STELLAR MAGNETIC ACTIVITY (PAP351)

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6. OBSERVING STARSPOTS

- The Sun can be studied by ”direct” observations…
- … but stars are typically too distant to be angularly resolved => inversion problems.
- Optical observations:
  - Photometry (usually UBVR, or satellite filters)
  - Spectrometry
  - Spectropolarimetry
  - Interferometry

6.1 MAPPING STARSPOTS

- Three classes of methods to resolve stellar surfaces:
  - “Direct imaging”: But the objects are too distant.
  - Interferometry: May succeed for a small number of stars, but with poor resolution.
  - Inversion methods:
    - Doppler-imaging
    - Magnetic (”Zeeman”) Doppler-imaging
    - Photometric inversion
    - Exoplanetary transit mapping

6.1.1 DIRECT IMAGING OF A STELLAR SURFACE

- Diffraction limit for the angular resolution of a telescope:

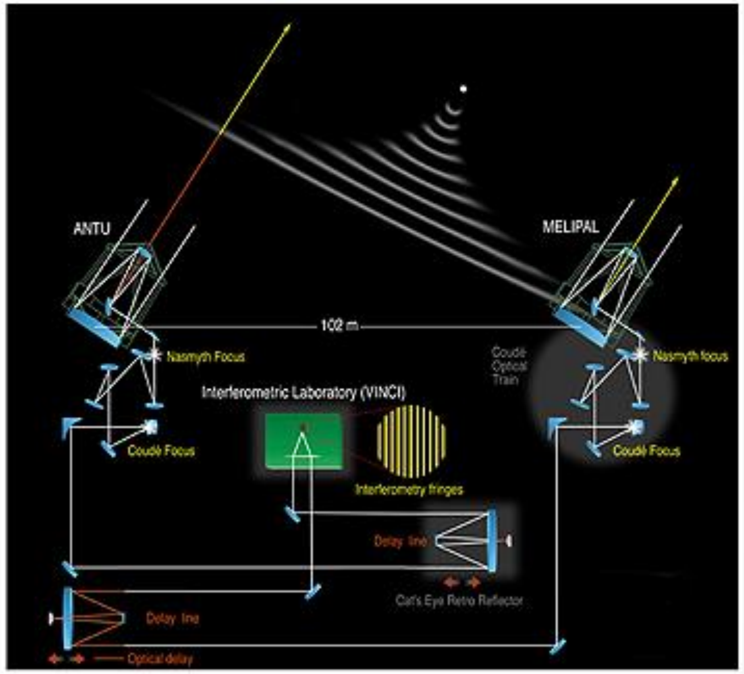
$$\theta \sim \frac{\lambda}{D},$$

where D is the diameter of the telescope.

- Largest optical telescopes of the near future ~ 40 m, $\lambda \sim 6000$ Å => $\theta \sim 3$ mas
- A typical nearby active star:
  - $\boldsymbol{r}$ = 10-500 pc
  - $\boldsymbol{R}$= 0.5-10 $\boldsymbol{R}_{\mathrm{sol}}$
- $\mapsto$ Not sufficient resolution.

