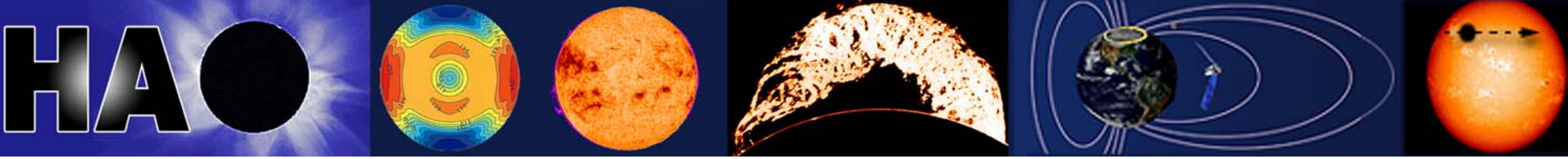

Evolution of Twisted Magnetic Flux Ropes Emerging into the Corona

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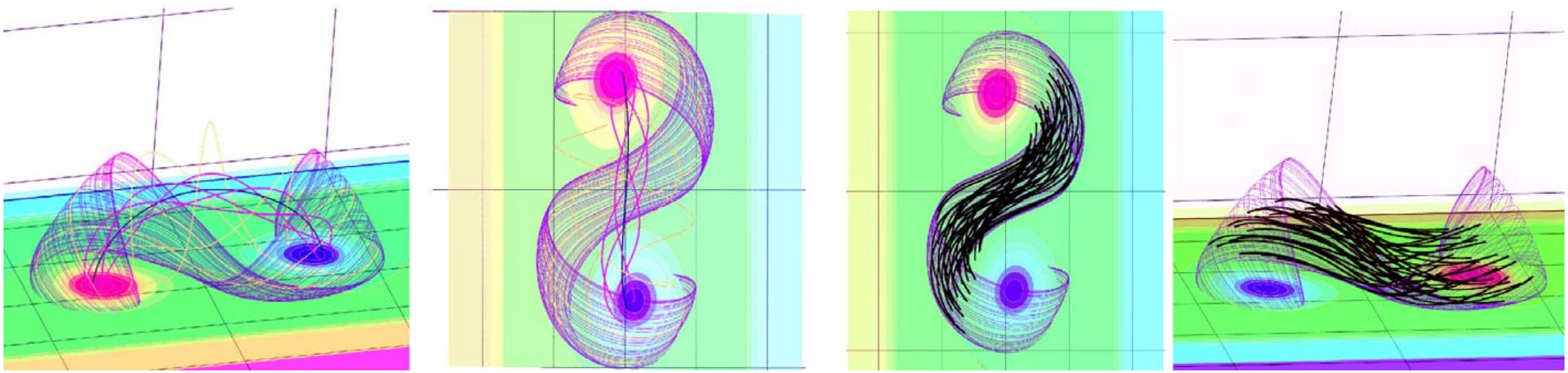
Outline

- Twisted magnetic flux ropes as CME precursors: simulations of the dynamic evolutoin of the coronal magnetic field driven at the lower boundary by a kinematic emergence of a twisted magnetic flux rope.
  - 2D axisymmetric flux ropes
  - 3D line-tied flux ropes
- Simulations of the dynamic emergence of twisted flux tubes through the photosphere.

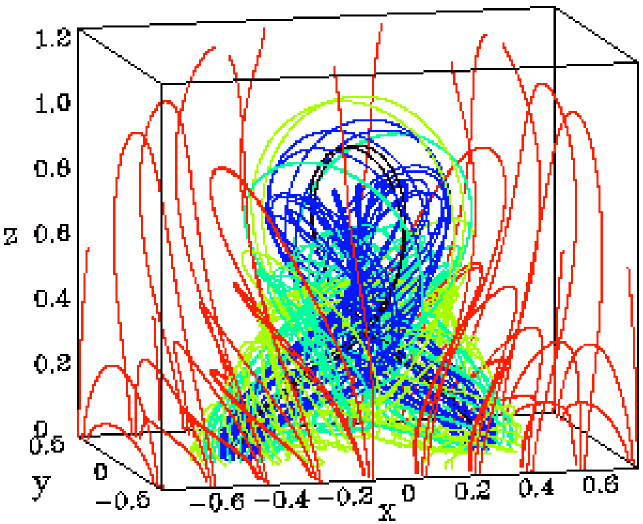
- **Twisted magnetic flux ropes as CME precursors** (e.g. Low 2001):
  - – may result from the emergence of twisted flux tubes from the interior (e.g. Fan 2001; Magara & Longcope 2001; Manchester et al. 2004), or form as a result of turbulent diffusion of magnetic fields on the photosphere (Mackay & van Ballegooijen 2001, 2005; Amari et al. 2003).
  - – contain free magnetic energy
  - – dipped field lines support prominence material against gravity
  - – current sheet formation along the "bald-patch" separatrix surface (BPSS) of a partially emerged, line-tied flux rope → X-ray sigmoids (Titov & Demoulin 1999; Low and Berger 2003; Fan & Gibson 2004; Gibson et al. 2004):

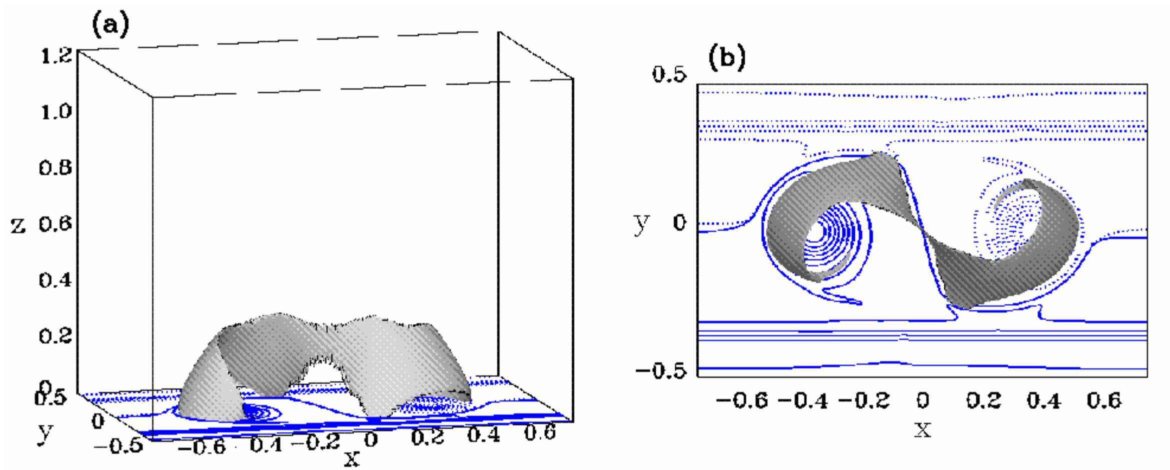
From Gibson et al. (2004)



Fan & Gibson (2004)

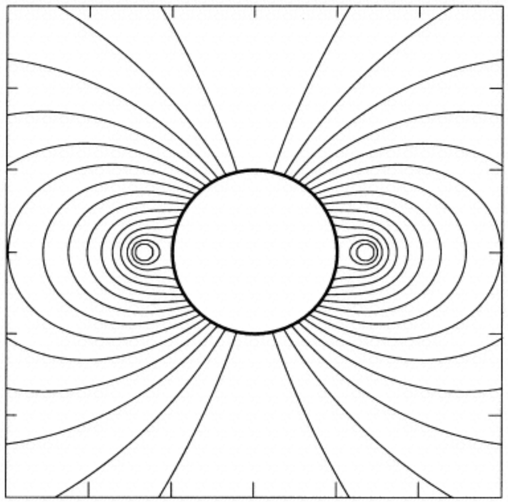
iso-surface of current density from 2 perspective views

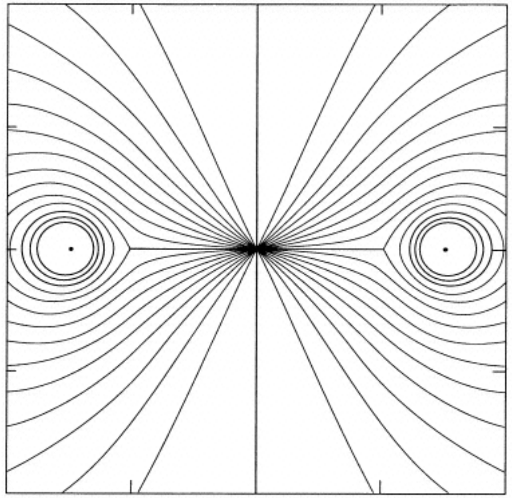


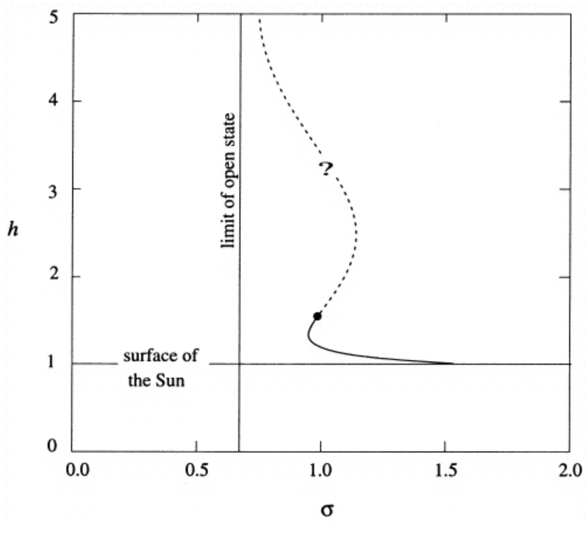


- **The loss of equilibrium of a twisted magnetic flux rope may be a major cause for CME onset (e.g. Priest & Forbes 2002; Sturrock 2001):**

