STELLAR MAGNETIC ACTIVITY (PAP351)

Lecture 5, February 14,2024

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6.7 ANALYSES OF PHOTOMETRY

- Photometry => 0-dimensional data => More non-uniqueness problems.
- Still:
  - Rotational phase of minim => longitude of spots
  - Shape of spot induced minima => latitude of spot
- Analyses methods:
  - Time series analyses
  - Parametric spot modelling
  - Physical spot modelling

6.7.1 GROUND-BASED PHOTOMETRY

- Ground based photometry:
  - Very long time series of observations.
  - APT (automated photometric telescopes) and wide field monitoring.
  - Typically, 1 observation/night (weather permitting).
  - Accuracy typically $0.005 < \sigma_{mag} < 0.01$ mag.

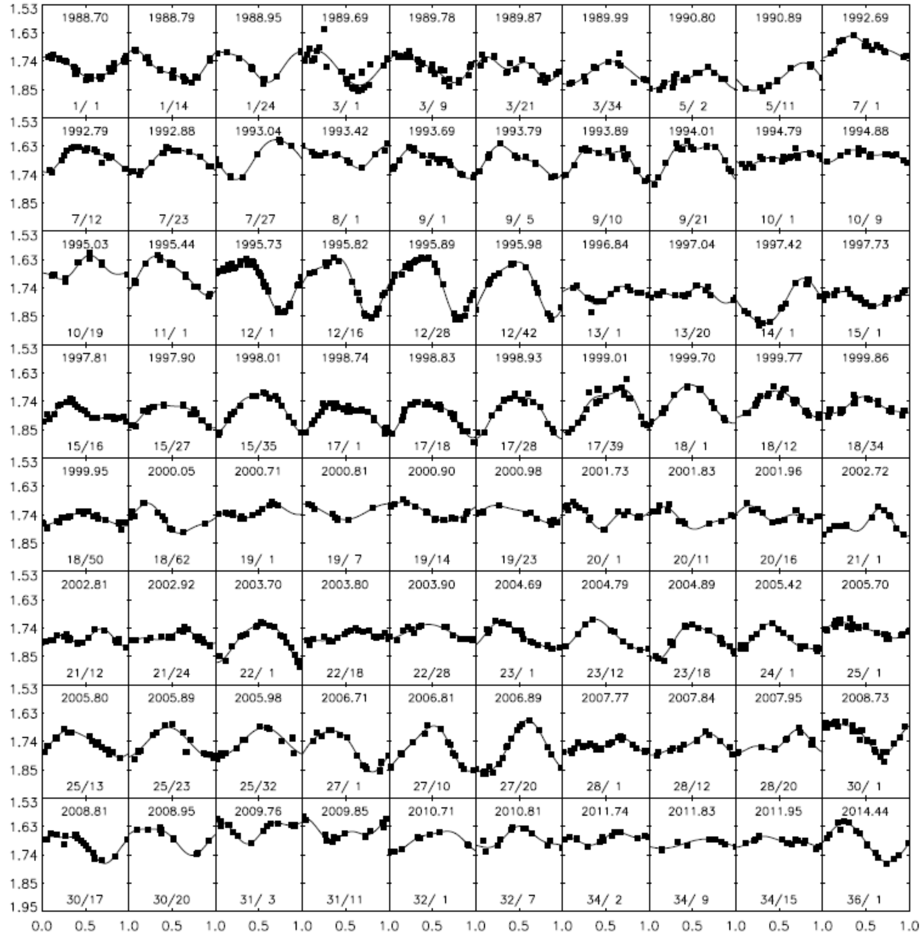
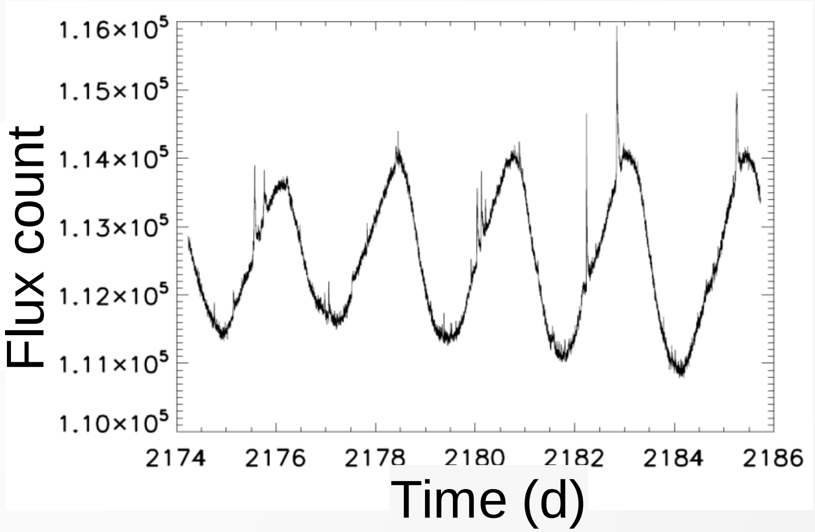


Figure 4.1: CPS fits for the independent datasets of PW And. For each dataset, the mean epoch τ is given in years above the fit and the segment/dataset numbers below the fit.

Lehtinen et al. 2016.

6.7.2 SATELLITE PHOTOMETRY

- Satellite observations:
  - Small optical space telescopes, mainly intended for other purposes.
  - MOST, Kepler, Corot, TESS …
  - Accuracy at least an order of magnitude better than for ground-based observations …
  - … but observing not optimised for long-term monitoring.



TESS light curve of EK Dra.

6.7.3 TIME SERIES ANALYSIS

- Parametric methods:
  - A periodic function fit to the data.
  - E.g., Fourier/power-spectrum or fitting of a truncated Fourier series.
- Non-parametric methods:
  - Search for periodicity in certain events, e.g., maximum or minimum of data.
  - E.g., *Kuiper*- or *Swanepoel & De Beer* –methods.

6.7.4 THE TSPA METHOD

- TSPA = *Three stage period analysis* (Jetsu & Pelt, 1999):
  - *Pilot search* $\mapsto$ *Grid search* $\mapsto$ *Refined search*
- Model:

$$g(t) = M + \sum_{k=1}^{K} B_k \cos(k2\pi ft) + C_k \sin(k2\pi ft) \ ,$$

where M, B_k, C_k and $f = \frac{1}{P}$ are free parameters.

- The model is non-linear => solution cannot be retrieved directly by the least squares method.

