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Magnetic flux emergence in fast rotating stars

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Outline

1. Introduction
2. The Solar Paradigm
3. Effects of stellar rotation
4. ‘Polar Spots’
5. Pre-MS and binary stars
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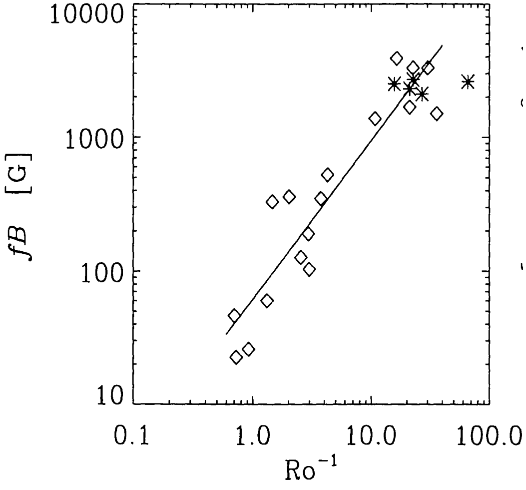
From the Sun to *cool* stars

- increasing quality and quantity of observations of stellar magnetic activity
- concept: convective motions & rotation → dynamo → magn. flux emergence
- How does **amount** of emerging magn. flux depend on stellar rotation?
  - observation:

    $$\Phi \propto \Omega^n \quad \text{with} \quad n \sim 1 - 3$$

    (Saar 2001; Schrijver et al. 2003)
  - back-reaction of magn. field on flow → saturation of dynamo operation
  - theory: no consistently closed dynamo model yet (e.g., Ossendrijver 2003)

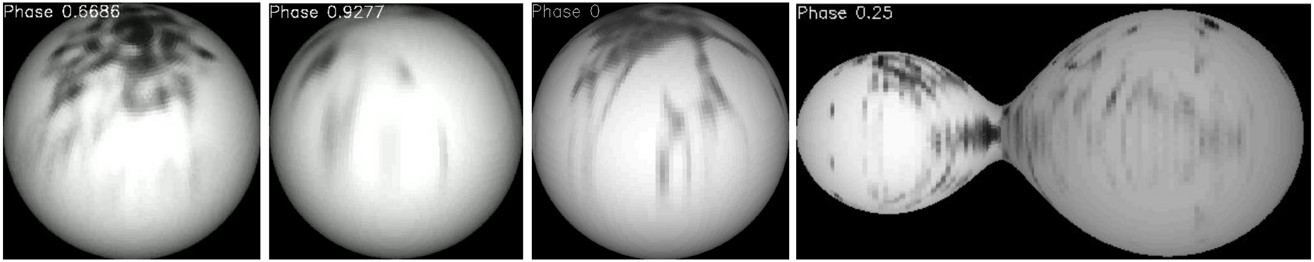


Saar (2001)

inv. Rossby number $Ro^{-1} \propto \Omega$

- How does **surface distribution** of emerging flux depend on stellar rotation?

Sun (G2V, $\gtrsim$**25d**)[1] UZ Lib (K0III, **4.76d**)[3] LQ Hya (K2V, **1.61d**)[2] AB Dor (K1V, **0.51d**)[4] (radial field strength)



He 699 (G2V, **0.49d**)[5] HK Aqr (M1Ve, **0.41d**)[5] BO Mic (K3V, **0.38d**)[5] AE Phe (G1V, **0.36d**)[5]

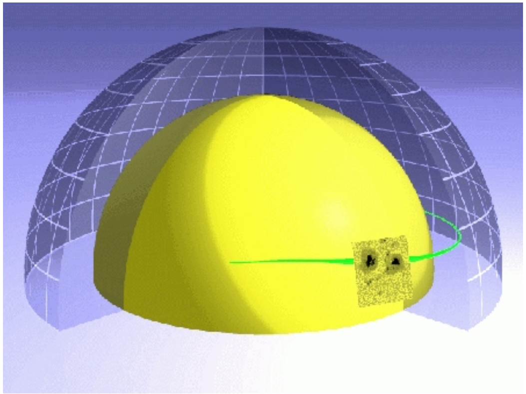
[1] SoHO/NASA; [2] Kovári et al. (2004); [3] Oláh et al. (2002); [4] Donati & Collier Cameron (1997); [5] Barnes et al. (2001a,b, 2004a,b)

- **high-latitude spots** on rapidly rotating stars (e.g. Strassmeier 2002)
- spot coverage up to 40% (O'Neal et al. 2004) ; Sun: $< 0.5\%$

The Solar Paradigm

- strong magnetic fields (flux tubes) originate from **bottom of convection zone** (e.g. van Ballegooijen 1982; Moreno-Insertis 1986)

- basic model:
  - field amplification in tachocline
  - storage at interface to radiative core
  - beyond critical field strength onset of instability
  - flux loops rising through convection zone
  - emergence at stellar surface
  - disconnection from sub-surface roots
  - dispersal and transport with large-scale flow



Caligari et al. (1995)

- predictions in agreement with emergence latitudes, tilt angles, proper motions of sunspot groups (e.g. D'Silva & Choudhuri 1993; Fan et al. 1994; Caligari et al. 1995)

