Flux Emergence

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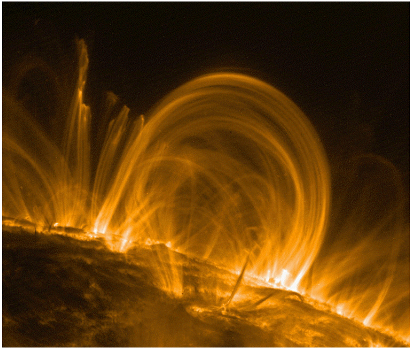
3 March 2010



Thanks to Michelle Murray, Vasilis Archontis and David MacTaggart.

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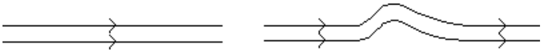
- Simulations of emergence to corona.
- Interaction with coronal magnetic field.
- Magnetic Breakout.
- Conclusions.

Buoyancy

Buoyancy of a magnetic field is the reason large flux tubes rise to photosphere. Sunspots from as field breaks through the photosphere and emerges.



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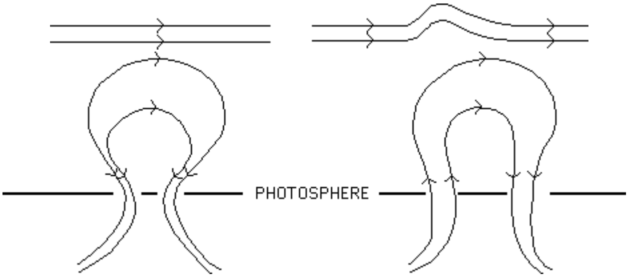

Figure: Formation of sunspots.

Buoyancy Instability

First, consider a stratified, unmagnetised atmosphere, satisfying

$$\begin{aligned} \frac{dp}{dz} &= -\rho g, \\ p &= \frac{\rho R T}{\tilde{\mu}}, \\ T &= T_0(1 - mz). \end{aligned}$$

The linear temperature profile unstable to buoyancy instability that may develop into convection. Assume *no dissipation*. Use simple physical argument for instability conditions.

Consider a small fluid element, as shown in Figure 2. Imagine that this fluid element is lifted up a distance dz.

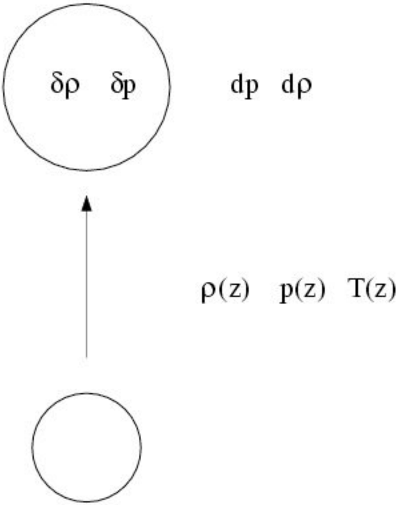

Figure: Physical explanation of the buoyancy instability.

- Surrounding plasma has pressure change of dp, where

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- Fluid element initially has higher pressure than the surrounding plasma and so expands until

$$\delta p = dp.$$

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- Instability if

$$\delta\rho < d\rho = \frac{d\rho}{dz}dz,$$

or

$$-\frac{\rho g}{c_s^2} < \frac{d\rho}{dz}.$$

This can be written in a variety of different ways.

- For example, defining *density scale height* $H = -\frac{\rho}{d\rho/dz}$, buoyancy instability if

$$\frac{1}{H} - \frac{g}{c_s^2} < 0.$$

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- Multiply this by g, gives units of frequency squared. Define the Brünt-Vaïsïla frequency, N, as

$$N^2 = g\left(\frac{1}{H} - \frac{g}{c_s^2}\right), \tag{1}$$

- Plasma is unstable to buoyancy if

$$N^2 < 0.$$

- Another equivalent form for the Brünt-Vaïsïla frequency is

$$\boxed{N^2 = \frac{g}{\gamma}\frac{d}{dz}\left[\log\left(\frac{p}{\rho^\gamma}\right)\right].}$$

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  Remember that the temperature gradient is negative.
- Instability occurs when the temperature gradient (negative) is sufficiently large and exceeds the adiabatic temperature gradient, $(dT/dz)_{ad}$, (entropy of the equilibrium is constant).