6.7.5 LIGHT CURVE QUANTITIES

- B_k and C_k are not as such useful descriptions of the light curve
- The light curve is best described by:
  - Mean magnitude M
  - Period P_{phot}
  - Amplitude A
  - Minimum phases $\phi_{\mathrm{min}_{1,2}}$ or epochs of minima $t_{\mathrm{min}_{1,2}}$

6.7.6 CONTINUOUS PERIOD SEARCH (CPS)

- The model $$g(t) = M + \sum_{k=1}^{K} B_k \cos(k 2\pi f t) + C_k \sin(k 2\pi f t) \,,$$

  $$M, B_k, C_k \text{ and } f = \frac{1}{P} \text{ are free parametres.}$$

 is applied with a moving window => better time resolution.

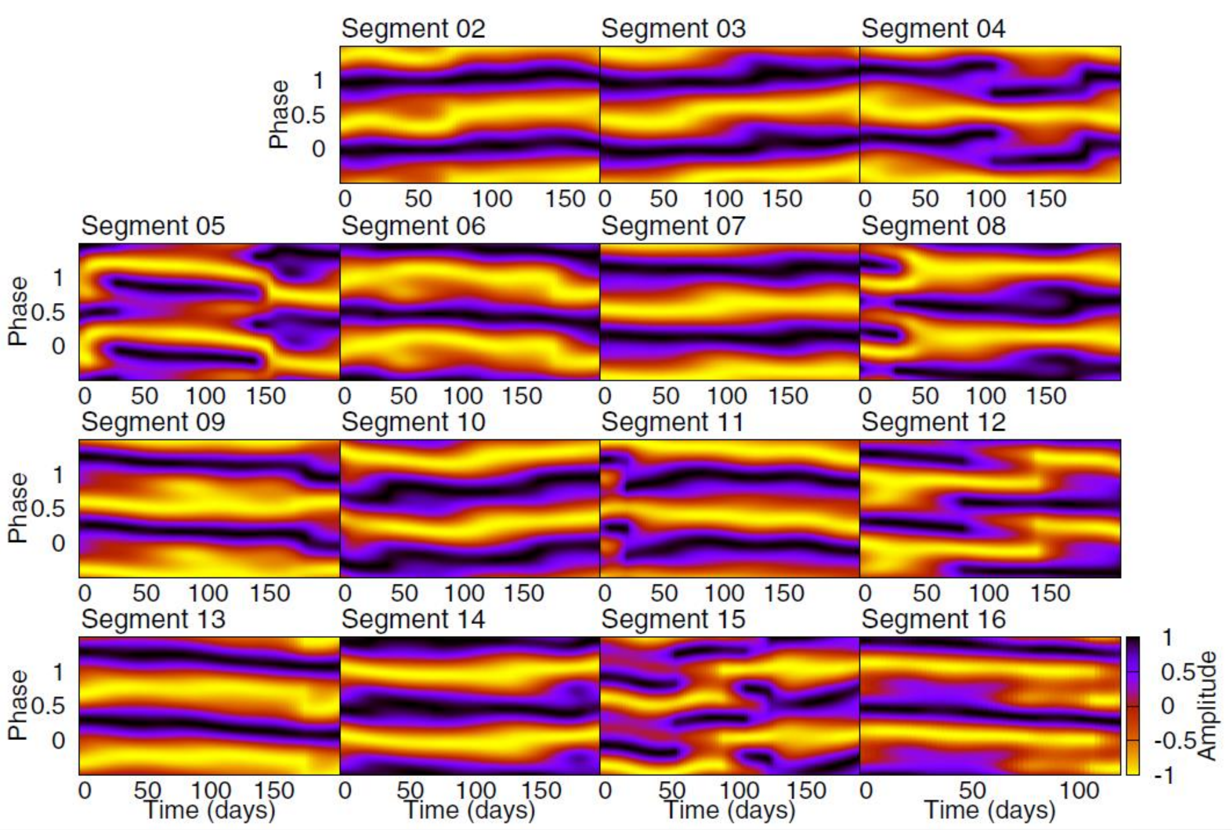
- Method published in Lehtinen et al. (2011).
- From the model: Light curve mean $\boldsymbol{M}$, amplitude $\boldsymbol{A}$, period $\boldsymbol{P}$ and times of photometric minima $\boldsymbol{t}_{\mathbf{min}}$ as functions of time.

6.8 CARRIER FIT METHOD

- *CF-method* (Pelt et al. 2011):

$$y_{\mathrm{cf}}(t) = a_0(t) + \sum_{k=1}^{K} \left(a_k(t)\cos(2\pi k f_0 t) + b_k(t)\sin(2\pi k f_0 t)\right)$$

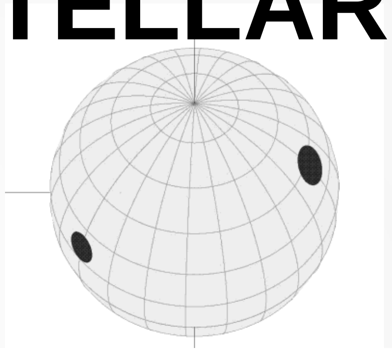
- Carrier frequency f_0.
- $a_k(t)$ and $b_k(t)$ slowly changing time dependent functions.



CF analysis for FK Com (carrier period $P_0 = 2.^{\mathrm{d}}40$). The amplitudes normalized separately for each segment (Hackman et al. 2013).

6.9 SPOT MODELLING OF STELLAR LIGHT CURVES

ε Eri (Croll et al. 2006).



- Star spot models => spot positions and P_{rot}.
- Ex. *MOST* satellite observations (Croll et al. 2006, Walker et al. 2007).

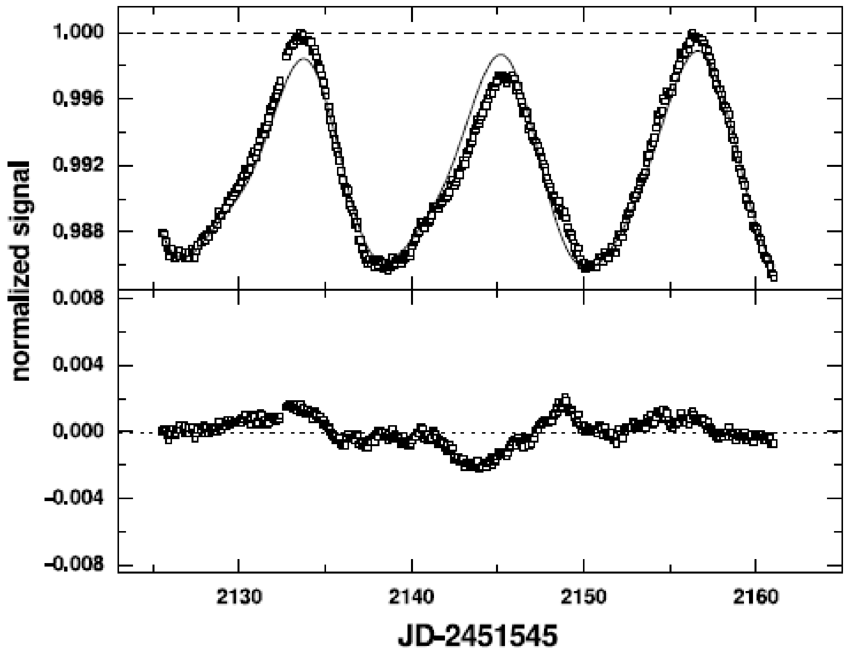


Fig. 2.—*Top:* ε Eri spots (Table 3) as seen from the line of sight (*left*) and the visible pole (*right*). *Middle:* The light curve of Fig. 1, with a linear trend removed. The solid line is the model from Table 3. The dashed line indicates the unspotted intensity of the star ($U = 1.0000$). *Bottom:* Residuals from the model on the same scale.