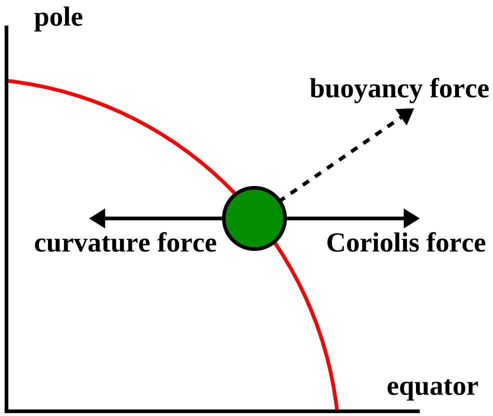
Equilibrium properties

- toroidal flux tube in mechanical equilibrium, parallel to equatorial plane
  (e.g. Spruit & van Ballegooijen 1982; Moreno-Insertis et al. 1992)
  - non-buoyant ($\rho_\mathrm{i} = \rho_\mathrm{e}$)
  - prograde internal flow with velocity excess

$$\Delta v = v_\mathrm{i} - v_\mathrm{e} = \sqrt{v_\mathrm{e}^2 + v_\mathrm{A}^2} - v_\mathrm{e}$$

v_e: flow velocity of environment ($= \Omega r \cos\lambda$)
v_A: Alfvén velocity

  - **curvature force balanced by Coriolis force**

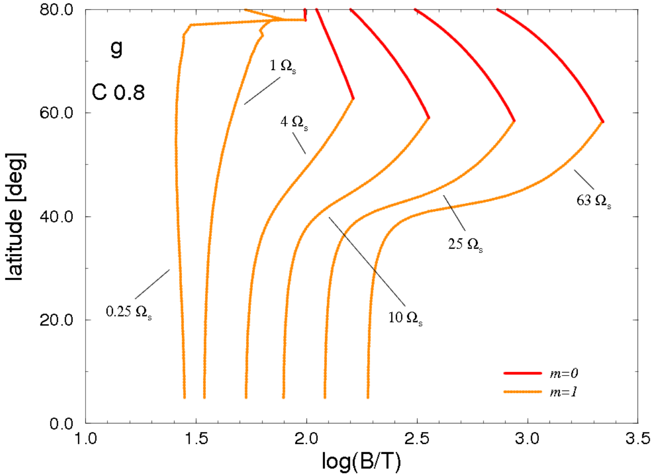


- faster stellar rotation → lower Δv, but larger angular momentum of int. plasma
- basic scheme:

$$\text{if internal flow velocity} \left\{ \begin{array}{c} \text{larger} \\ \text{smaller} \end{array} \right\} \rightarrow \text{net} \left\{ \begin{array}{c} \text{outward} \\ \text{inward} \end{array} \right\} \text{force}$$

Stability properties

- beyond critical magnetic field strength onset of buoyancy driven instability (e.g. Spruit & van Ballegooijen 1982; Ferriz-Mas & Schüssler 1995)
- high angular momentum **stabilises** flux tubes



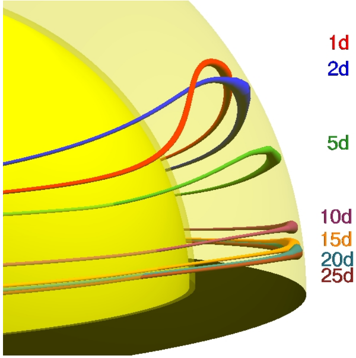
Granzer (2000)

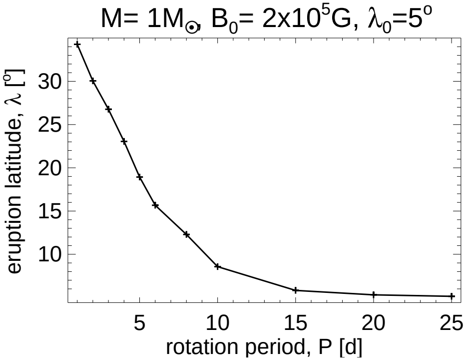
- flux emergence on ‘solar-like’ time scales requires higher field strengths

→ fast rotators: stronger magn. buoyancy & Coriolis forces

Eruption properties

- if AM conserved, v_{i} decreases → curvature force outbalances Coriolis force

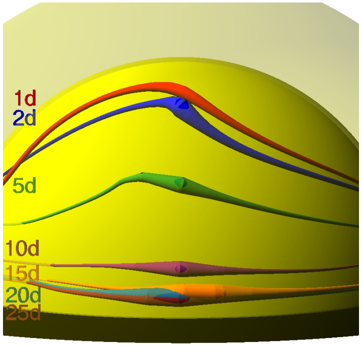


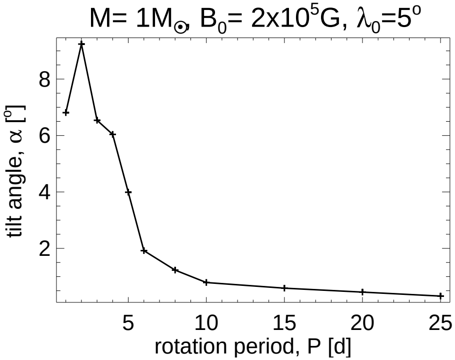


poleward deflection

(e.g. Choudhuri & Gilman 1987)

