Why do stars have such weak magnetic fields?

Flux, helicity and buoyancy in protostars

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Zakopane, 23rd August 2011

Contents

- Introduction: the flux problem in star formation
- Disconnection of star from surroundings
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“Magnetic flux problem” in star formation

- For cloud to collapse, gravitational (negative) energy must overcome the positive energies
- In adiabatic collapse, both gravitational and magnetic energy grow as R^{-1}.
- [Thermal and rotational kinetic grow faster, so need to radiate heat and transport angular momentum outwards.]
- On scales > 1000 AU, observations show $E_{grav} \sim E_{mag}$
- In stars, $E_{grav} \gg E_{mag}$
- What happens to all the flux?
- Proposition: as star becomes disconnected from parent cloud, field is destroyed by instability
- [Not to be confused with the other flux problem: how to get from $E_{grav} < E_{mag}$ on large scales to $E_{grav} > E_{mag}$ and so allow collapse in the first place]

Observations of cores

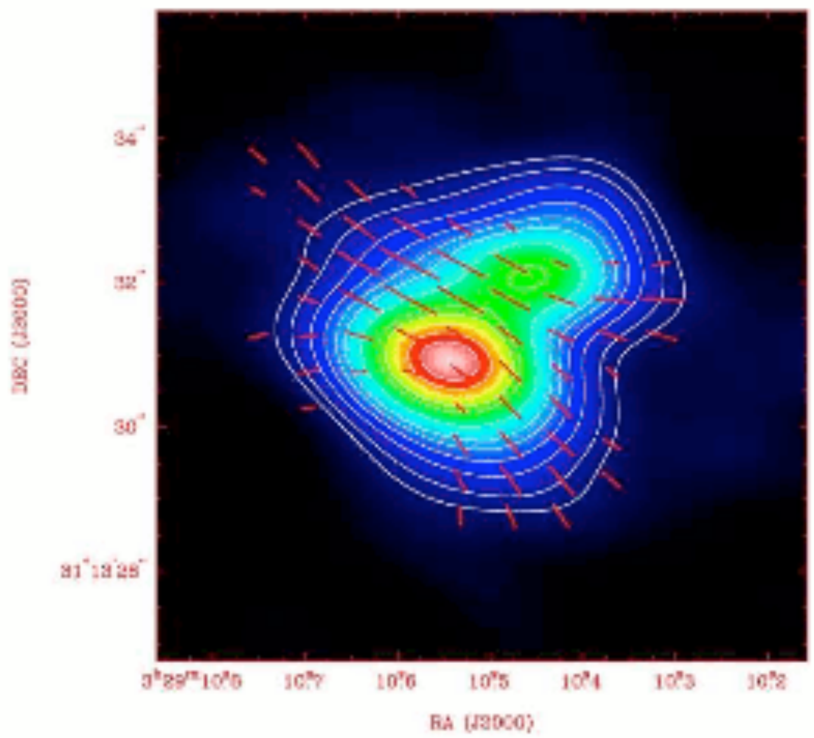
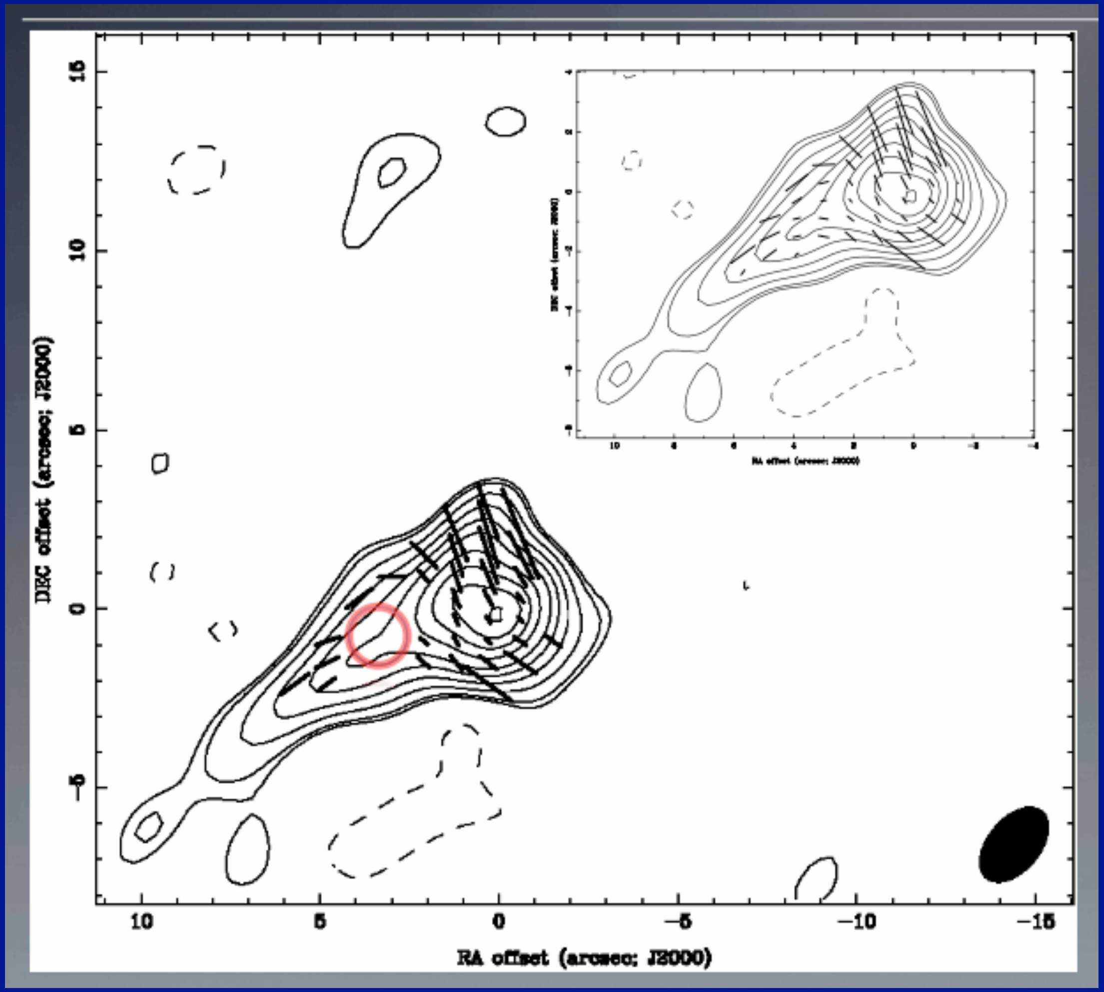


