Numerical modelling of flux emergence in the solar atmosphere:

Effects of partial ionisation

J.E. Leake, T.D. Arber

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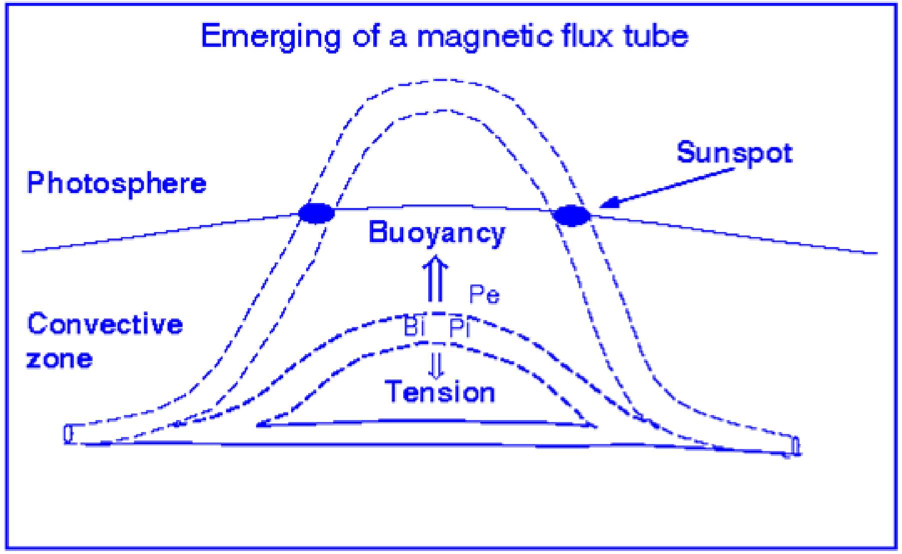
THE UNIVERSITY OF WARWICK

What is flux emergence?

- Origins of coronal magnetic field in solar interior
- Large scale toroidal field
- Instabilities - Flux tubes – buoyant in CZ
- Expansion of field through atmosphere