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6.10 IMPROVEMENTS OF PHOTOMETRIC TIME SERIES ANALYSIS

- Multiple periods => differential rotation.
- Changes in spot configuration => spot evolution time scale.
- Visibility of spots => different form of light curve.
- MCMC approach => statistical significance of model.

$$g(t) = g(t, K_1, K_2, K_3) = h(t) + p(t),$$

$$h(t) = h(t, K_1, K_2) = \sum_{i=1}^{K_1} h_i(t)$$

$$h_i(t) = \sum_{j=1}^{K_2} B_{i,j} \cos(2\pi j f_i t) + C_{i,j} \sin(2\pi j f_i t)$$

$$p(t) = p(t, K_3) = \sum_{k=0}^{K_3} p_k(t)$$

$$p_k(t) = M_k \left[\frac{2t}{\Delta T}\right]^k.$$

Direct χ^2 -method (DCM; Jetsu 2020).

6.11 NON-PARAMETRIC METHODS

- No model fit, search for periodicity in e.g. light curve minima.
- For circular data one can use e.g., *Kuiper* test (1960).
- Time points transformed into circular data by folding the points with a period.
- Can be used to detect active longitudes:
    - Test distribution of minimum phases: Significant difference from a random distribution => sign of active longitudes.

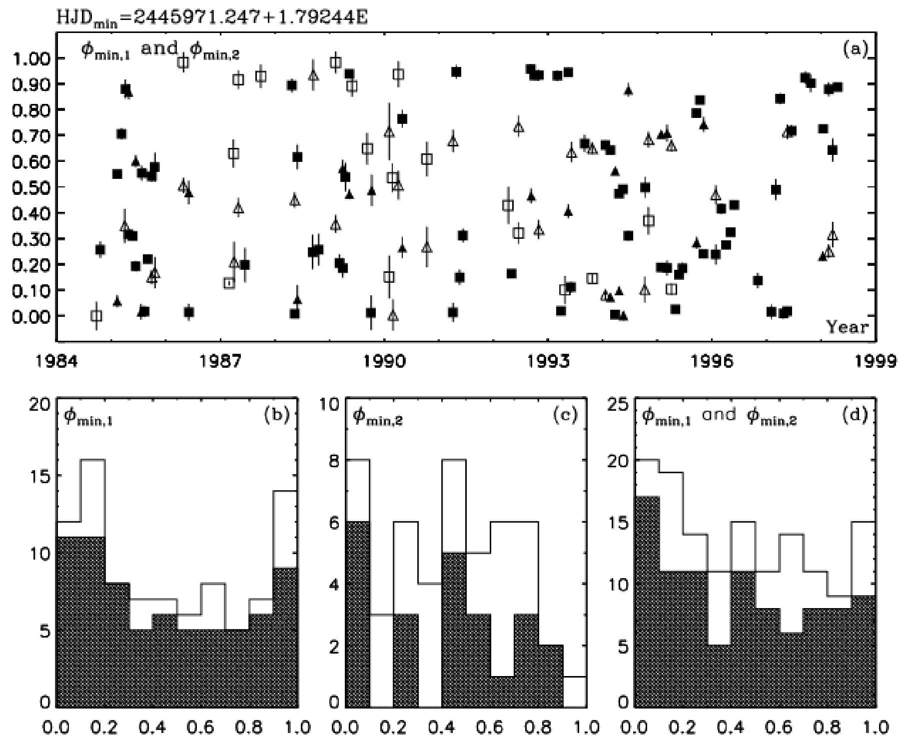
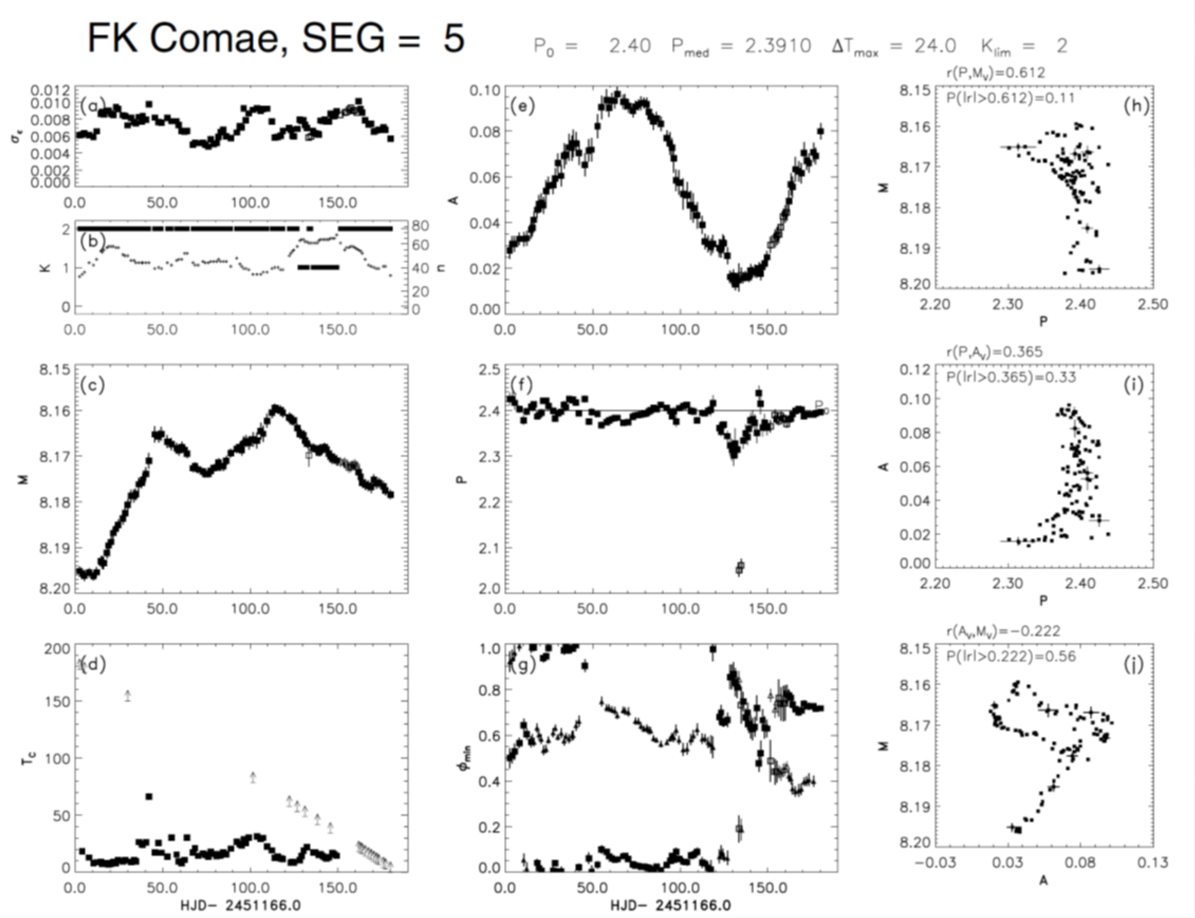