Fig. 1. Contour map of the 877 μm dust emission in the low-mass protostellar system NGC1333-IRAS4A. The direction of the vectors corresponds to the position angle of linear polarization (Girart, Rao, & Marrone 2006)



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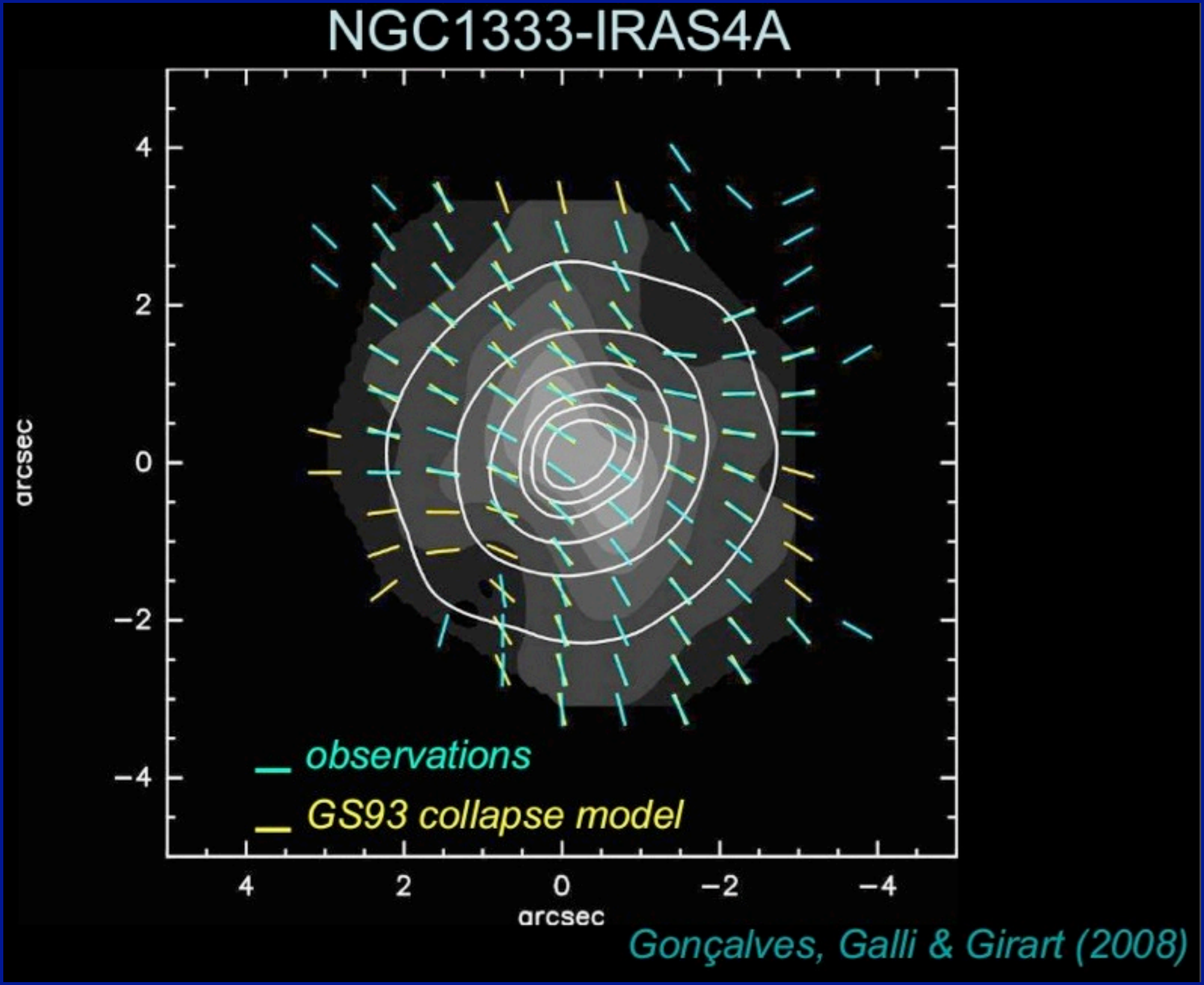
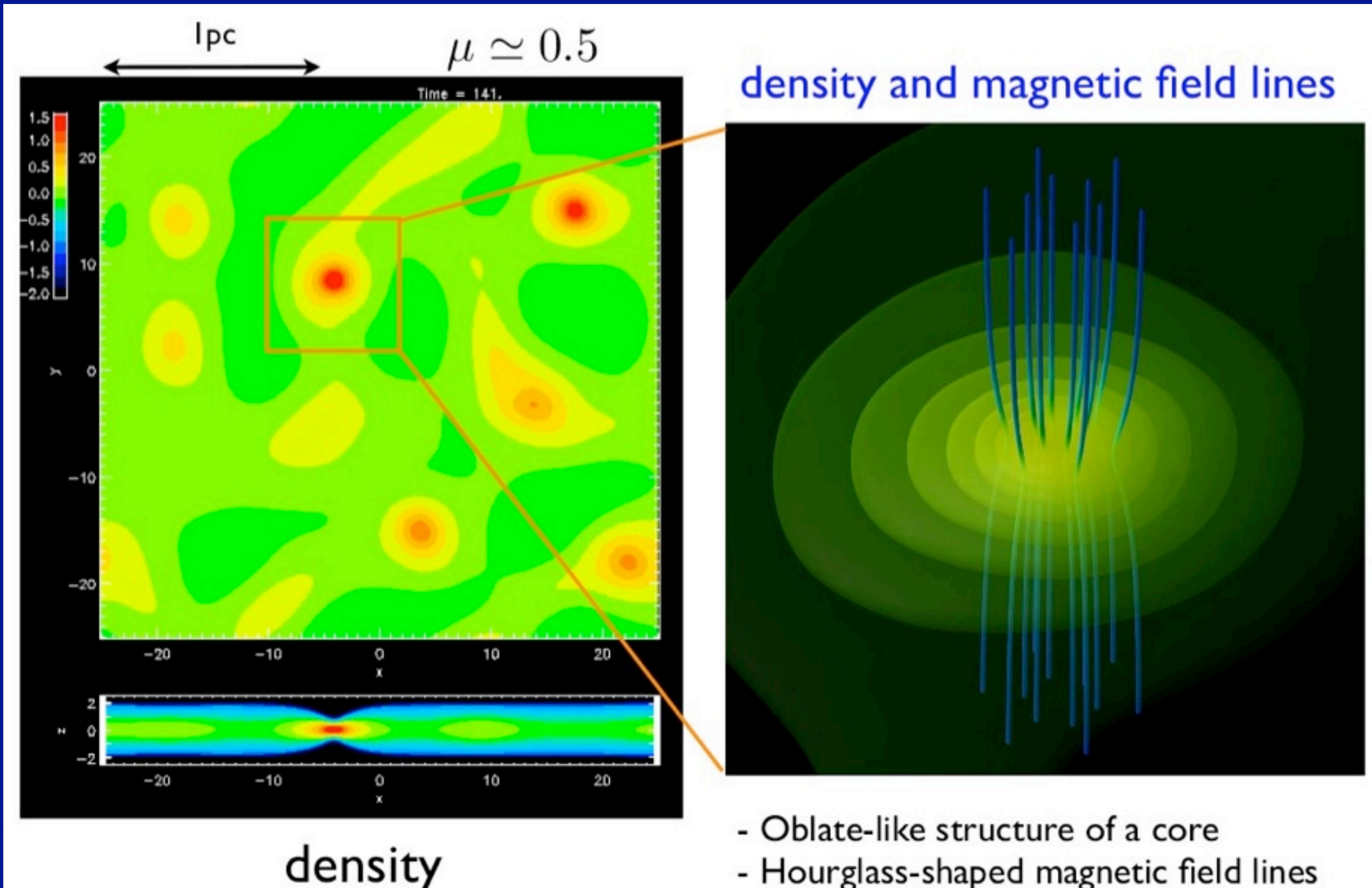


