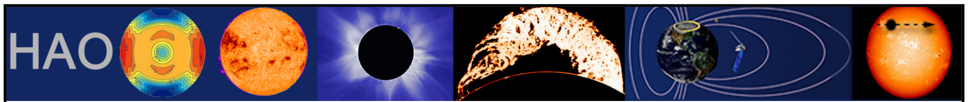

Multi-dimensional Simulations of Emerging Flux Tubes

Yuhong Fan
National Center for Atmospheric Research

High Altitude Observatory (HAO) – National Center for Atmospheric Research (NCAR)
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Jan. 16, 2002

Physical Questions Concerning Flux Emergence

- How does toroidal magnetic flux at the base of the solar convection zone destabilizes and form buoyant flux tubes?
- How do buoyant flux tubes rise in a reasonably cohesive manner through the solar convection zone to the surface?
- How do active region flux tubes emerge into the solar atmosphere?

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Effects of Twist

- Maintaining cohesion of buoyantly rising flux tubes:
  - 2D simulations show a minimum twist needed (e.g. Longcope, Fisher, & Arendt 1996; Moreno-Insertis & Emonet 1996; Emonet & Moreno-Insertis 1998; Fan, Zweibel, & Lantz 1998):

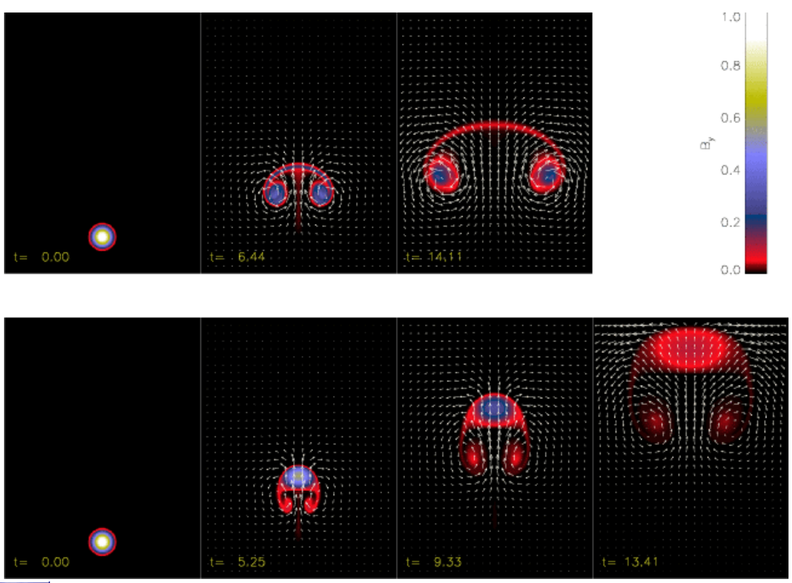
$$V_{A\perp} > V_{rise} \quad , \text{ or } \quad q > (H_p a)^{-1/2}$$

  - 3D arched tubes may require less twist (e.g. Abbett, Fisher, & Fan 2000; Fan 2001)
- Causes a tilt (writhe) of tube axis:
  - Kink unstable if twist is sufficiently high (e.g. Linton et al. 1996):

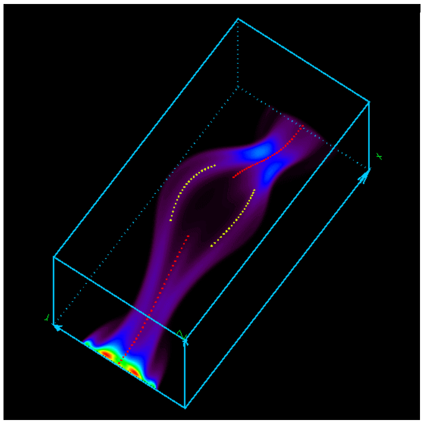
$$q \geq a^{-1}$$

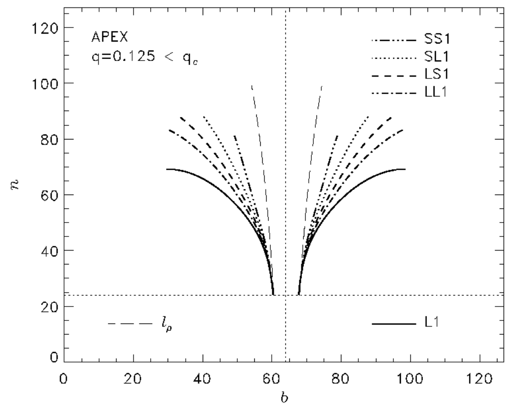
Where $q \equiv B_\theta / rB_z$

Fan, Zweibel & Lantz (1998)

