The Source of Magnetic Shear That Drives CMEs

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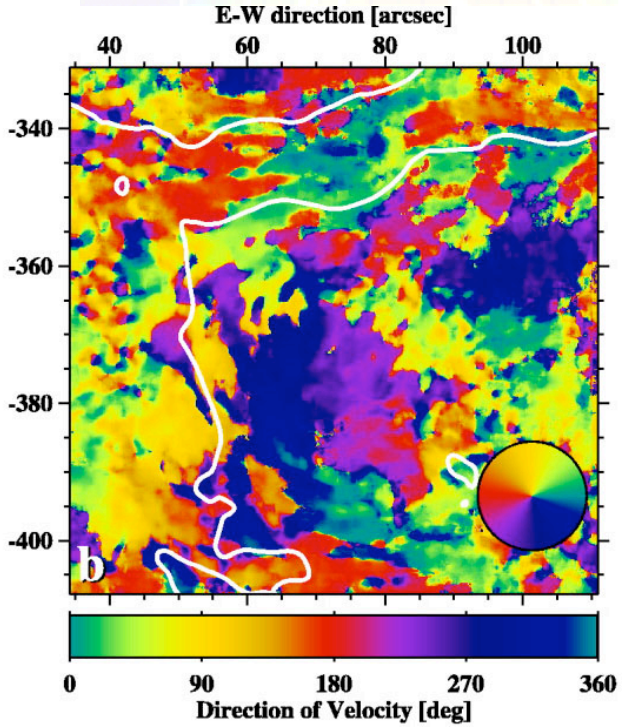
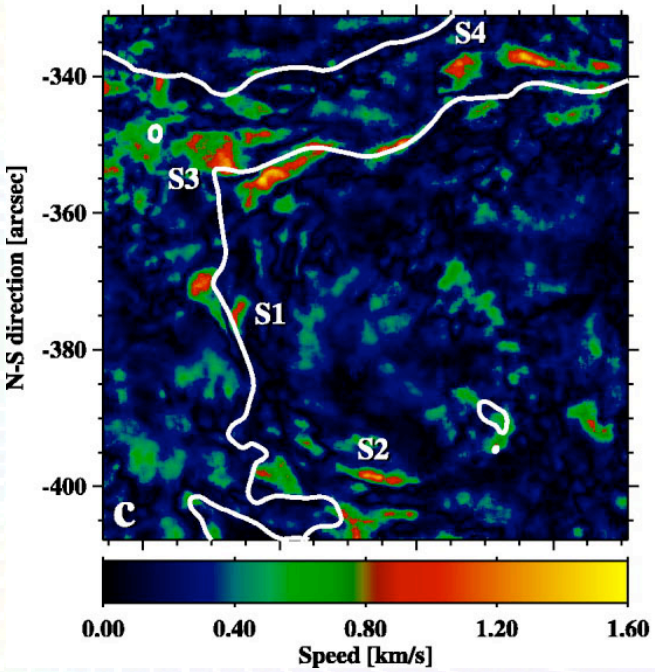
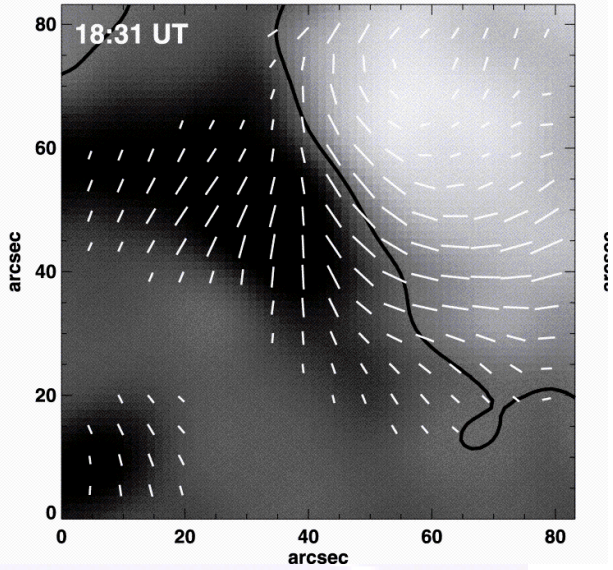
Velocity and Magnetic Shear in AR 10486
Source of the Halloween Events

- Velocity Shear Yang et al. 2004, ApJ 617 L151, Magnetic Shear Liu et al. 2005 ApJ 622, 722