Fig. 6. **a** The phases of the primary and secondary minima with $HJD_{min} = 2445971.247 + 1.79244E$: $\phi_{min,1}$ (filled squares $\equiv T_A$; open squares $\equiv T_B$) and $\phi_{min,2}$ (filled triangles $\equiv T_A$; open triangles $\equiv T_B$) **b** The $\phi_{min,1}$ distribution (dark$\equiv T_A$; white$\equiv T_B$) **c** The $\phi_{min,2}$ distribution (dark$\equiv T_A$; white$\equiv T_B$) **d** The combined $\phi_{min,1}$ and $\phi_{min,2}$ distributions

Search for active longitudes in V815 Her (Jetsu et al. 1999).

7. OBSERVATIONAL RESULTS

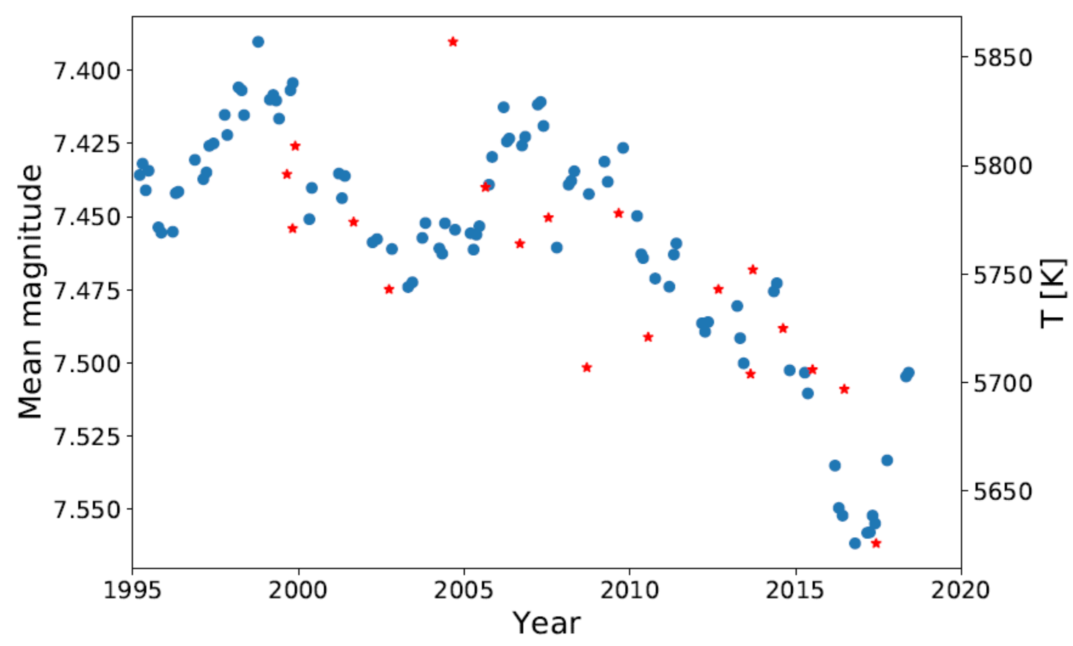
- Active latitudes.
- Active longitudes, “flip-flops” and possible dynamo waves.
- Spot cycles.
- Magnetic polarity reversals.
- Differential rotation.



CPS-results for FK Comae (Hackman et al. 2013).

7.1 SPOT CYCLES

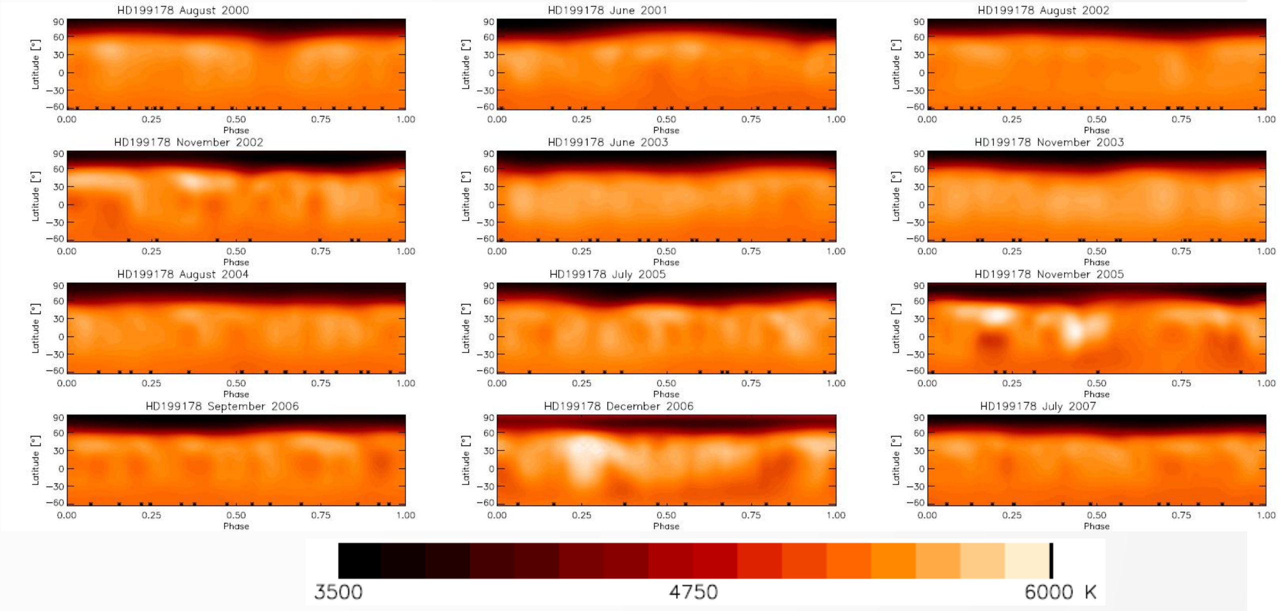
- Spot cycles for active stars are usually quasi periodic.
- Cycles can be seen from both long-term photometric and DI monitoring.