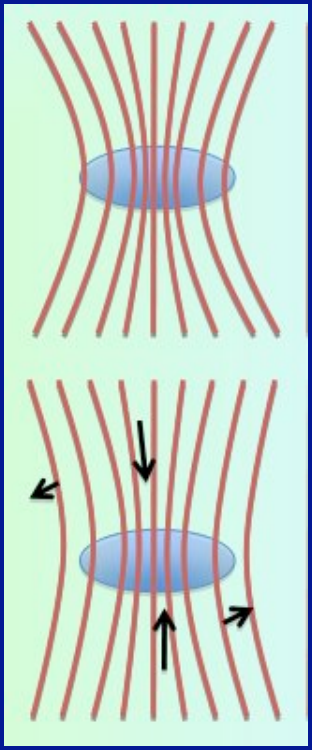
Hourglass forming in simulations

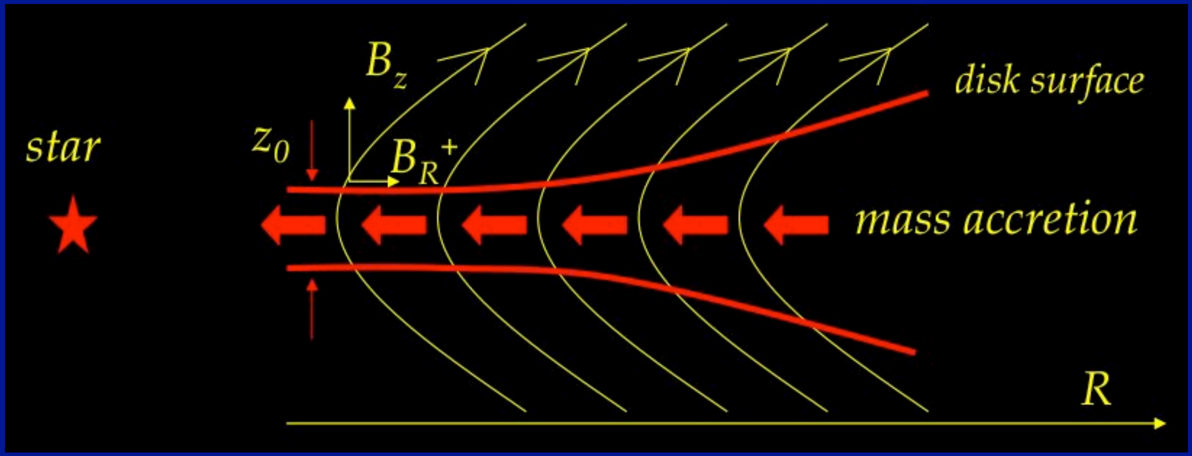


Kudoh & Basu 2007

"Magnetic flux problem" in star formation

- Oft-heard solution
  - magnetic field somehow avoids being dragged inwards





Diffusion in disc: matter accretes, slipping past field lines (e.g. van Ballegooijen 1989)

Diffusion allows matter to collapse across field lines (e.g. Mestel & Spitzer 1956)