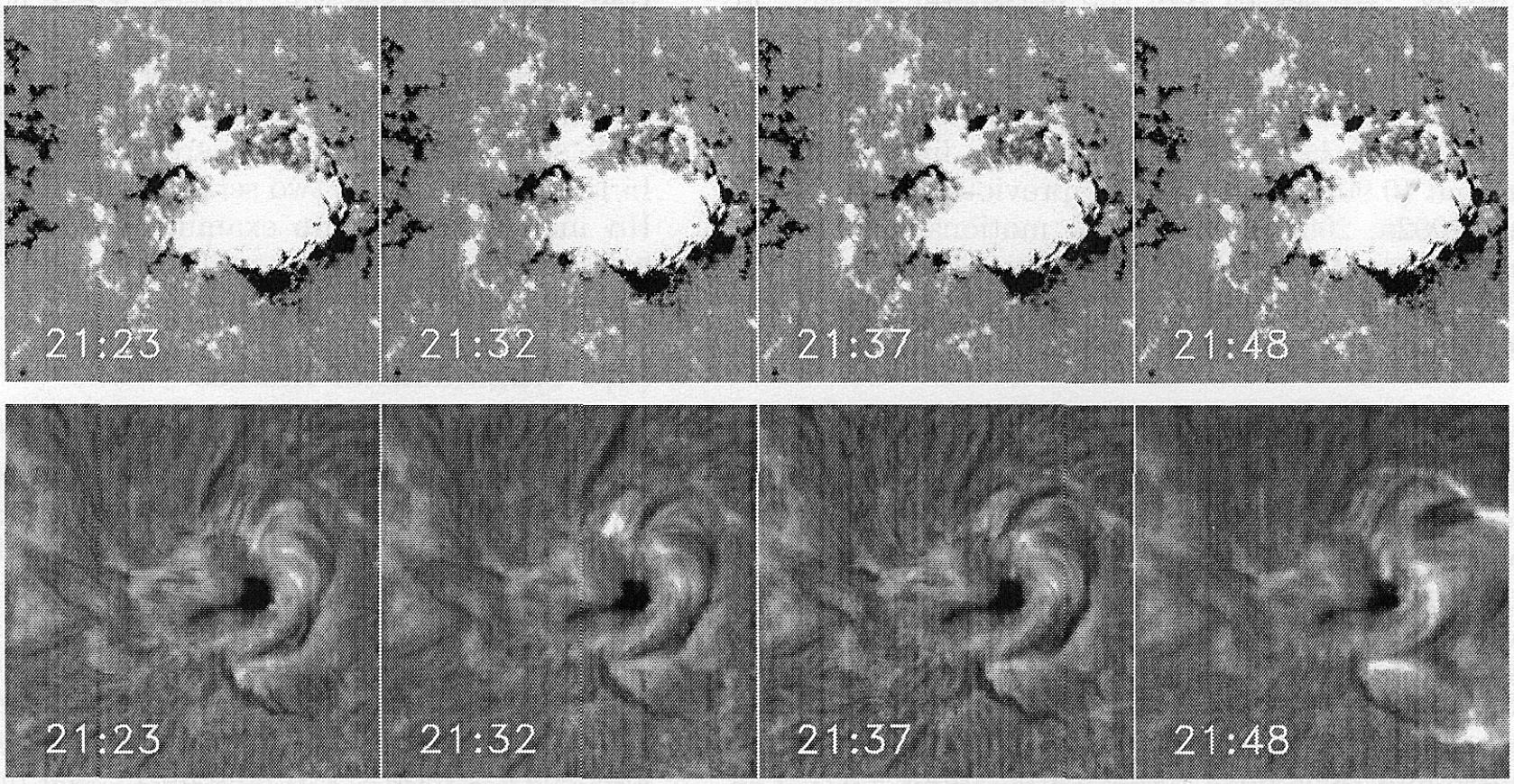






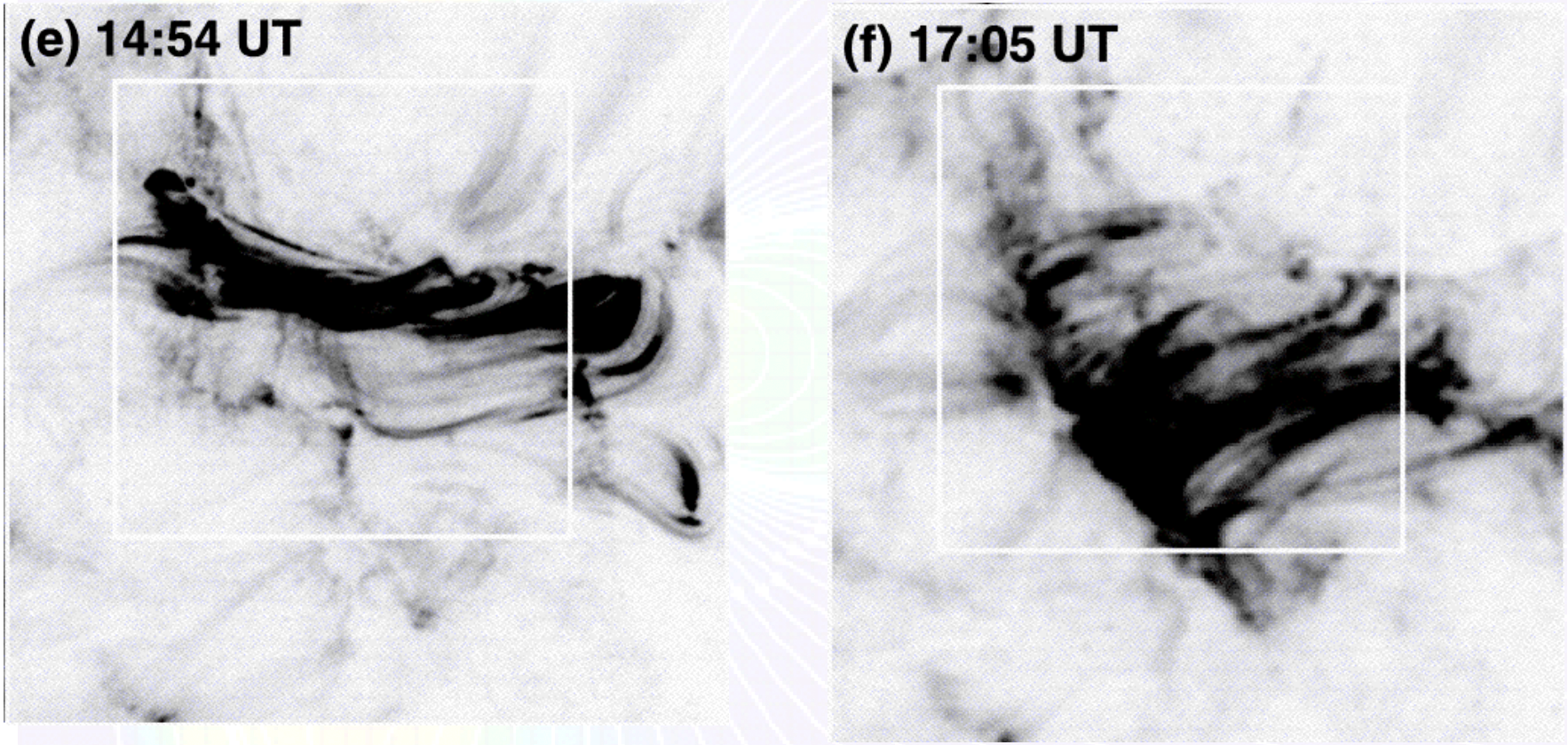
Magnetic Shear Indicated by Ha Filaments