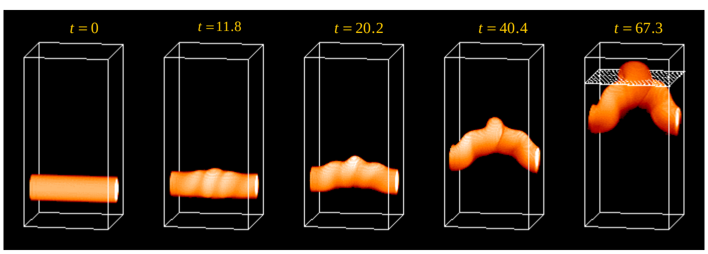


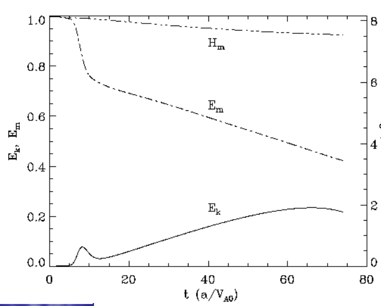
Abbett, Fisher, & Fan (2000)

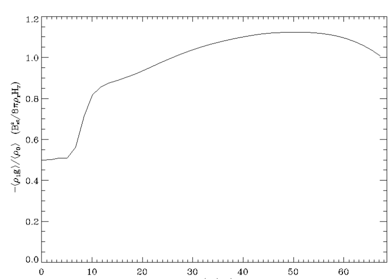


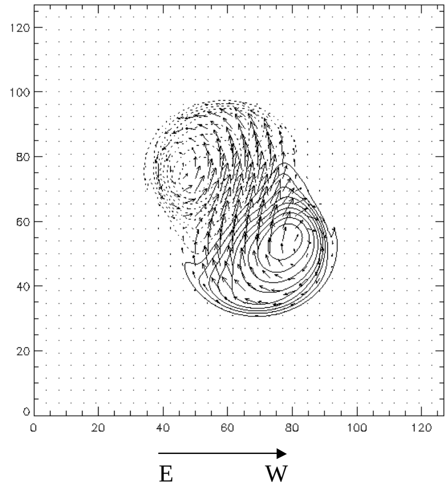


- Rise of kink-unstable tube as a mechanism of delta-spot formation: (Linton et al. 1996, 1998, 1999; Fan et al. 1998, 1999):









Left-handed twist: anti-clockwise rotation

right-handed twist: clockwise rotation

Destabilization of Toroidal Flux at the Base of SCZ

- Magnetic buoyancy instability of a horizontal magnetic field $\vec{B} = B(z)\hat{x}$ embedded in a vertically stratified plasma with constant gravity $-g\hat{z}$ (Newcomb 1961; Hughes & Proctor 1988):
  - Unstable to general 3D modes if:

$$\frac{d\rho}{dz} > -\frac{\rho^2 g}{\gamma\, p} \quad \text{or} \quad \frac{V_a^2}{C_s^2}\frac{d\ln B}{dz} < -\frac{1}{c_p}\frac{ds}{dz}$$

  - Unstable to 2D interchange modes if:

$$\frac{d\rho}{dz} > -\frac{\rho^2 g}{\gamma\, p + B^2/4\pi} \quad \text{or} \quad \frac{V_a^2}{C_s^2}\frac{d}{dz}\left[\ln\left(\frac{B}{\rho}\right)\right] < -\frac{1}{c_p}\frac{ds}{dz}$$

- Simulations of the magnetic buoyancy instability and the formation of buoyant flux tubes:
  - Initial equilibrium magnetic layer that supports a top-heavy density stratification:

    e.g. Cattaneo & Hughes (1988); Cattaneo, Chiueh, & Hughes (1990); Matthews, Hughes, & Proctor (1995);
    - Most unstable modes are the 2D interchange modes.
    - 2D simulations show formation of strong vortices which rapidly destroys the coherence of the buoyant flux tubes and prevent the rise of magnetic flux.
    - 3D simulations show that the flux tubes formed by the initial 2D interchange instability become unstable to 3D motion in the non-linear regime as a result of interaction between vortex tubes → formation of arched tubes.
    - 2D simulations of sheared magnetic layer show formation of twisted tubes which are able to rise cohesively.