Lin et al. (1998): 2D axisymmetric catastrophe model for eruption

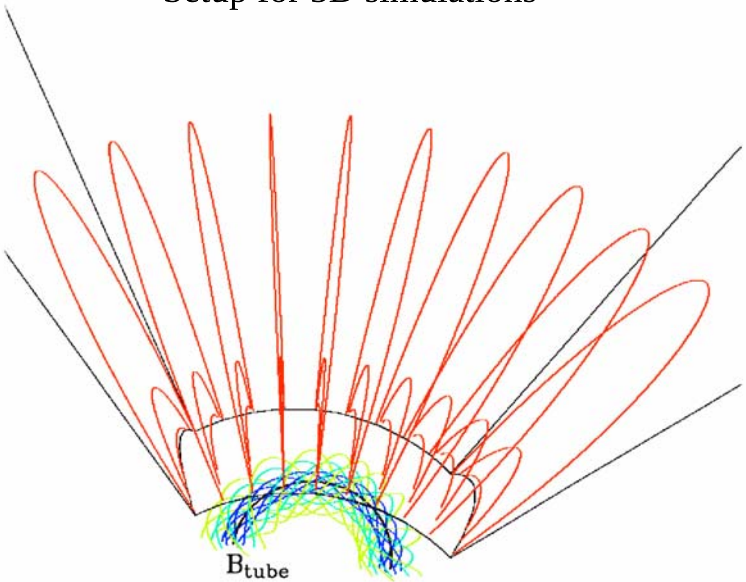


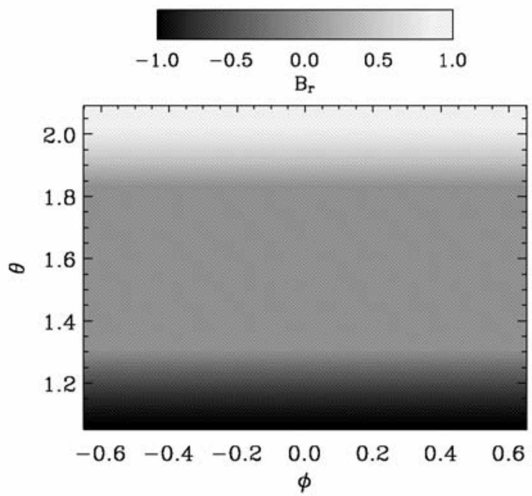




Model Description

Setup for 3D simulations





Initial Br on the lower boundary

- Simulation domains:
  - 2D axisymmetric: $r = [R_\odot, 14.4R_\odot], \theta = [\pi/3, 2\pi/3]$, grid: 816×384
  - 3D: $r = [R_\odot, 6R_\odot], \theta = [\pi/3, 2\pi/3], \phi = [-\pi/4.8, \pi/4.8]$, grid: $360 \times 192 \times 240$
- Initial state: static isothermal atmosphere with a potential arcade field:

$$\rho = \rho_0 \exp\left(-\frac{R_\odot}{H_{p0}}\left(1 - \frac{R_\odot}{r}\right)\right)$$

$$p = \frac{RT_0\rho}{\mu}$$

where

$T_0 = 2$ MK

$a_s = \sqrt{RT_0/\mu} = 128$ km s^{-1}

$H_{p0} = (RT_0/\mu)(GM_\odot/R_\odot^2)^{-1} = 60$ Mm

$\rho_0 = 8.365 \times 10^{-16}$ g cm^{-3}

peak vertical field at the foot points of the arcade $B_0 = 20$G

$V_{a0} = B_0/\sqrt{4\pi\rho_0} = 1951$ km s^{-1}

- Solve the following isothermal MHD equations in a global spherical geometry:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0,$$

$$\rho\left(\frac{\partial \mathbf{v}}{dt} + (\mathbf{v} \cdot \nabla)\mathbf{v}\right) = -\nabla p - \rho\frac{GM}{r^2}\hat{\mathbf{r}} + \frac{1}{4\pi}(\nabla \times \mathbf{B}) \times \mathbf{B} + \rho\nu\nabla^2\mathbf{v},$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}),$$

$$\nabla \cdot \mathbf{B} = 0,$$

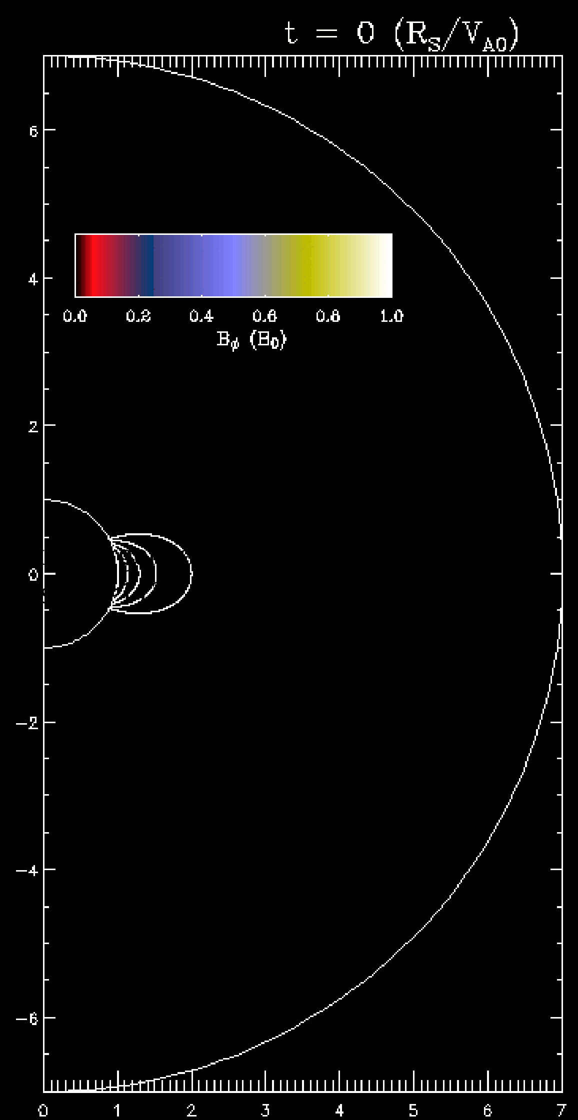
$$p = a_s^2\rho.$$

- At the lower boundary, a twisted flux tube is transported kinematically into the domain by imposing at the $r = R_\odot$ boundary a time dependent transverse electric field $\mathbf{E}_\perp|_{r=R_\odot}$ that corresponds to the flux tube rising at a constant velocity $\mathbf{v}_0$:

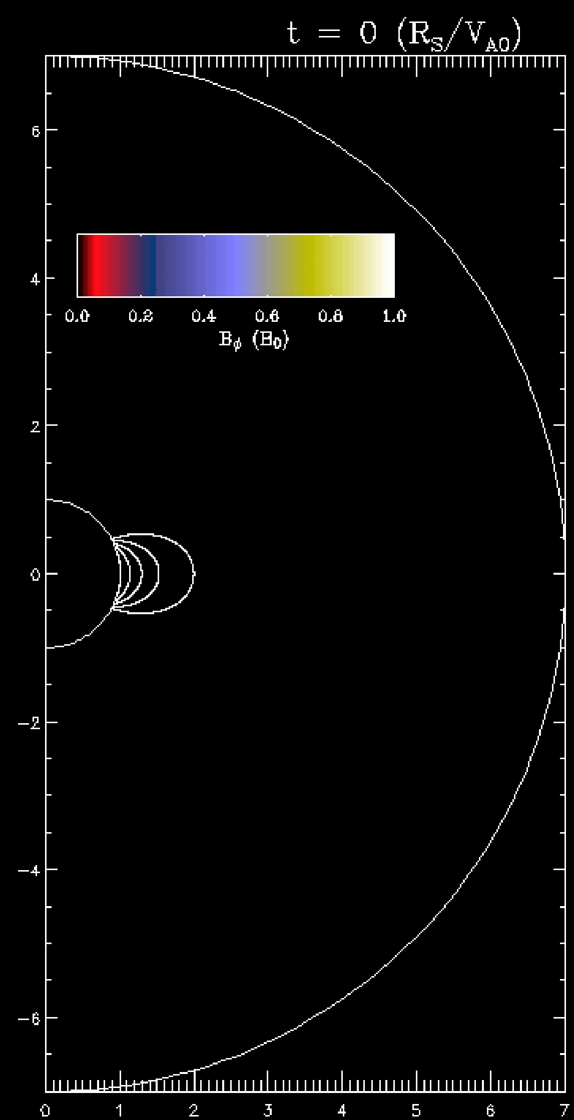
$$\mathbf{E}_\perp|_{r=R_\odot} = \hat{\mathbf{r}} \times \left[\left(-\frac{1}{c}\mathbf{v}_0 \times \mathbf{B}_{\rm tube}(R_\odot, \theta, \phi, t)\right) \times \hat{\mathbf{r}}\right],$$