- AR 9236

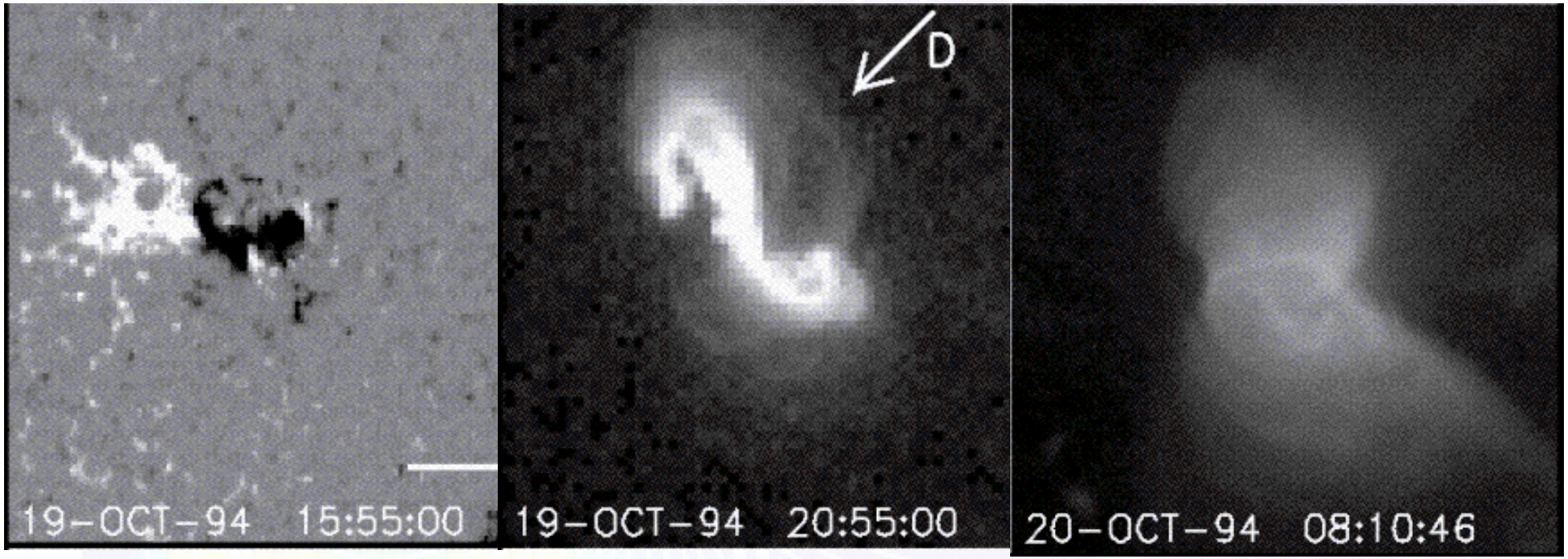


Magnetic Shear in the Corona seen by TRACE

- AR 9026 before and after a CME
- Liu et al. 2005, ApJ 622, 722



Magnetic Shear in the Corona: X-Ray Sigmoids

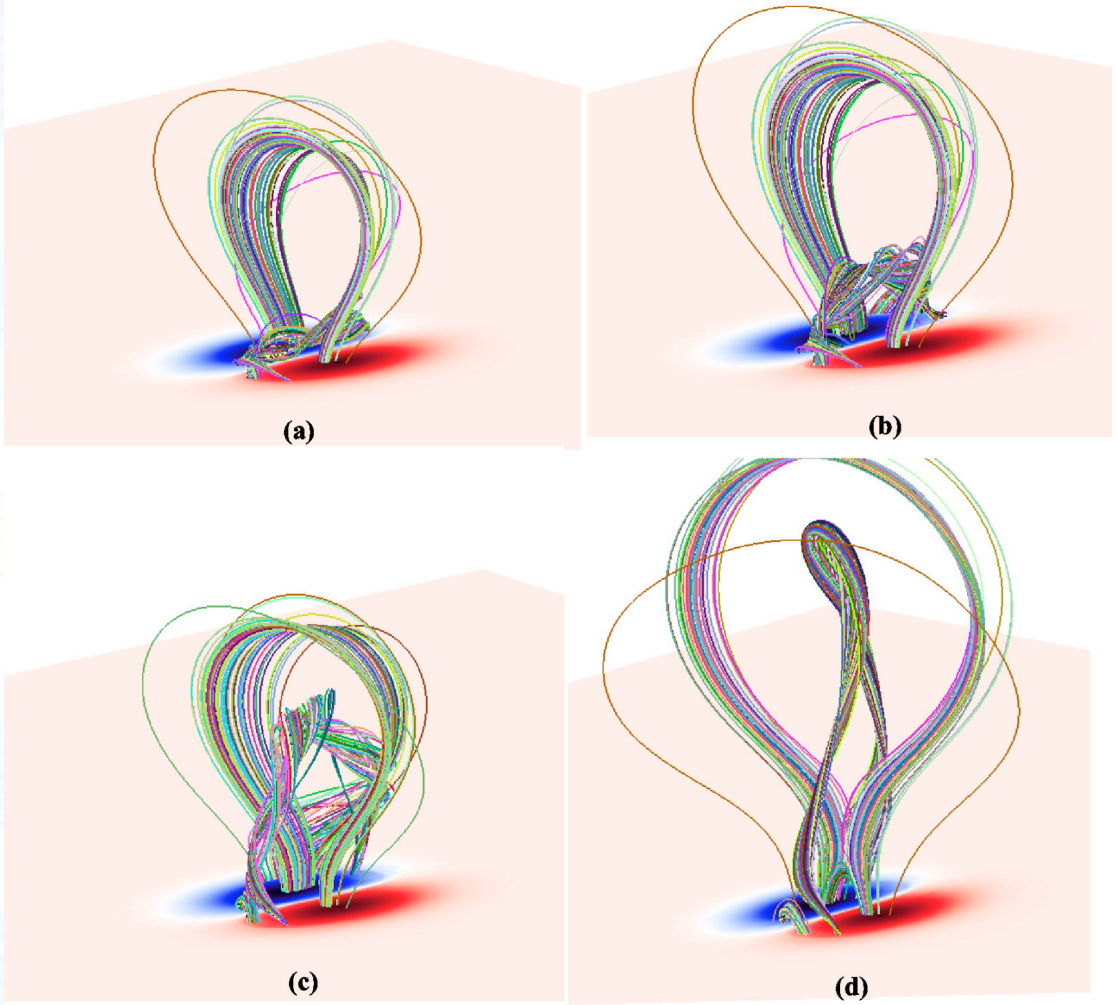


- Moore et al. 2001, ApJ 552, 833

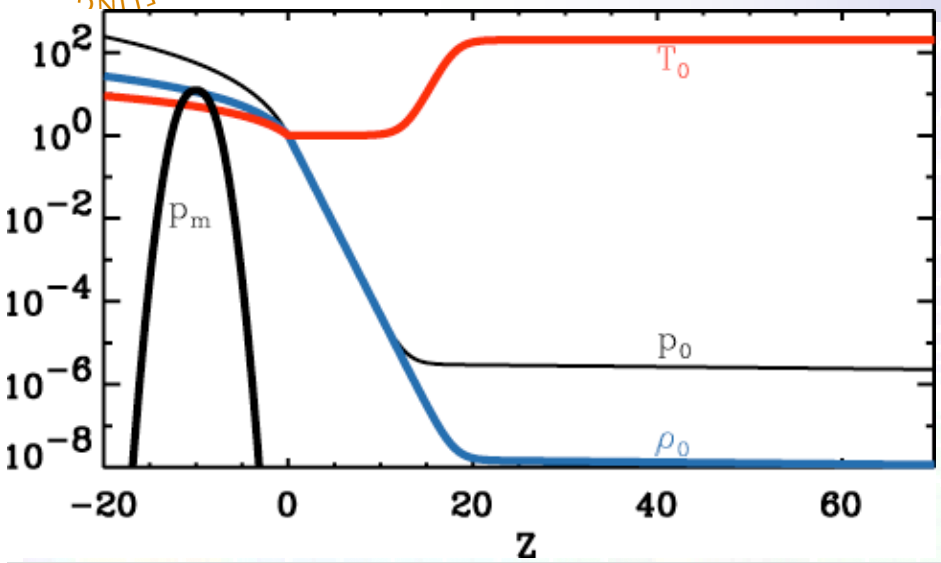
CME Models Including Photospheric Shear

Magnetic Arcade Models

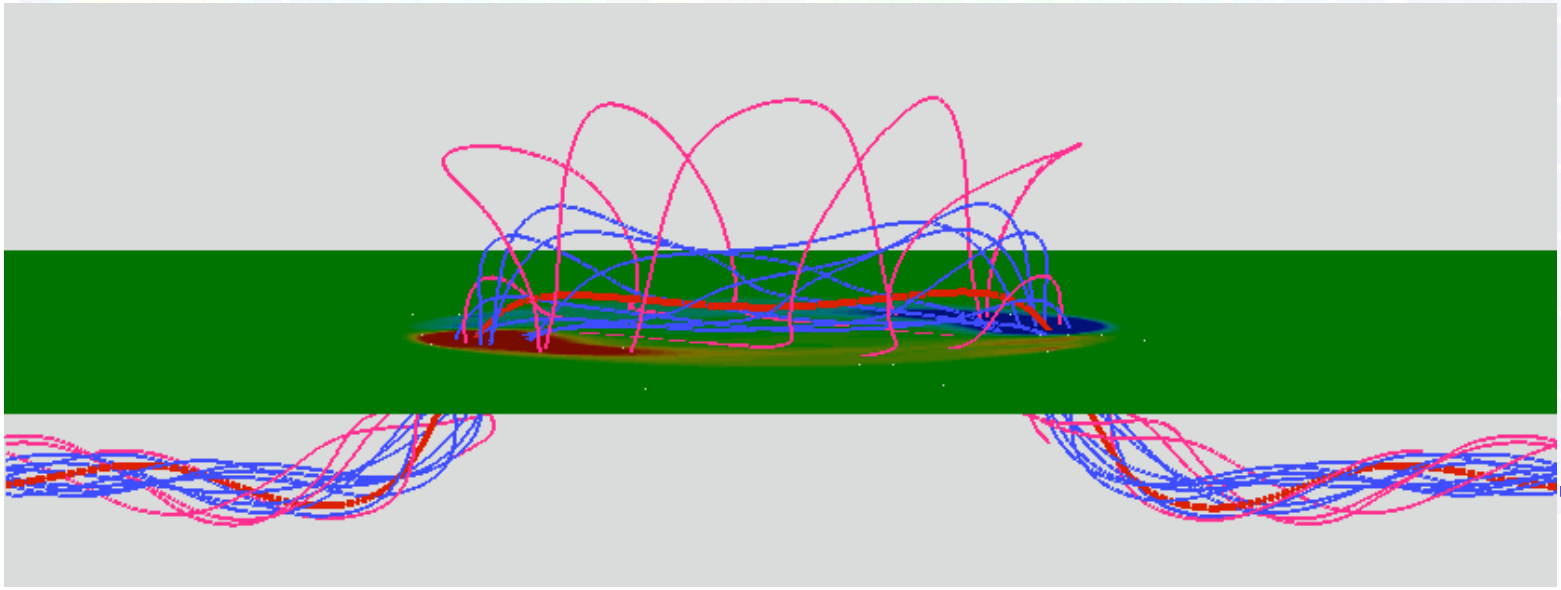
- *Imposed* shearing of foot points with magnetic reconnect at the base of the arcade (Mikic 1988, Mikic and Linker 1994, Choe and Lee 1996, Amari 2003)
- Break-out model: *Imposed* shearing motions and reconnection above the arcade in a quadruple system