Magnetic buoyancy instability

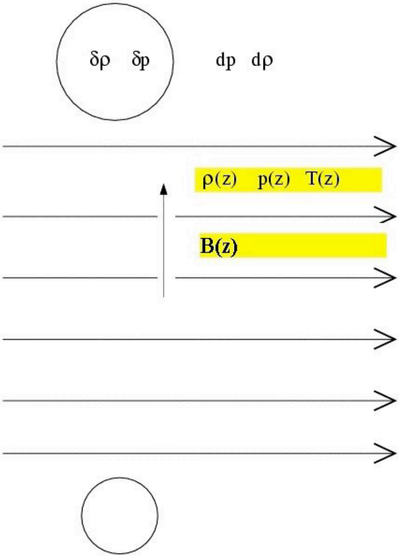

Figure: Physical explanation for the magnetic buoyancy instability.

- Include a horizontal magnetic field $(B(z), 0, 0)$ as well as $p(z)$ and $\rho(z)$.
- The perturbations

$$f(z)e^{i(kx+ly-\omega t)}.$$

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- External atmosphere changes by $dp = (dp/dz)dz$, BdB/mu and $d\rho$.
- Fluid element changes by δp, $B\delta B/\mu$ and $\delta\rho$.
- There will be an instability if $\delta\rho < d\rho$.

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Using our expressions for δp and δB in terms of $\delta \rho$, we have

$$\left(c_s^2 + c_A^2\right) \delta \rho = dp + \frac{B}{\mu} dB,$$

and for an instability this must be less than $(c_s^2 + c_A^2) d\rho$.

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- Note that the plasma can be unstable with a magnetic field even when the square of the Brünt-Vaïsïla frequency is positive.

Dispersion Relation

- If $l \to \infty$, a local dispersion relation can be obtained from the linearised MHD equations.

$$\begin{aligned} \left(c_s^2 + c_A^2\right)\omega^4 \quad - \\ \left[\left(c_A^4 + 2c_s^2 c_A^2\right)k^2 + c_A^2 g \frac{d}{dz}\log\left(\frac{B}{\rho}\right) + c_s^2 N^2\right]\omega^2 \\ +k^2 c_A^2\left[k^2 c_s^2 + g\frac{d}{dz}\log B + \frac{c_s^2}{c_A^2}N^2\right] = 0 \qquad . \end{aligned}$$

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- Instability occurs if $\omega^2 < 0$.
- If $k = 0$, this reduces to the same condition derived in (2).
- This is called the *magnetic buoyancy* instability.

Parker Instability

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- However, dense plasma (lifted up by perturbation) can drain along field.
- Instability, called the *Parker* instability (or *undular* mode).
- From the general solution for ω^2, the plasma is unstable if

$$\boxed{k^2 c_s^2 + g \frac{d}{dz} \log B + \frac{c_s^2}{c_A^2} N^2 < 0.} \tag{3}$$

Conditions for emergence

Acheson (1979) derived the more general expression.

$$\boxed{-H_p \frac{\partial}{\partial z}(\log B) > -\frac{\gamma}{2}\,\beta\delta + \tilde{k_\parallel}^2 \left(1 + \frac{\tilde{k_\perp}^2}{\tilde{k_z}^2}\right)\ ,} \tag{4}$$

with $\delta = -0.4$ the superadiabatic excess, $\delta = \nabla - \nabla_{ad}$, ∇ the logarithmic temperature gradient and ∇_{ad} its adiabatic value, and $\tilde{k_\parallel}, \tilde{k_\perp}$ the horizontal wavenumbers.

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Key term is β. Need $\beta \approx 1$ for emergence!

Not so simple!

To get to photosphere and emerge cylindrical tube requires twist (Emonet and Moreno-Insertis).

(b2cont2.mpg)

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- Evidence of twist?

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3. 3D toroidal loop - axis can emerge.

Michelle Murray

1. 3D cylinders
2. Parameter study.

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3. Form ‘complex’ field with two cylinders interacting in interior.

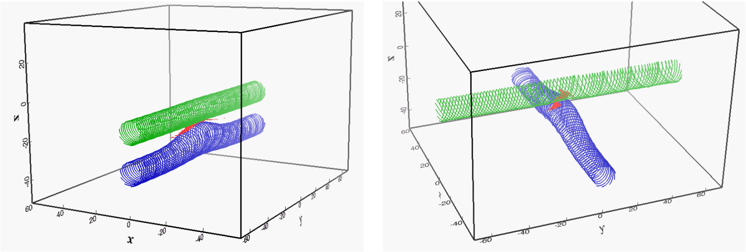

Figure: Two tubes interacting in the interior before emerging.