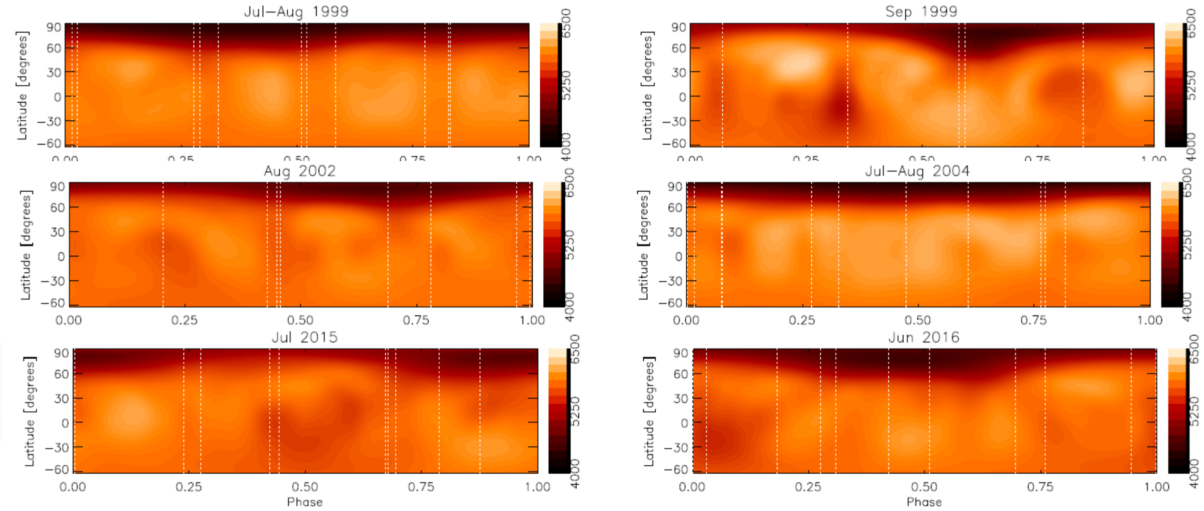


Mean magnitudes (blue dots) vs. mean temperature of DI maps (red stars) for V889 Her (Willamo et al. 2018).

7.2 ACTIVE LATITUDES

- Long-term DI monitoring of HD 199178 (G2III-IV) and V889 Her (G2 V):
  - Persistent high-latitude spot activity.
- Different evolutionary stages, but similar spot distribution.

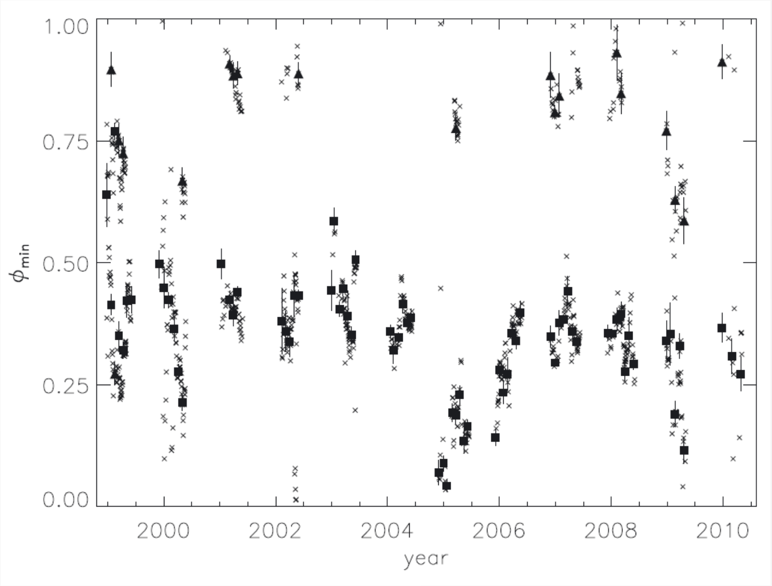




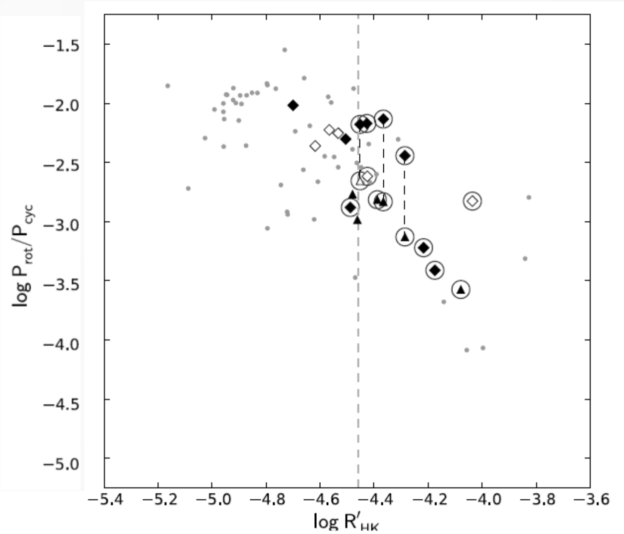
Figs. from Hackman et al. (2019) & Willamo et al. (2019).

7.3 ACTIVE LONGITUDES

- Persistent photometric minima at certain rotation phases <=> active longitudes.
- Often 2 active longitudes separated by $\Delta\varphi \sim 0.5$.



Active longitudes of HD 116956 (G9V, age ~100 Myr; Lehtinen et al. 2011).



Circles => stars with detected active longitudes. Grey vertical dashed line => approximate divide between stars with active longitudes and the one without them (Lehtinen et al. 2016).