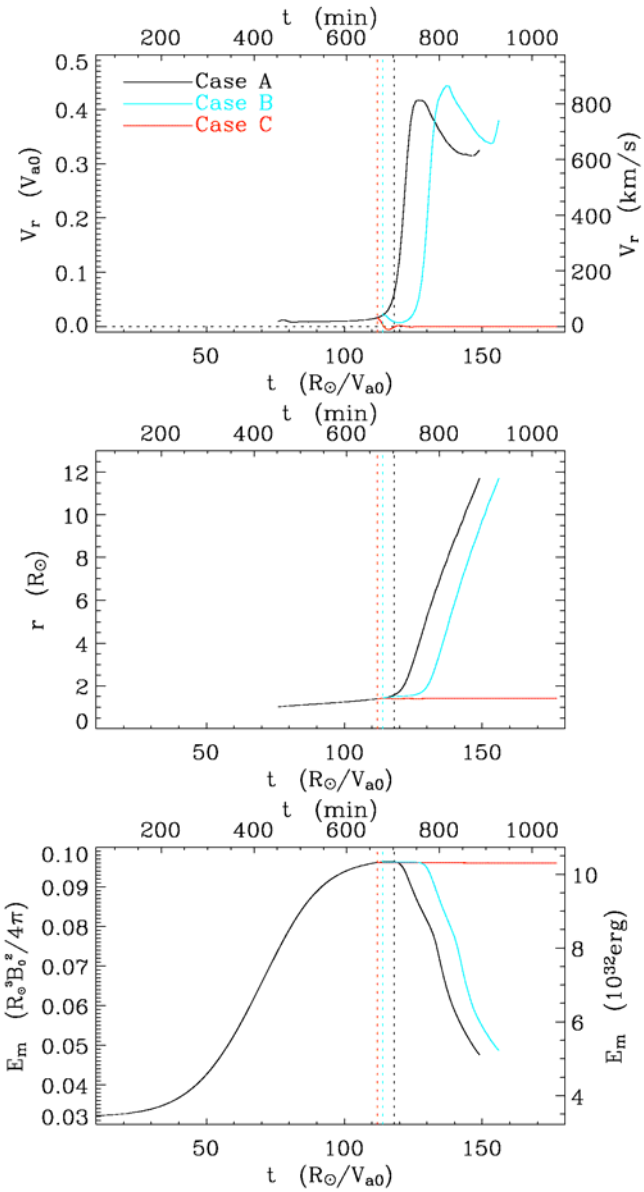
Results from 2D axisymmetric simulations