Cattaneo & Hughes (1988)

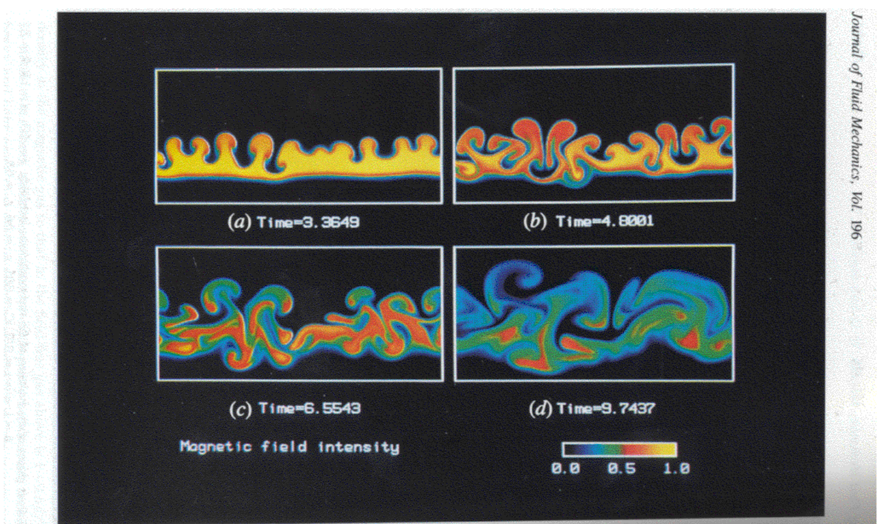
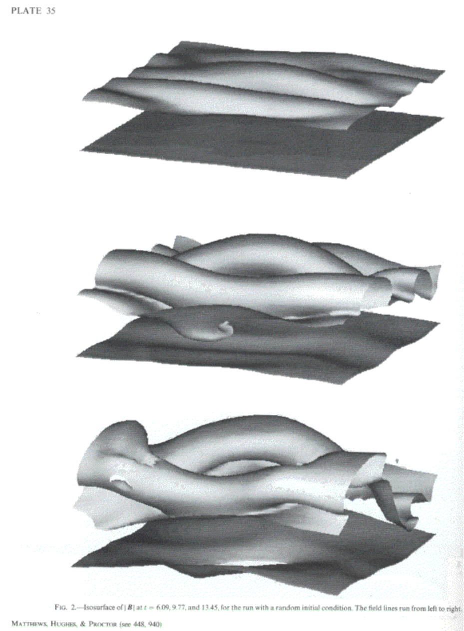


FIGURE 8. Evolution of the magnetic field for the instability started from random initial conditions. $\gamma = 5/3$, $m = 1.6$, $\theta = 2$, $\beta = 1$, $\sigma = 0.1$, $\tau = 0.01$, $C_k = 0.01$, $z_1 = 0.6$, $z_2 = 0.8$.

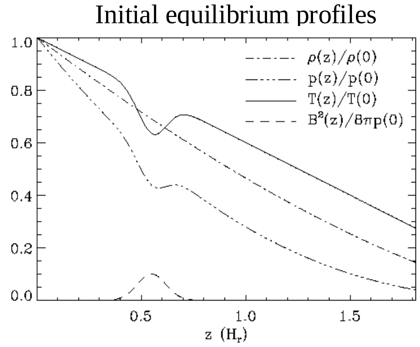
Matthews, Hughes, & Proctor (1995)