- rising flux loop expands in longitude → ‘cyclonic effect’





tilted bi-polar spot group

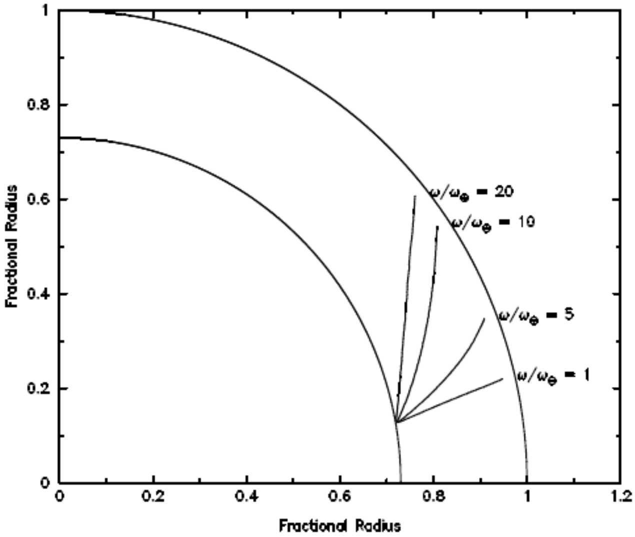
(e.g. D’Silva & Choudhuri 1993)

- effects depend on ratio between magn. buoyancy and Coriolis force

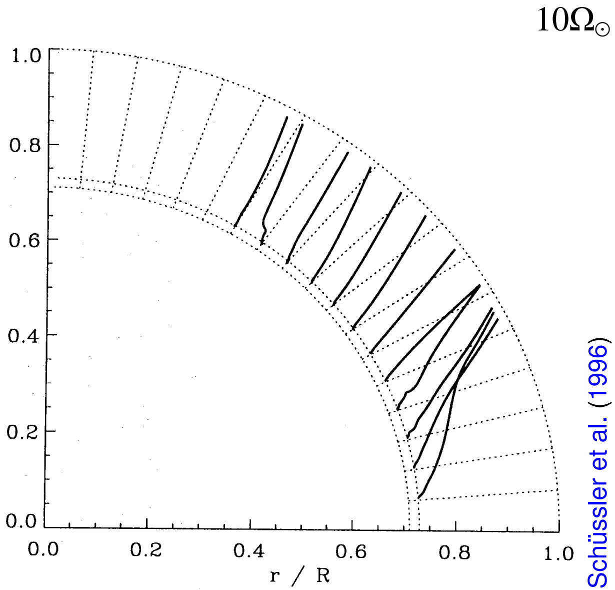
High-latitude spots through flux tube eruption

- the faster the rotation, the stronger the poleward deflection
  → formation of **polar spots** on rapid rotators (Schüssler & Solanki 1992; Buzasi 1997)
- **axisymmetric** flux tubes
  → maximal deflection: rise parallel to rotation axis

non-axisymmetric flux tubes
→ poleward deflection decreases with latitude



Buzasi (1997)



Schüssler et al. (1996)

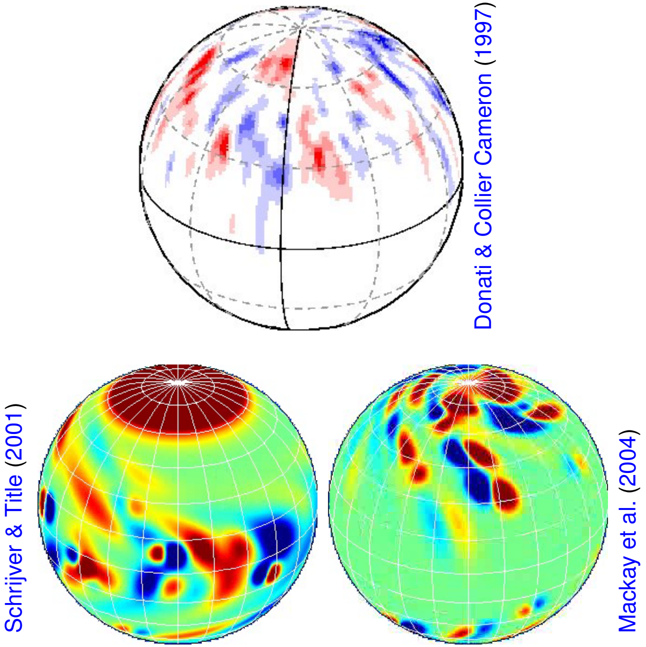
- high-latitude flux eruption on fast rotating solar-like stars

High-latitude spots supported by meridional flows

- combination of pre-eruptive & post-eruptive flux transport to high latitudes

- observation: mixture of polarities at high latitudes (e.g. Donati & Collier Cameron 1997)
    - $30\times$ solar flux emergence $\rightarrow$ unipolar polar spot (Schrijver & Title 2001)
    - $30\times$ flux emergence, larger latitudinal range, strong meridional flows $\rightarrow$ mixture of polarities (Mackay et al. 2004)

- strong meridional circulation enhances pre-eruptive poleward deflection (Holzwarth et al. 2006)