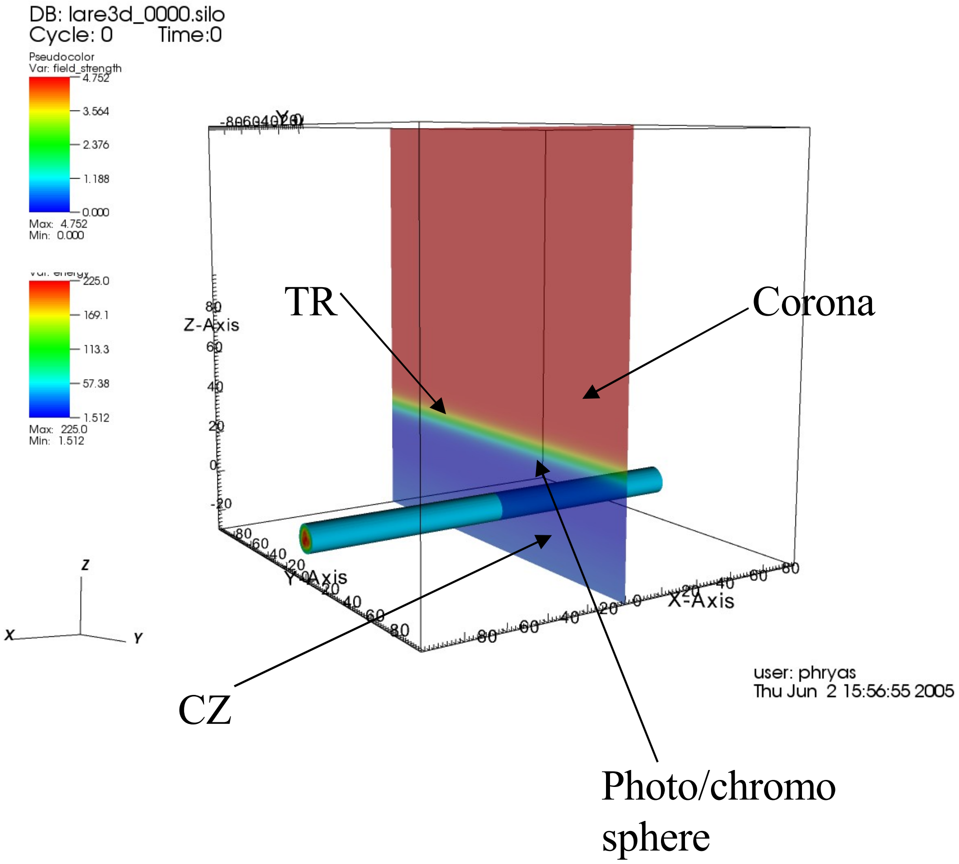


Modelling flux emergence

- Model Solar atmosphere – add buoyant flux tube
- MHD (fully ionised plasma)
- CZ – β >1 non-force-free
- Corona – β << 1 force-free

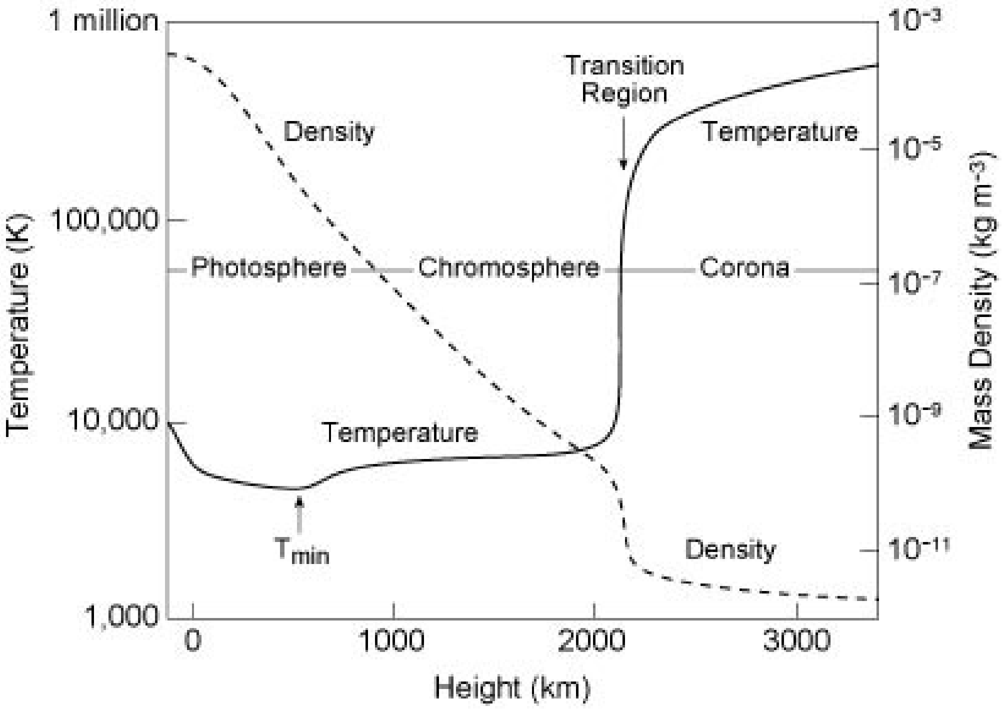
$$\underline{j} \wedge \underline{B} = 0$$

- **Question – How is sub-surface field turned into force-free coronal field?**



Partial Ionisation in the solar atmosphere

- MHD –fully ionised plasma
- T < ionisation of H – neutrals present
- Calculate neutral fraction and modify MHD eqns to include neutrals
  - Ohm's law - collisional momentum transfer



Partial ionisation - equations

Fully ionised plasma (FIP)