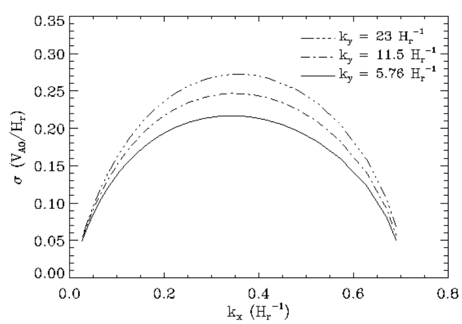


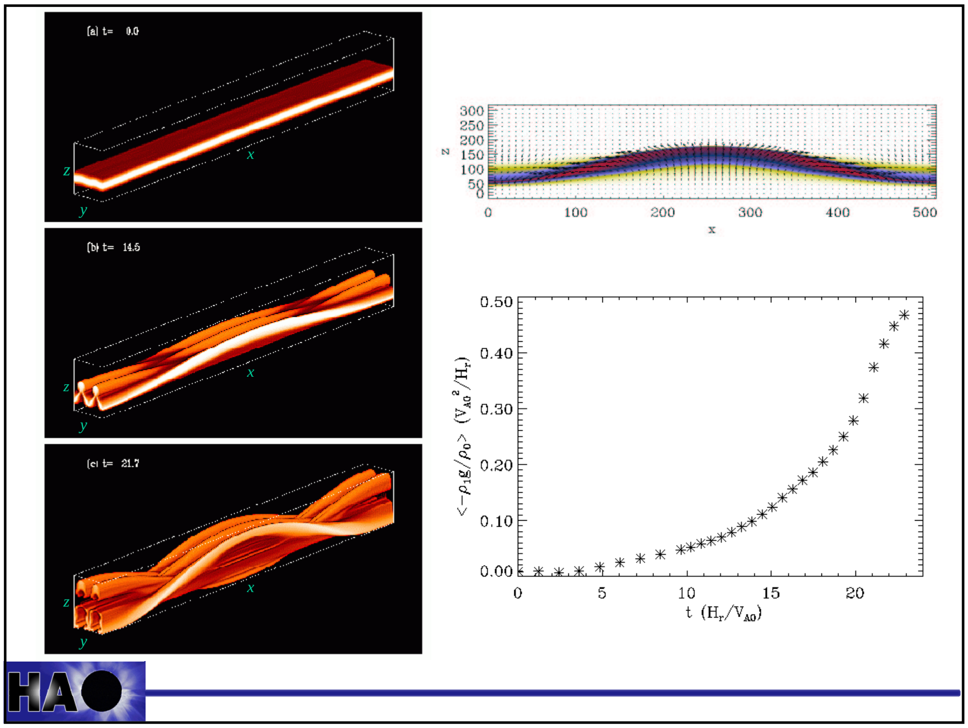
– Simulations of 3D undulatory instability of a neutrally buoyant magnetic layer (Fan 2001):

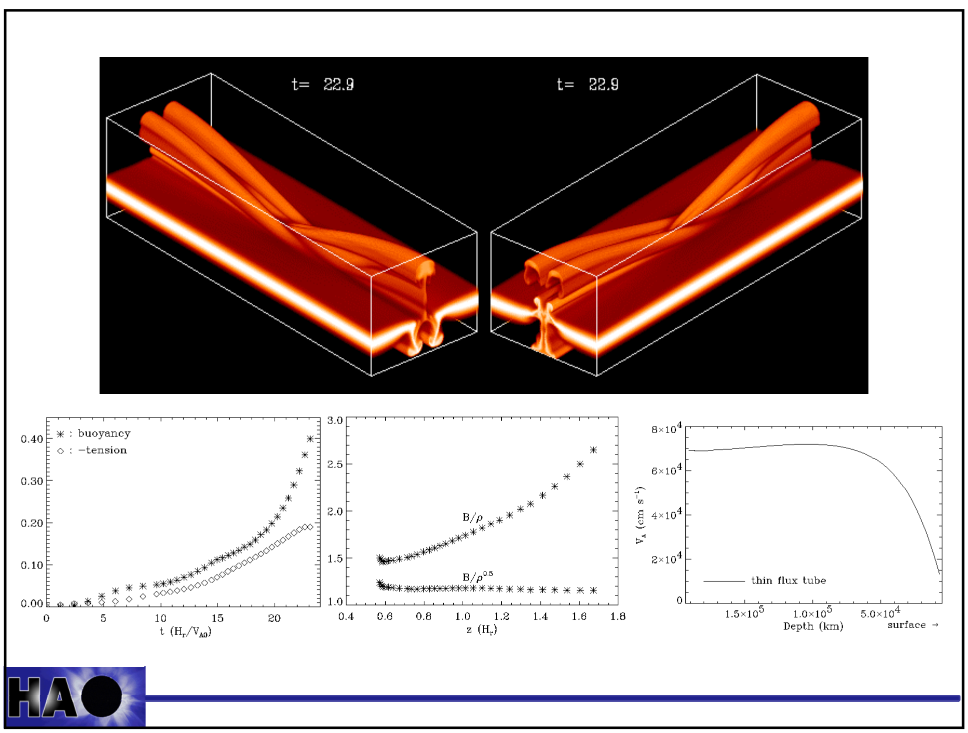
Initial equilibrium is unstable to 3D undulatory modes, but is stable to 2D interchange modes:

