STELLAR MAGNETIC ACTIVITY

(PAP351)

Lecture 12, April 17,2024

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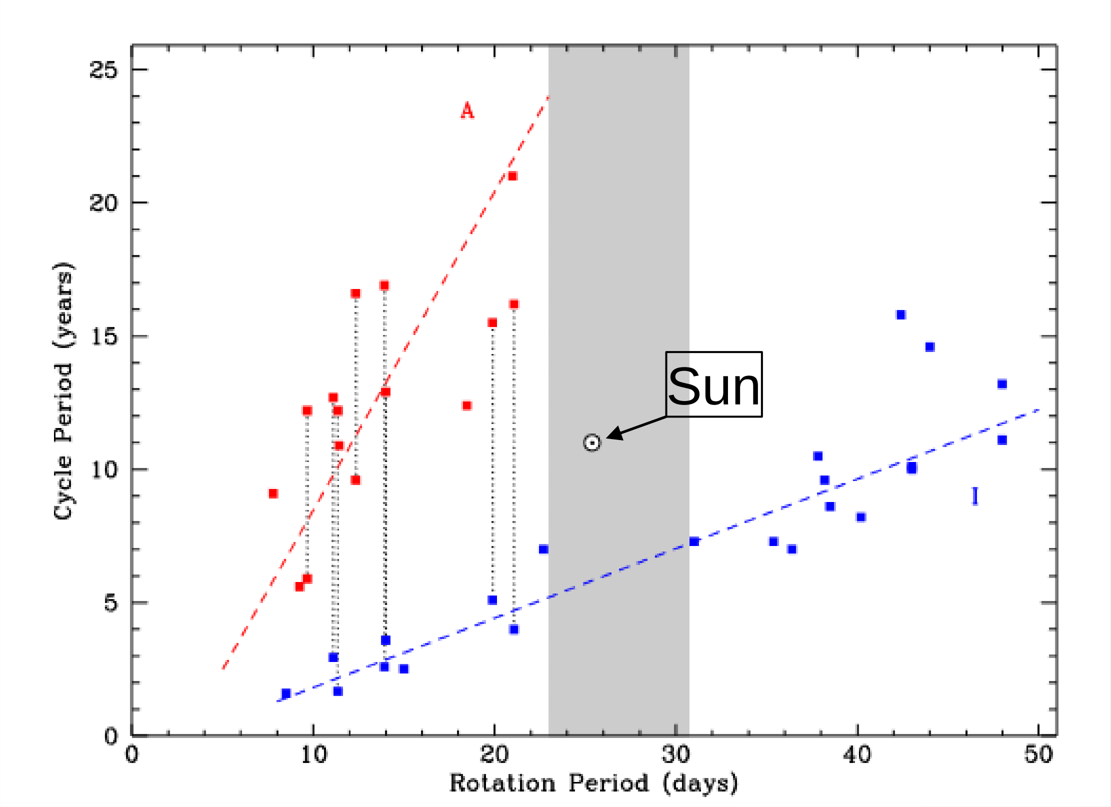
9. OPEN QUESTIONS IN STELLAR MAGNETIC ACTIVITY

- How typical is the Sun?
- How well do results from inversion methods represent real stars.
- Are there other mechanisms that can produce cool spots?
- Where does the solar dynamo operate?
- How does the corona get heated?
- What is the differential rotation of different late-type stars?
- Do tidal effects contribute to the timing of activity cycles?
- Can solar/stellar magnetic activity be predicted?