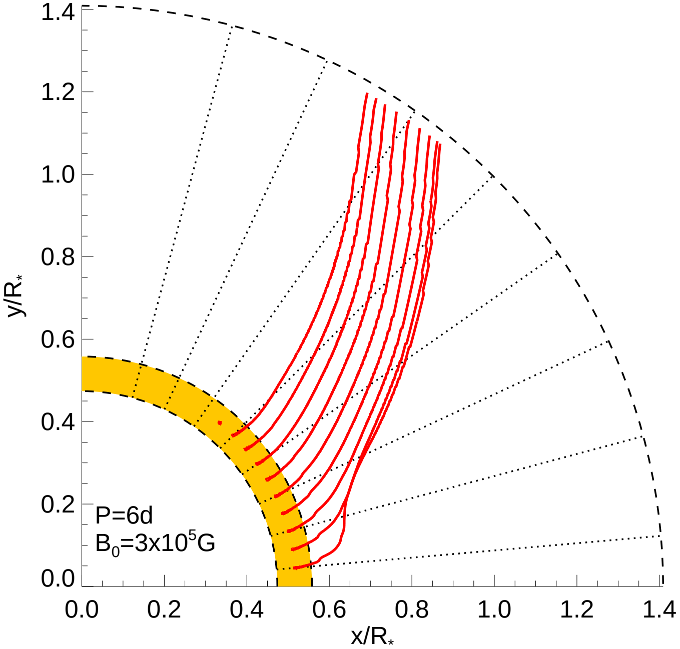
Images courtesy D. Mackay

Dependence on stellar structure

- pre-MS stars in spin-up phase, hardly braked by magnetised winds
  → **rapid rotators**

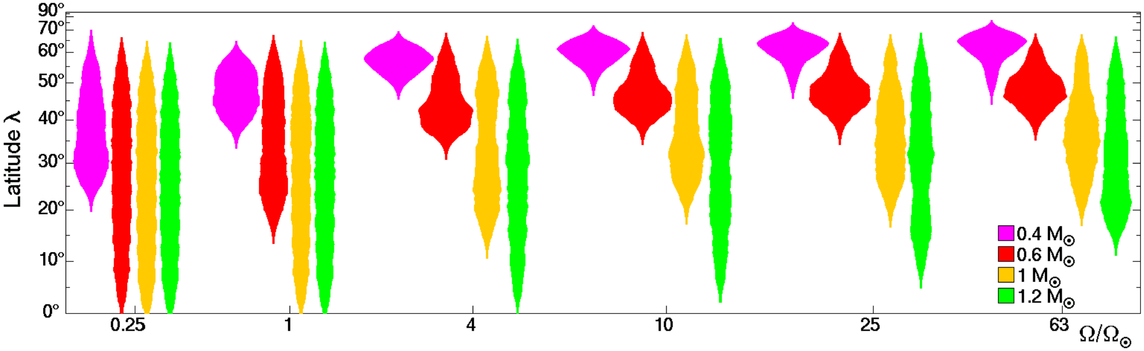
- young stars:
  - larger stellar radii & deeper convection zones imply **longer rise times**
  - lower superadiabaticity/larger pressure scale heights in CZ imply **weaker magn. buoyancy**

- Coriolis force dominates over magn. buoyancy
  → **large poleward deflection**

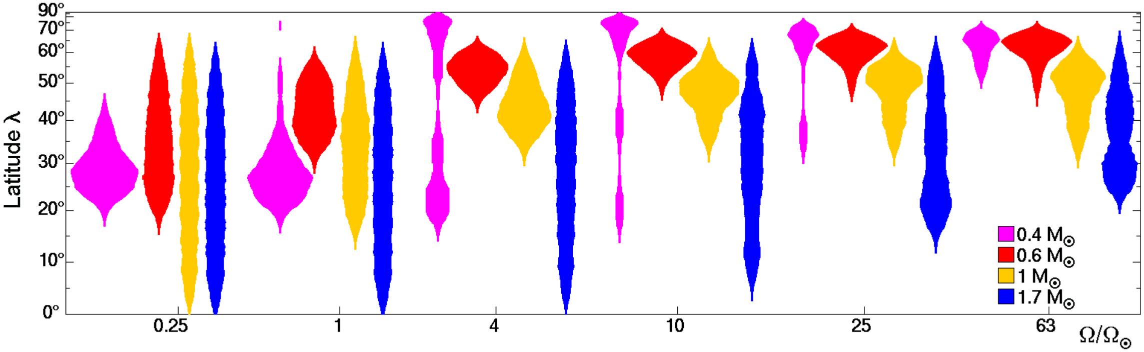


Latitudinal probability distributions (Granzer 2000; Granzer et al. 2000)

- ZAMS stars (age $1500 - 84\,\mathrm{Myr}$ for $0.4 - 1.2\,\mathrm{M}_\odot$)

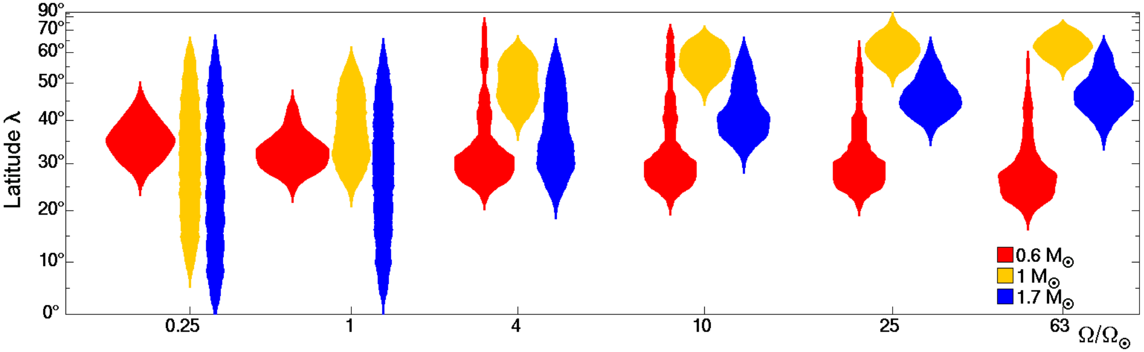


- pre-MS stars (age $27 - 7\,\mathrm{Myr}$ for $0.4 - 1.7\,\mathrm{M}_\odot$)

