (and couple with micro-scales)
  - tearing occurs in small scale
  - formation of large plasmoids (flux ropes) by coallescense => fast reconnection in global scale

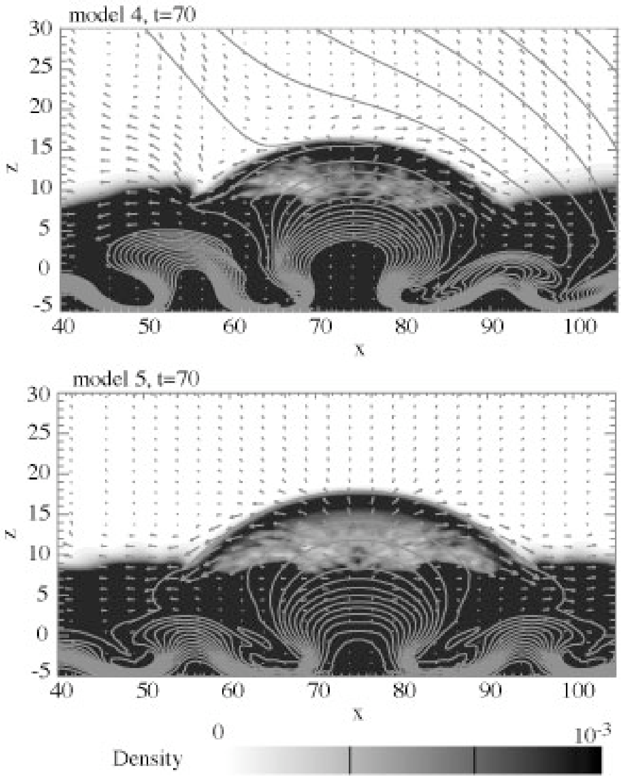
Summary

- Observational evidence for important role of plasmoid in fast reconnection, supporting plasmoid-induced reconnection model.
- Observational evidence for turbulence and fractal structure in flare-related current sheet.
  - How about in the current sheet where quasi-steady heating is occurring?
  - Self-consistent modeling of turbulence excitation and its consequence to global reconnection dynamics is necessary.

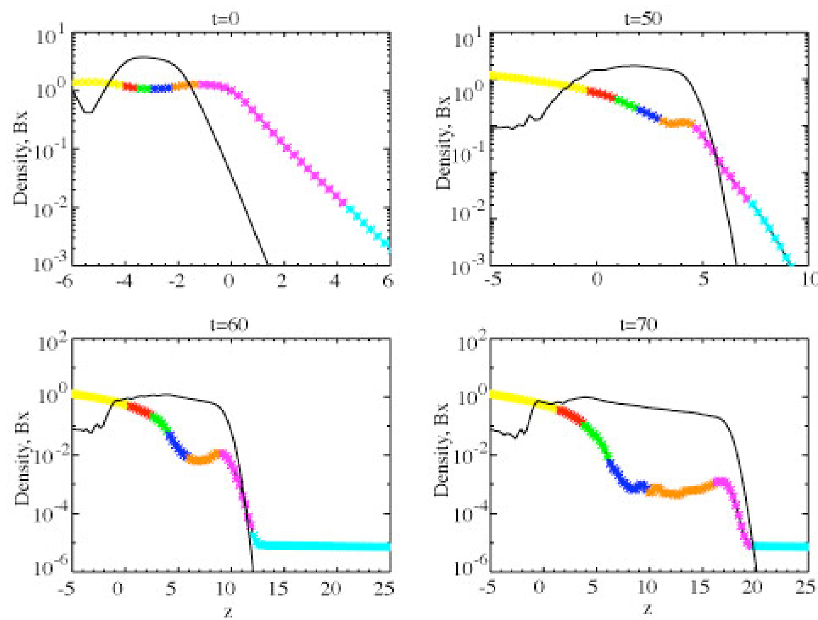
- Our 3D high-resolution MHD simulation shows:
  - filamentary structure spontaneously arises due to the magnetic Rayleigh-Taylor instability in the emerging flux.
  - current sheets are formed in the periphery of arch filaments by the filed deformation by R-T instability.
  - magnetic reconnection becomes patchy, due to the interchanging of the current sheet.

Why top-heavy?

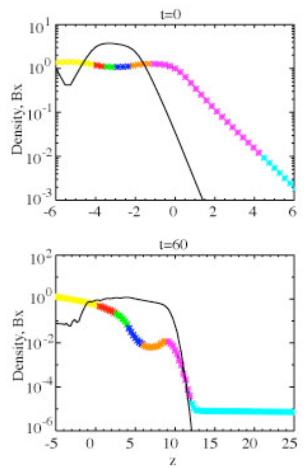
dark = larger density



Density profile along a vertical line at the middle point of the emeging flux. Colors indicate the Lagrangea trace of the same field line.