Complex field with two cylinders

(Fig7.9.mpg)

Complex field with two cylinders

(Fig7.11.mpg)

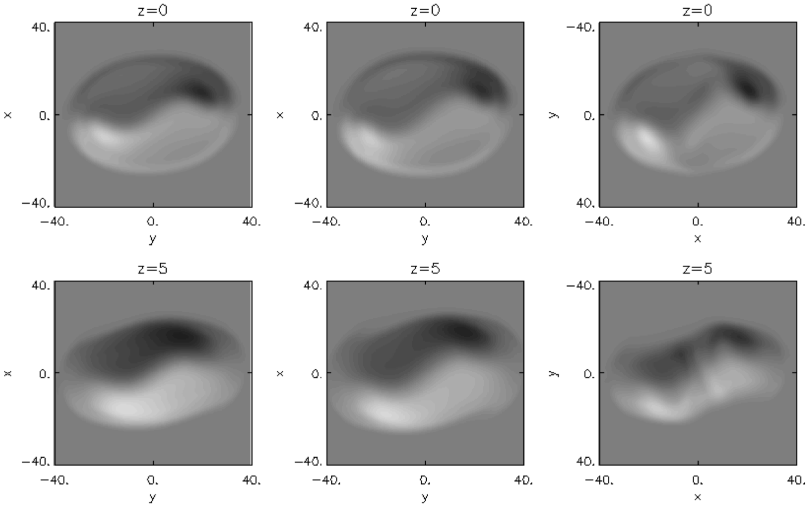

Figure: Photospheric magnetograms. Can't tell the difference!

Cylinder Initial State

- Cylinder - too flat, too close to surface?
- Sunspots not round.

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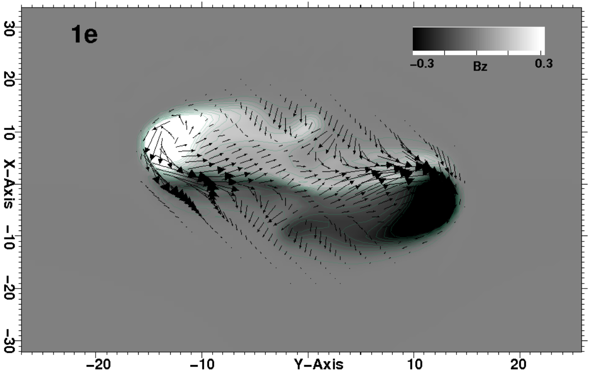

Figure: ‘Tails’ shape depends on twist.

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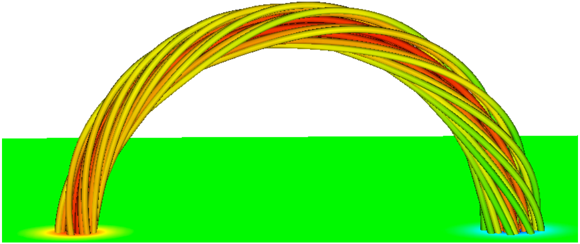

Figure: Initial toroidal field. *No dip*.

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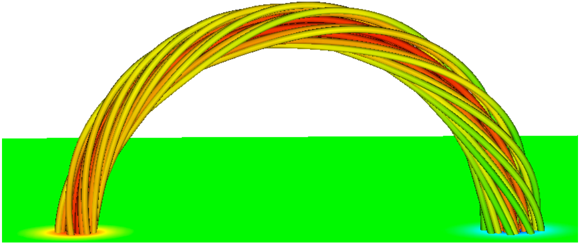

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- Axis of toroidal loop emerges.
- Sunspot rounder!

Emergence and Sunspot Rotation

Toroidal loop beneath the photosphere.

(B9db4.mpg)

Sunspot Formation

Is it a simple tube?

(hinodesotemergingtrilobite.mov)

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- David – eruptions. Toroidal loop plus uniform coronal field. Several ejections!

Toroidal loops - eruptions (David MacTaggart)

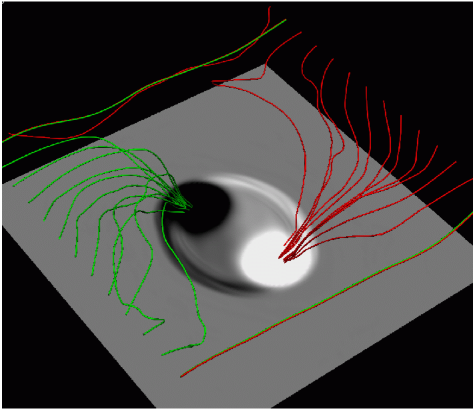

Figure: Emerging field reconnects with corona.