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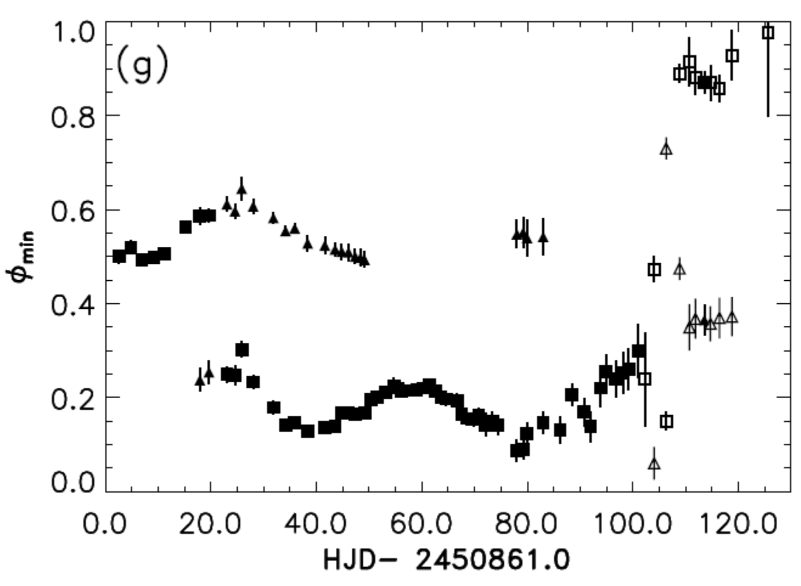
7.4 FLIP-FLOPS

- Concept of ”flip-flop” introduced by Jetsu et al. (1993).
- A sudden phase jump of the photometric minimum by $\Delta\varphi \sim 0.5$.
- => implies that the main spot activity has shifted to the opposite side of the star.
- In reality a more complicated phenomenon:
  - Photometric minima can be caused by complicated spot structures.
  - Both sudden phase jumps and gradual migration may look like ”flip-flops” (Hackman et al. 2013).

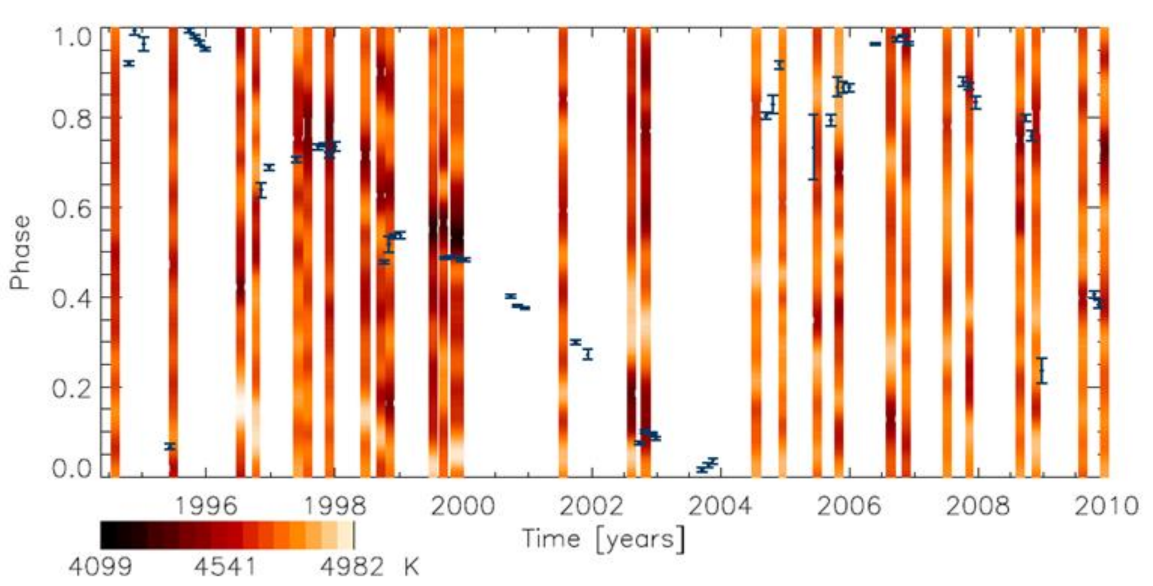


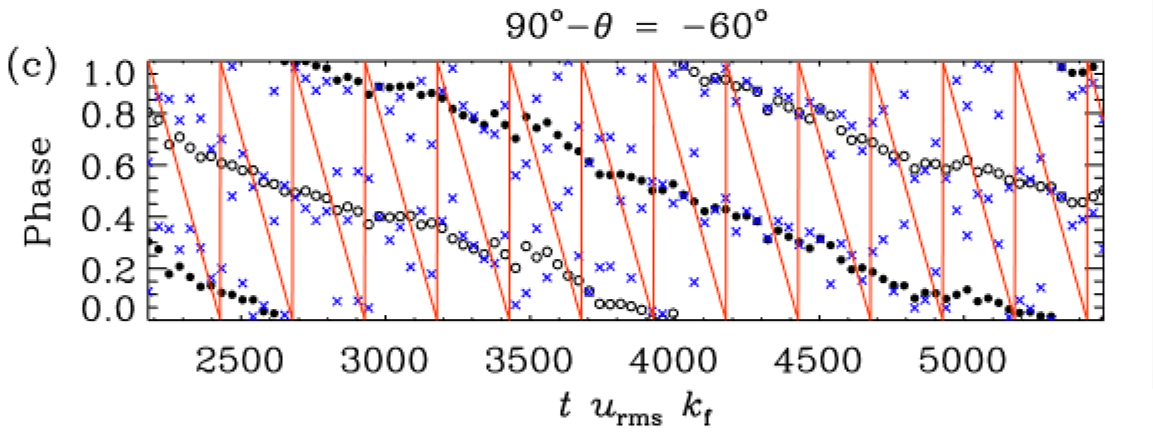
Claimed flip-flop in FK Com (Hackman et al. 2013).

7.5 DYNAMO WAVES?

- The photmetric minimum may migrate in the stellar rotational frame.
- Easiest to discover in tidally locked binaries => $P_{\rm rot}$ is accurately known.
- Theoretical interpretation: Azimuthal dynamo wave.

