Magnetic flux emergence in the photosphere of the Sun

M. Cheung[☼]
F. Kneer[♠]
M. Schüssler[☼] & F. Moreno-Insertis[♦]

☼ Max-Planck-Institut für Sonnensystemforschung, Katlenburg-Lindau, Germany
♠ Institut für Astrophysik, Göttingen, Germany
♦ Instituto de Astrofísica de Canarias, La Laguna (Tenerife), Spain.

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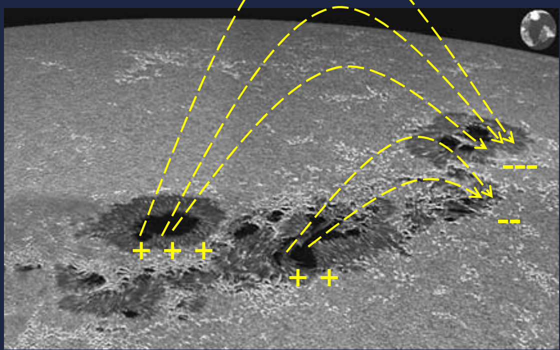
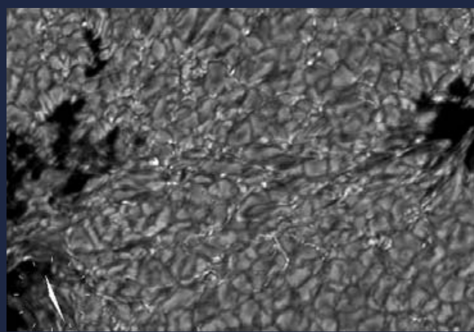
Active regions and sunspots



430 nm (*G*-band) image of a sunspot group (Dutch Open Telescope)

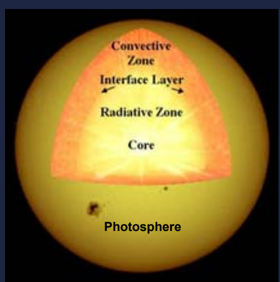
An emerging flux region



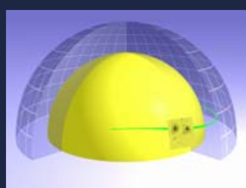
80-min speckle-reconstructed *G*-band movie of AR 8737 (Dutch Open Telescope). Area: 51 × 35 arcsec^2

Where do they come from? And how?

- To understand solar magnetism, we need to look at:
  – the origin of magnetic fields in the Sun AND
  – how they are transported to the surface
- Dynamo theory
  – Addresses first topic
- Sunspot groups are bipolar
  => flux emerges in bundles (magnetic flux tubes).

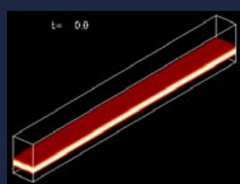


Developments so far…



- Simulations of buoyant toroidal flux tubes are able to reproduce:
  – Latitude range of flux emergence
  – Tilt angles of active regions
  – Asymmetry in morphology between the leading and following polarities of active regions. (Caligari et al, 1995, 1998)

- Non-linear development of Parker's undulatory instability in a magnetic flux sheet => formation of arched flux tubes. (Fan 2001, ApJ, 546, 509)



Simulation of flux emergence at the photosphere

- Essential physics for photospheric flux emergence:
  - Fully-compressible MHD in 3D
  - Energy exchange via radiative transfer in Local Thermodynamic Equilibrium (LTE)
  - Effects of partial ionization in Equation Of State (EOS)
  - Open boundary condition(s)
- MPS/University of Chicago Radiative MHD (MURaM) code (Vögler et al 2005)

MURaM code - MHD Equations

- Continuity equation

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

- Momentum equation

$$\frac{\partial\rho\mathbf{u}}{\partial t} + \nabla\cdot\left(\rho\mathbf{u}\mathbf{u} + \left(p + \frac{|\mathbf{B}|^2}{8\pi}\right)\mathbf{1} - \frac{\mathbf{B}\mathbf{B}}{4\pi}\right) = \rho\mathbf{g} + \nabla\cdot\underline{\tau}$$

- Equation of state

- Energy equation

$$\frac{\partial e}{\partial t} + \nabla\cdot\left[\mathbf{v}\left(e + p + \frac{|\mathbf{B}|^2}{8\pi}\right) - \frac{1}{4\pi}\mathbf{B}(\mathbf{v}\cdot\mathbf{B})\right] = \frac{1}{4\pi}\nabla\cdot(\mathbf{B}\times\eta\nabla\times\mathbf{B}) + \nabla\cdot(\mathbf{v}\cdot\underline{\tau}) + \nabla\cdot(K\nabla T) + \rho(\mathbf{g}\cdot\mathbf{v}) + Q_{rad}$$

- Radiative Transfer Equation

$$\frac{dI_\nu}{ds} = -\kappa_\nu\rho(I_\nu - S_\nu)$$

$$Q_{rad} = -\nabla\cdot\mathbf{F} = 4\pi\rho\int\kappa_\nu(J_\nu - S_\nu)d\nu$$

- Induction equation

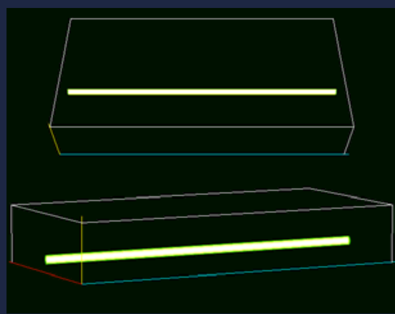
$$\frac{\partial\mathbf{B}}{\partial t} + \nabla\cdot(\mathbf{u}\mathbf{B} - \mathbf{B}\mathbf{u}) = -\nabla\times(\eta\nabla\times\mathbf{B})$$

MURaM model of solar convection

- Size of simulation domain: 12,000 km by 1,400 km by 6,000 km
  - 576 by 100 by 288 gridpoints (grid-spacing 21 by 14 by 21 km)
- Optical depth unity located ~ 800 km above bottom boundary
- 'Open' bottom boundary
- Periodic side boundaries
- Compressibility => asymmetry between upflows (broad + gentle) and downflows (narrow + strong)

Right: Volume rendering of temperature in the numerical model.