Emergence of a 3D flux rope

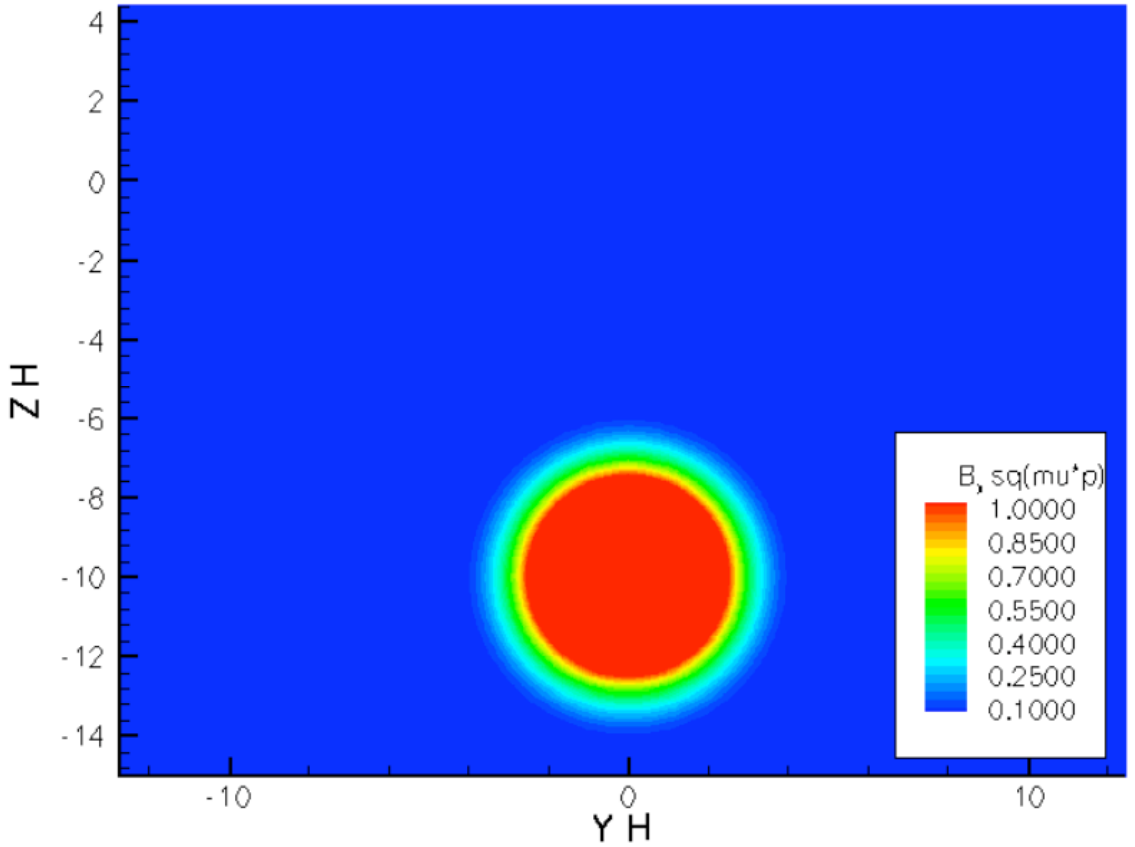


- Manchester et al. 2004, ApJ 610, 588
  Initial state from Fan 2001, ApJ 554 L111



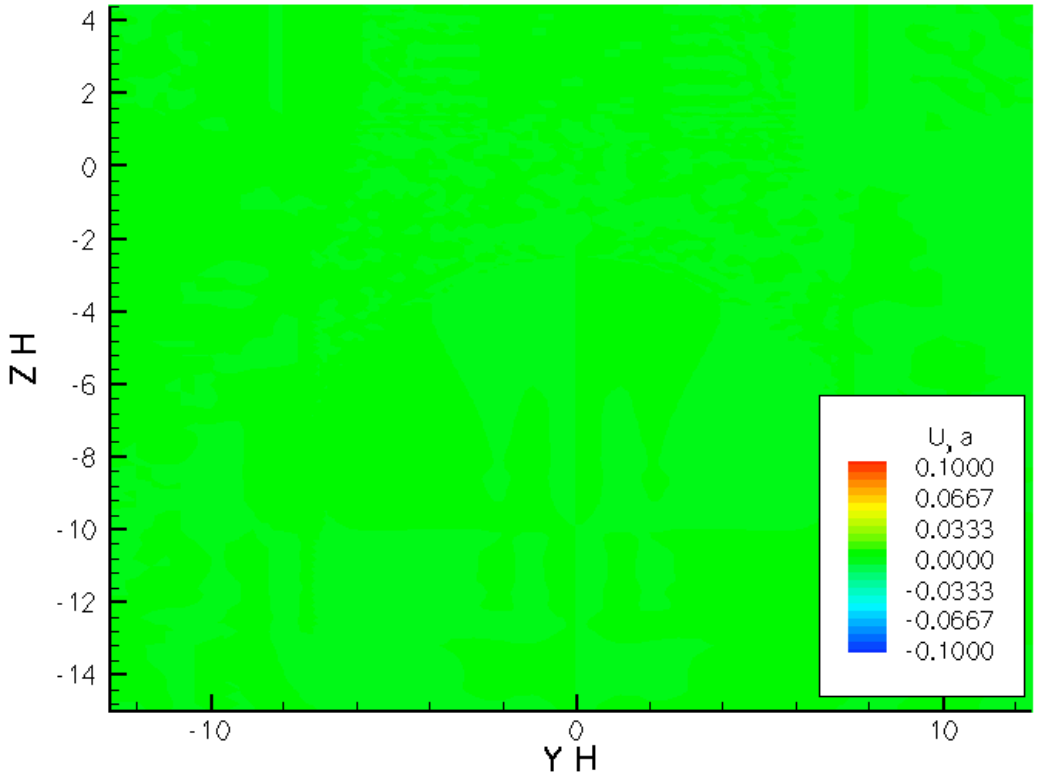
Flux Rope Emerging From the Convection Zone into the Corona

- Initial state from Fan (2001)
- Buoyant section of the flux rope reduced by a factor of two

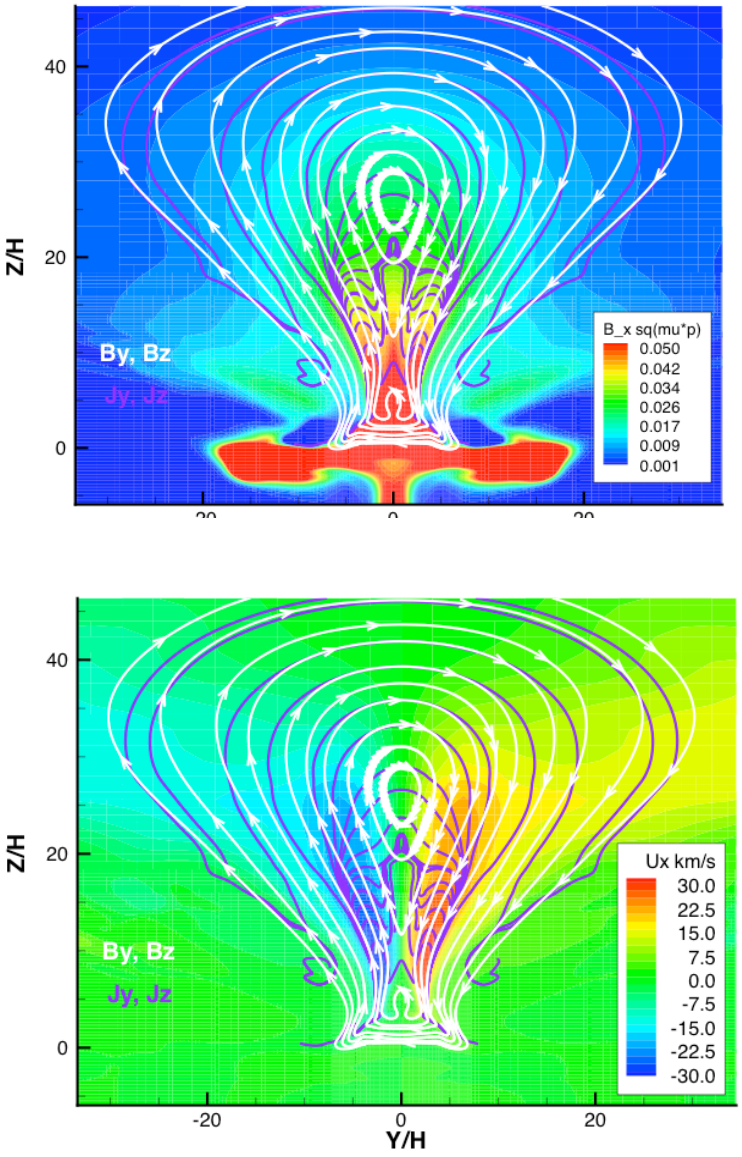


Spontaneous Shearing Motions

- Opposite sides of the flux rope move in opposite directions as the flux rope expands.
- Motions are driven by the Lorentz force!