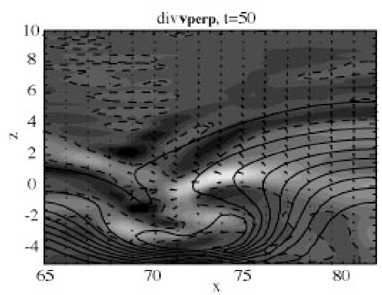


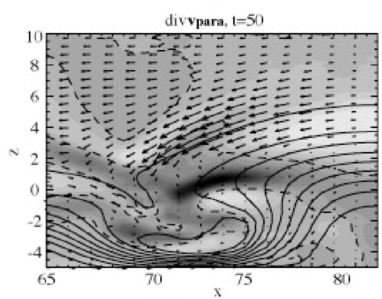
Why top-heavy?

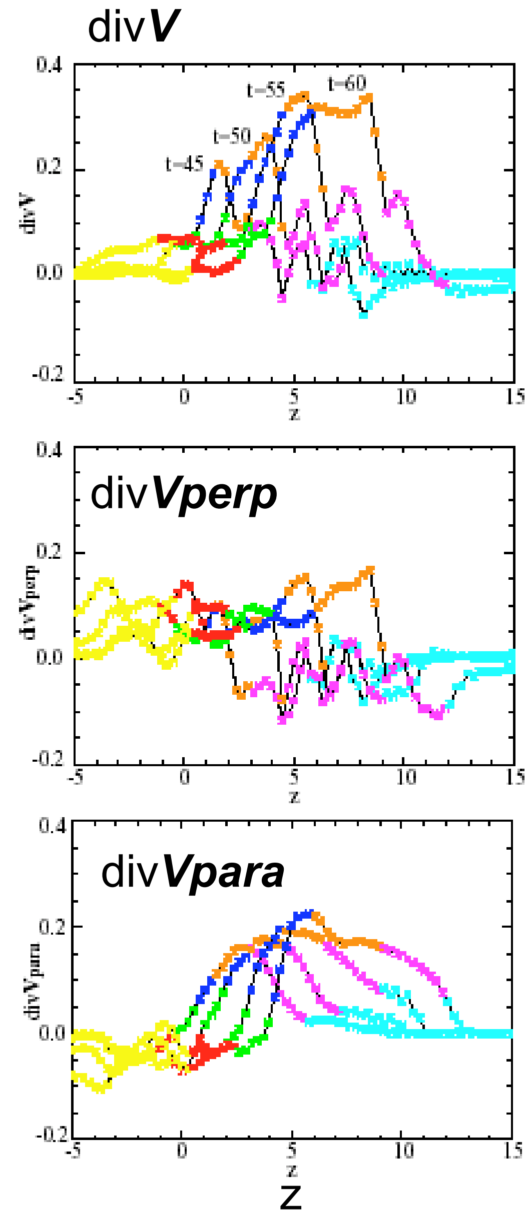


Divergence of ***Vpara*** (parallel to ***B***) and ***Vperp*** (perpendicular to ***B***).

div***V*** (particularly ***Vperp***) changes the sign near the top-heavy part (between orange and magenta).

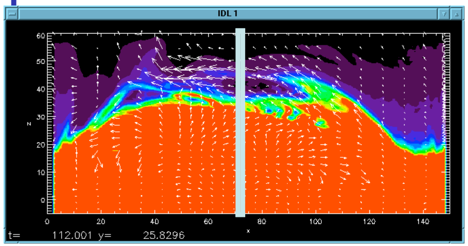


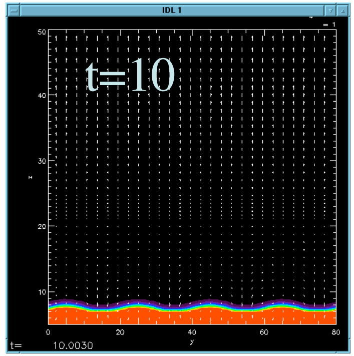


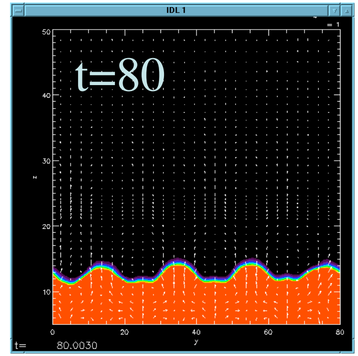


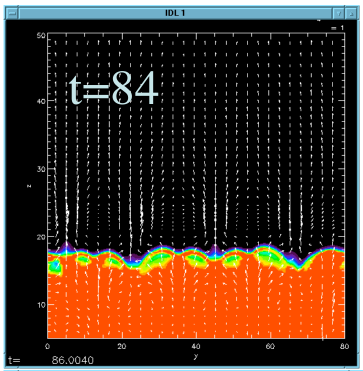
With finite amplitude initial perturbation in y direction