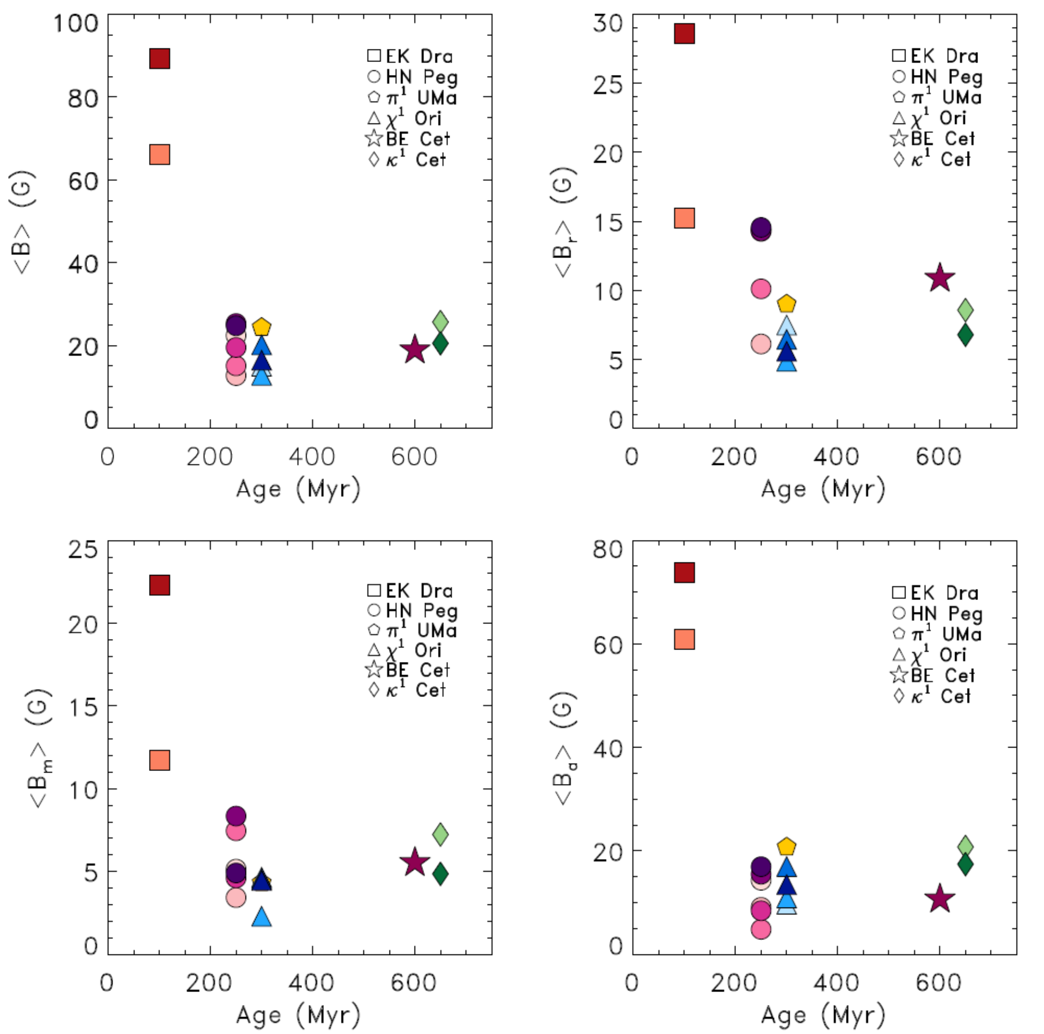
Possible dynamo wave in II Peg (RS CVn-type; Hackman et al. 2011) and MHD simulation (Cole et al. 2014).





7.6 MAGNETIC FIELD STRENGTH WITH AGE

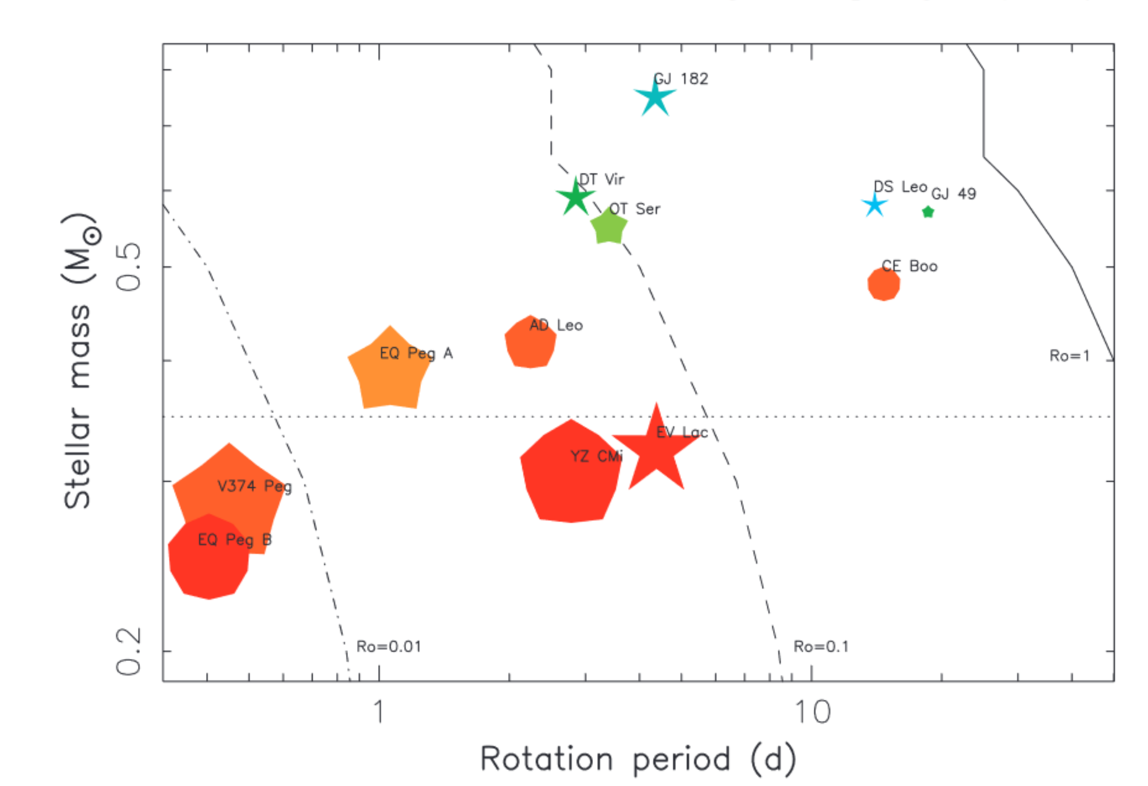
- A clear tendency compatible with magnetic breaking:
  - B strength decreasing with age.
- Note 1: Only large-scale B detectable by ZDI.
- Note 2: Insufficient recovery of B_m and B_a with only Stokes V.



Mean of total ($\langle B \rangle$), radial $\langle B_r \rangle$, meridional $\langle B_m \rangle$ and azimuthal $\langle B_a \rangle$ field strengths as a function of age for some young solar analogues (Rosen et al. 2016).