Non-ideal Ohm's law

$$\underline{E} + \underline{v} \wedge \underline{B} = \eta \underline{j}$$

Coulomb resistivity η – ion-electron collisions

Isotropic diffusion

$$\frac{\partial \underline{B}}{\partial t} = \nabla \wedge (\underline{v} \wedge \underline{B}) - \nabla \wedge \eta \underline{j}$$

Partially ionised plasma (PIP)

3 species fluid – generalised Ohm's law

$$\underline{E} + \underline{v} \wedge \underline{B} = \eta \underline{j_{\mathrm{P}}} + \eta_c \underline{j_{\perp}}$$

Cowling resistivity η_c – ion-neutral collisions

Anisotropic diffusion

$$\frac{\partial \underline{B}}{\partial t} = \nabla \wedge (\underline{v} \wedge \underline{B}) - \nabla \wedge \eta \underline{j_{\mathrm{P}}} - \nabla \wedge \eta_c \underline{j_{\perp}}$$

Anisotropic diffusion

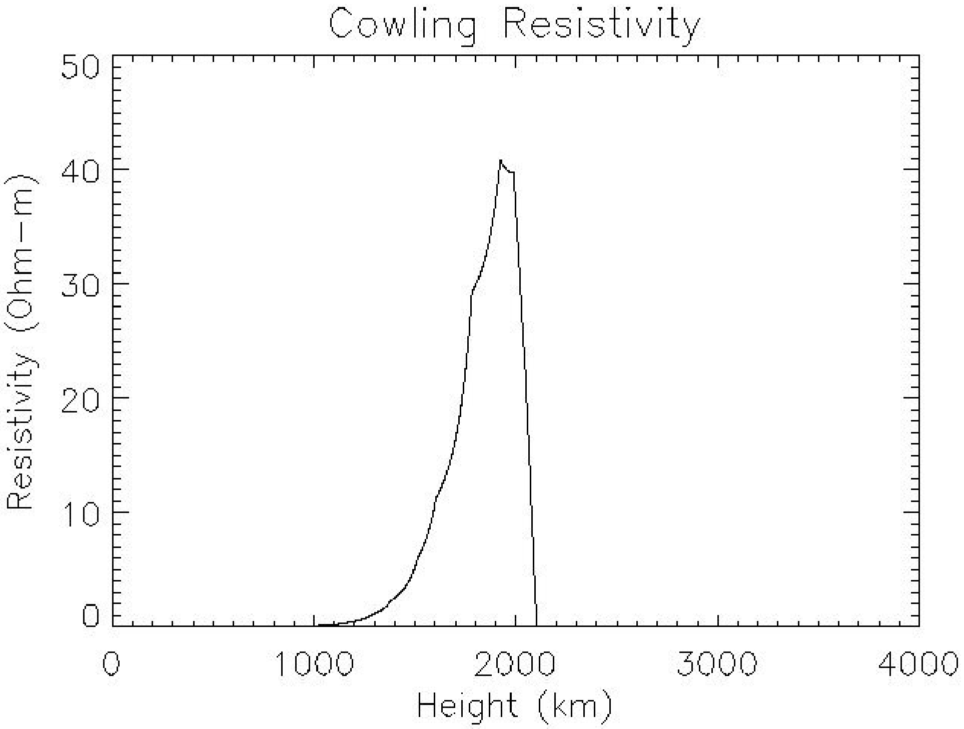
- Using model T,n,B

$$\frac{\eta_c}{\eta} : 10^{12}$$

- ***Only $j_\perp$ diffused directly***

$$\frac{\tau_{transit}}{\tau_{diffusive}} \approx 500$$

- ***Efficient diffusion of $j_\perp$***



Numerical method

$$\frac{\partial \rho}{\partial t} = -\nabla.(\rho \underline{v})$$

$$\frac{\partial}{\partial t}(\rho \underline{v}) = -\nabla.(\rho \underline{v}\underline{v}) - \nabla P + \underline{j} \wedge \underline{B} + \rho \underline{g}$$