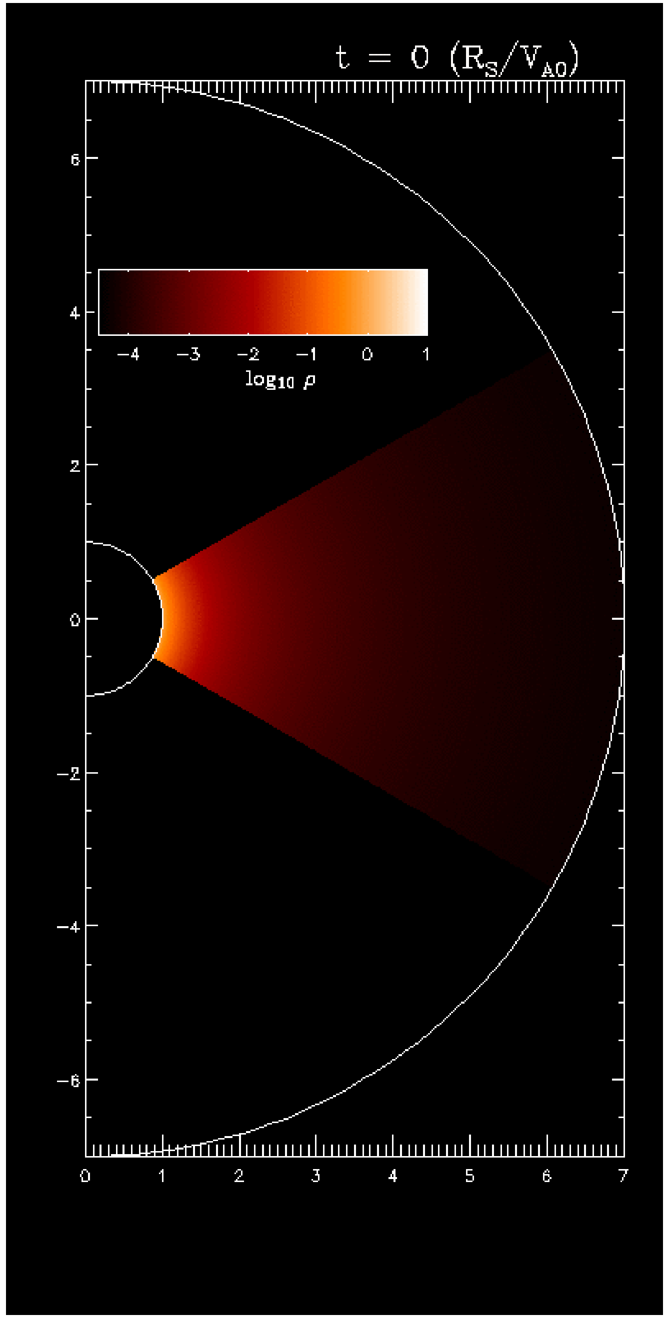
Case C: emergence stopped at t=112



Case A: emergence stopped at t=118



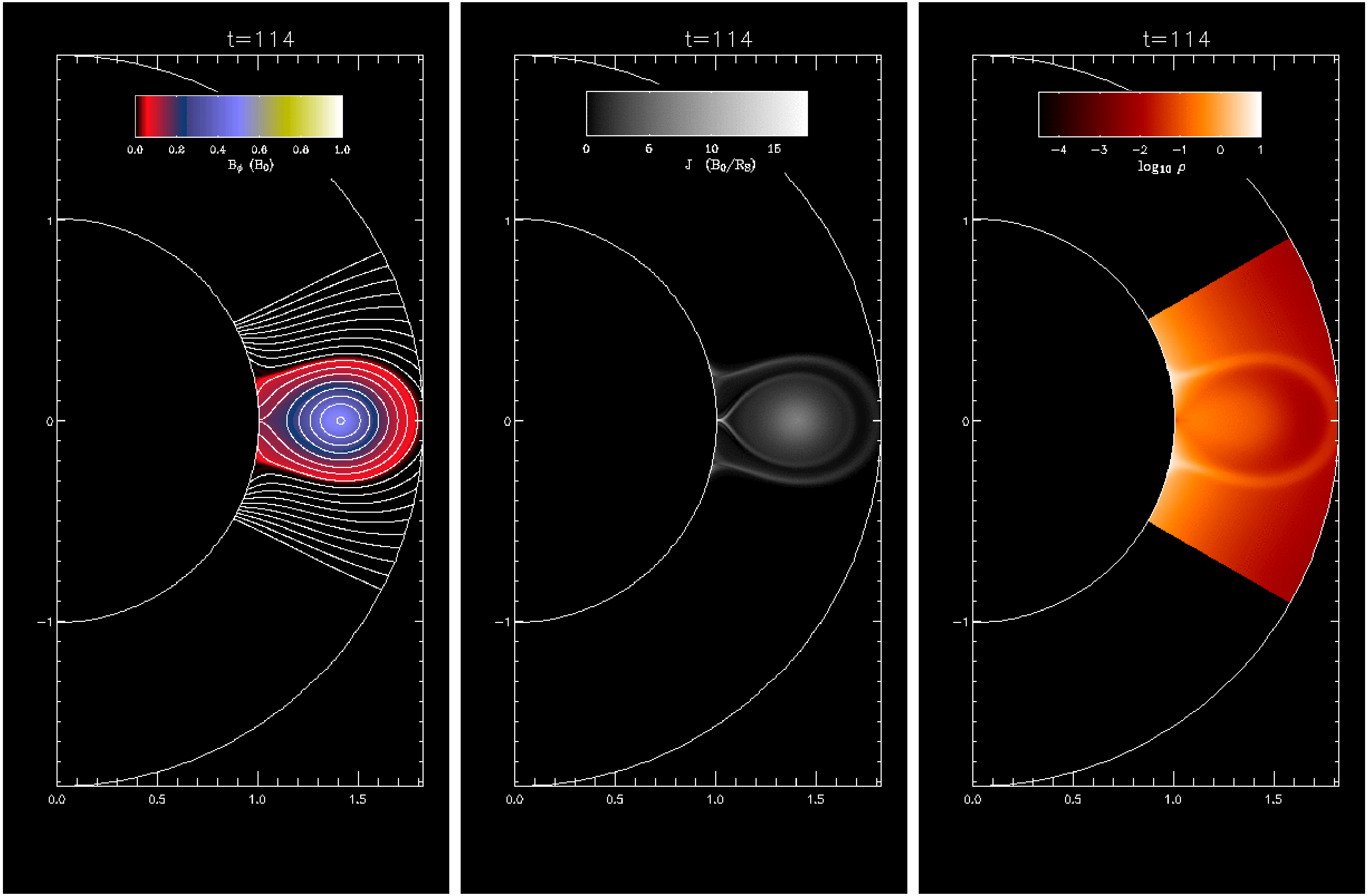




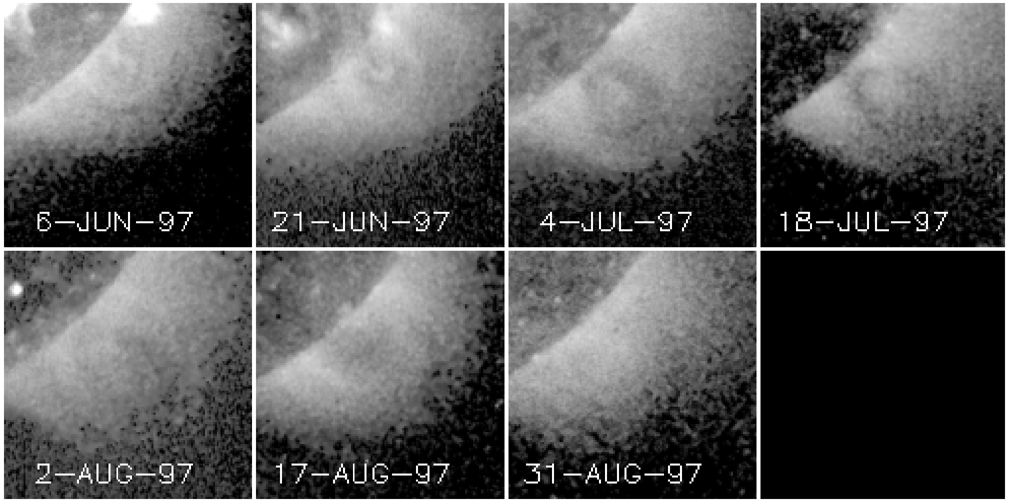
t = 0 (R_S/V_A0)
−4 −3 −2 −1 0 1
log10 ρ
6
4
2
0
−2
−4
−6
0 1 2 3 4 5 6 7

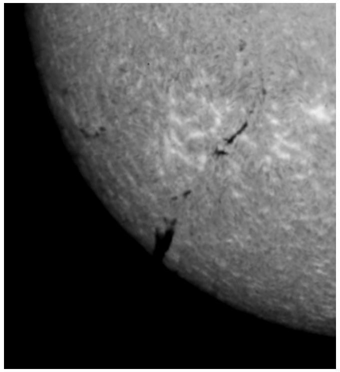
Current sheet formation → “chewy nougat” (Hudson et al. 1999)

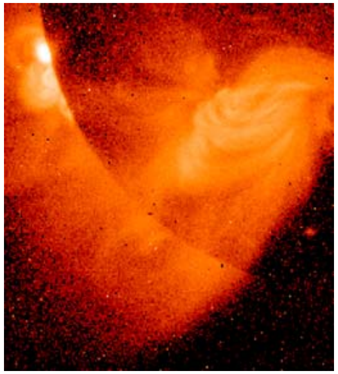
Case C: stable flux rope

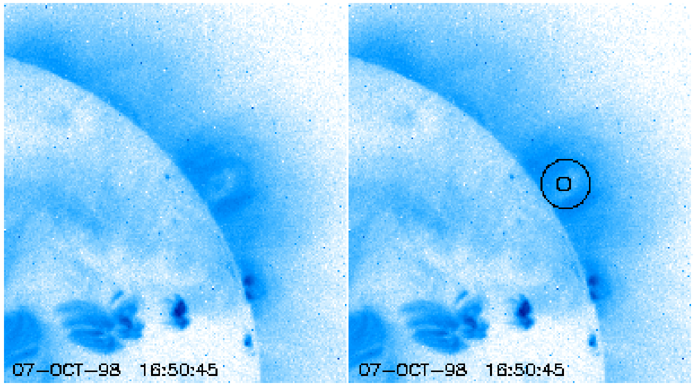


Stable filament cavity with a hot (bright) core seen in soft X-ray (Hudson et al. 1999): Chewy nougat





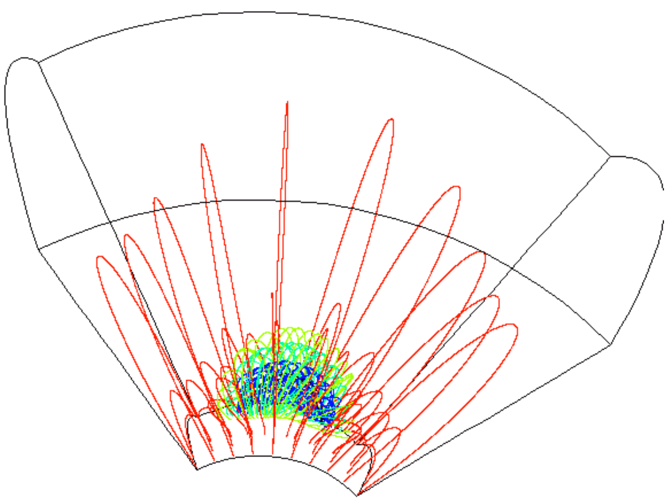


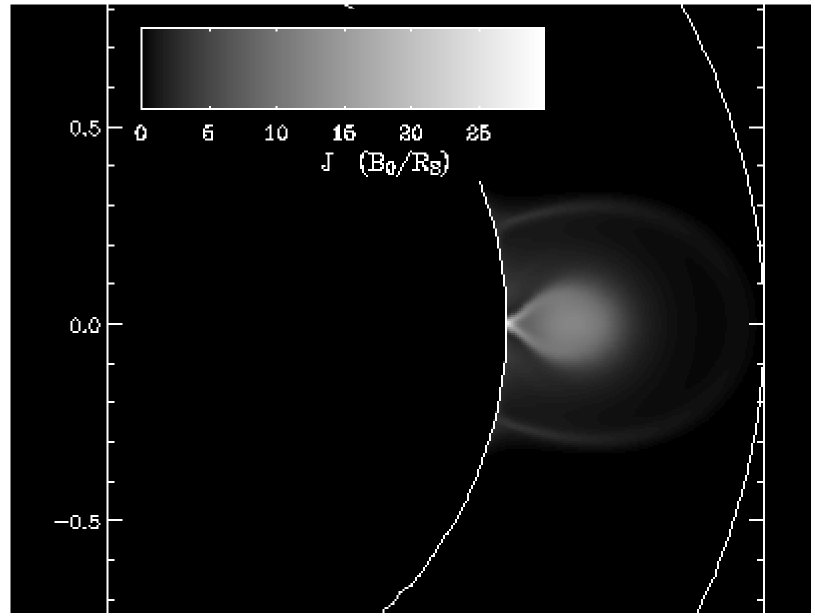


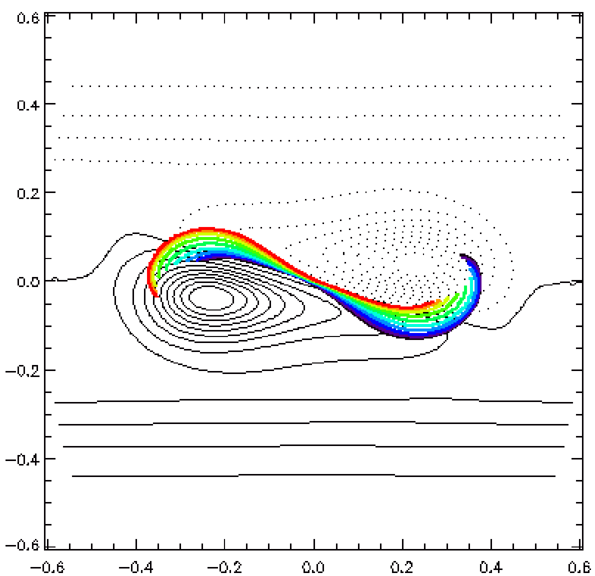
SXT has seen several cases of bright region situated above and around the projected location of the cool filament in the core of a filament cavity. See:

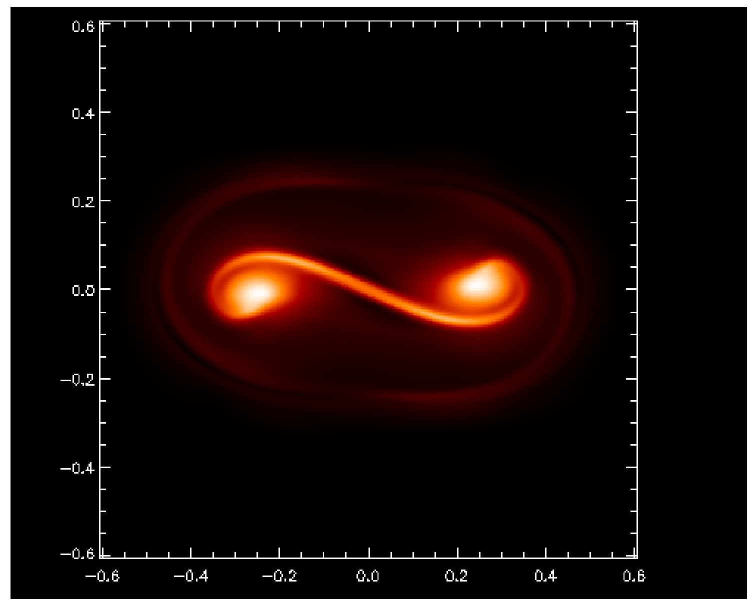
http://solar.physics.montana.edu/YPOP/Nuggets/1998/981009/981009.html

3D Simulation Results

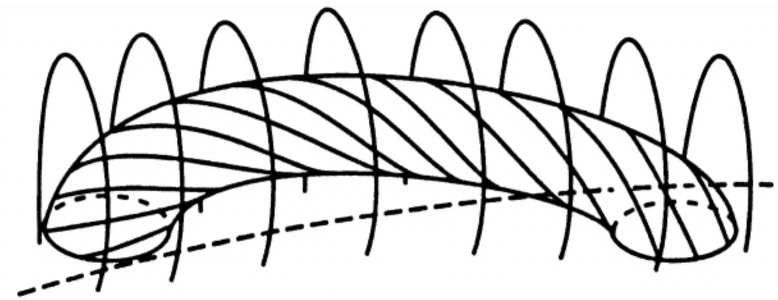


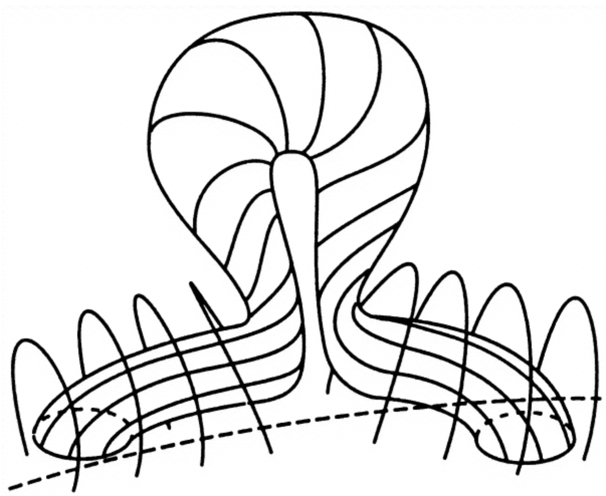






Sturrock et al. (2001)





- Free energy associated with a force-free twisted flux tube of total flux Φ, rate of twist b, total length L, confined by an external magnetic pressure P:

$$E_{\rm free} = \frac{L}{R_0}\frac{R_0^3}{8}\left(\frac{\Phi}{\pi R_0^2}\right)^2 [(1+b^2R^2)^{1/2} - 1]$$

where,
R: radius of the twisted tube
$R_0 = (\Phi^2/8\pi^3 P)^{1/4}$: radius of the corresponding untwisted tube

- Increase in energy of the arcade as the flux rope rupture through:

$$W_a \sim (2\pi R_0^3)\frac{1}{8\pi}\left(\frac{\Phi}{\pi R_0^2}\right)^2 = \frac{1}{4}R_0^3\left(\frac{\Phi}{\pi R_0^2}\right)^2$$

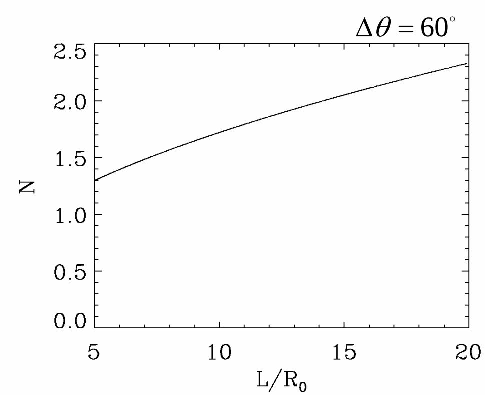
- Energy of the ruptured flux rope expanding to infinity:

$$W_b \sim \frac{1}{4}R_0^3\left(\frac{\Phi}{\pi R_0^2}\right)^2 (1-\cos\Delta\theta)^{-1/2}$$

- Requiring $E_{\rm free} > W_a + W_b$ leads to:

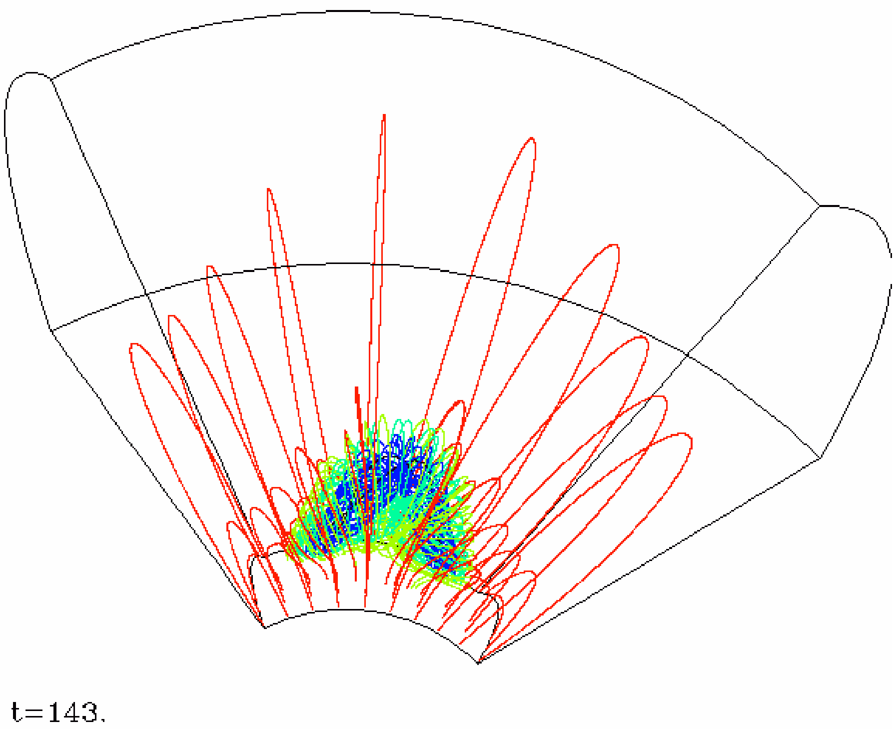
$$N \equiv bL > \frac{1}{2^{1/2}\pi}\lambda\left[1+\frac{2(1+Q)}{\lambda}\right]^{1/2}\left[\ln\left(1+\frac{2(1+Q)}{\lambda}\right)\right]^{1/2}$$