Initial equilibrium profiles





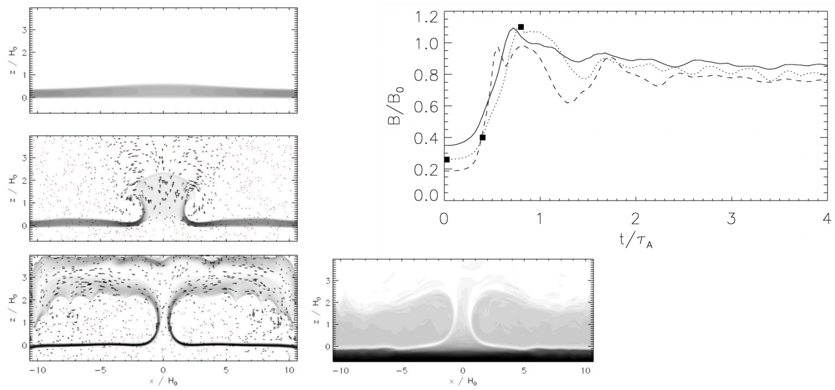

(a) t= 0.0
(b) t= 14.5
(c) t= 21.7
z
x
y
<−ρ1g/ρ0> (VA0^2/Hr)
t (Hr/VA0)
HAO


t= 22.9
t= 22.9
∗ : buoyancy
◇ : −tension
t (Hr/VA0)
B/ρ
B/ρ^0.5
z (Hr)
Vx (cm s^-1)
thin flux tube
Depth (km)
surface →
HAO

Intensification of Magnetic Field by Conversion of Potential Energy

(Rempel & Schuessler 2001)

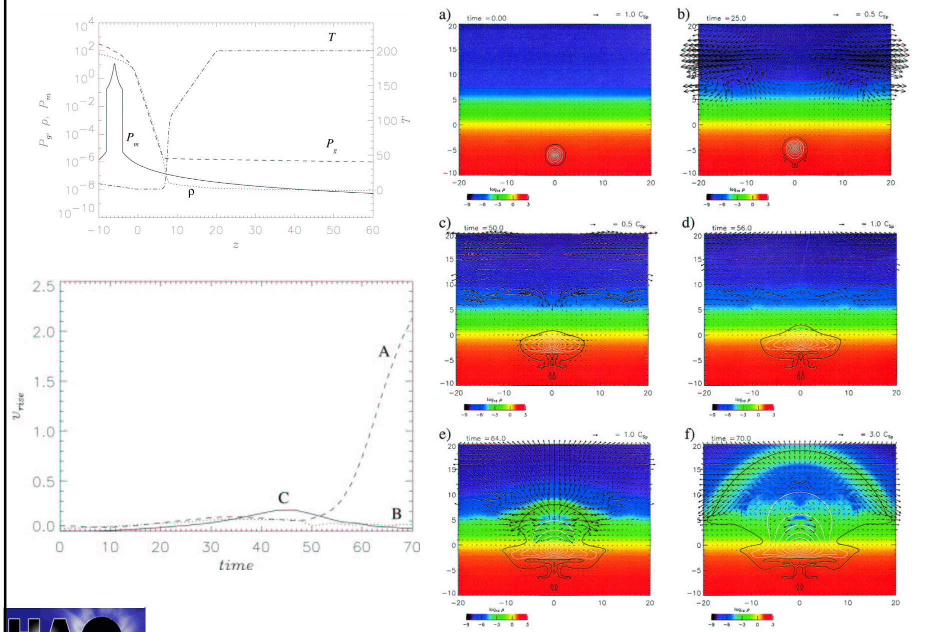
- Weak flux tube rising through the superadiabatically stratified CZ can experience a sudden loss of pressure equilibrium ("explosion") ⟶ intensification of submerged field at base of CZ: $z_{expl} \approx H_p c_p / \beta \, \Delta s$