9.1 THE SUN AS A MODEL FOR OTHER STARS

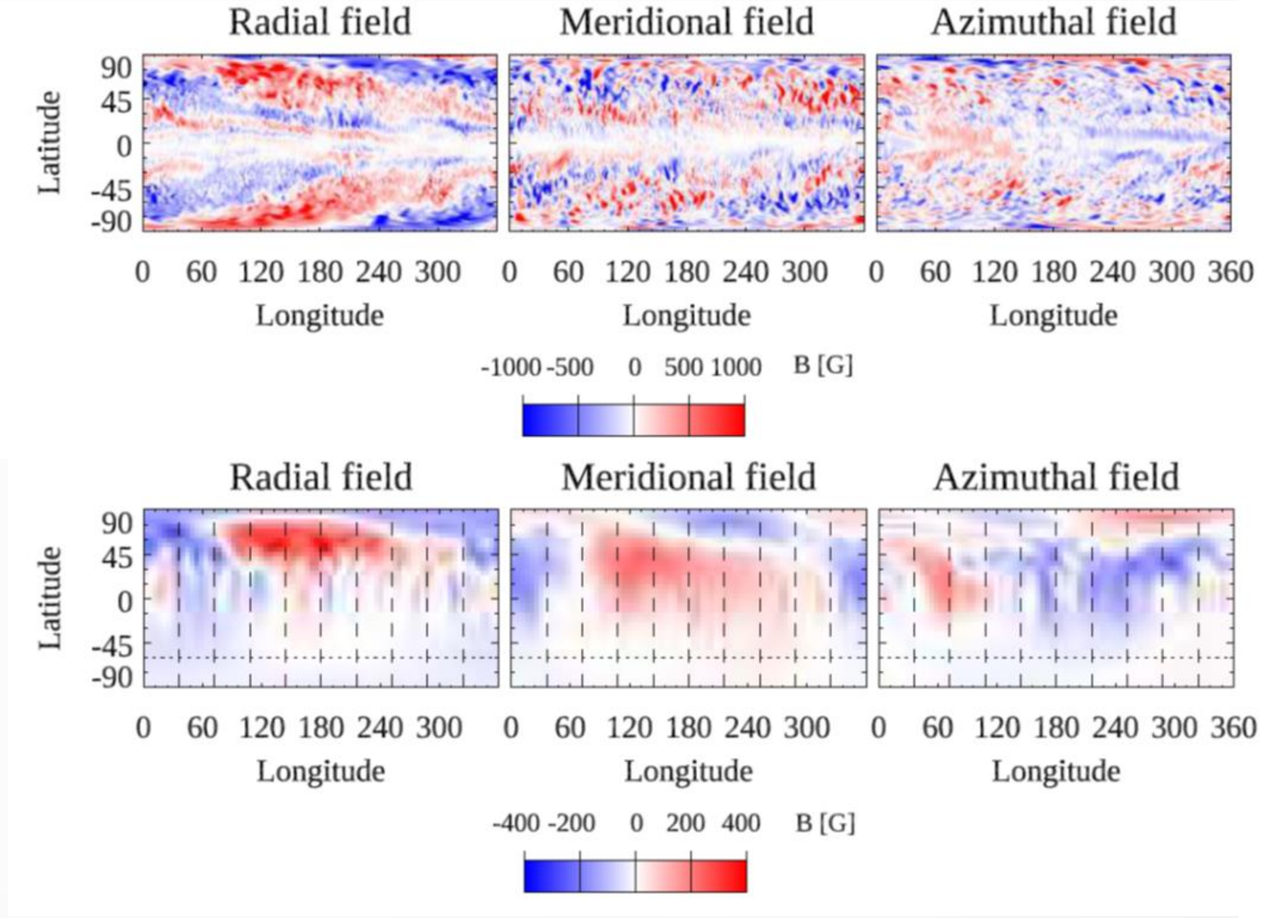
- Basis:
  - The Sun is a normal case of its spectral class and age.
  - The Sun is the only star we can observe in detail.
- Problems:
  - The Sun is just one case.
  - The Sun may be in a transition phase in terms of magnetic activity.
  - The Sun itself is impossible to model in detail.



"Active" and "inactive" branches of stars. The shaded region indicates the range of rotation periods around the Sun (Metcalfe et al. 2016).