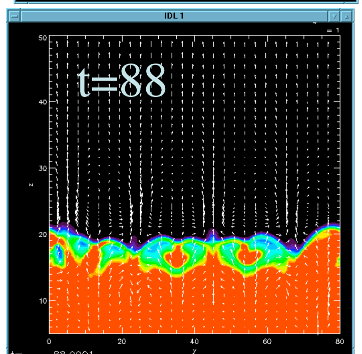
Density@mid t

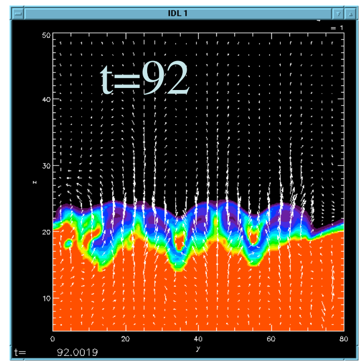


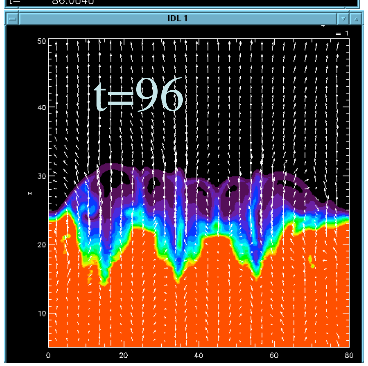


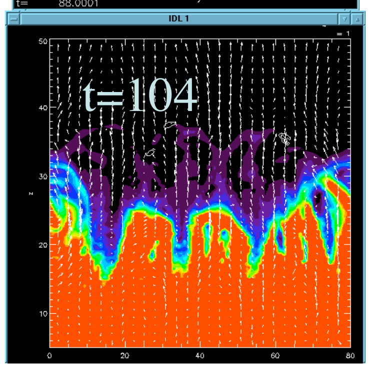


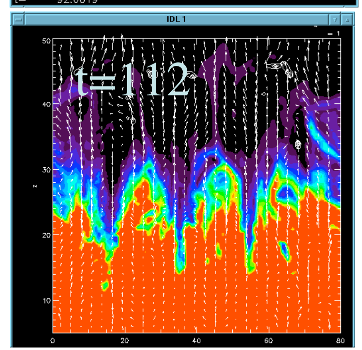






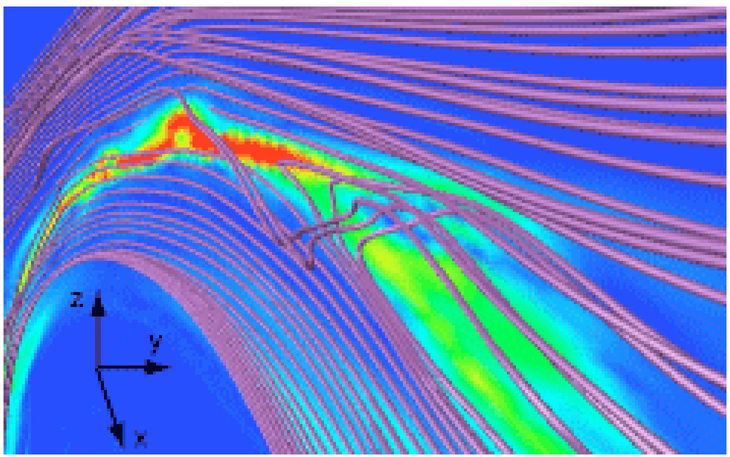




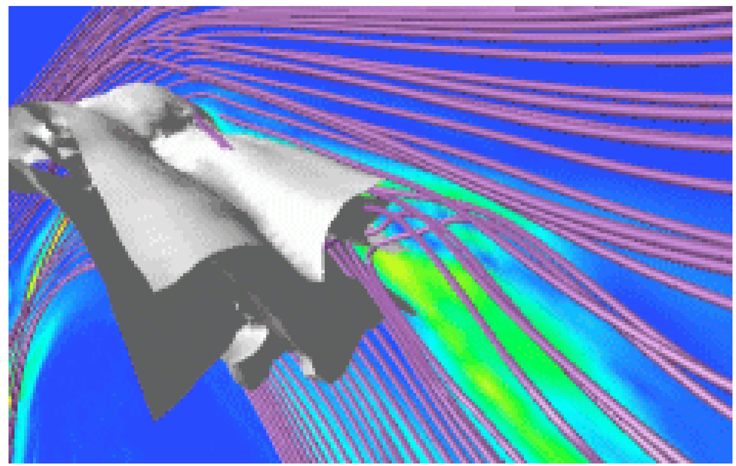


Reconnecition in 3D

Current density + field line

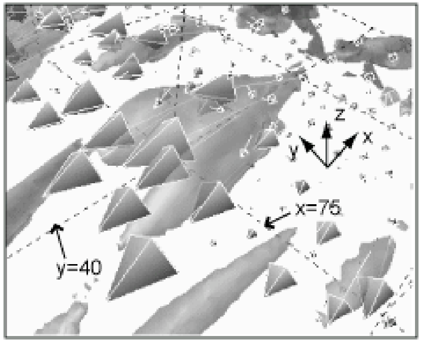


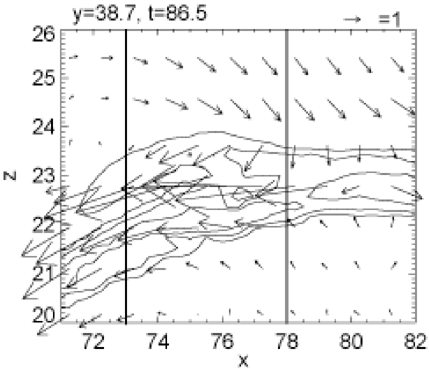
Current density + field line
+ isosurface of current density



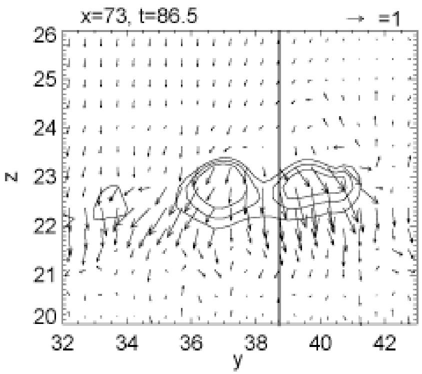
Reconnection in/out flows in 3D

isosurfaces of |V| and velocity field