Toroidal loops - eruptions (David MacTaggart)

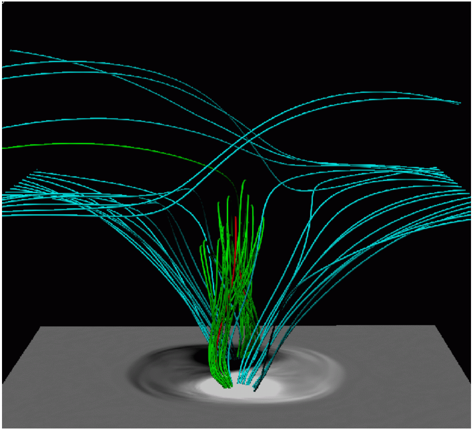

Figure: Newly formed flux rope.

If overlying field 'removed' then flux rope erupts.

Eruption

Movie showing a toroidal loop emerging and the density ejected into the atmosphere.

(Toroidal.mpg)

Solar phenomena and flux emergence

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- Either ‘failed’ or full ejection.

CMEs - Breakout Model

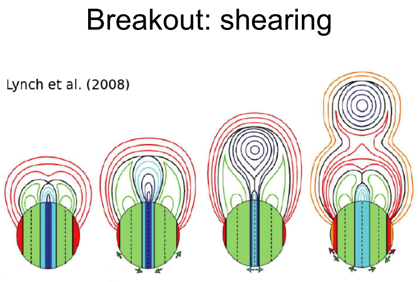

Figure: Breakout model of CME. Needs large scale imposed shearing.

See also Zuccarello et al 2008.

CMEs - Magnetic Breakout (David MacTaggart)

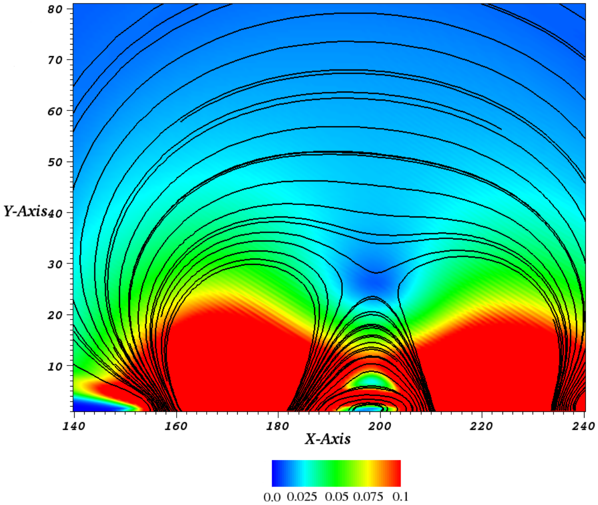

Figure: Two regions of emergence for breakout configuration.

CMEs - Magnetic Breakout

Contours of the magnitude of $\mathbf{B}$.

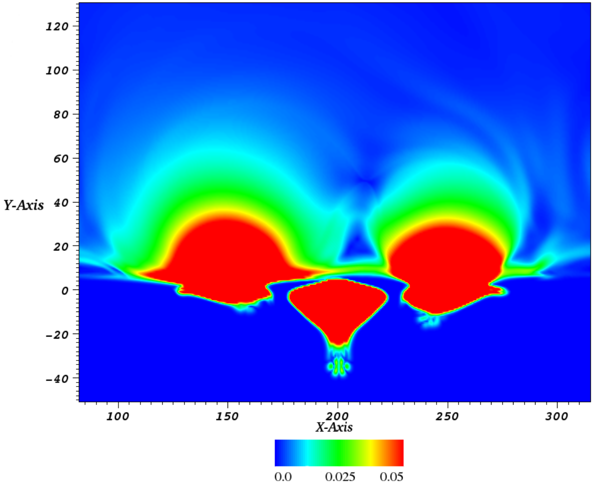

Figure: Third emergence in the middle.

CMEs - Magnetic Breakout

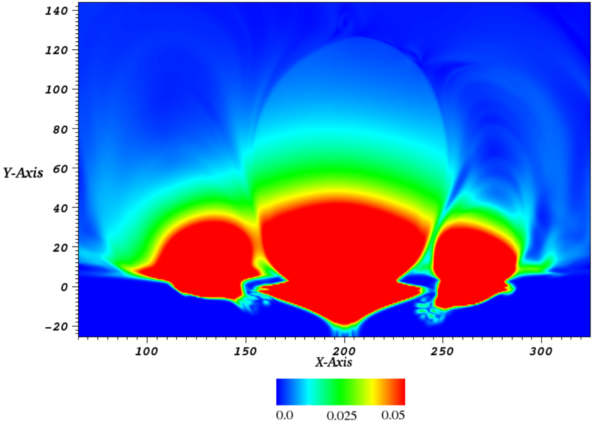

Figure: Middle emergence pushes other fields apart.

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- Lots of problems still to do!!