Opinions differ as to how efficient these processes are, and how they work

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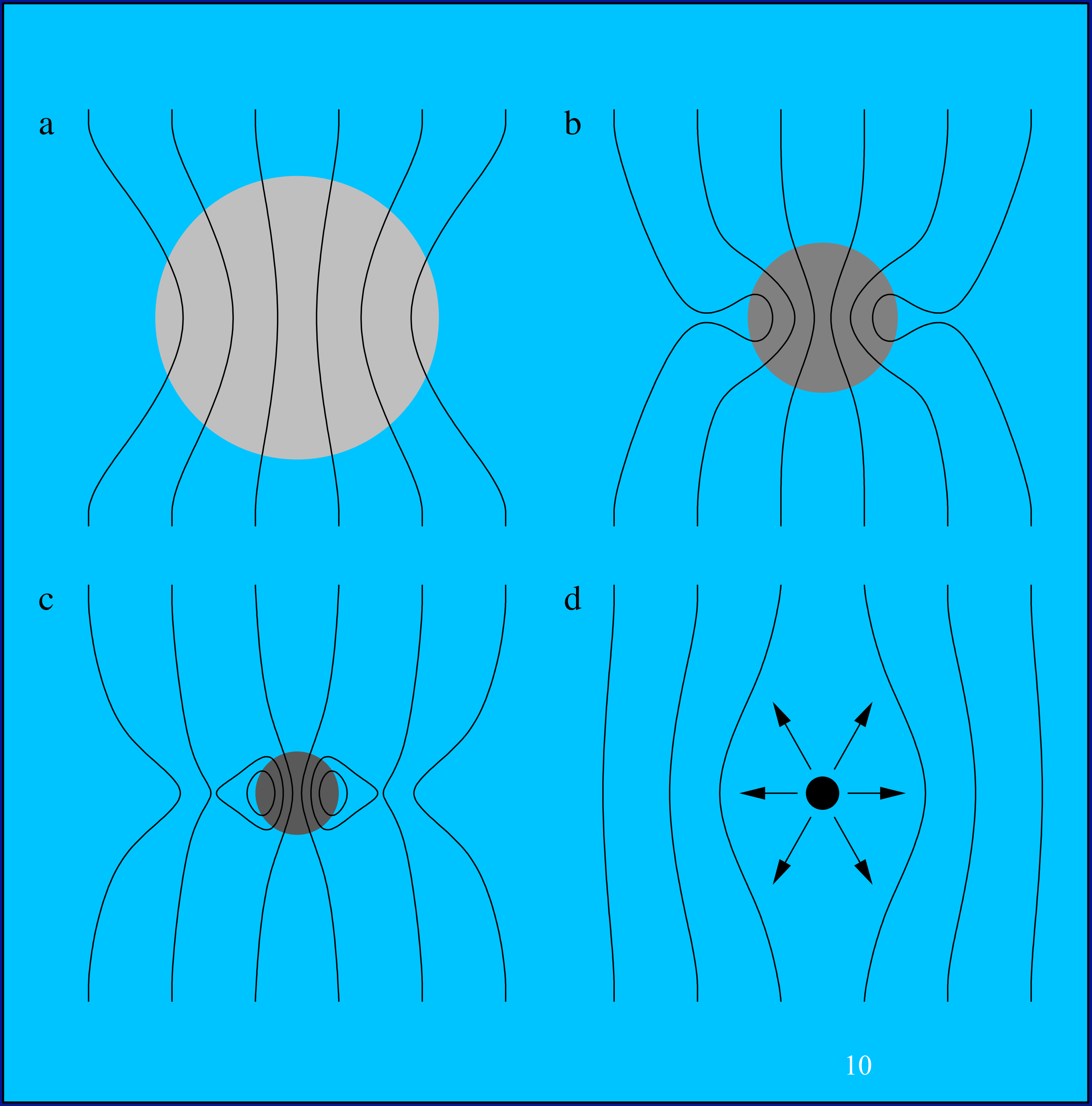
Hourglass picture: flux frozen into core as it collapses

Later on, field lines disconnect (as we see in pre-MS stars, after main accretion phase)

Disconnection happens at latest when super-Alfvénic wind appears

then field can reorganise internally



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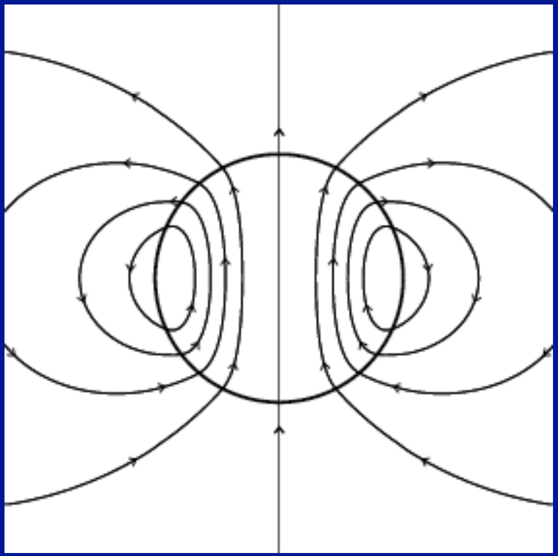
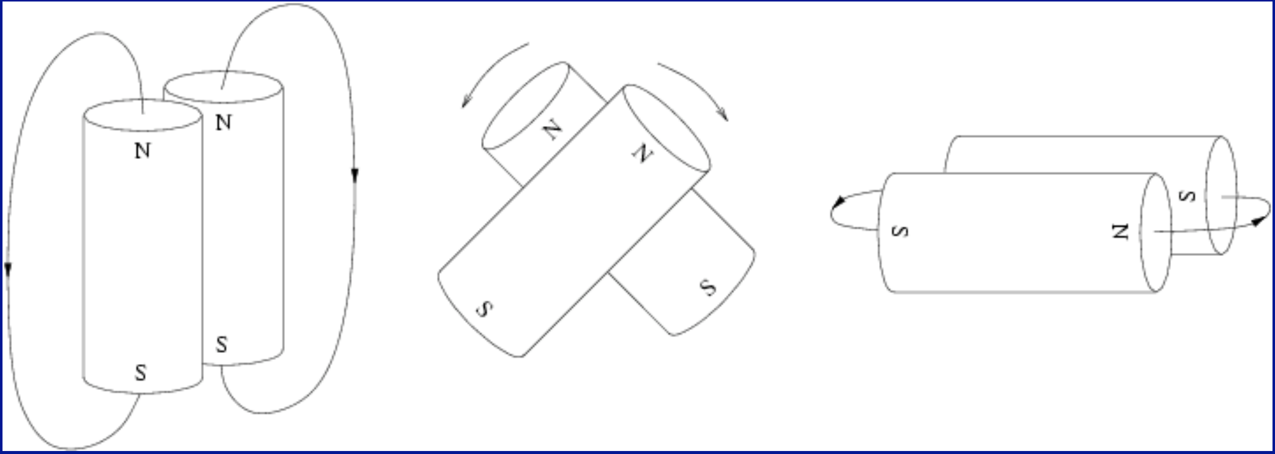
Reconnection in radiative stars as means to reduce flux

- Imagine star contains a large poloidal flux
- Instability --> reconnection
  --> magnetic energy destroyed





Poloidal field:
star can be thought of as fluid of aligned bar magnets

*(Markey & Tayler 1973,74;
Wright 1973;
Flowers & Ruderman 1977)*

Simulations confirm this........

End result of reconnection

- Reconnection/relaxation ends when equilibrium is reached
- This equilibrium is called a “fossil field” and lasts for ~Hubble time
- How to predict strength of fossil field?