Case study: small flux tube

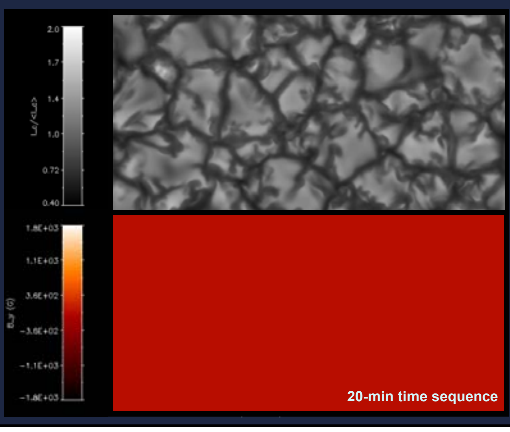


Snapshots of |B| at 4-minute intervals

Initial flux tube properties:

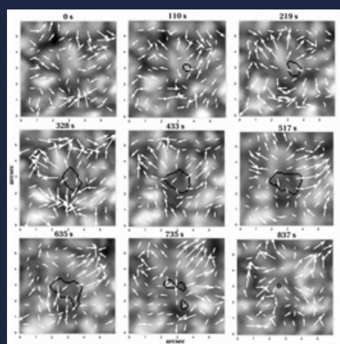
- Longitudinal flux $\Phi = 10^{18}$ Mx
- B_0 = 3500 G
- Internal plasma β =1
- Twisted, B_θ/B_l = 0.5 at r =120 km
- Specific entropy s = value at base of solar convection zone

At the photosphere

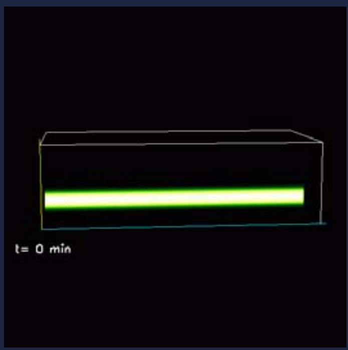


Observations of small-scale flux emergence

- De Pontieu (ApJ, 569:474-486, 2002)
  - Flux emergence at scales < 1 '' (300 km on solar surface).
  - Emergence sites of flux tubes with flux of 5×10^{17} Mx coincident with upflows.
  - Emerged flux buffeted by surrounding granulation, subsequently transported to the intergranular lanes, timescale ~ 5 – 10 minutes.



Bigger tube

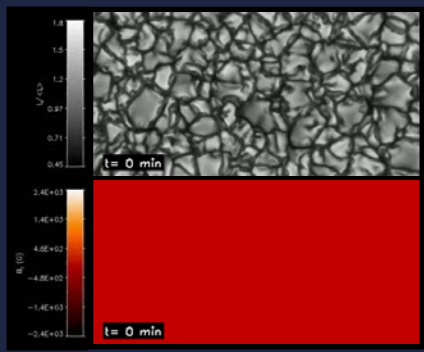


Size of domain:
24,000 by 2,300 by 12,000 km^3

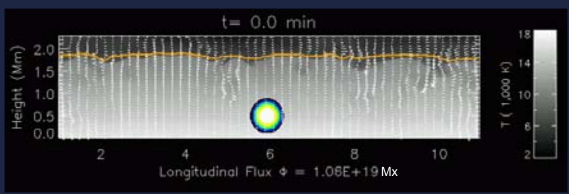
Initial flux tube properties:

- Longitudinal flux Φ = 10^{19} Mx
- B_0 = 8500 G
- Internal plasma β =1
- Twisted, B_θ/B_l = 0.5 at r =200 km
- Specific entropy s = value at base of solar convection zone

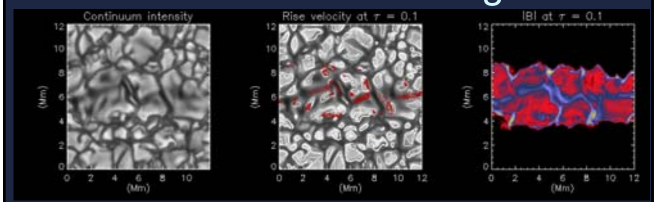
At the photosphere



Cross-sectional view



Transient darkening



- Left: continuum intensity at t=14.6 min
- Middle: white contours (upflow velocities 0.5,1 km/s), red contours (magnetic regions, upflow velocities 0.5, 1 km/s)
- Right: Distribution of magnetic field strength
- This effect has been observed by Strous & Zwaan (1999) and De Pontieu (2002).

Summary

- Summary
  - For flux emergence at the photosphere, need 3D radiative MHD simulations.
  - Results highlight the importance of magneto-convection.
  - ‘Anomalous’ transient dark lane coincident with an upflow is associated with emerged, cooled magnetic material.
- See also
  - Poster S6 by Lotfi Yelles Chaouche, titled “Stokes diagnostics of a simulated flux tube emergence”