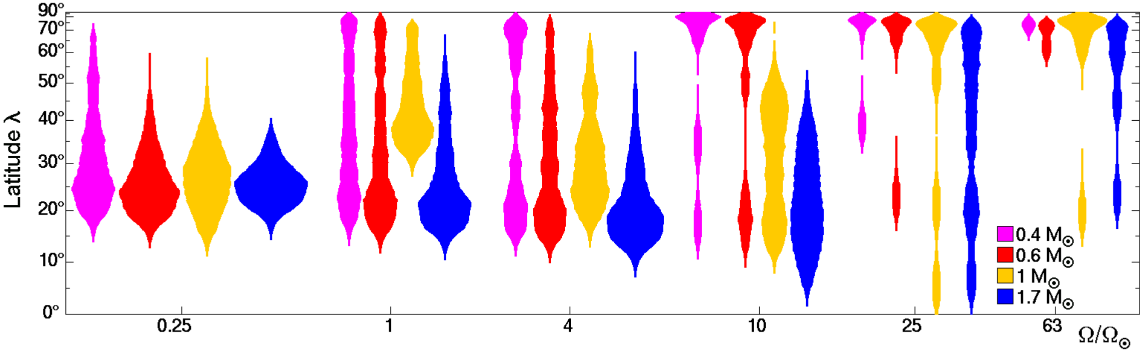


- increase of eruption latitudes for younger stars and for decreasing stellar mass

- TTauri stars (age $11 - 5\,\mathrm{Myr}$ for $0.6 - 1.7\,\mathrm{M}_\odot$)



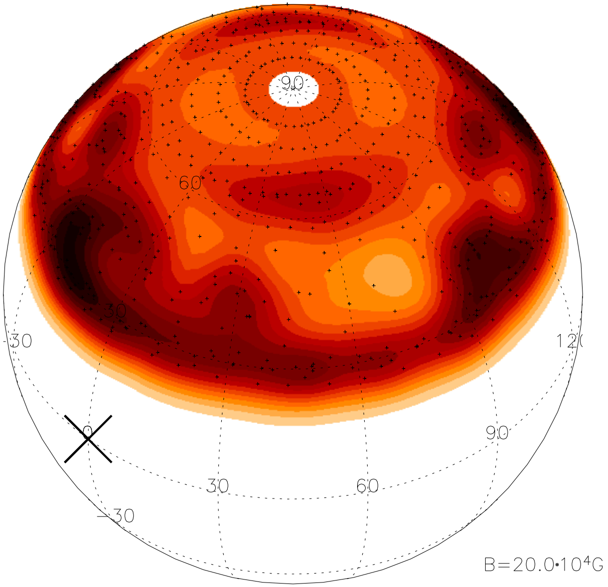
- ‘Hayashi’ stars (age $25 - 0.6\,\mathrm{Myr}$ for $0.4 - 1.7\,\mathrm{M}_\odot$)

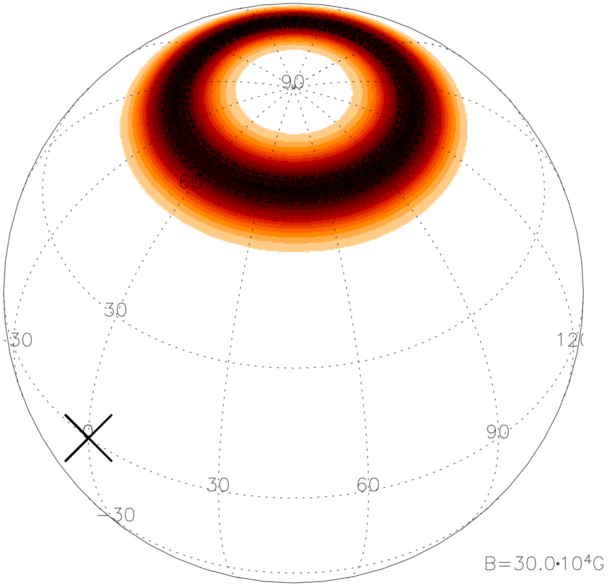


- for stars with very small radiative cores: detached flux tubes emerge at low latitudes ($\Omega \lesssim 10\Omega_\odot$) or pole ($\Omega \gtrsim 10\Omega_\odot$)

Close binary stars

- non-uniform longitudinal distribution through tidal effects (e.g. Holzwarth 2004)
- $1\,\mathrm{M}_\odot$-stars, $P_{\mathrm{sys}} = 2\,\mathrm{d}$: **MS** ($4.7\,\mathrm{Gyr}, 1\,\mathrm{R}_\odot$, left); **post-MS** ($11.8\,\mathrm{Gyr}, 2.3\,\mathrm{R}_\odot$)