Formation of equilibria:
helicity conservation and strength of equilibrium field

- Magnetic helicity definition:

$$H \equiv \int \mathbf{A} \cdot \mathbf{B} \, \mathrm{d}V \quad \text{where} \quad \mathbf{B} = \nabla \times \mathbf{A}$$

- *H* is perfectly conserved in a fluid of infinite conductivity (Woltjer 1958)
- *H* has units length x energy, so is *roughly* conserved while energy is dissipated on small scales

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- *H* has units length x energy, so is *roughly* conserved while energy is dissipated on small scales
- A given equilibrium type *n* has an associated dimensionless length scale λ_n

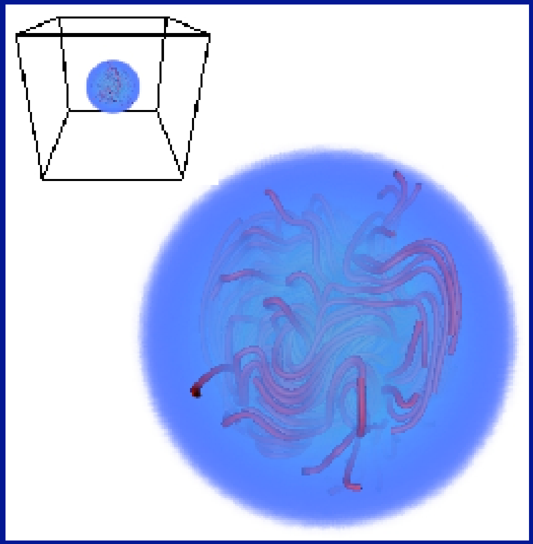
$$\frac{H_{\rm eq}}{E_{\rm eq}} \approx \lambda_n R \qquad \text{and} \qquad H_{\rm eq} \approx H_{\rm init} \qquad \text{therefore} \qquad E_{\rm eq} \approx \frac{H_{\rm init}}{\lambda_n R}$$

- Energy of final equilibrium (and strength of ‘fossil field’) can be predicted if we know the initial *helicity*. *Energy* (or poloidal flux) of initial field is not relevant.
- Helicity can be thought of as

$$H \sim \Phi_{\rm pol} \Phi_{\rm tor}$$

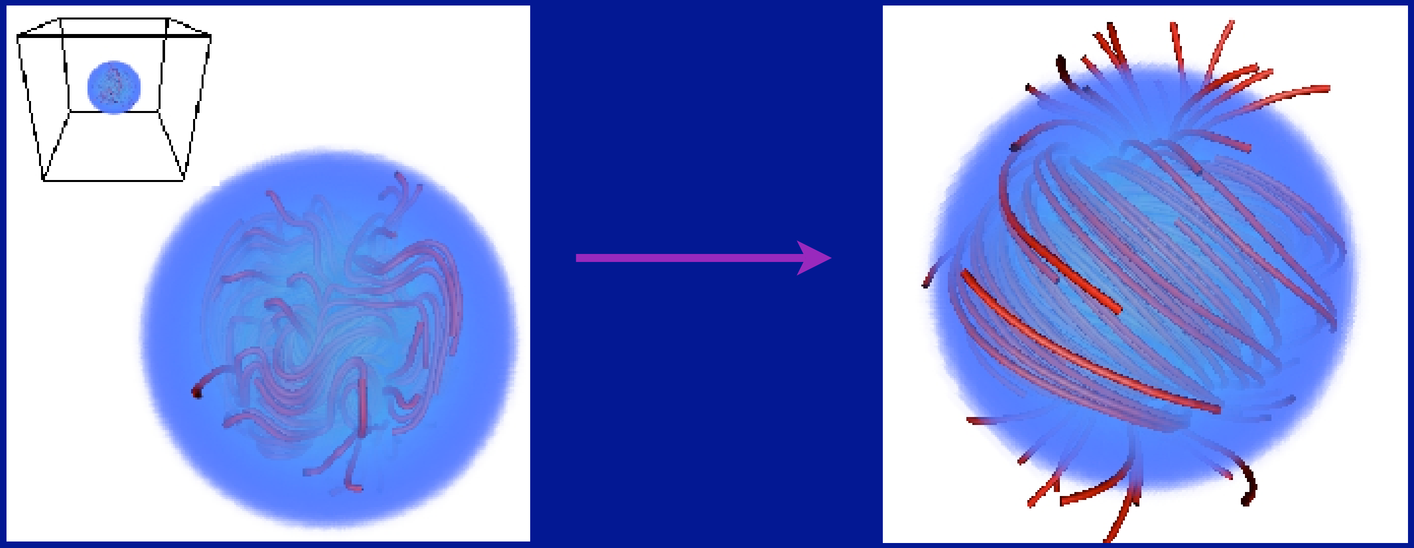
Finding equilibria: numerical methods

- Concept
  - Make numerical model of radiative star with arbitrary B-field
  - Star has stable entropy profile
  - Follow evolution of field as it relaxes into an equilibrium