9.2 HOW WELL DO INVERSIONS REPRESENT REAL STARS?

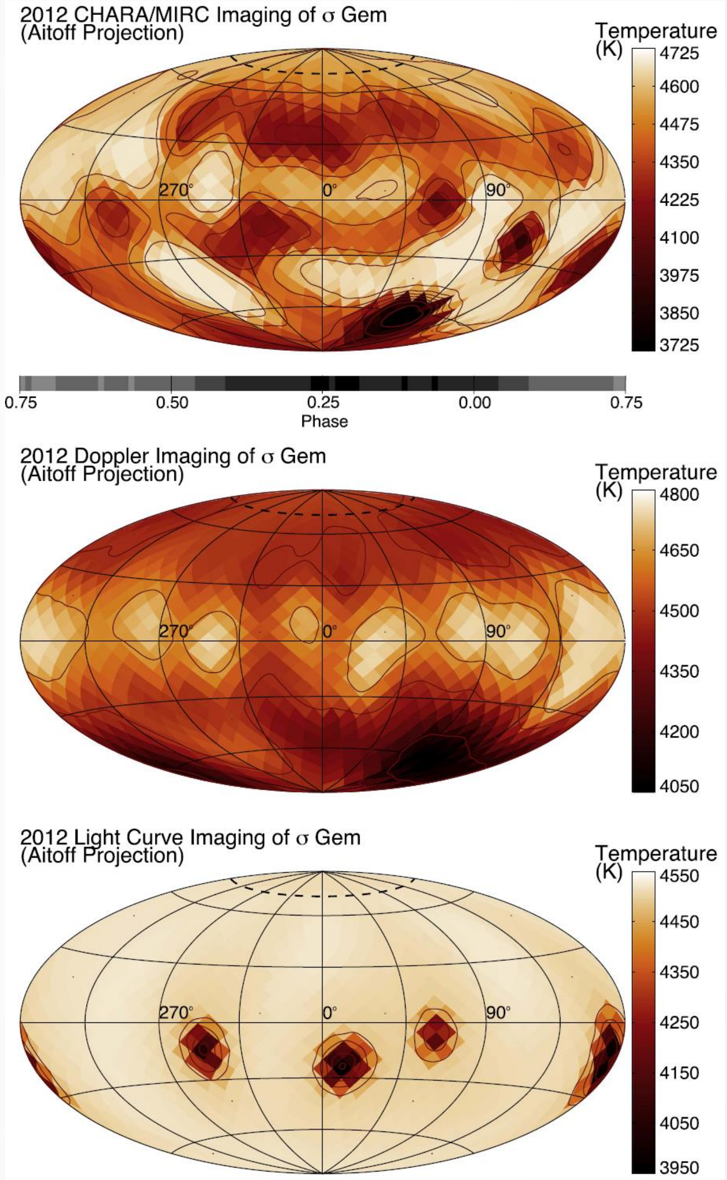
- Testing with simulated data => good recovery.
    - Problem: Inversion crime!
- Independent inversion methods => promising results.
- Main problems:
    - Symmetry effects.
    - Typical artifacts.
    - Low resolution.



MHD-simulations => ZDI inversions (Hackman et al. 2024).

9.3 COMPARISON OF SPOT MAPS

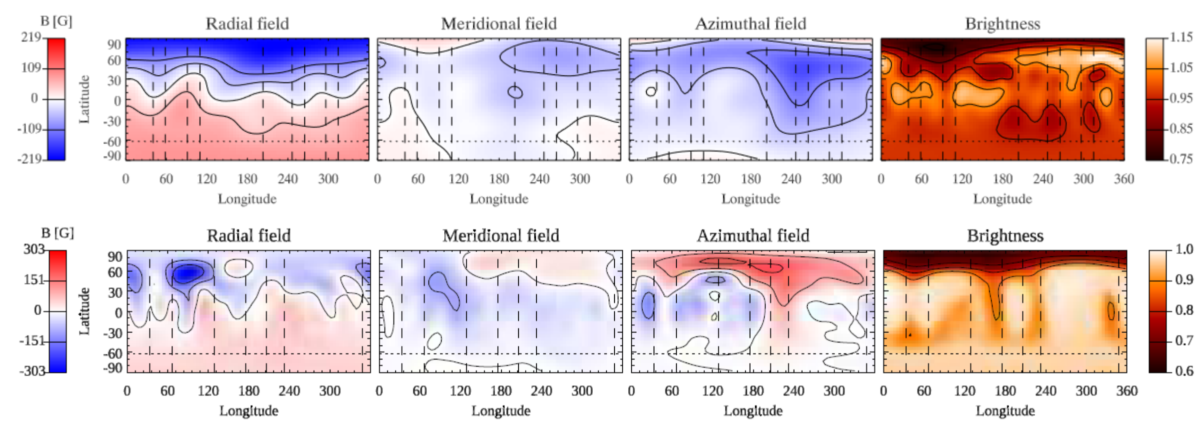
- Most convincing comparisons by using near-IR interferometry.
- Only possible for a few stars because of limited angular resolution + brightness constraints, e.g. ζ And and σ Gem.
- Requires simultaneous interferometry, photometry and high-resolution spectroscopy.
- Verification of e.g., polar spot structures.



The RS CVn star σ Gem mapped with simultaneous data (Roettenbacher et al. 2017).

9.4 FORMATION OF COOL SPOTS: ZDI-MAPS

- Solar analogy:
  - Magnetic field loops penetrate the photosphere.
  - => Inhibition of convection.
- Problem:
  - ZDI maps do not show very strong correlation between radial magnetic field and cool spots.
- Explanations:
  - ZDI recovers large only scale fields.
  - Opposite small-scale polarities cancel.
  - Recovered field is ”weighted” by the surface intensity.



ZDI maps of HD 29615 (G3V; 203 & 2017): Correlation between Br and brightness $r \sim 0.2$ (Hackman et al. 2016; Willamo et al. 2022).