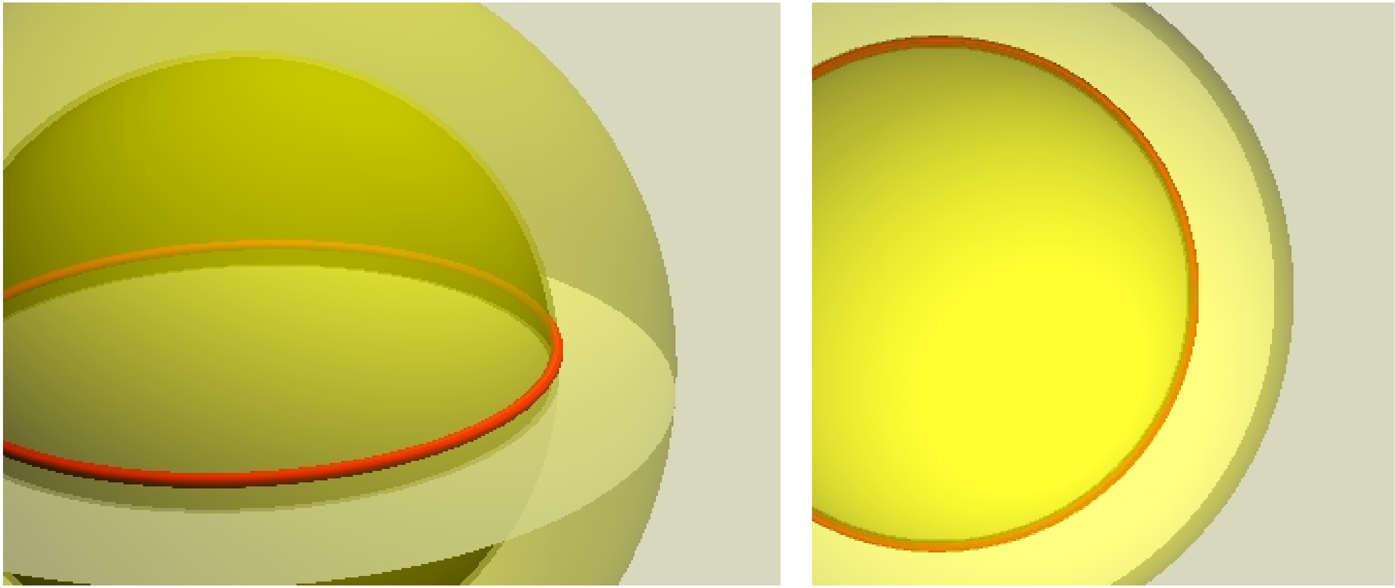


- flux emergence pattern depends on evolutionary stage and field strength

Summary

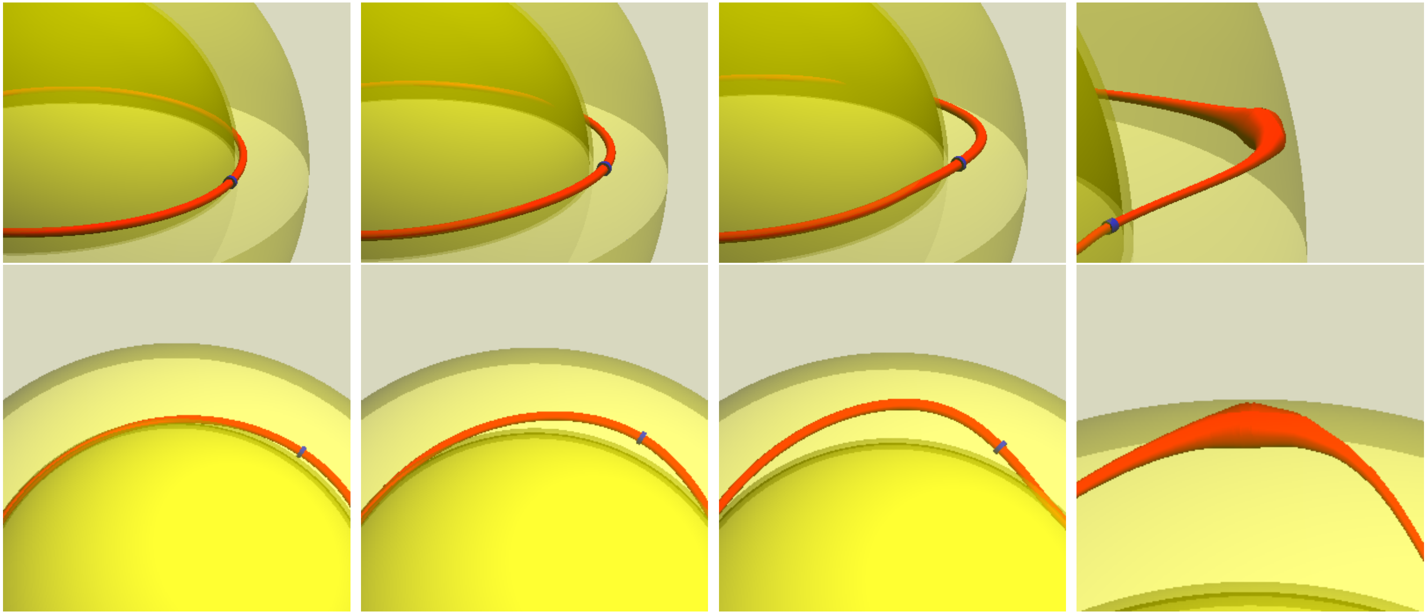
- solar flux emergence model **applicable to cool stars**
- equilibrium, stability, and eruption properties depend on **stellar rotation rate** and **stellar structure**
- poleward deflection and tilt angle depend on **ratio between Coriolis force and buoyancy**
- mean **latitude of flux emergence** increases with
  - increasing stellar rotation rate
  - decreasing stellar mass
  - decreasing stellar age
  - decreasing size of radiative core
- fast rotation: polar spots on young stars, high-latitude spots on (ZA)MS stars, likely supported by meridional circulation
- flux emergence at intermediate and low latitudes still possible