Tension component of the Lorentz Force Drives the Shearing!!



$$F_x = \nabla B_x \cdot (B_y, \quad B_z)$$

$$\frac{\partial B_x}{\partial t} + \nabla_{yz} \cdot (B_x(V_y, \quad V_z)) =$$

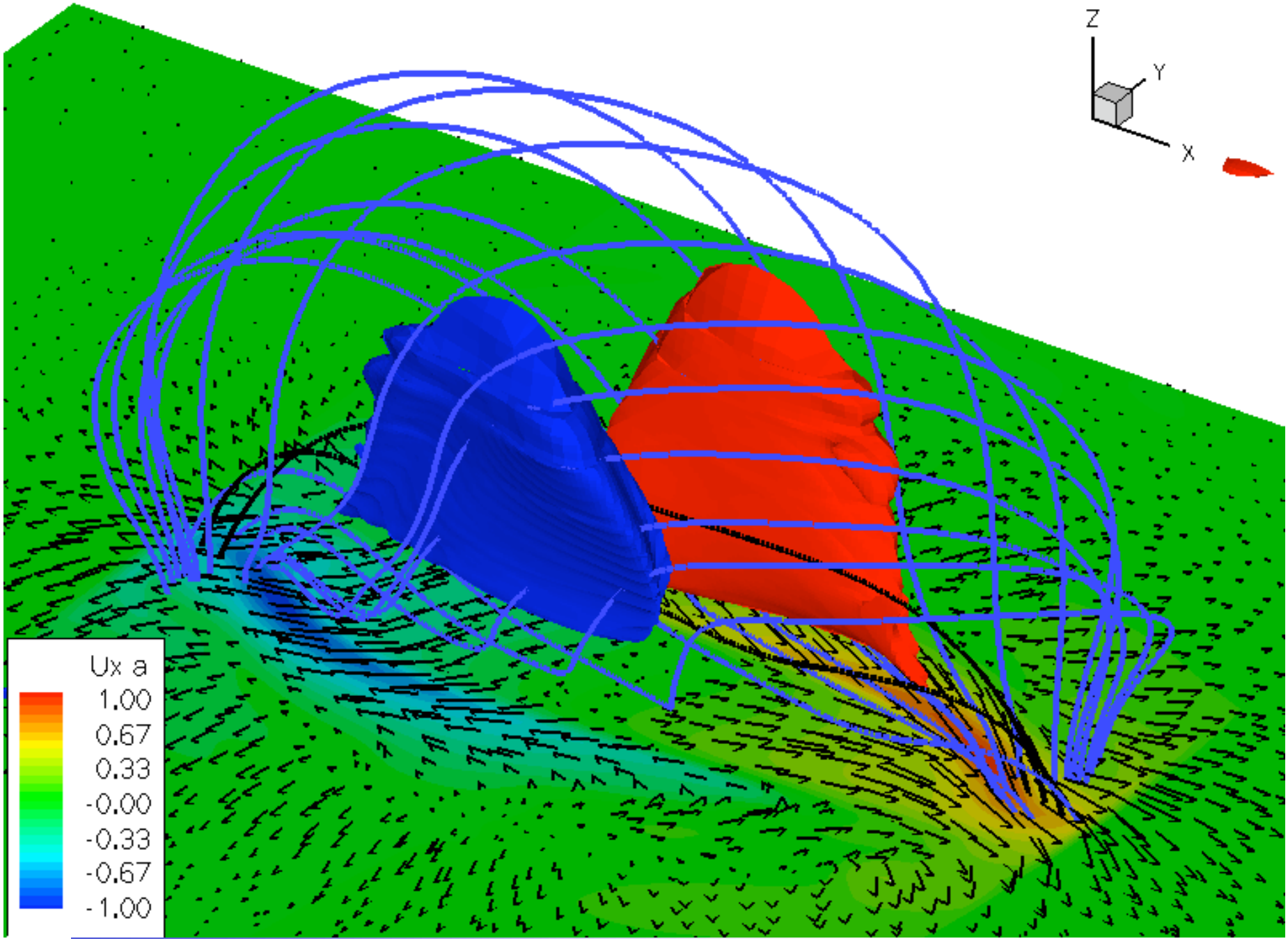
advection in the yz plane

$$\frac{\partial}{\partial y}(V_x B_y) + \frac{\partial}{\partial z}(V_x B_z)$$

shearing displacement

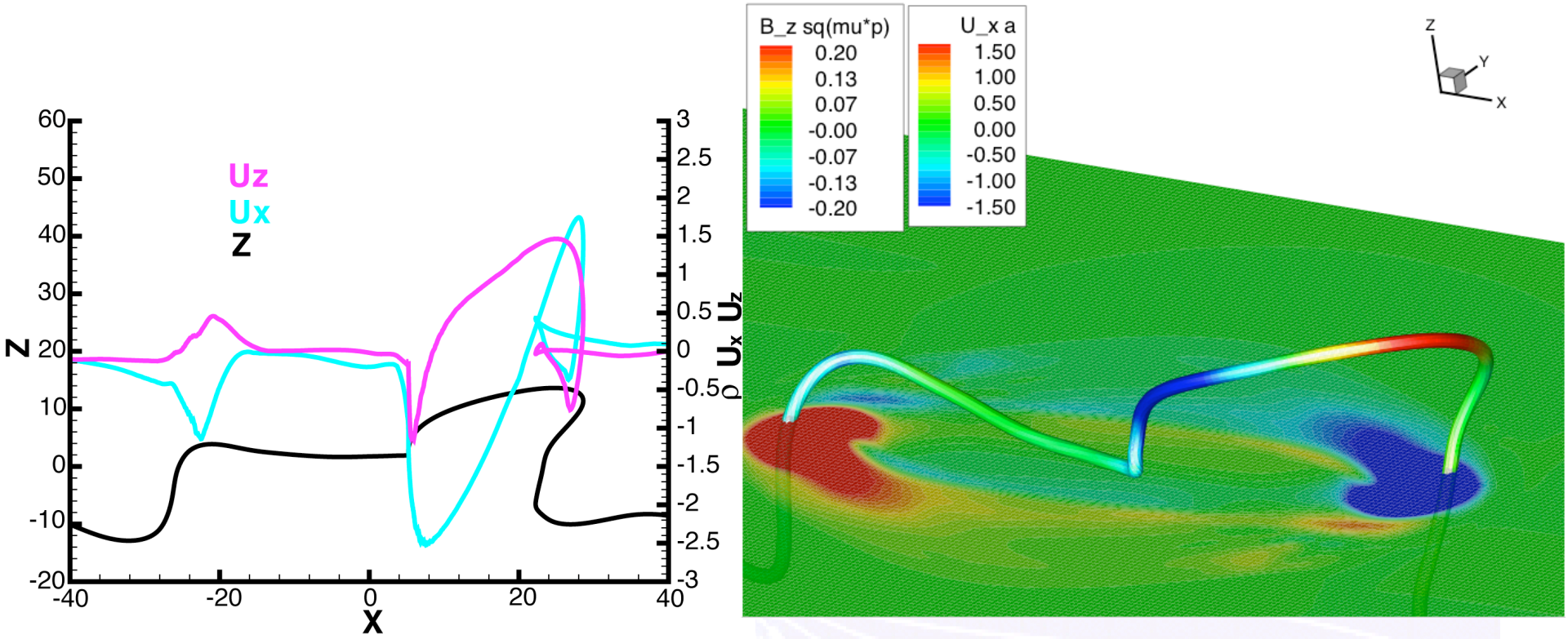
- Shearing motions transport Bx flux into the expanding portion of the flux rope and tends to return Bx to constant values along field lines to restore force balance
- Loss of equilibrium occurs from a shearing catastrophe when the field traverses many pressure scale heights and Bx can not be equilibrated