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9.5 FORMATION OF COOL SPOTS: MAGNETIC FIELD STRENGTH

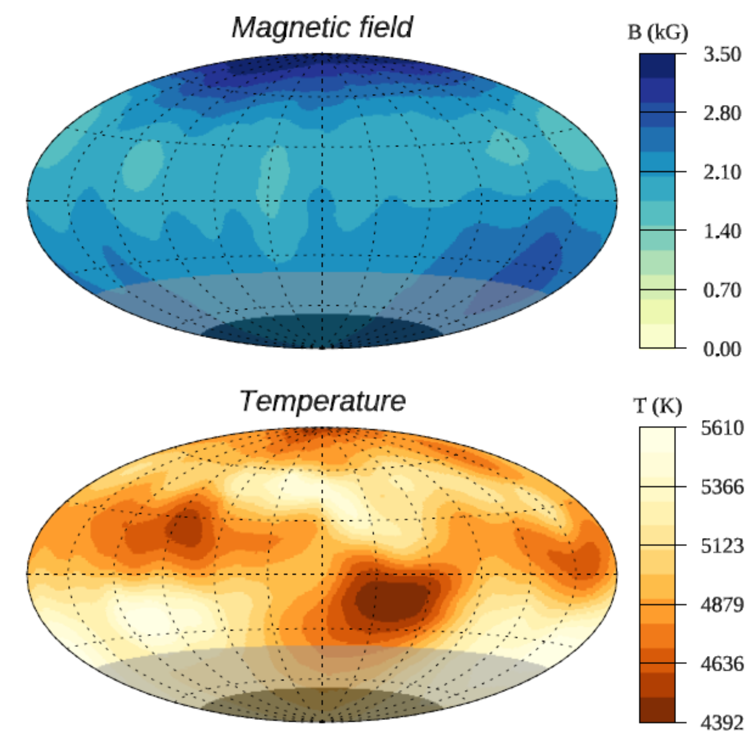
- Zeeman splitting => stronger and broader absorption lines.

Landé factor

- Zeeman broadening: $\Delta v_B \approx 1.4 \times 10^{-3} g_{\mathrm{eff}} \lambda B$ [km/s]

Magnetic field strength

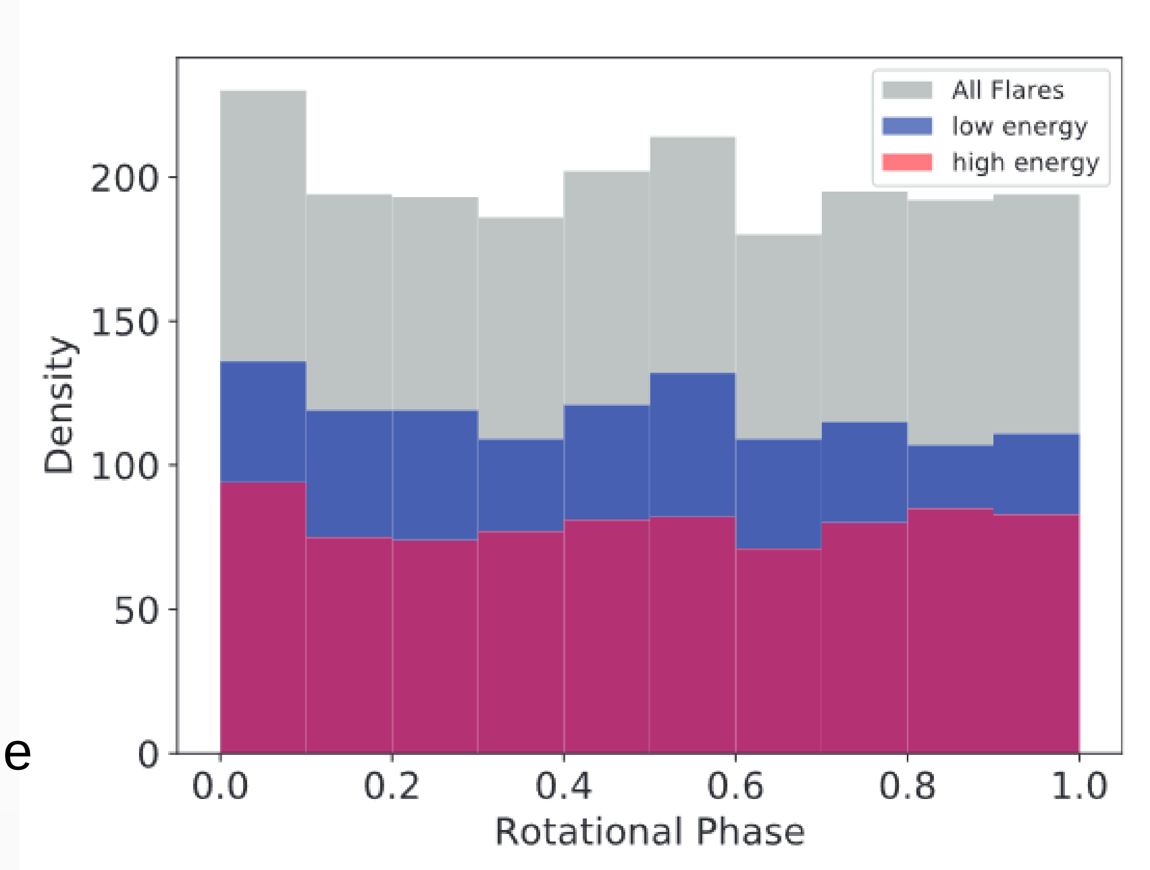
- Using lines with different g_{eff} => Distinguish between T_{eff} and B.
- Results for LQ Hya: Still no clear correlation between B and T_{eff}.