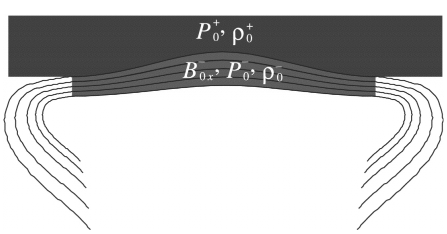
Flux Emergence into the Solar Atmosphere

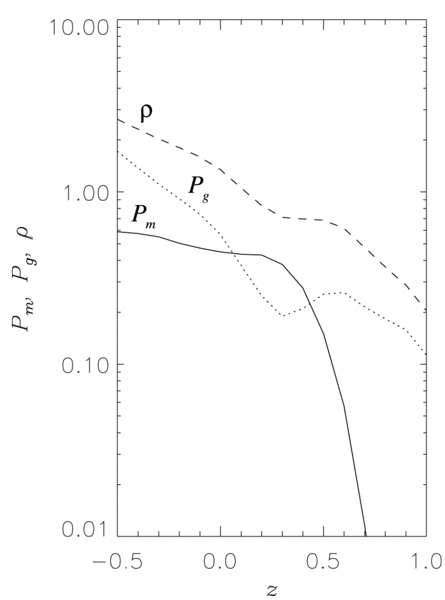
- Magnetic buoyancy instability is a mechanism through which magnetic flux reaching the photosphere can expand dynamically into the stably stratified solar atmosphere:
  e.g. Shibata et al. 1989
- 2D and 3D simulations of flux emergence into the solar atmosphere:
  e.g. Shibata et al. 1989; Nozawa et al. 1992; Matsumoto et al. 1993; 1996; Manchester 2001; Magara 2001; Fan 2001; Magara & Longcope 2001

2D simulations of the emergence of twisted flux tubes (Magara 2001):



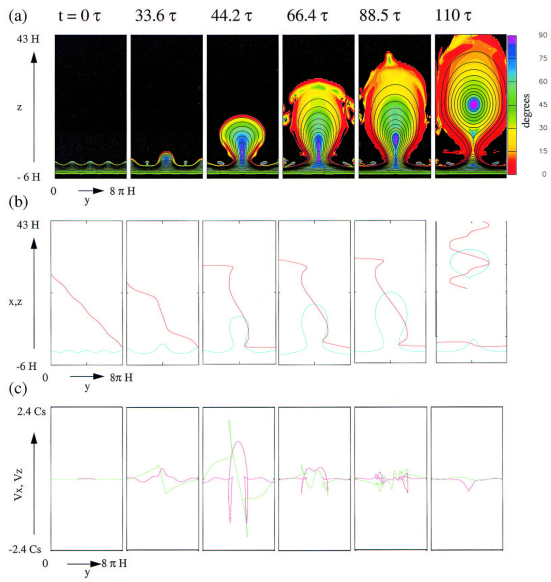
2D simulations of the emergence of twisted flux tubes (Magara 2001)





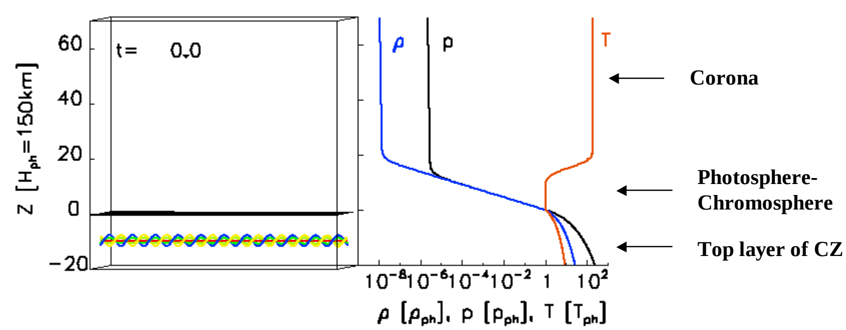
The Role of Nonlinear Alfven Waves in Shear Formation During Solar Magnetic Flux Emergence (Manchester 2001)