deling



http://csem.engin.umich.edu

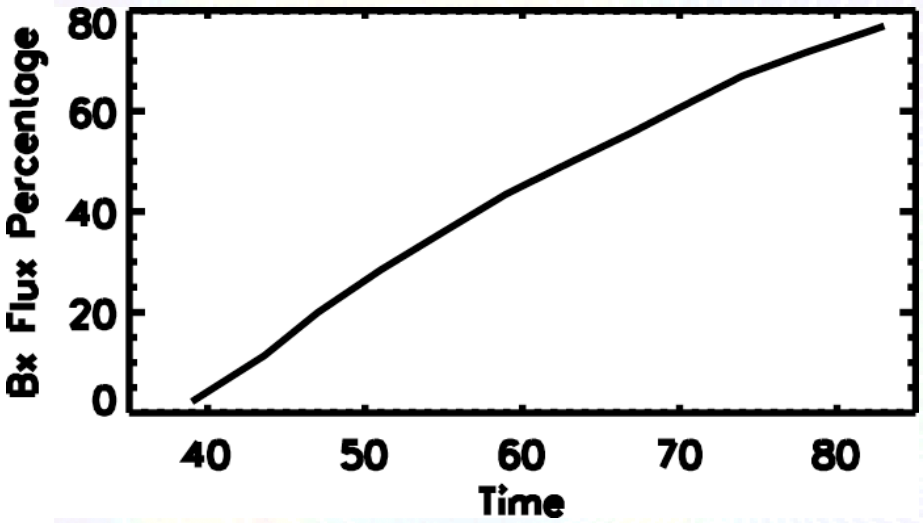
Eruption of a Magnetic Field Line



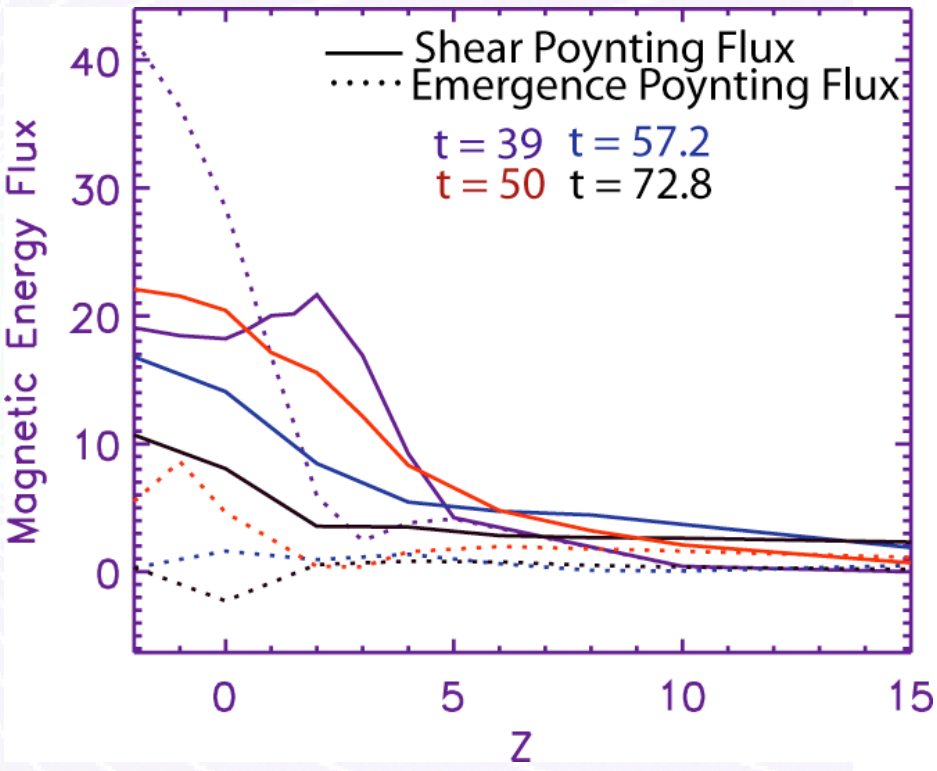
The field line locally eruption where the field line is being sheared and propagates as a shear Alfven wave along the field line.

Shearing motions are a transport process!

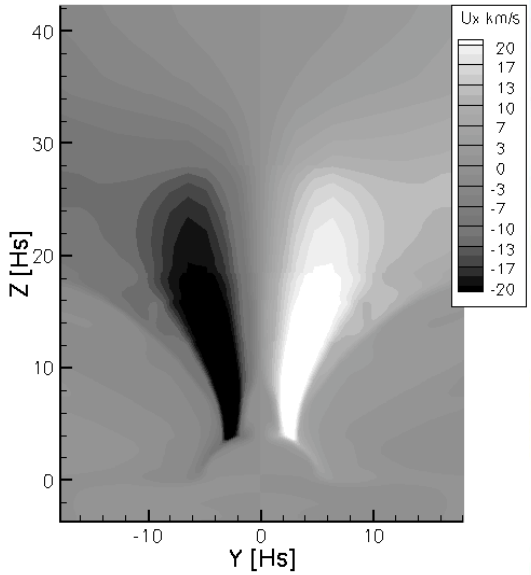
Axial Flux Transport

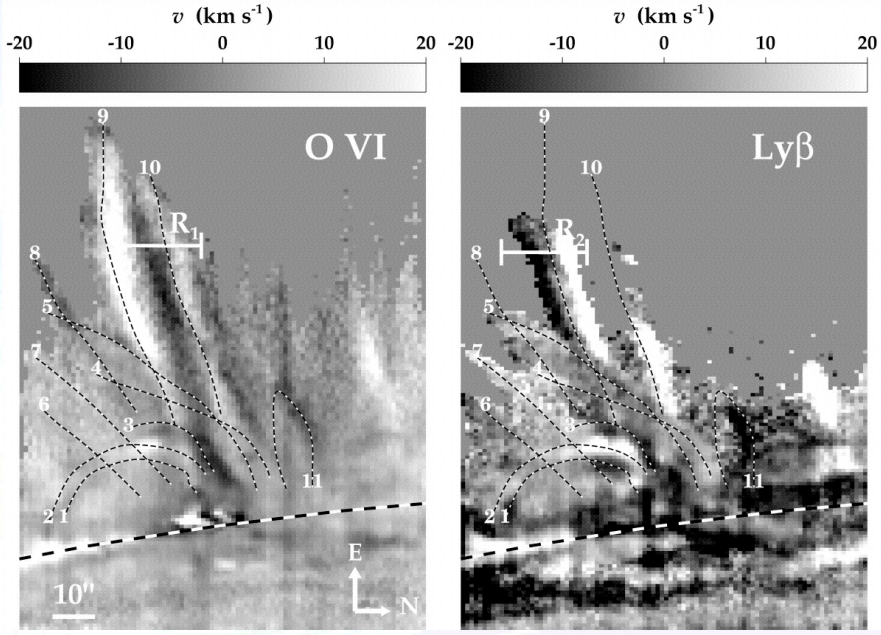


Energy Transport (Poynting Flux)



Comparison of Shear Velocity



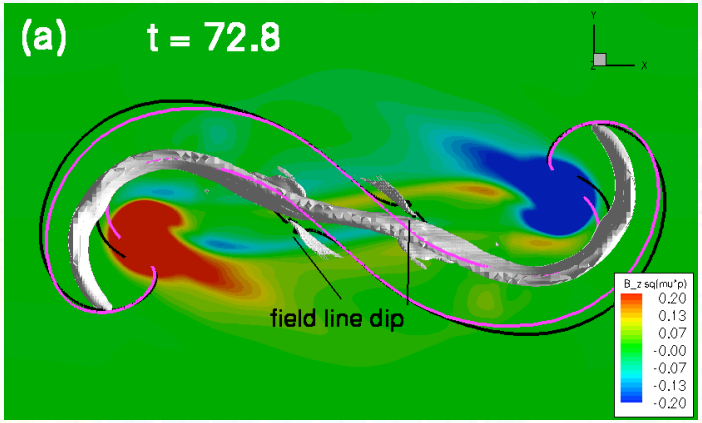


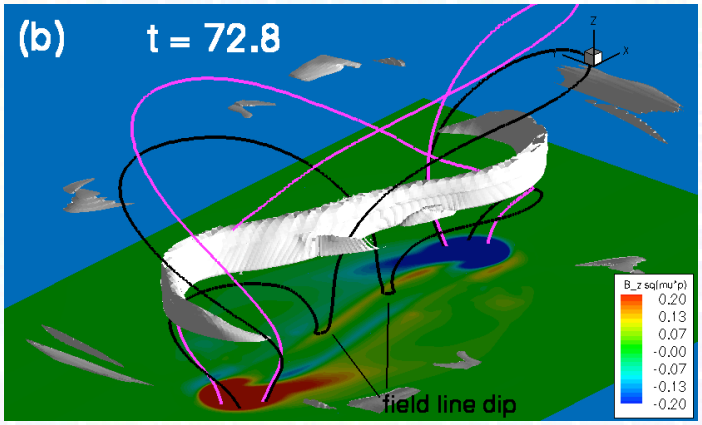
The image on the left, the shear velocity at the mid-plane of the simulation is shown. On the right, Doppler velocity maps of active regions at the limb made with SUMER