Maps of surface B and T_{eff} for LQ Hya (K2V; 2011): Weak B in low latitude spots (Kochukhov et al. 2023).

9.6 COOL SPOTS AND FLARES

- In the Sun flares are associated with complex magnetic active regions.
- => flares happen in large spot structures.
- => rotational phases of flares should coincide with those of spots.
- Not always the case.
- Explanation:
    - High latitude spots can be constantly visible due to rotation axis inclination.



Rotational phase distribution of flares for 209 solar-type stars (Doyle et al. 2020).

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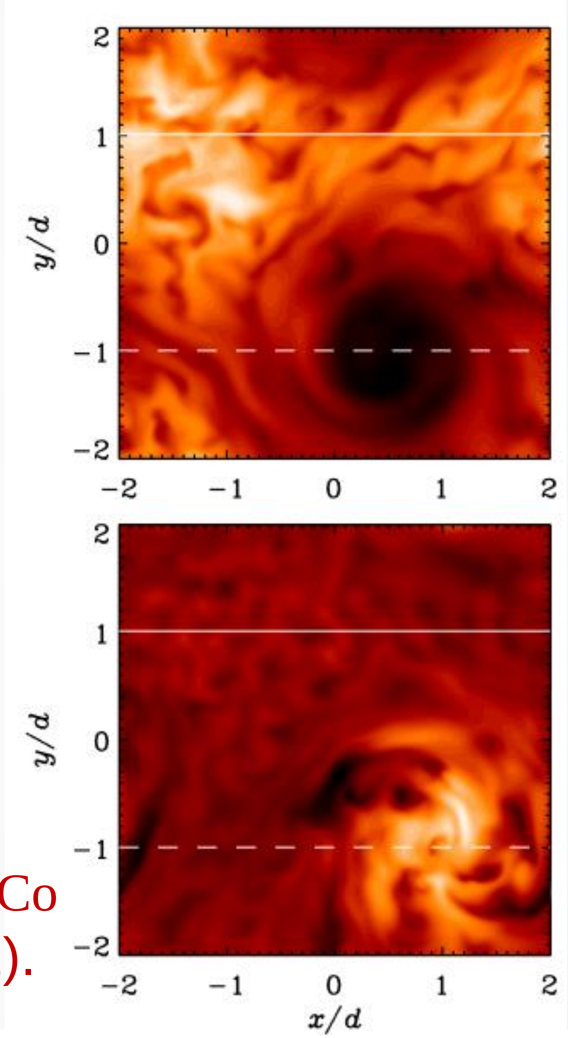
9.7 ALTERNATIVE SPOT FORMATION?

- Numerical simulations (e.g., Käpylä et al. 2011):
  - Starspots generated without magnetic fields by large-scale vortices due to rotation + turbulent convection.
  - Analogues to Jupiter’s red spot.
  - Cyclons => cool spots.
  - Anticyclons => hot spots.
- Problems:
  - Fast rotation => more anticyclons.
  - Interaction with magnetic fields?



Models with two different values of Co (Käpylä et al. 2011).

9.8 STELLAR DYNAMO MODELS

- Babcock-Leigthon dynamo:
  - Operates in the tachocline.
  - Rising flux tubes + Coriolis force => twist => poloidal field.
  - Meridional flow determines activity cycle.
- Parker (distributed) dynamo:
  - Not restricted to the tachocline.
  - Magnetic loops “frozen” in rising convective bubbles + Coriolis force => α-effect => poloidal field.
  - Convection is the central ingredient.
- Other models: Near-surface shear layer Dynamo (Vasil et al. 2024).