$$\frac{\partial \underline{B}}{\partial t} = \nabla \wedge (\underline{v} \wedge \underline{B}) - \nabla \wedge (\eta \underline{j_{\mathrm{P}}}) - \nabla \wedge (\eta_c \underline{j_{\perp}})$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) = -\nabla.(\rho \varepsilon \underline{v}) - P\nabla.\underline{v} + \eta j_{\mathrm{P}}^2 + \eta_c j_{\perp}{}^2$$

Heating effects

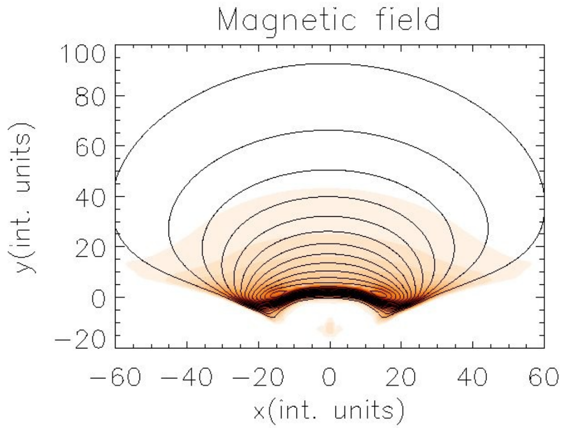
$$\frac{\partial \varepsilon}{\partial t} = -\frac{\varepsilon - \varepsilon_0}{\tau}$$

models heating/cooling mechanisms – thermal conduction, small scale shock heating, radiative transfer etc