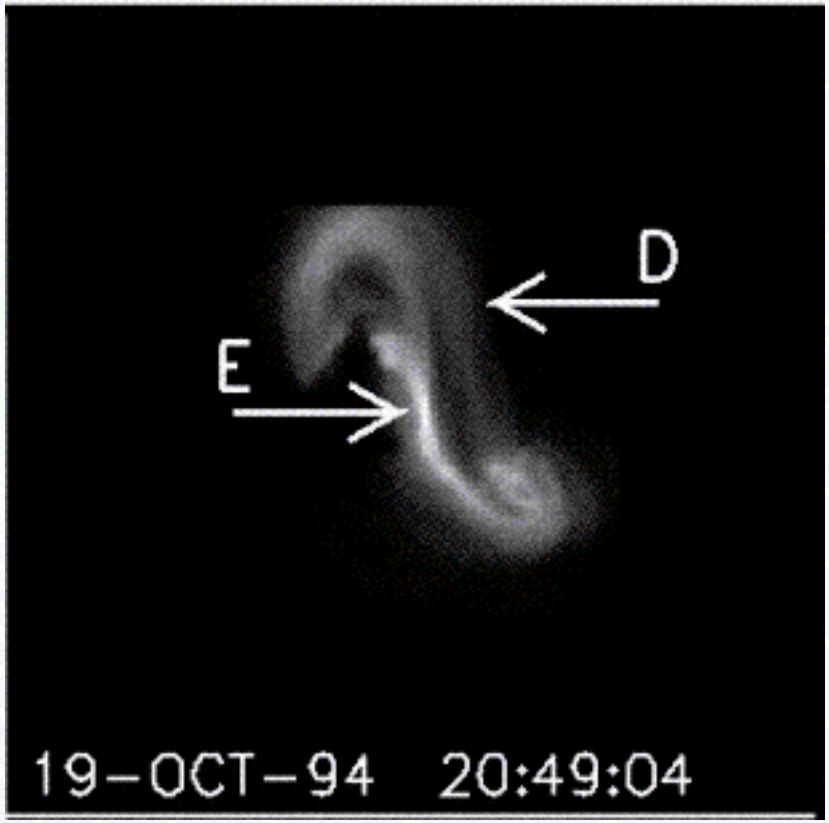
Chae et al. 2000, ApJ 533, 535,

Formation of a Sigmoid Current Sheet

To the left, an iso-surface of current density and field lines are shown over the photosphere colored to show Bz. To the right, observations of X-ray sigmoids by Moore et al. (2001)







Conclusions

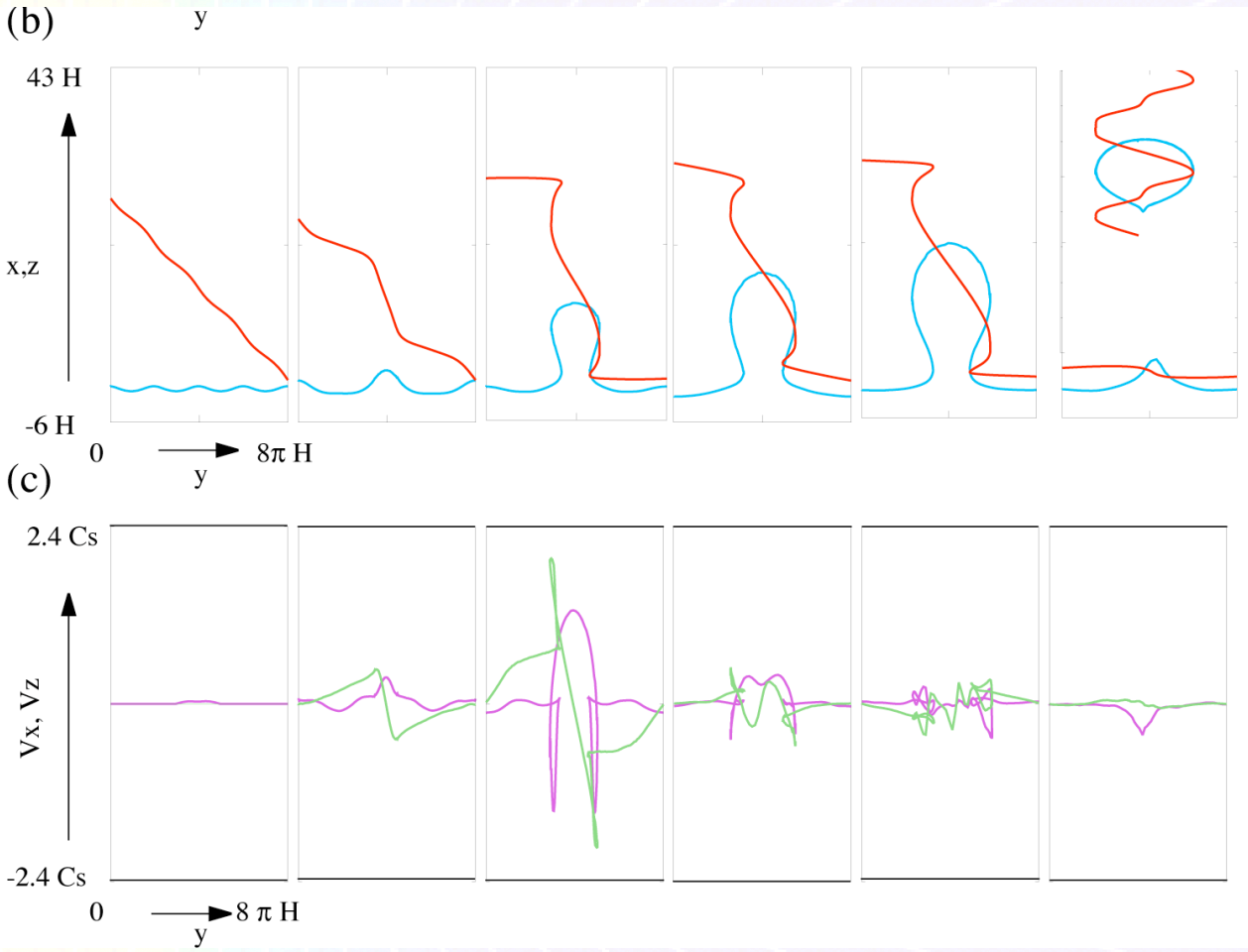
- Shearing motions are an inevitable consequence of the Lorentz force that arises as the magnetic field expands in a highly stratified atmosphere which naturally explains:
- Coincidence of the magnetic neutral line and the velocity neutral line
- Impulsive nature of shearing in newly emerged flux
- Magnitude of the shear velocity in the photosphere, chromosphere and corona that occur at a characteristic fraction of the local Alfven speed.
- The large scale pattern of shear in active regions which increases with proximity to the neutral line
- Shearing motions transport axial flux into expanding portion of the flux rope and strongly couple the low β corona to the high β photosphere and below
- The eruption of the flux rope and arcade occur with shearing motions and reconnection explains CMEs and flares
- Multiple (homologous) eruptions from arcades that occur as a slow build up and expansion followed by eruption
- Formation of a sigmoid shaped current-sheet