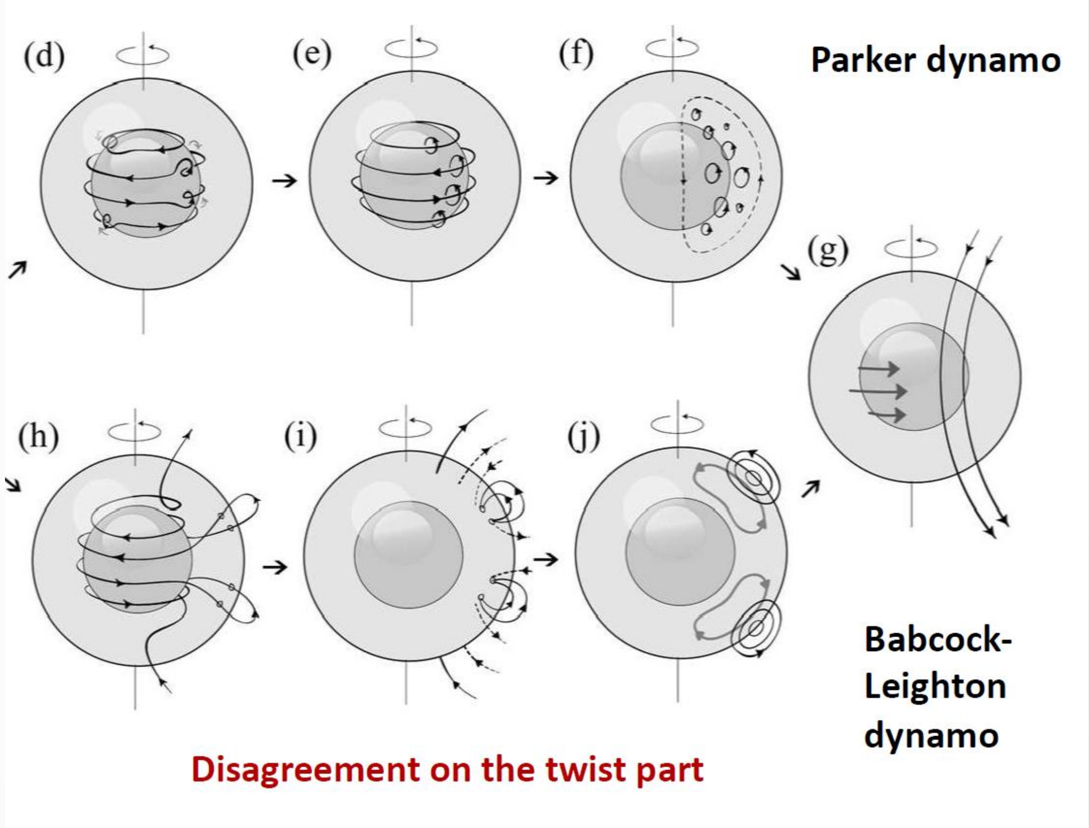
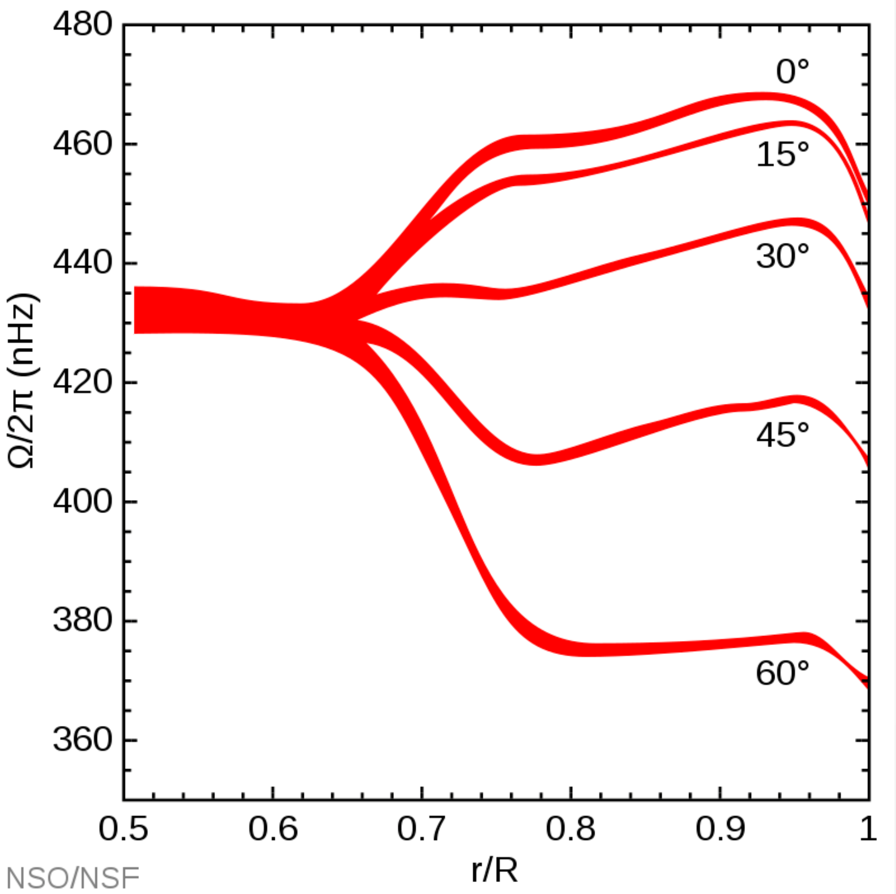