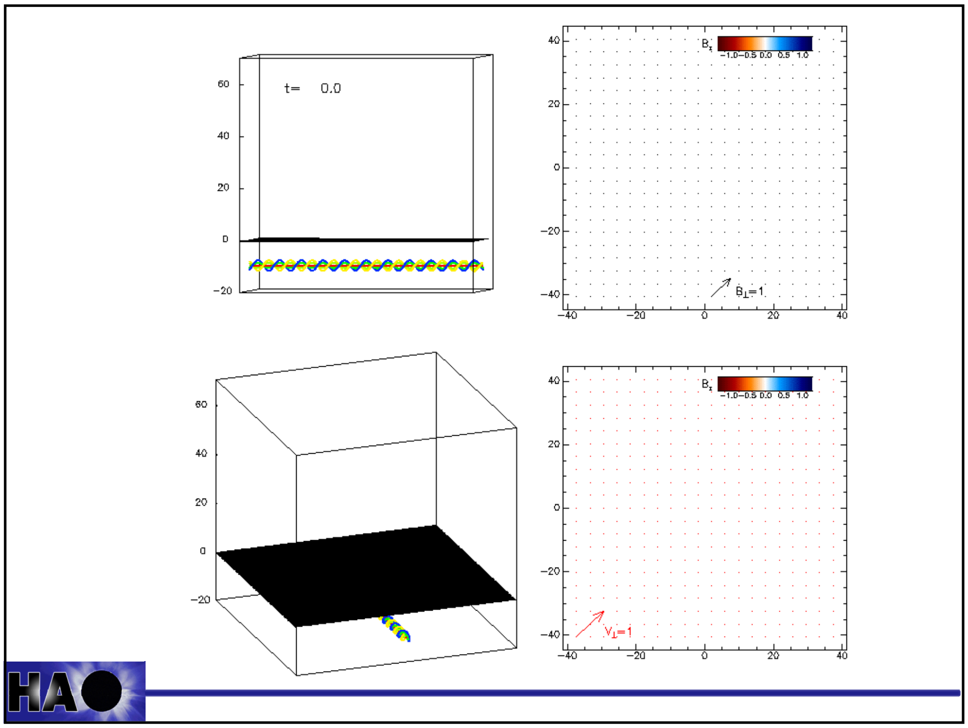
$$F_x = \vec{B} \bullet \nabla B_x$$

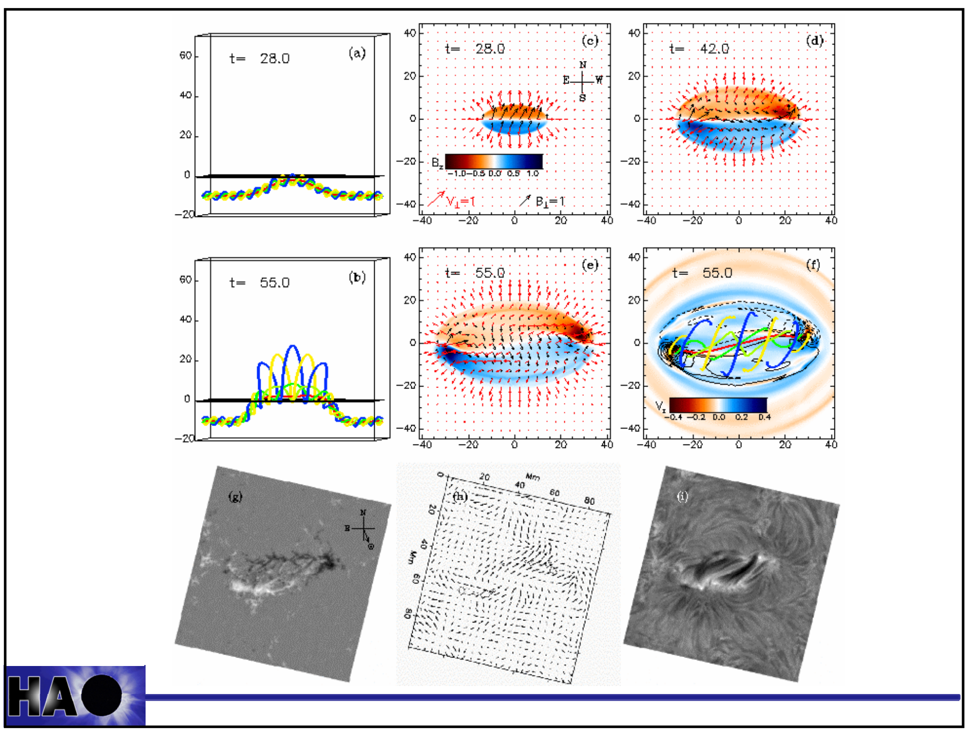


Emergence of a Twisted Ω-Tube (Fan 2001)