where $\lambda \equiv L/R_0$, $Q \equiv (1-\cos\Delta\theta)^{-1/2}$

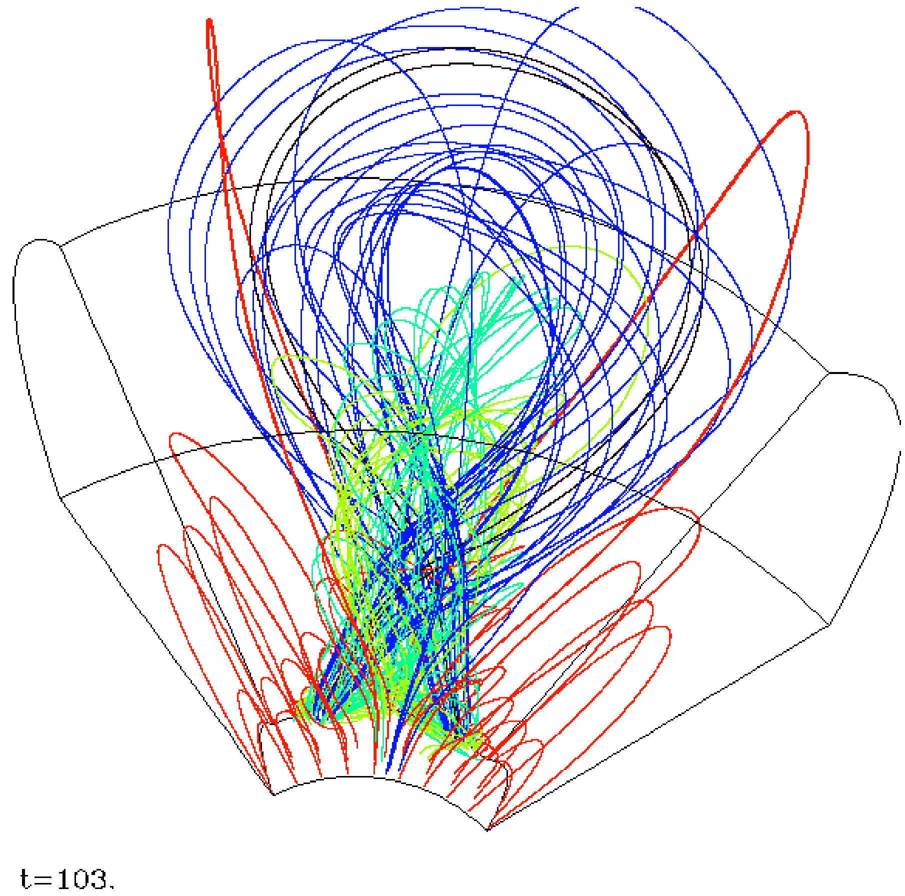


3D Simulation Results

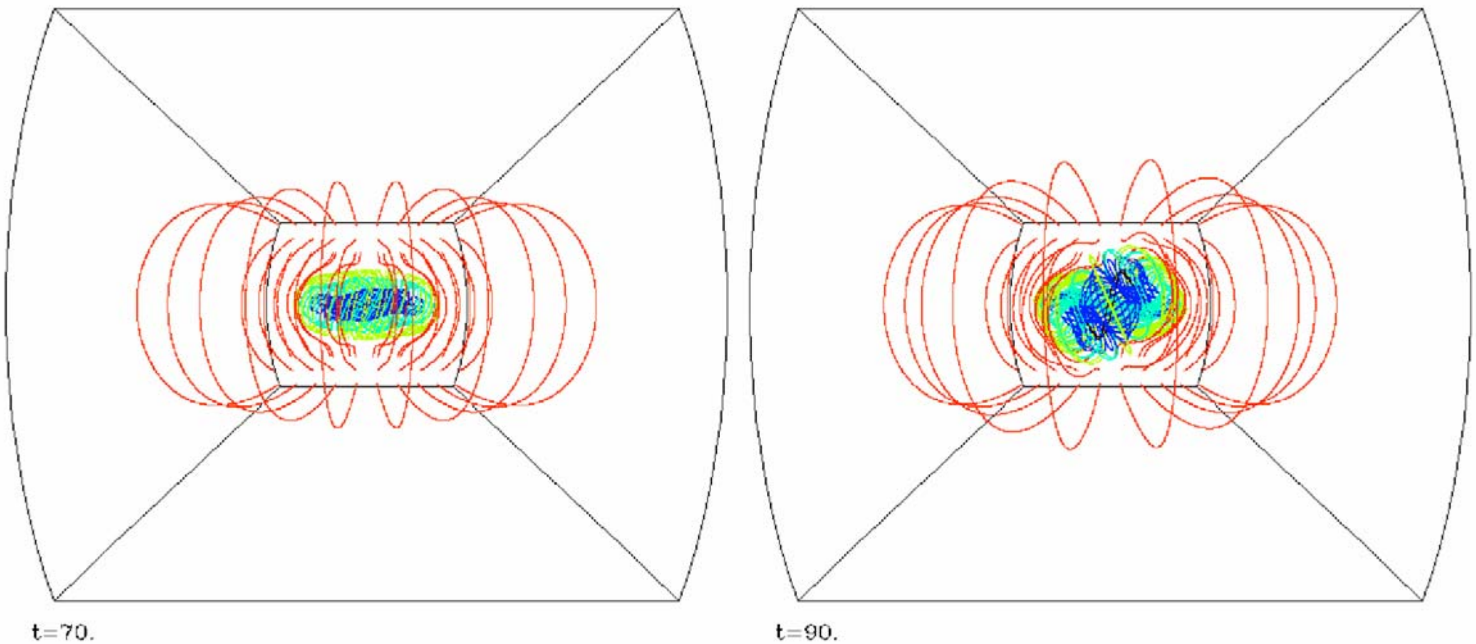
Fan (2005)



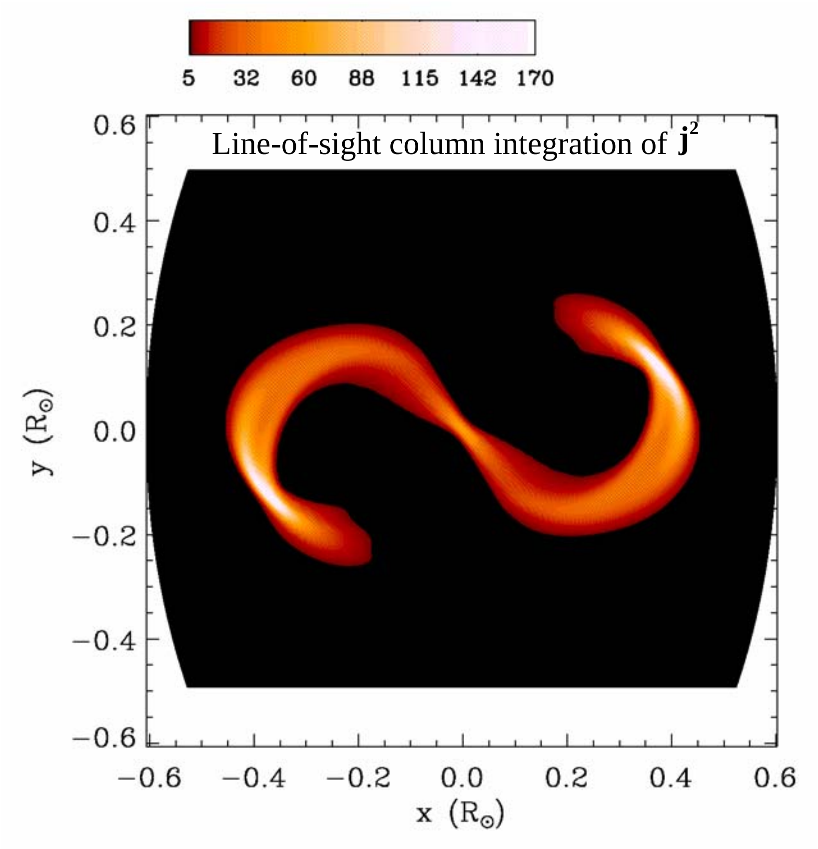
run B: emergence stops at t=83, total twist is about 1.6 winds.



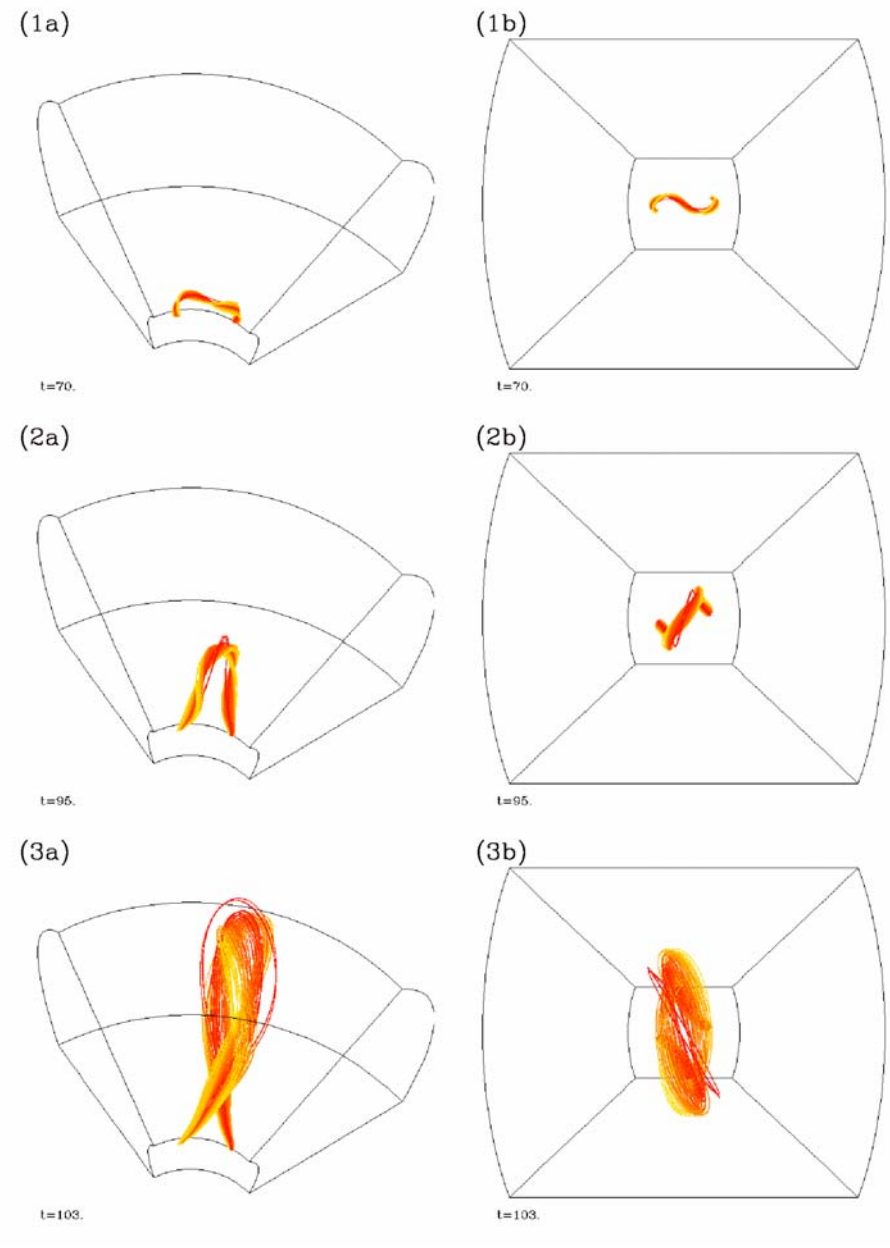
run A: emergence stops at t=96.4, total twist is about 1.88 winds