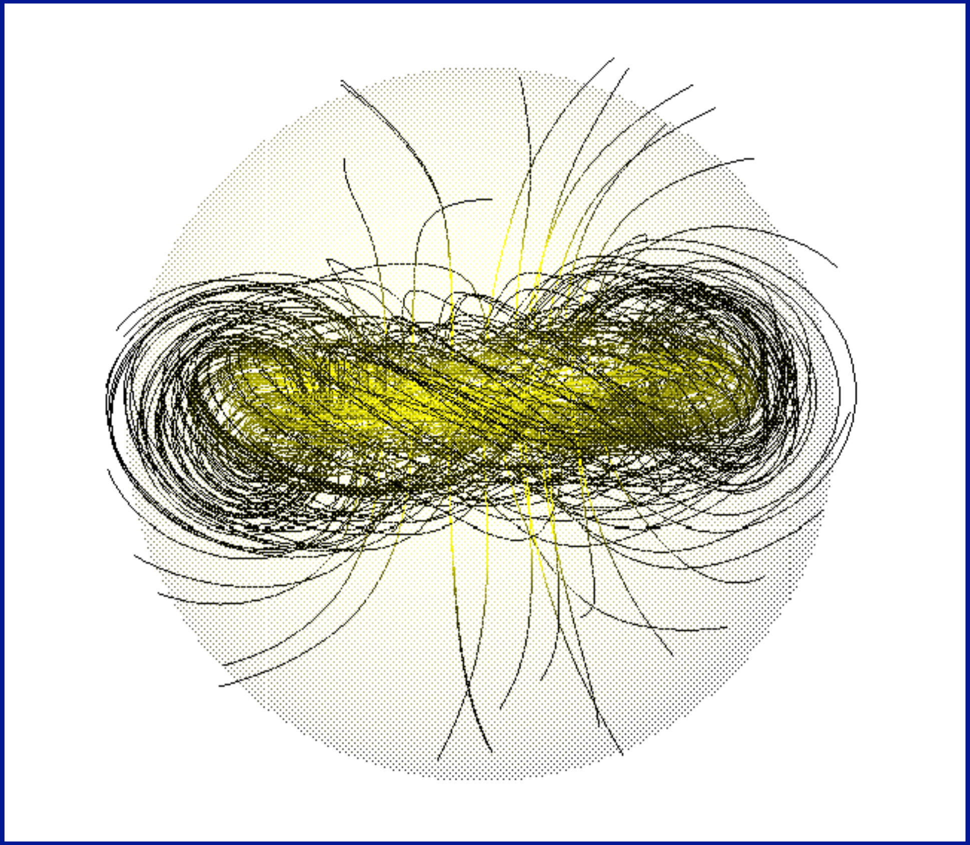


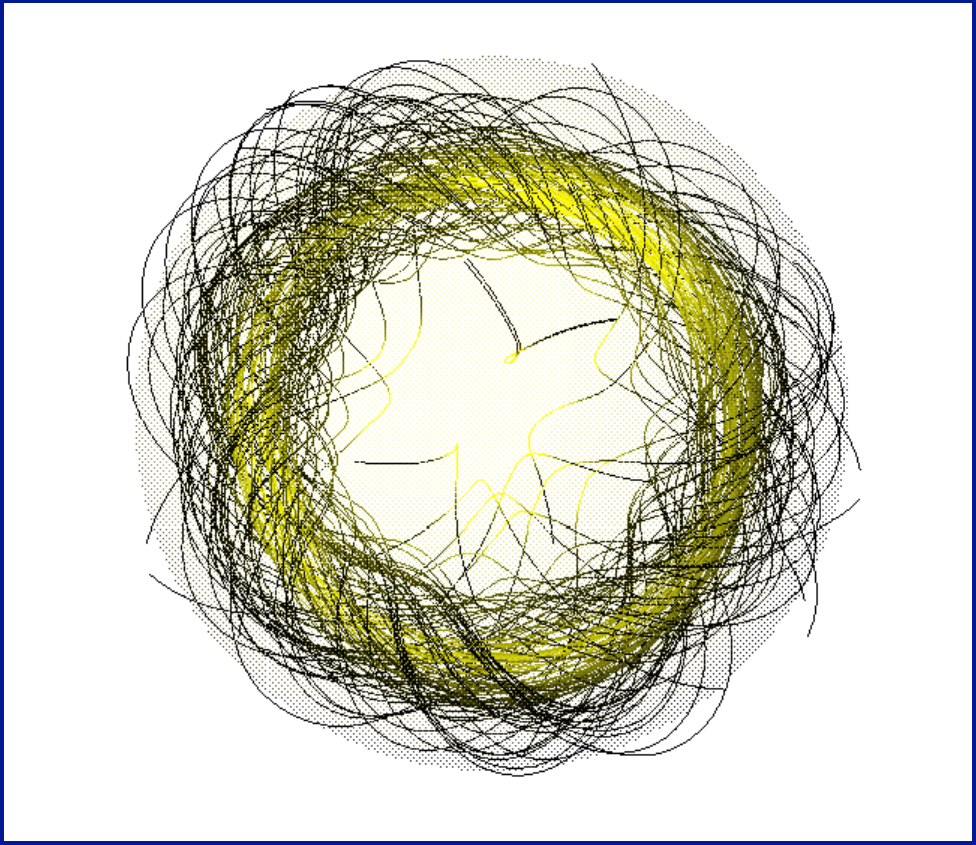
Finding equilibria: numerical methods

- Concept
  - Make numerical model of radiative star with arbitrary B-field
  - Star has stable entropy profile
  - Follow evolution of field as it relaxes into an equilibrium
- First results
  - Simple axisymmetric equilibria are found (Braithwaite & Spruit 2004)