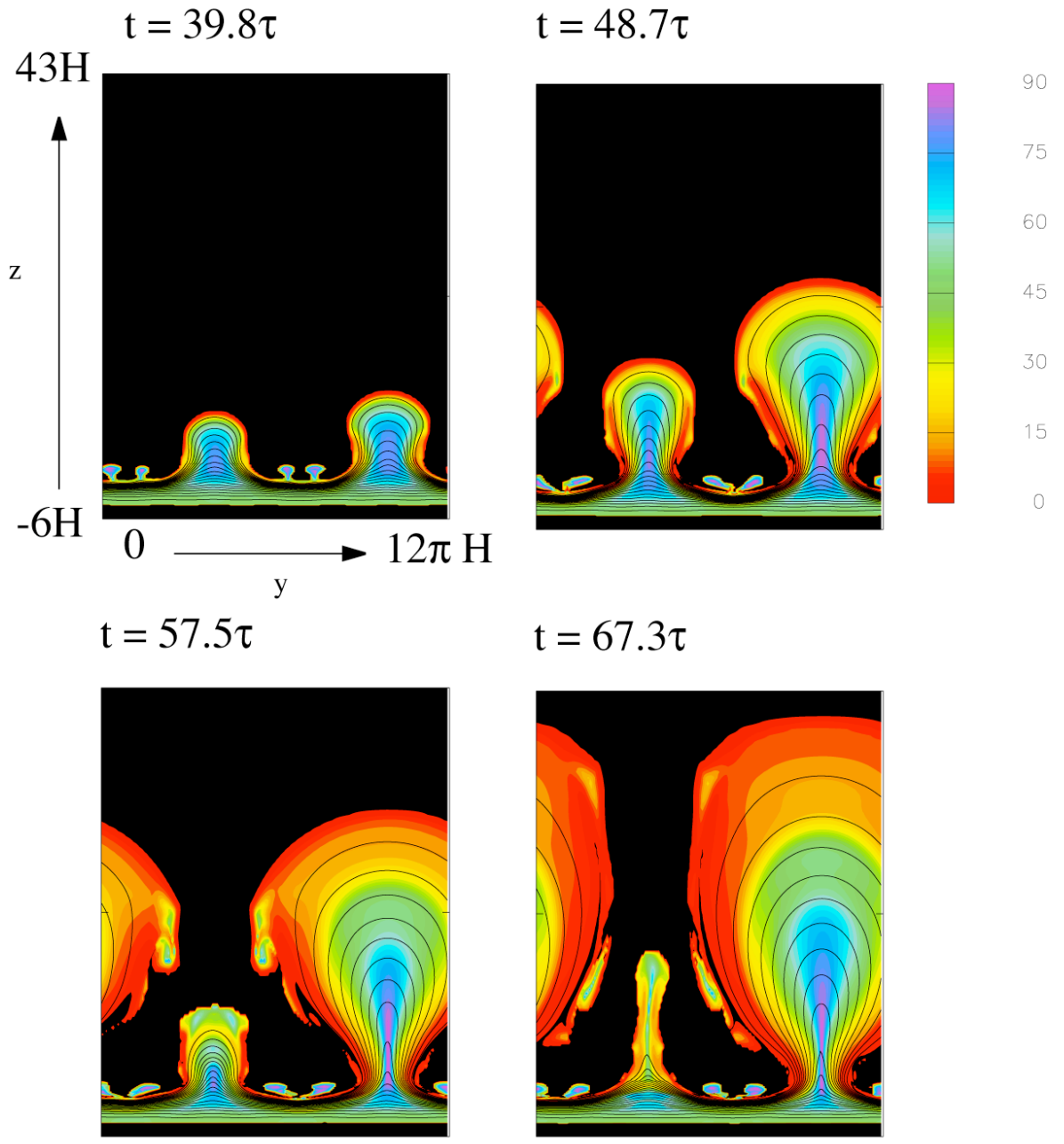
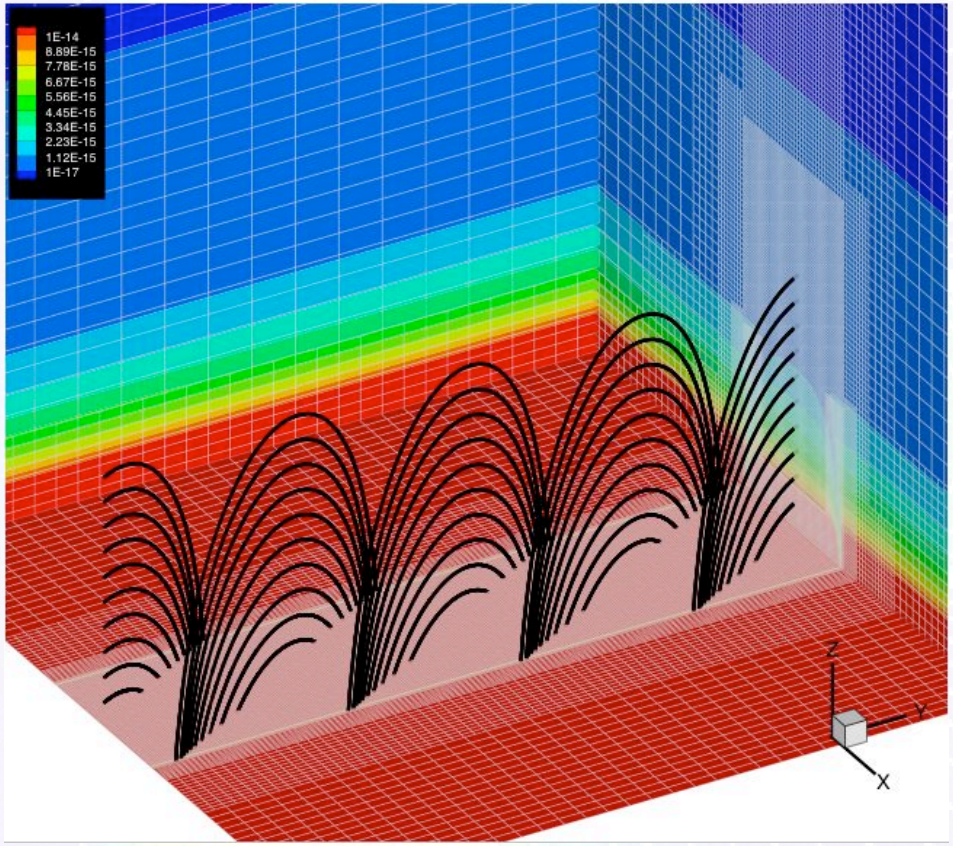
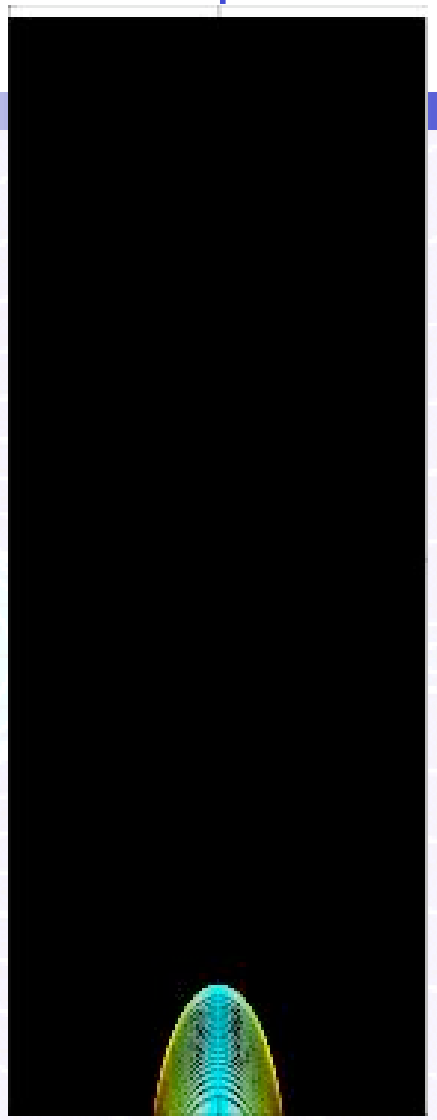
- The force-free paradigm is incorrect. With a more complete model of magnetic field traversing a large range of plasma beta, the ad hoc application of shearing motions can be put to rest

Fundamental Assumptions

- The Sun possesses a gravitational field that results in large pressure stratification of the atmosphere
- Non-force-free magnetic structures pass that through the photosphere into the corona to form active regions are larger than pressure scale height at the photosphere (140 km)
- Magnetic field possess a horizontal axial component in addition to an azimuthal component
- The Lorentz force can be represented by (curl B) X B

- Applies to arcades and flux ropes


(b)
y
43 H
x,z
-6 H
0
8π H
y
(c)
2.4 Cs
Vx, Vz
-2.4 Cs
0
8 π H
y


t = 39.8τ
t = 48.7τ
43H
z
-6H
0
12π H
y
90
75
60
45
30
15
0
t = 57.5τ
t = 67.3τ

Shear-Driven Arcade Eruption