Fig. by M. Korpi-Lagg (lecture 8).

9.9 STELLAR DIFFERENTIAL ROTATION

- Solar differential rotation is well known:
    - Angular velocity of surface features.
    - Helioseismological observations (p-modes).
- Stellar differential rotation is hard to measure <= stars in general point sources.
- Indirect methods:
    - Tracking spots with Doppler imaging.
    - Fitting differential rotation in Doppler or Zeeman-Doppler imaging.
    - Time-series analysis of photometry.
    - Asteroseismology.



NSO/NSF

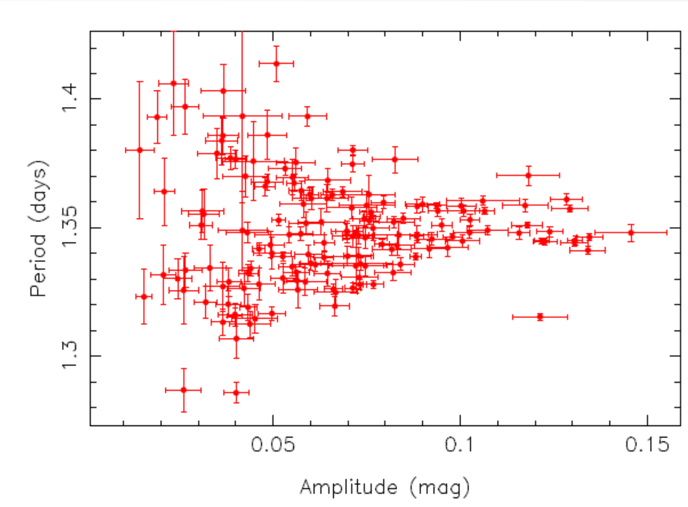
Solar differential rotation (Global Oscillation Network Group 2008).

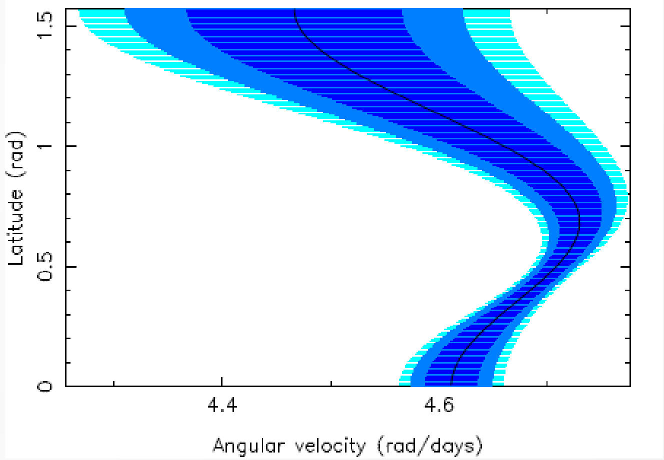
9.10 STELLAR DIFFERENTIAL ROTATION: PROBLEMS

- Usually the monotonic solar differential rotation (DR) curve is applied:

$$\Omega(\theta) \approx \Omega_{eq} - \Delta\Omega \sin^2(\theta)$$

- But numerical simulations indicate non-monotonic differential rotation.
- Recent support for non-monotonic DR from observations.
- Conflicting results for some stars.
- Asteroseismology currently not very accurate.