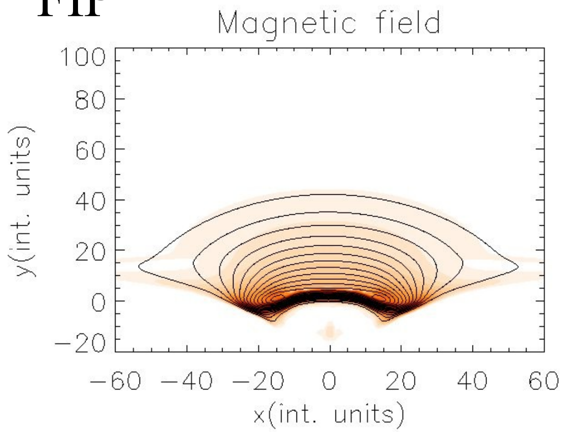
Results 1 - emergence of flux

2D Field lines

PIP

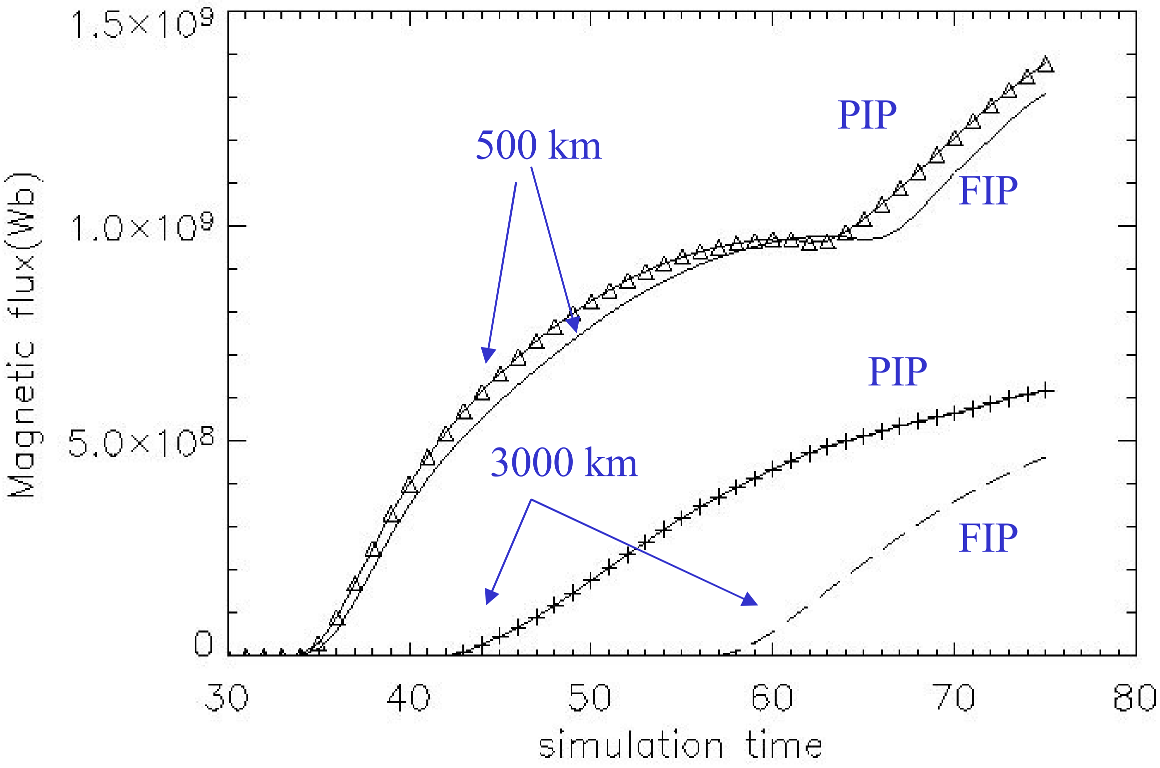


FIP



Flux emergence at two different heights

$$\int |B_y| dx(t)$$



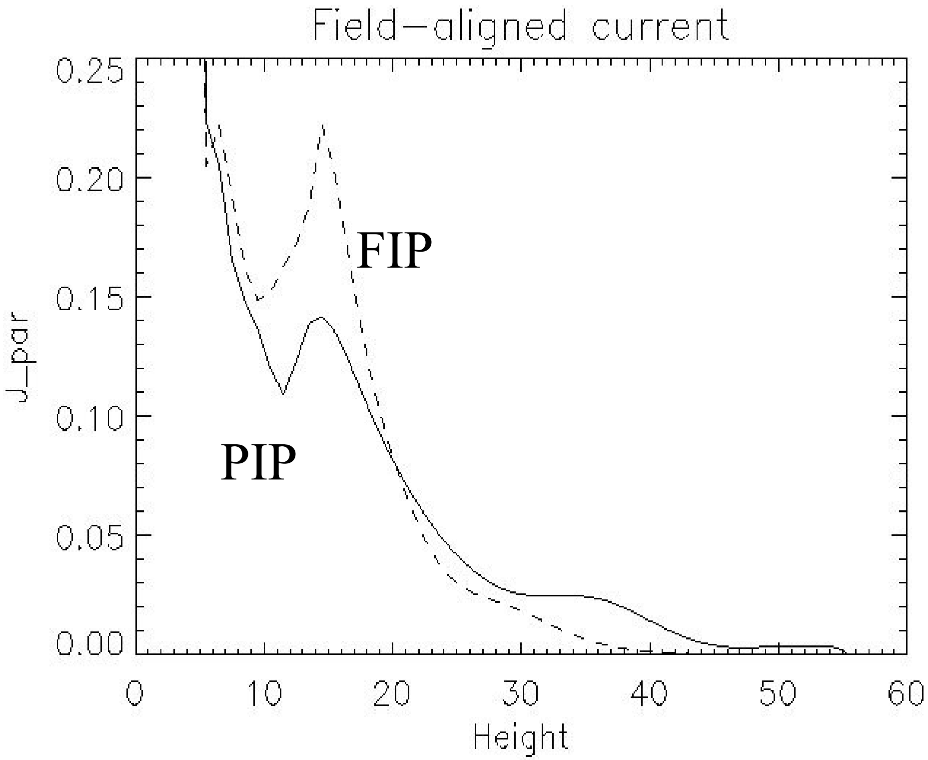
Results 2 – Force-free?