Eruption of magnetic flux tubes

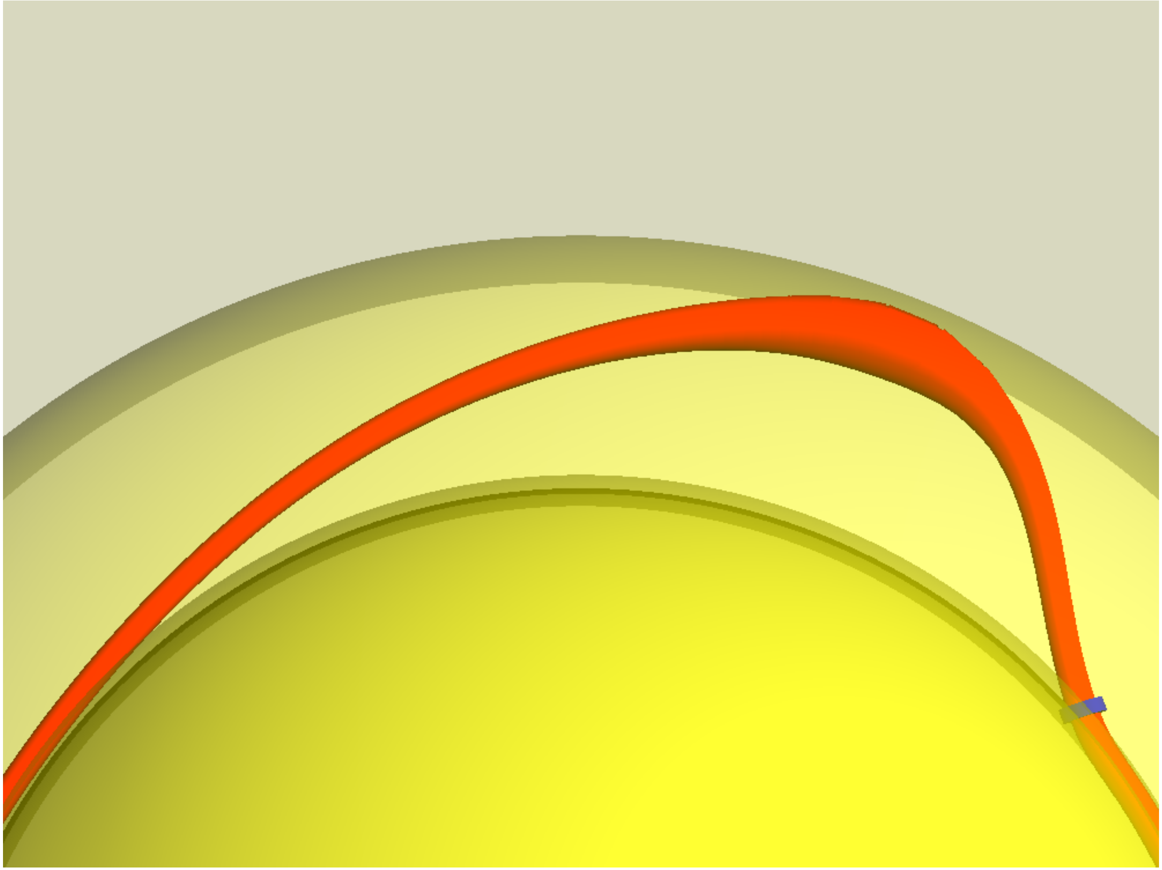


- solar-like MS star: $M = 1\,\mathrm{M}_\odot; R = 1\,\mathrm{R}_\odot; r_{\mathrm{cz}\to\mathrm{rc}} \simeq .72; \Omega = 2.8 \cdot 10^{-6}\ (P = 26\,\mathrm{d})$
- initial flux tube in mechanical equilibrium in mid overshoot region: $r_0 = 5.07 \cdot 10^{10}\,\mathrm{cm}; \lambda_0 = 5^{\mathrm{o}}; B_0 = 10^5\,\mathrm{G}; R_{\mathrm{tube}} = 1000\,\mathrm{km}$
- tube radius x5 for better visibility