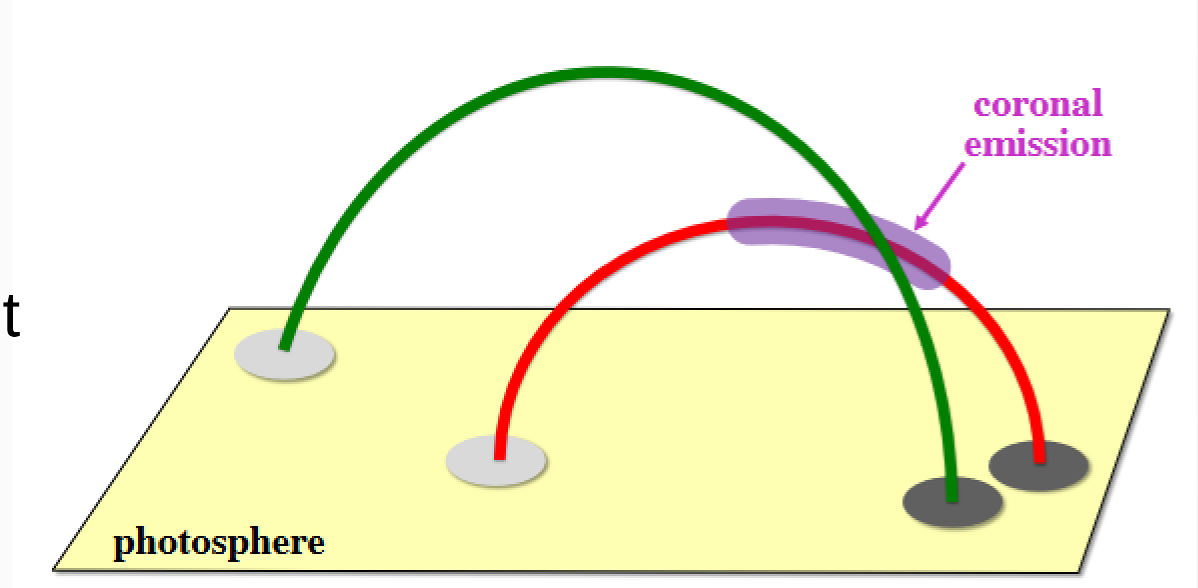




DR-model for V889 Her (G2V; Tuomi et al. 2024).

9.11 HEATING OF CORONA

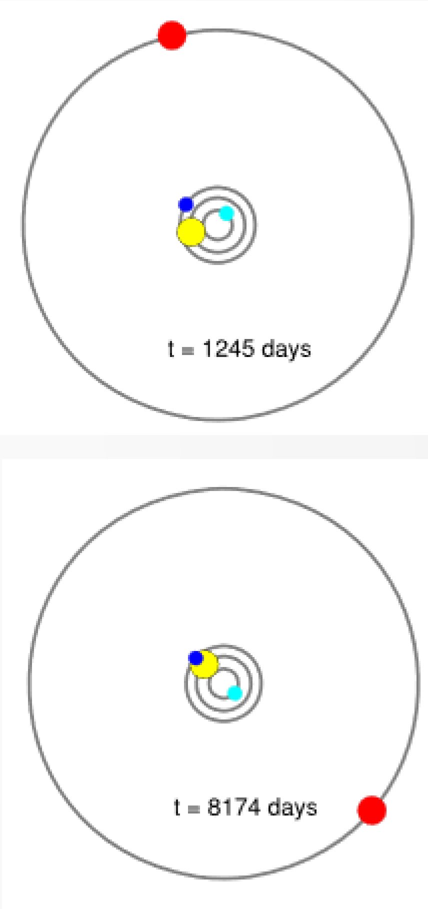
- Wave heating caused by convection:
  - Magneto-acustic and/or Alfvén waves.
  - E.g., local heating by Alfvén-cyclotron dissipation (Kasper et al. 2008).
- Magnetic reconnection:
  - Microflaring / ”camp fires”
  - Supported by observations by ESA's Solar Orbiter (Berghmans et al. 2021).



Magnetic structure of a campfire (Chen et al. 2021).

9.12 TIDAL TIMING EFFECTS?

- Historic background:
  - Jupiter’s orbital period $P_{\mathrm{orb}} \approx 11.9\ \mathrm{yr}$.
  - Solar spot cycle $\sim 11\ \mathrm{yr}$.
  - $=>$ Claims that the combined tidal effects of solar system planets could cause the solar spot cycle (e.g., Wood 1972; Scafetta 2023).
  - Disputed by e.g. Cionco (2023).
- Tidal effects clearly play a role in close orbits.
- But physical connection for e.g., the solar system has not been (indisputably) proven.



Positions of Jupiter, Earth, Venus and Mercury at the minimum and maximum tide (Nataf 2022) .

9.13 PREDICTING SOLAR MAGNETIC ACTIVITY

- Using previously observed patterns to predict.
- Numerical (physical) models => prediction.
- None of these very effective.
- Current predictions for the Sun:
  - Approximate timing of activity minima and maxima.
  - Estimates for amplitude of next cycle.
  - Connection between active regions and eruptions.
  - Historical estimates on frequency of solar energetic particle events.