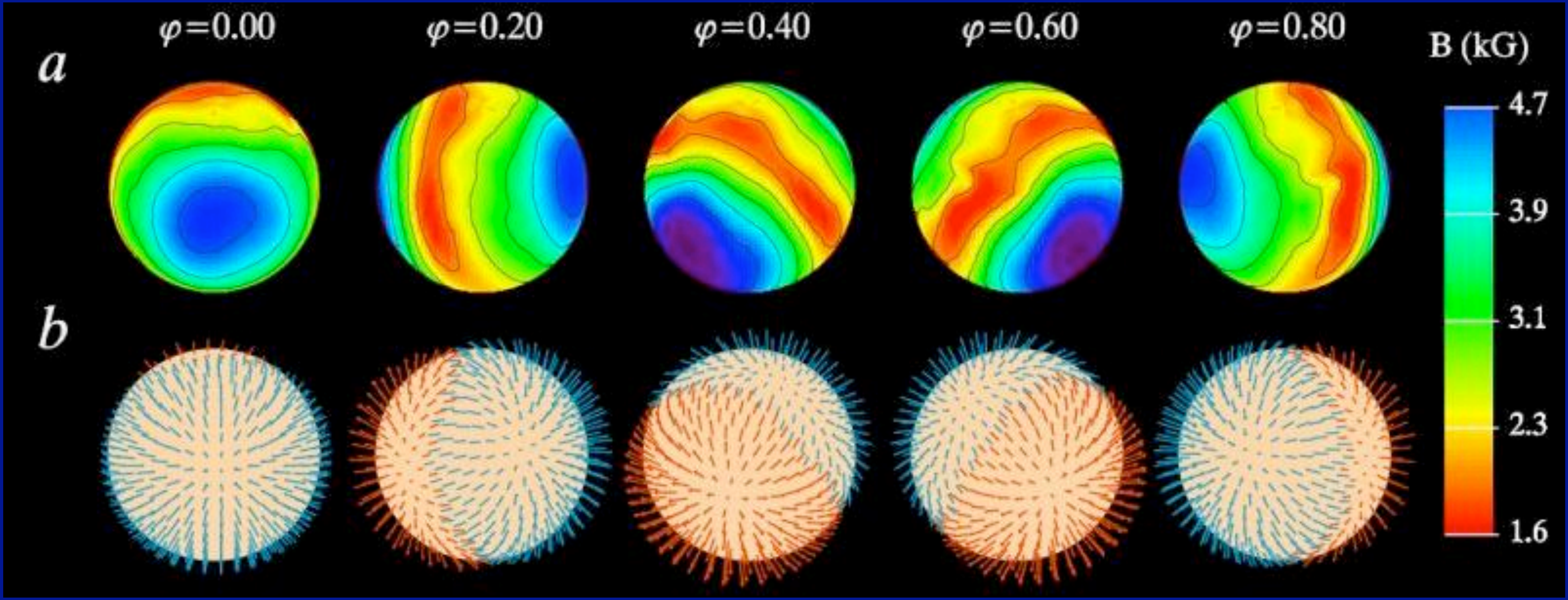
Most basic equilibrium





Braithwaite & Nordlund 2006

Comparison with observations

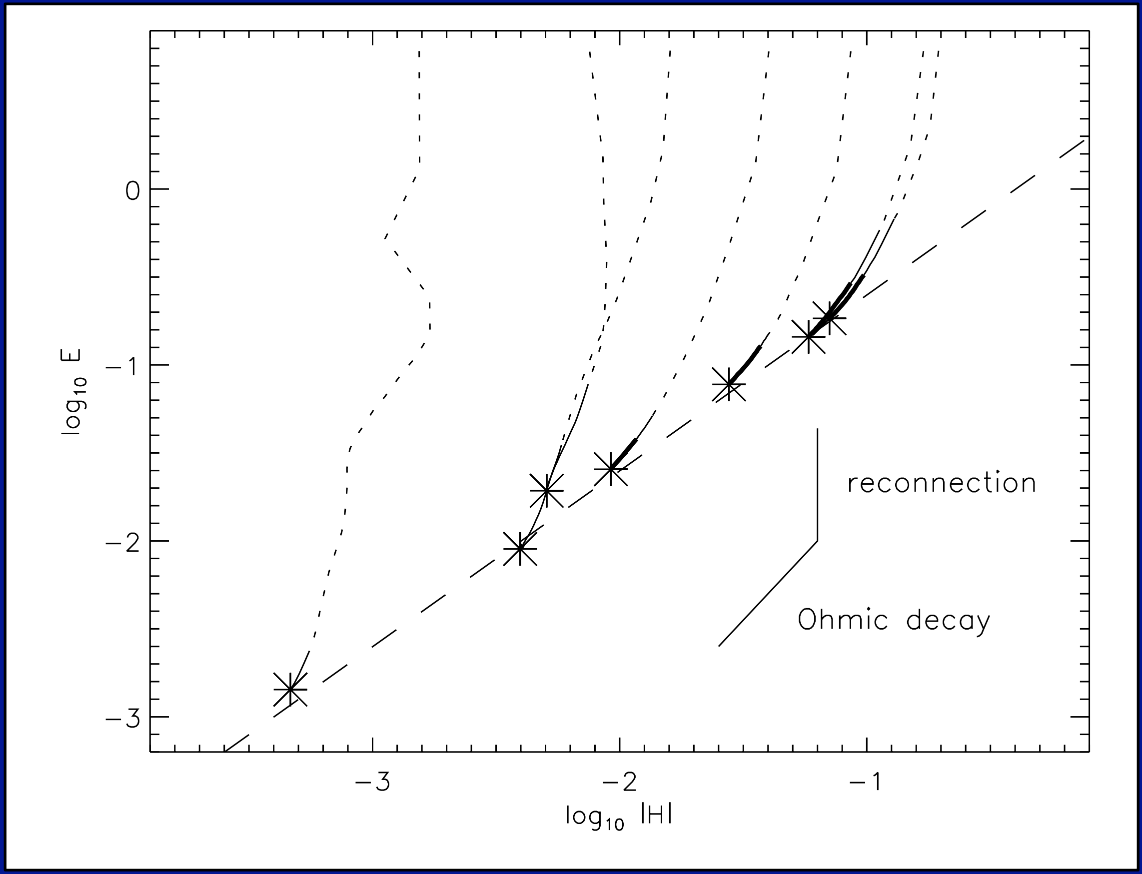


Field topology of α^2 CVn, an A-type main-sequence star
(Kochukhov et al. 2002, using Zeeman-Doppler imaging)

Energy and helicity in simulations

Braithwaite 2010

- Helicity falls only by ~20% during relaxation (depends on resolution)
- Energy of equilibrium depends on helicity

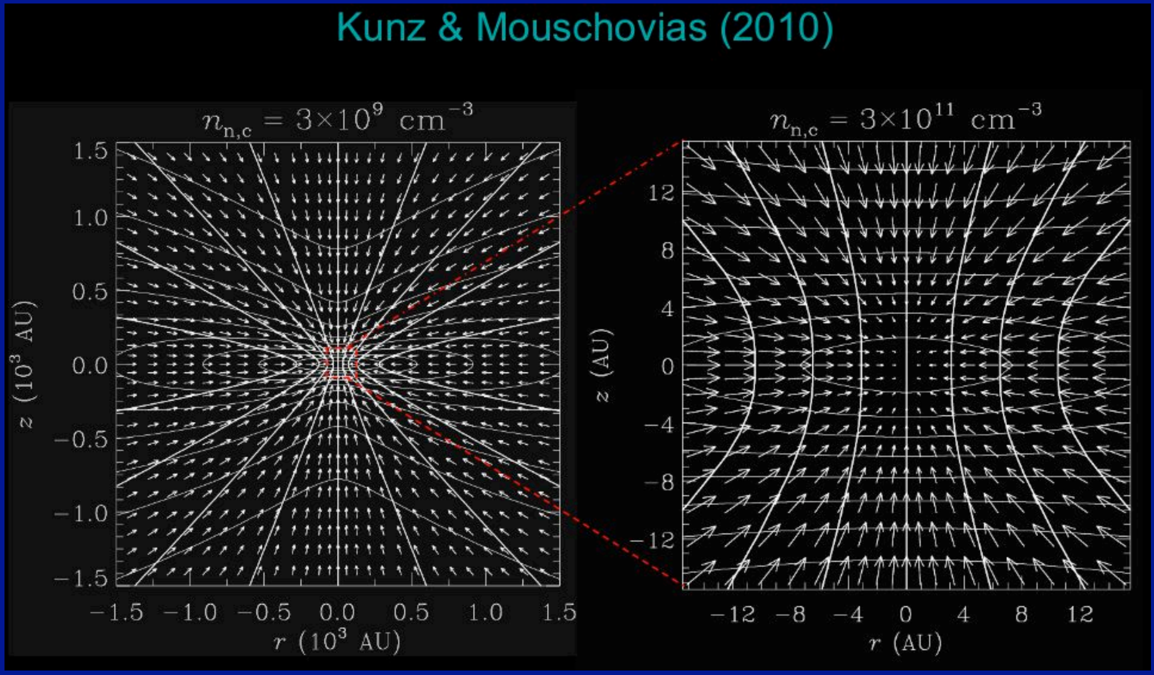


Log energy against log helicity
Solid lines represent equilibrium field

Straight dashed line shows: $\dfrac{H_{\rm eq}}{E_{\rm eq}} \approx \lambda_n R$

Summary so far

- Poloidal flux during formation is not relevant parameter for strength of fields seen in upper-main-sequence
- Helicity is relevant parameter: $H \sim \Phi_{\rm pol}\Phi_{\rm tor}$
- Net toroidal flux and therefore helicity might be very small...?
- In many hourglass models, $H = 0$
- Some asymmetry required for non-zero helicity