7.7 MAGNETIC FIELD TOPOLOGY

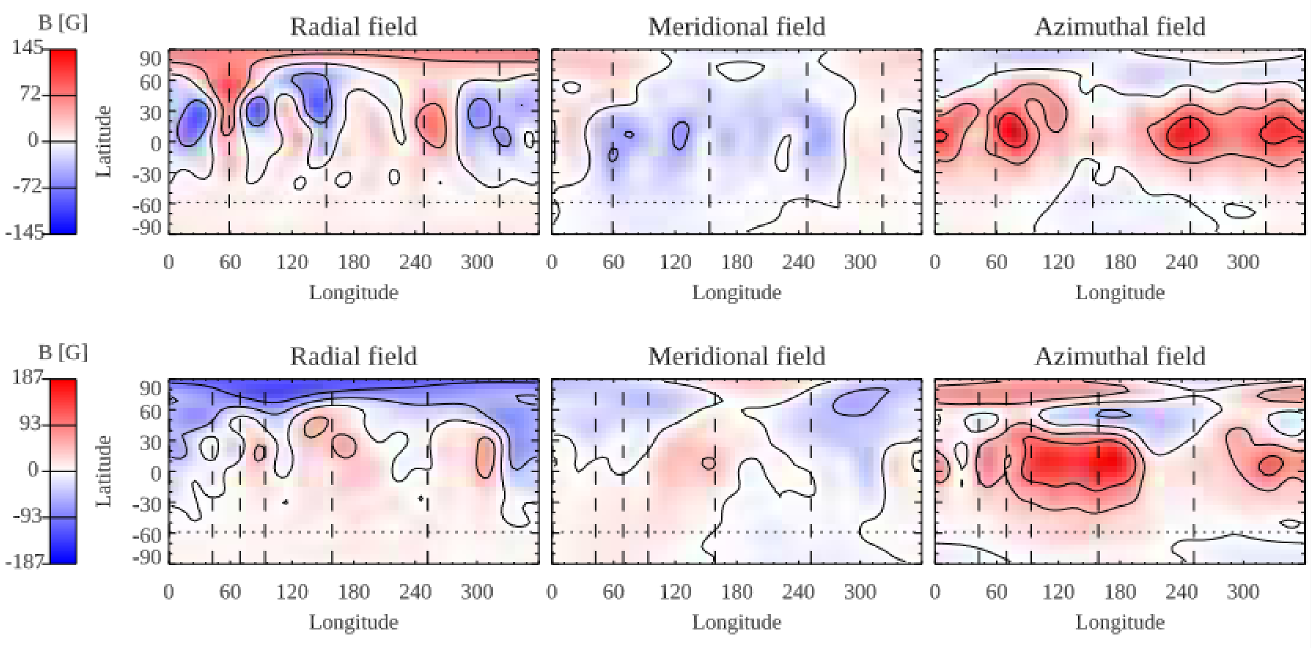
- Magnetic field energy is usually described in terms of:
  - *Axisymmetric* vs. *non-axisymmetric*.
  - *Poloidal* vs. *toroidal*.
  - Also, the energies of different spherical harmonics coefficients (ℓ, m) are reported.
- Plots often called *confusograms* (= confusingly much information).



Magnetic topologies of early M dwarfs: Size of symbol ⇔ B; Shape ⇔ axisymmetry; colour blue – red ⇔ toroidal – poloidal (Donati et al. 2008).

7.8 MAGNETIC FIELD POLARITY

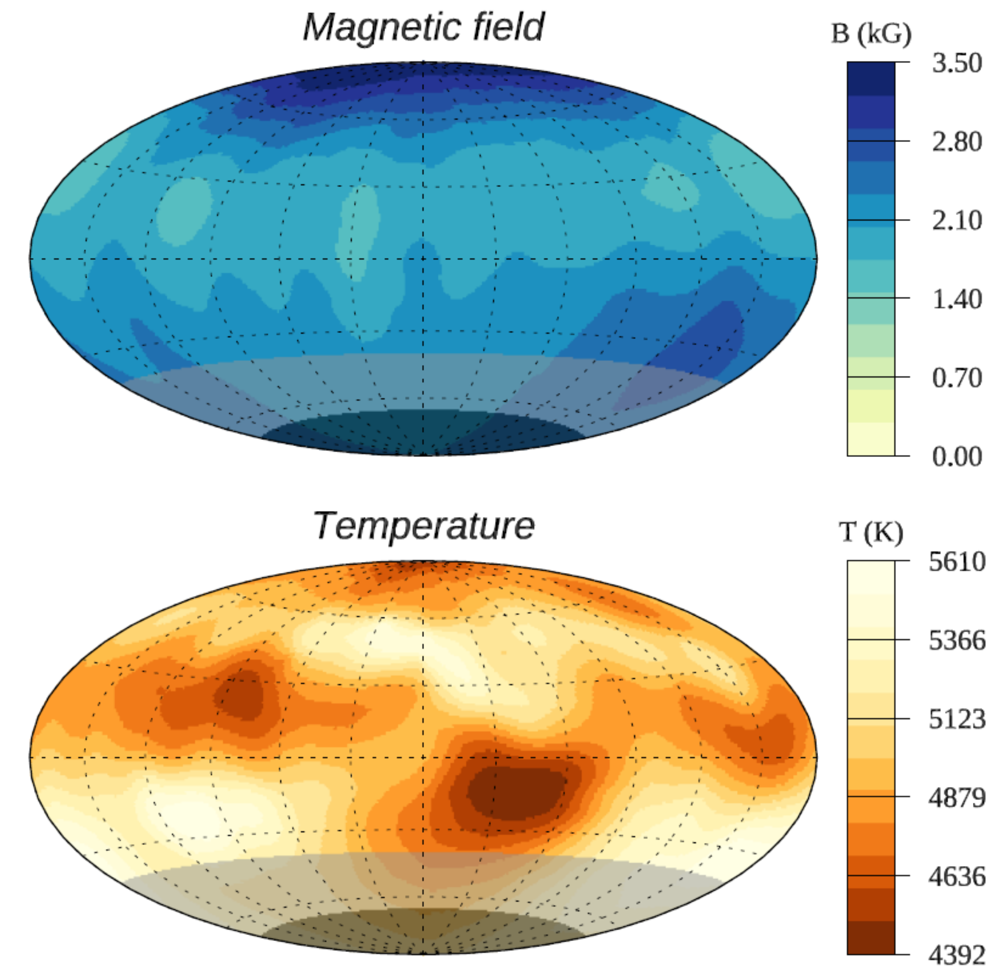
- ZDI images covering longer periods are used to track changes in the magnetic field.
- Reversals of the radial field around the stellar pole are observed in many stars.
- Indications of connections to spot activity cycles for some stars.



ZDI images of V1358 Ori (F9V) in 2013 and 2017 (Willamo et al. 2022).

7.9 CONNECTION BETWEEN B AND SPOTS

- Zeeman broadening and intensification of spectral lines => total B can be estimated.
- For the Sun the connection is clear...
- ... but for other stars not clear.



Distribution of magnetic field strength (upper panel) and temperature (lower panel) for LQ Hya 2011 data (Kochukhov et al. 2023).

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