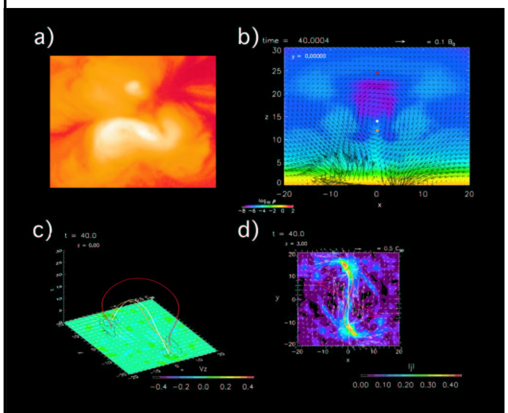
- Ideal MHD simulation using Zeus3D
- Adiabatic evolution, ideal gas with $\gamma = 5/3$

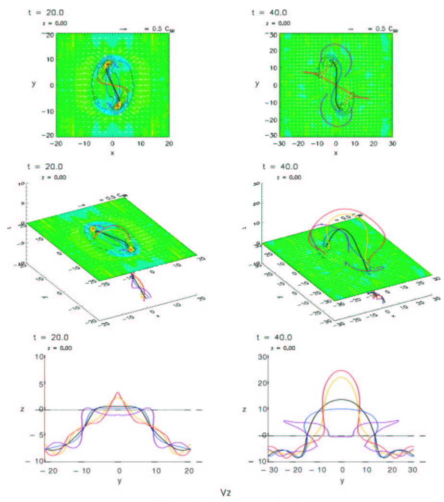



t= 0.0
HAO

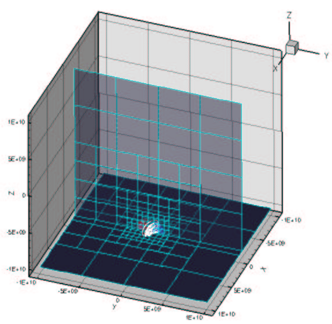

t= 28.0
(a)
t= 55.0
(b)
(c)
t= 42.0
(d)
(e)
(f)
(g)
(h)
(i)
HAO

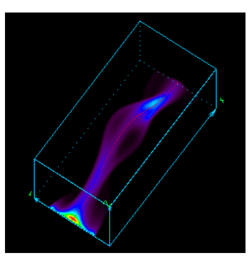
Sigmoid Structure of an Emerging Flux Tube (Magara & Longcope 2001)

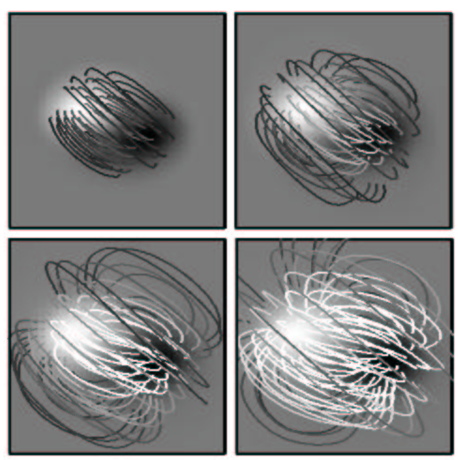




Flux emergence into the atmosphere driven by interior calculation of rising flux tube (Abbett & Fisher 2001)







Future Works

- Subsurface evolution:
  - Spherical geometry
  - Origin of twisted flux tubes
  - Effects of Coriolis force
  - Effects of Convection
- Flux Emergence into the solar atmosphere
  - Energy equation

    Photosphere-Chormosphere: thermal relaxation $\tau_R < \tau_{emg}$

    Heating mechanisms?
  - Interaction with pre-existing coronal field
  - Coupling to interior calculations of rising flux tubes