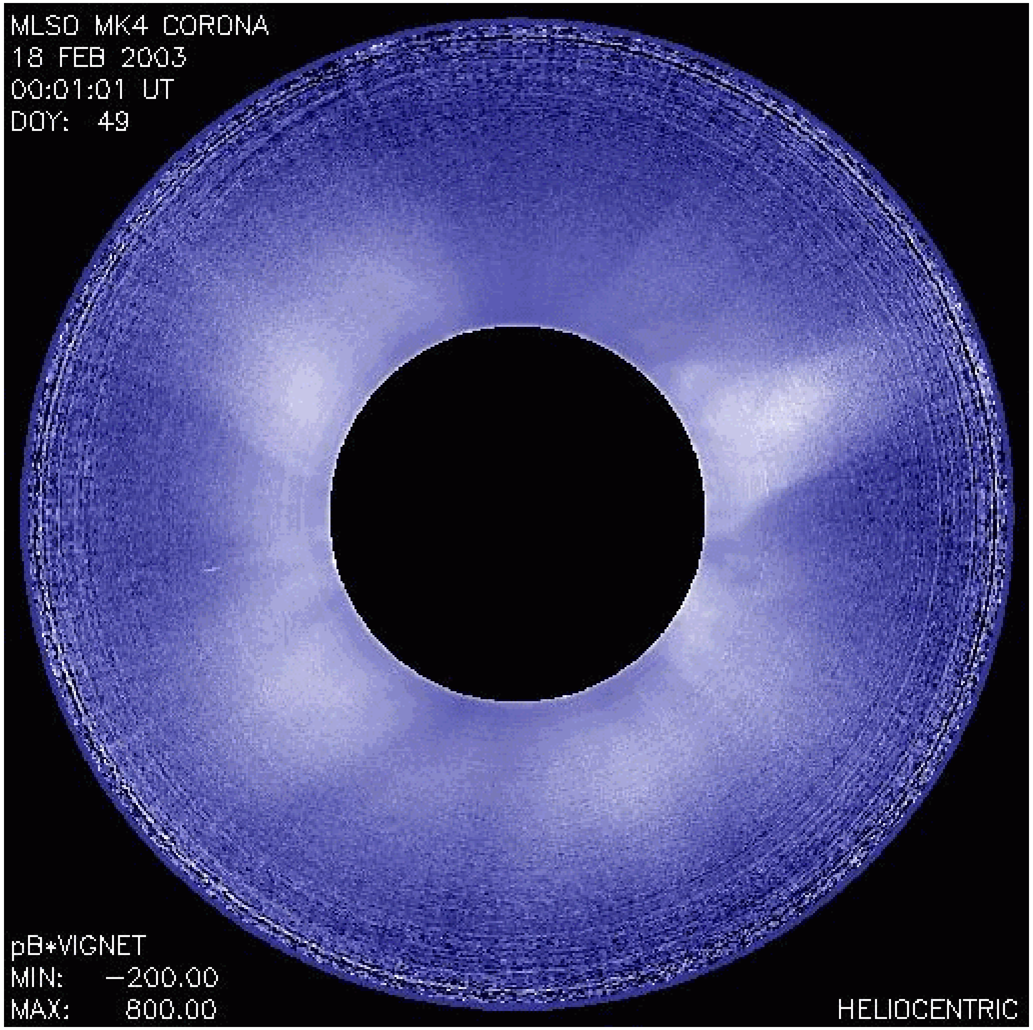

t=70.
t=90.

Formation of sigmoid-shaped current sheet



Prominence evolution




MLSO MK4 CORONA
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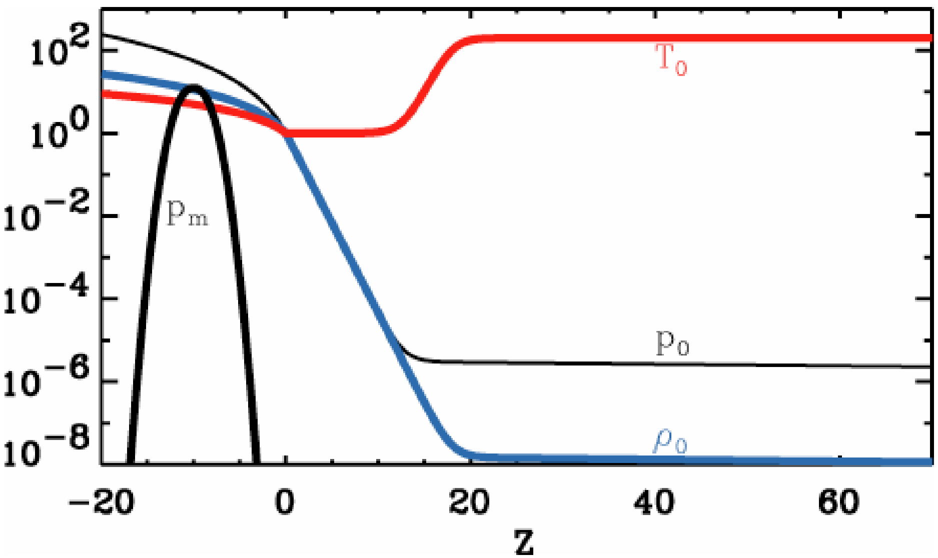
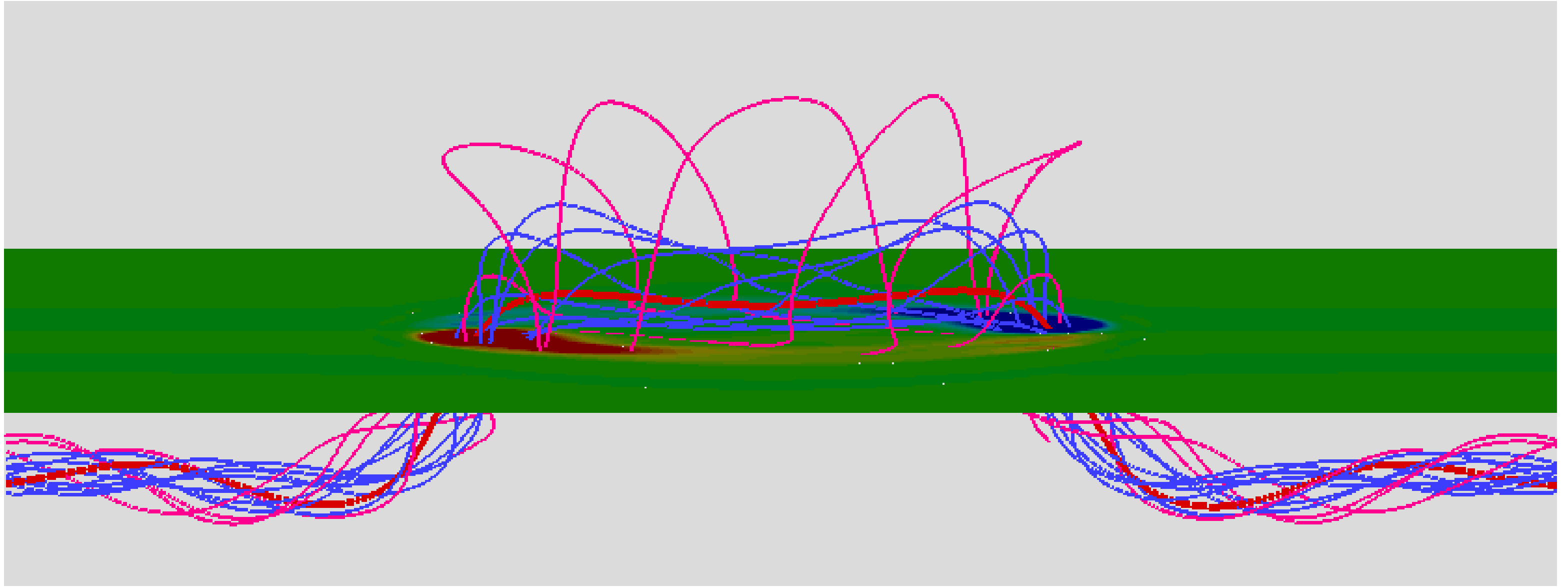
HELIOCENTRIC