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Isentropic stars: buoyant loss of magnetic field

- Reconnection & reorganisation towards an equilibrium proceeds at Alfvén speed or somewhat less
- Deuterium burning drives convection and star becomes isentropic
- In isentropic star, magnetic field provides buoyancy because it gives pressure without mass
- Regions of higher field strength are driven upwards
- This motion also happens at Alfvén speed:

$$\frac{\Delta\rho}{\rho} \sim \frac{\Delta P}{P} \sim \frac{B^2}{24\pi P} \sim \frac{v_{\rm A}^2}{c_{\rm s}^2} \quad \text{and} \quad F_{\rm buoy} \sim l^3 g \Delta\rho \sim \rho l^2 v_{\rm buoy}^2 \sim F_{\rm drag}$$

$$\text{and} \quad H_p \approx \frac{c_{\rm s}^2}{g} \quad \Rightarrow \quad \frac{v_{\rm buoy}}{v_{\rm A}} \approx \left(\frac{l}{H_p}\right)^{1/2}$$

- Convective motion is not relevant for a super-equipartition magnetic field

Isentropic stars: buoyant loss of magnetic field

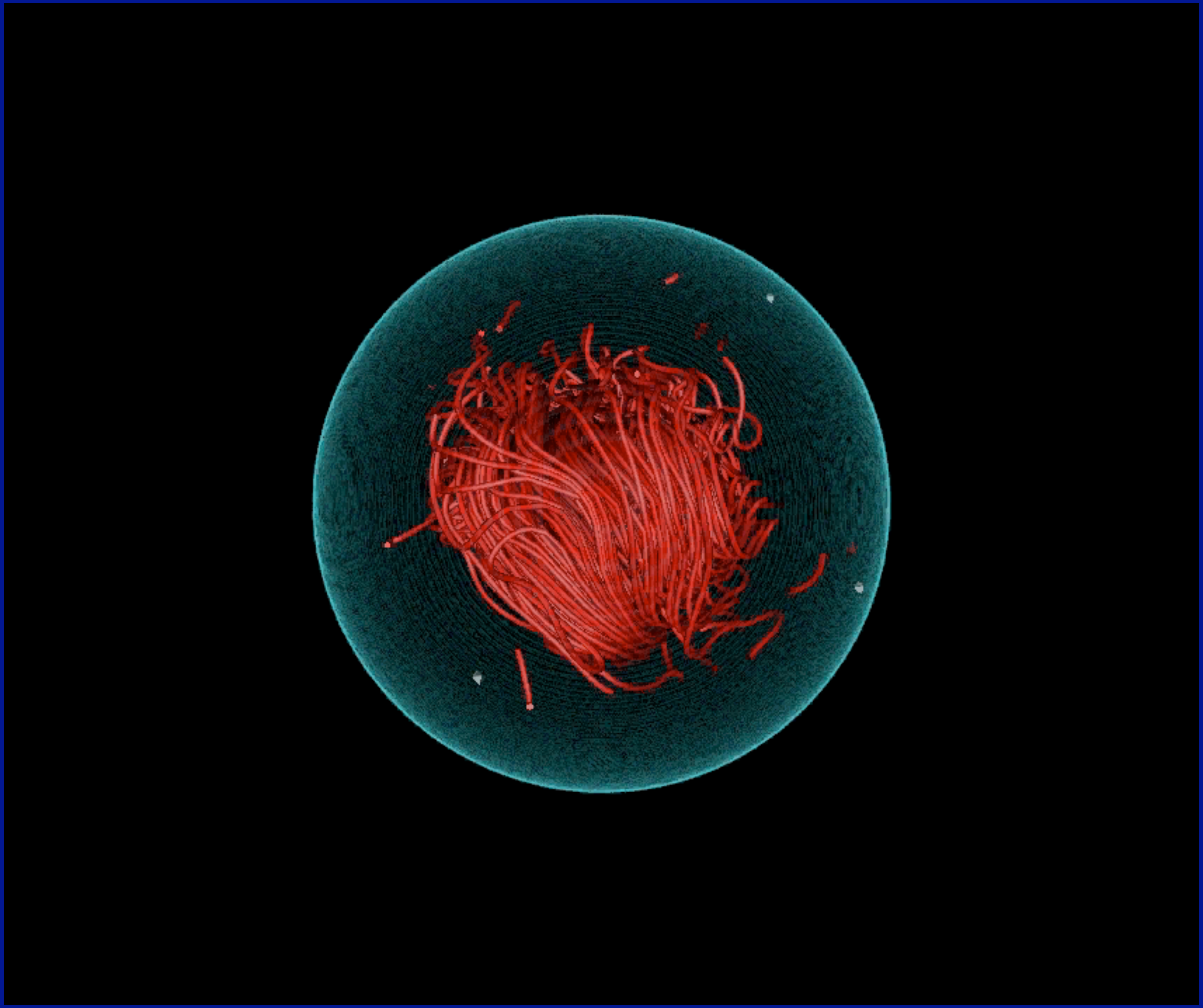
- End result: original magnetic field is lost into atmosphere
- Replaced by dynamo-driven field, at most at equipartition with convective motion
- Consequence: magnetic field independent of initial conditions

Simulations of relaxation in isentropic star

- “Star in box” simulation; star is polytrope of index n=3/2 with ideal gas e.o.s.
- Actual convection not modelled

Simulations of relaxation in isentropic star

- “Star in box” simulation; star is polytrope of index n=3/2 with ideal gas e.o.s.
- Actual convection not modelled
- Energy and helicity is lost into atmosphere



Braithwaite 2011,
Duez & Braithwaite, in prep.

Summary

- Poloidal flux during formation is not relevant parameter for strength of fields seen in upper-main-sequence
- Helicity is relevant parameter: $H \sim \Phi_{\rm pol}\Phi_{\rm tor}$
- Net toroidal flux and therefore helicity might be very small...? Asymmetry required for non-zero helicity
- Helicity can be destroyed efficiently while star remains isentropic, i.e. convectively unstable
- Therefore lower-main-sequence stars naturally lose all their original helicity; magnetic properties are independent of initial conditions
- In short: **any unwanted excess flux can be destroyed in protostar before stellar surface even becomes visible**
- If star accretes from disc: slippage mechanism still required, but it has extra “incentive” because star will not accept flux