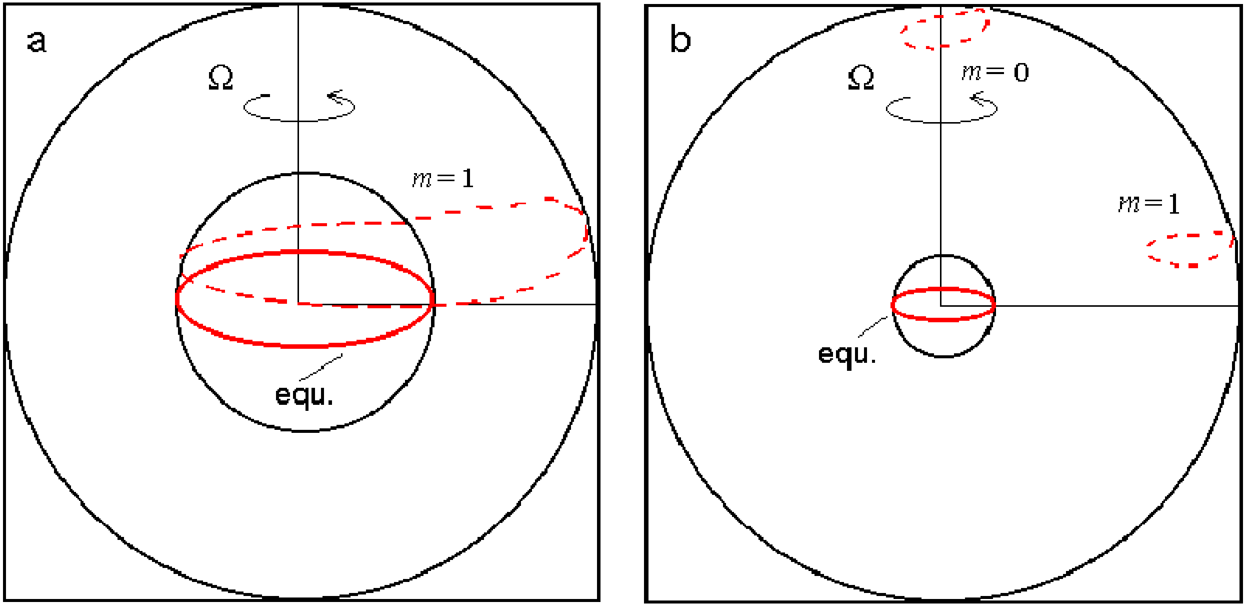
Eruption of magnetic flux tubes



Asymmetry of emerging flux tube

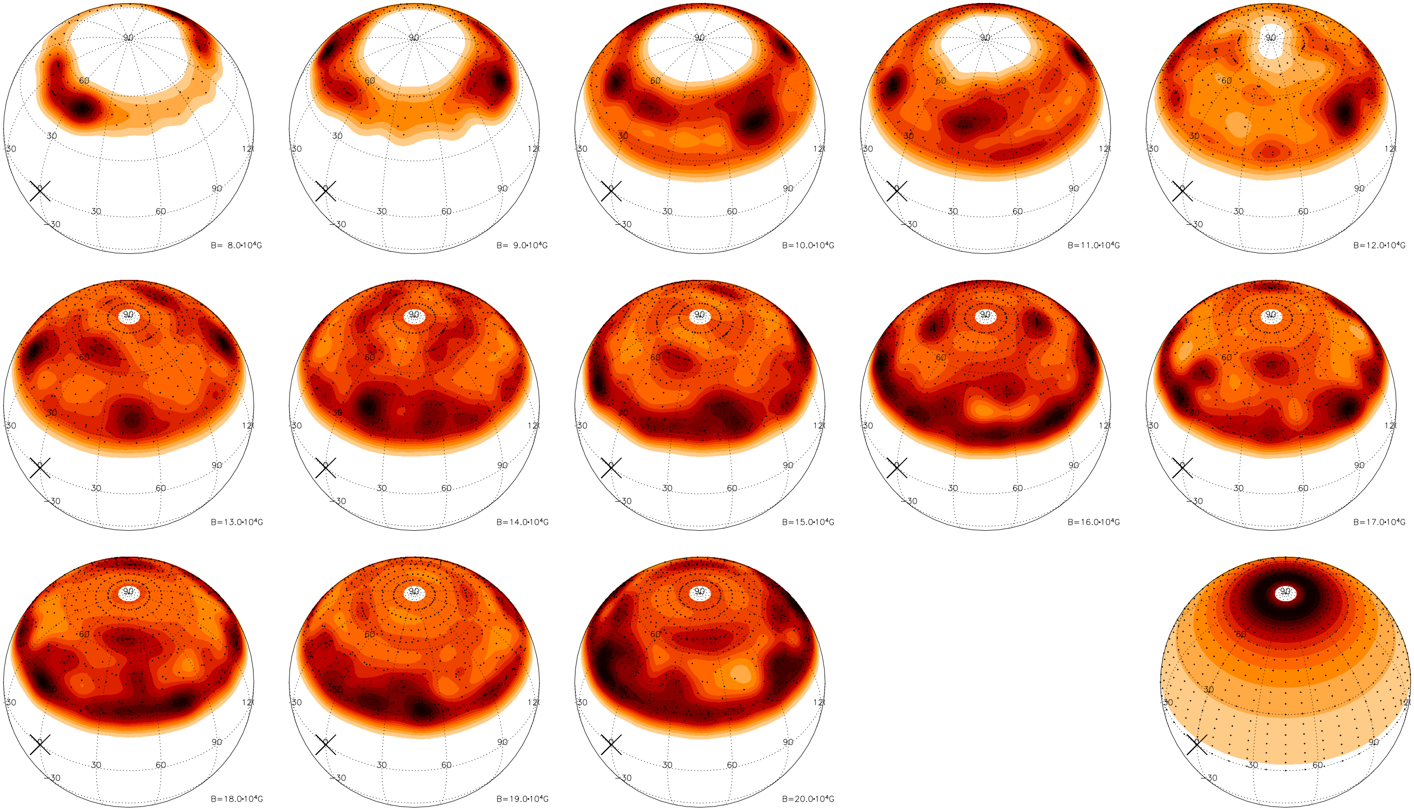


Eruption of magnetic flux tubes (II)



Granzer et al. (2000)

Flux emergence on close binary stars



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