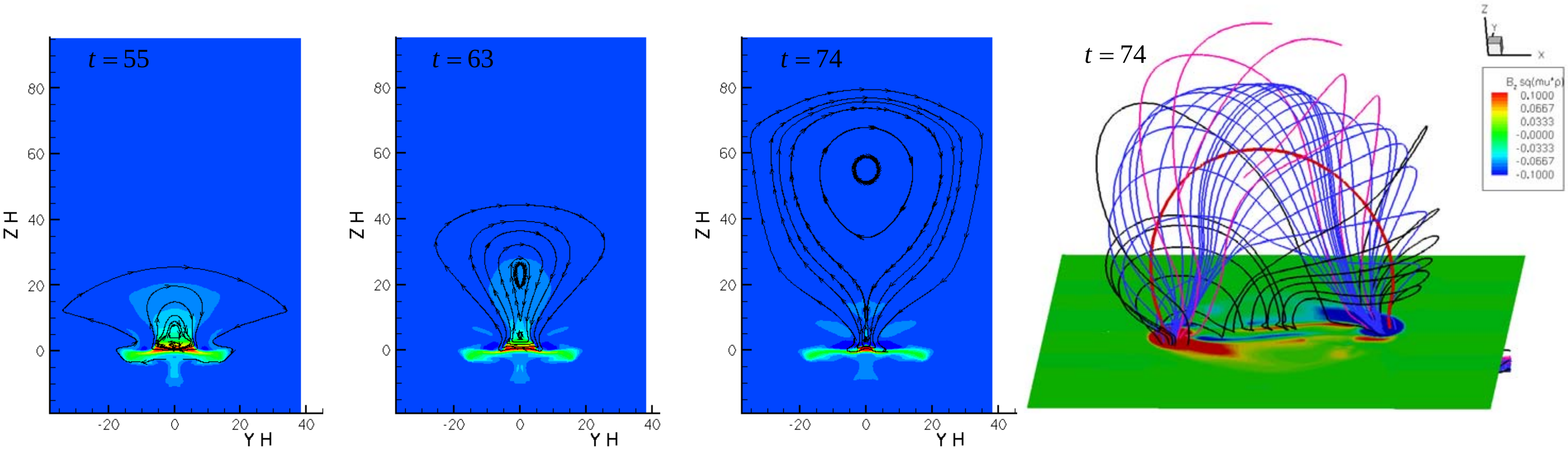
• The Dynamics of Flux Emergence through the Photosphere (e.g. Fan 2001, Magara & Longcope 2001, Magara 2004, Manchester et al. 2004):

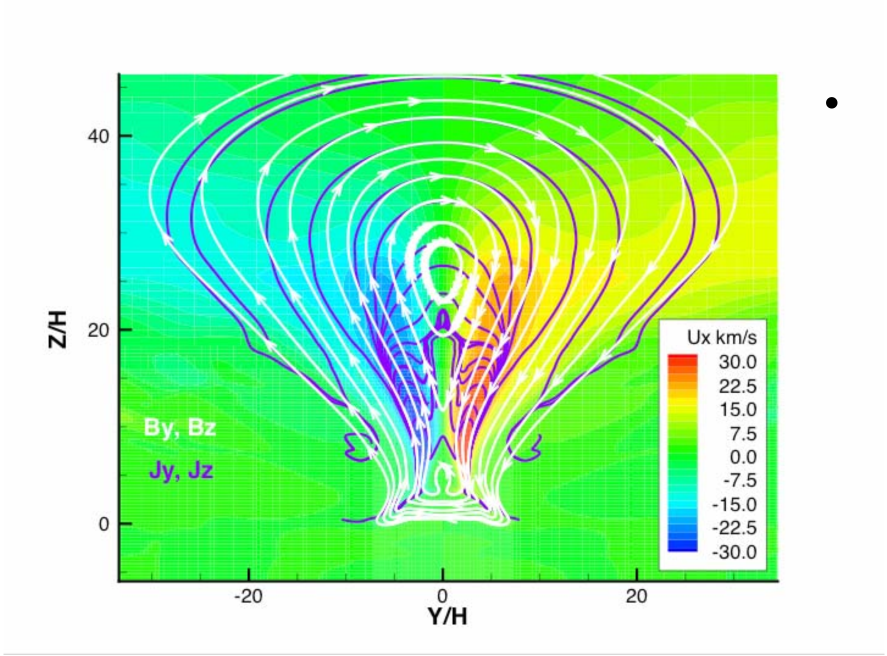


• Manchester et al. 2004, ApJ 610, 588



Manchester et al. (2004, ApJ, 610, 588)

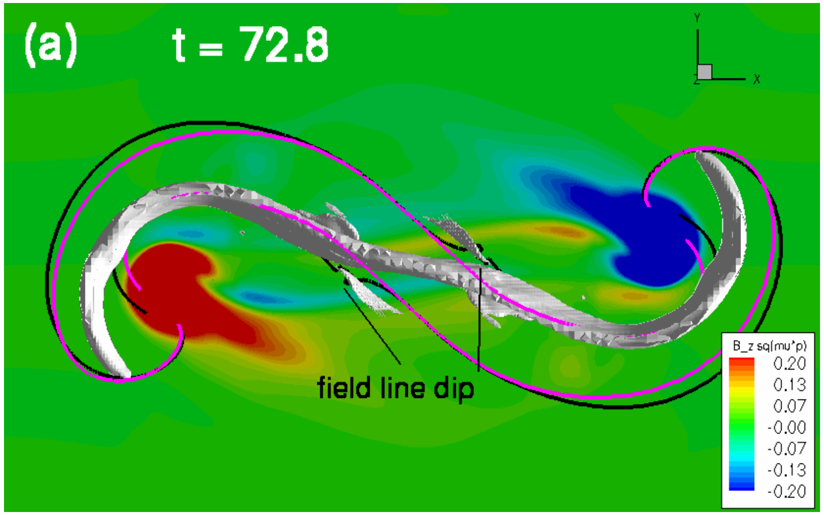


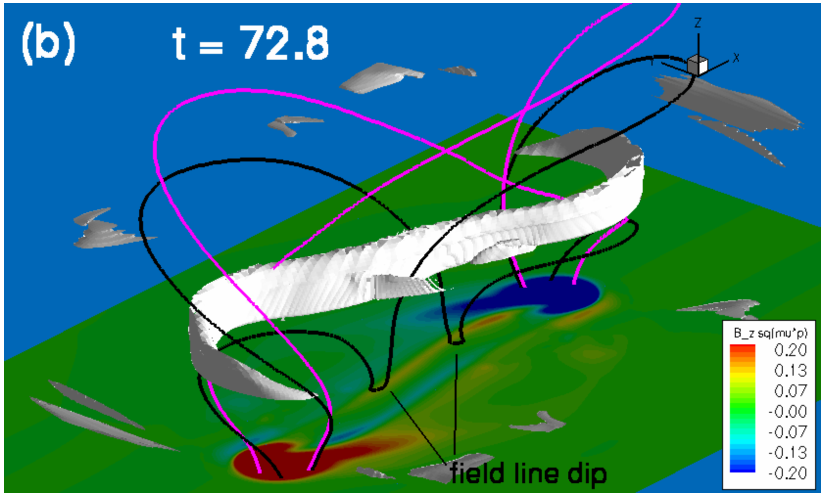


- Shearing motions transport axial flux (Bx) into the expanding portion of the flux rope trying to establish constant Bx along each field line:

$$F_x = (\mathbf{B} \bullet \nabla) B_x$$

Formation of a Sigmoid Current Sheet





Summary and Conclusions

• The emergence of twisted magnetic flux ropes from the interior into the solar corona most likely requires magnetic reconnection near the photosphere. Shearing motion along the polarity inversion line naturally develops for an emerging flux rope due to the magnetic tension force which drives the axial flux upward into the expanding part of the flux rope.

• A current sheet develops along the “bald-patch separatrix surface” of the partially emerged flux rope due to continuing flux emergence or other photospheric perturbations, explaining both the quiescent X-ray sigmoids and also the observed presence of a hot X-ray source at the prominence location within the cavity of a stable long filament.

• Loss of equilibrium and eruption of the flux rope are found for both the 2D axisymmetric flux rope and the 3D line-tied flux rope, when too much twisted magnetic flux is transported into the corona. In the 3D case, with the build-up of a moderate amount of twist (< 2 full winds of field-line twist about the axis), the line-tied flux rope becomes kinked and erupts through the arcade at a localized area with most of the arcade field remaining closed. A sigmoid-shaped current sheet forms below the flux rope during the eruption which may give rise to transient sharpening and brightening of the soft X-ray sigmoid. The eruption of the writhing flux rope also produces prominence field with Λ-shaped and cross-legged morphologies in the core of a CME.