- $\underline{j} \wedge \underline{B} = 0 \Leftrightarrow \underline{j} = \underline{j_P} \Leftrightarrow \underline{j_\perp} = 0$

- Field-aligned currents

$$\int_{-L}^{L} \left| \underline{j_P} \right| dx$$

- Small differences in two models

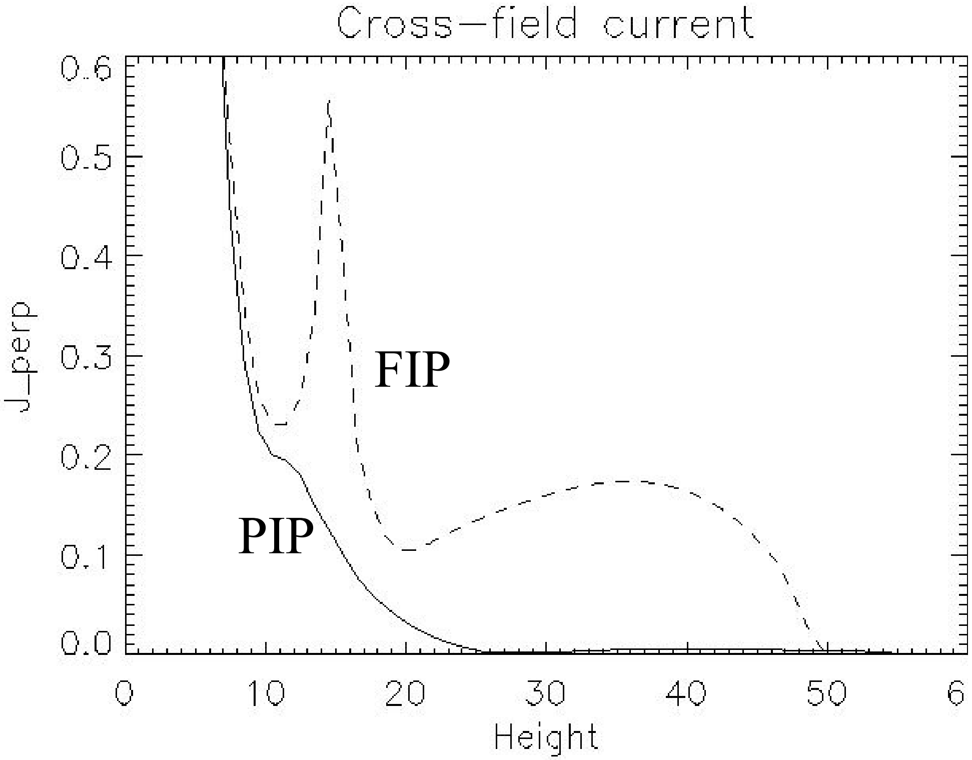


Results 3 – Force-free?

- Cross field currents

  $$\int_{-L}^{L} \left|\underline{j}_{\perp}\right| dx$$

- PIP $\underline{j} \wedge \underline{B} \rightarrow 0$
  above 2500 km (15Hp) ***force-free!***
- Observations – force-free above 1000km(5 H_p)



Conclusions

- ***Partial ionisation can provide mechanism for formation of force-free fields in corona***

$$\underline{j_\perp} \to 0$$

$$\underline{j} \wedge \underline{B} \to 0$$

- Mechanism is due to ion-neutral interactions leading to diffusion of cross-field currents
- Typical rates of emergence are much larger – more diffuse fields
- Further work
  - 3D – better diagnosis of height at which force-free
  - Effects of Joule heating on dynamics

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