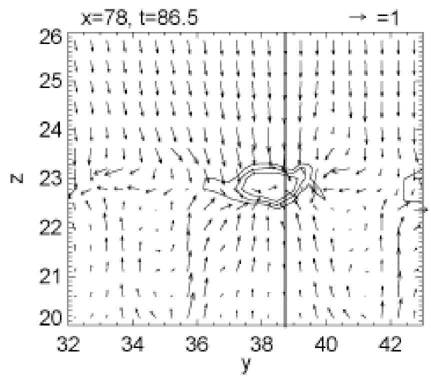




Velocity (arrows) and current density on x-z plane



Vy, Vz (arrows) and Vx (countour) on y-z plane near the outflow region
=> diverging

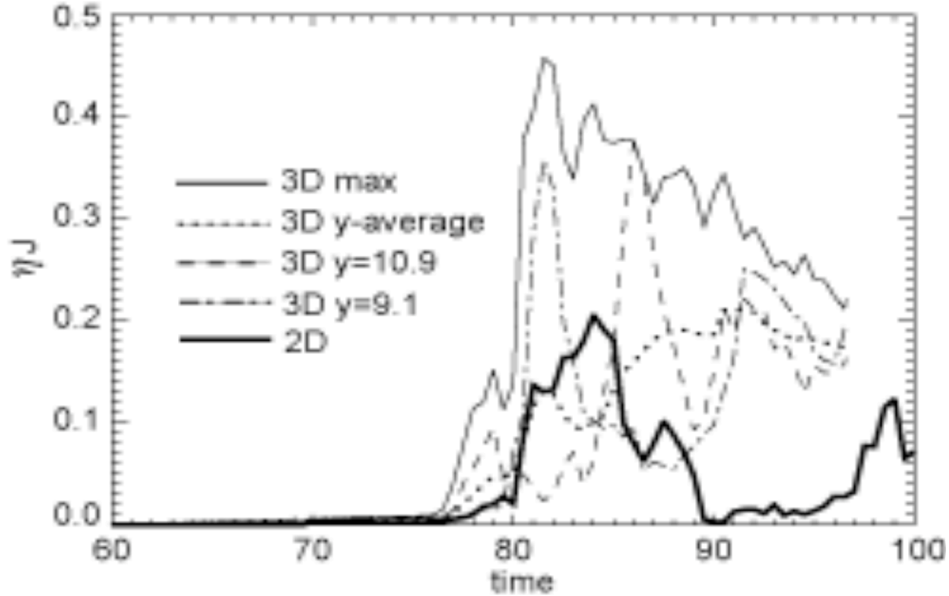


Vy, Vz (arrows) and Vx (countour) on y-z plane near the inflow region
=> converging

Reconnection faster in 3D?

Comparison of 2D simulation with the same initial condition.

Reconnection rate measured by ηJ



- Reconnection rate is larger and more bursty in 3D.
- The spatial average in 3D is comparable with 2D.
- Rayleigh-Taylor does not occur in 2D... so the local condition near the reconnection point is not the same.