6.2 INTERFEROMETRY

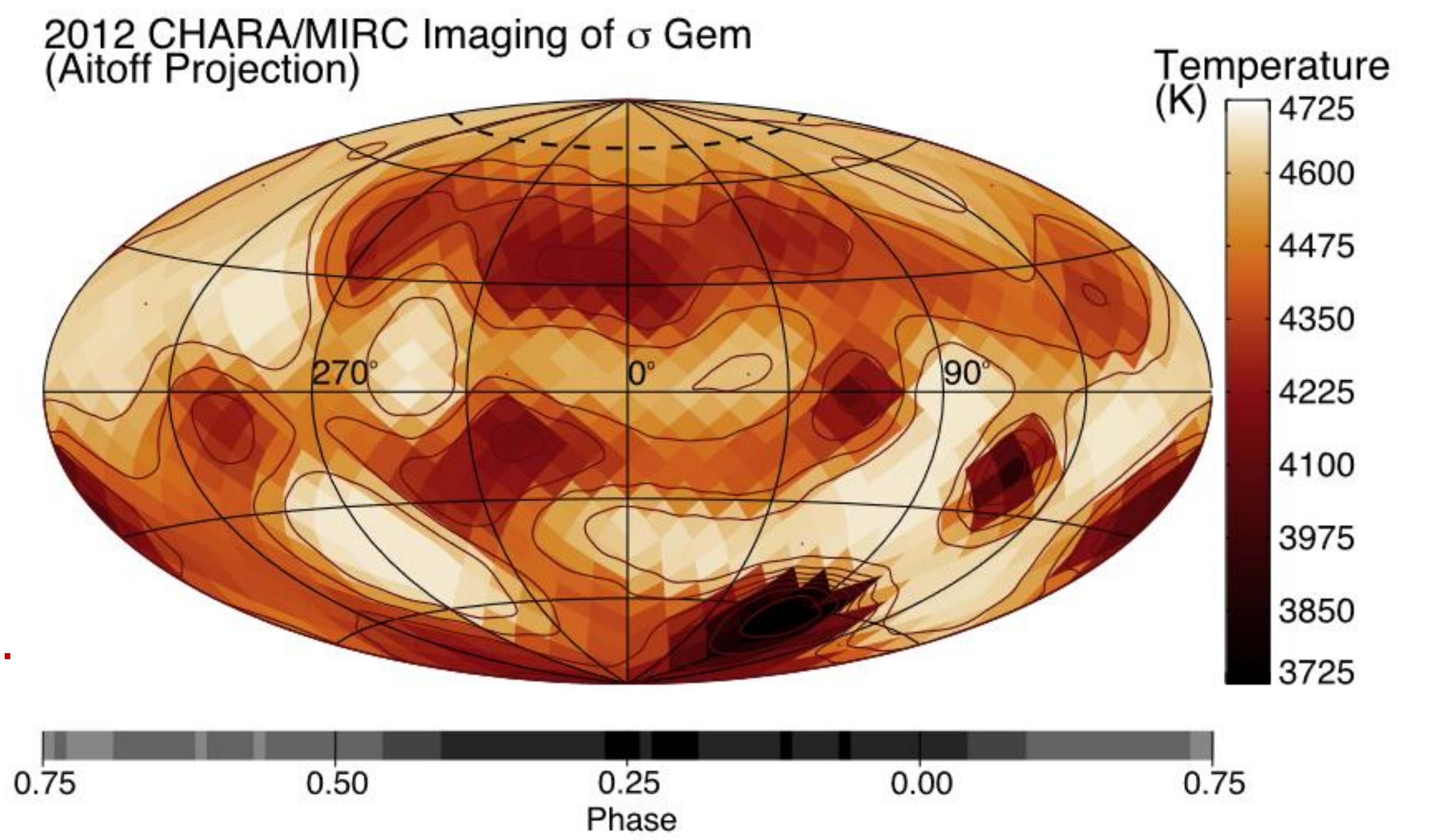
- ***D*** increased by combining telescopes.
- Optical interferometry:
  - Eg. CHARA, VLTI, Keck I-II, Large Binocular Telescope
- Note: Interferometry is not direct imaging, it involves inversion.



The VLT Interferometer with ANTU and MELIPAL

ESO PR Photo 30a/01 (5 November 2001) ©European Southern Observatory

6.2.1 INTERFORMETRY OF σ GEM



CHARA/MIRC interferometric image of σ Gem (Roettenbacher et al. 2017).

6.3 INVERSION METHODS

- The star is observed as a point source.
- Rotationally modulated changes in the light are observed due to spots:
  - Brightness changes $\mapsto$ Photometric light curve.
  - Changes in spectral lines $\mapsto$ Periodical deformation of spectral line profiles.
  - Changes in spectropolatimetric signal $\mapsto$ Periodical signal in Stokes V or $VQ\&U$.
- The surface, e.g. temperature distribution, is solved by inversion.

6.4 DOPPLER IMAGING

- Rapidly rotating star $\mapsto$ broad spectral lines.
- A spot will influence the part of a spectral line, which wavelength corresponds to the radial velocity of the surface element.
- *Doppler imaging*: Search for the surface distribution which best reproduces the spectral observations.

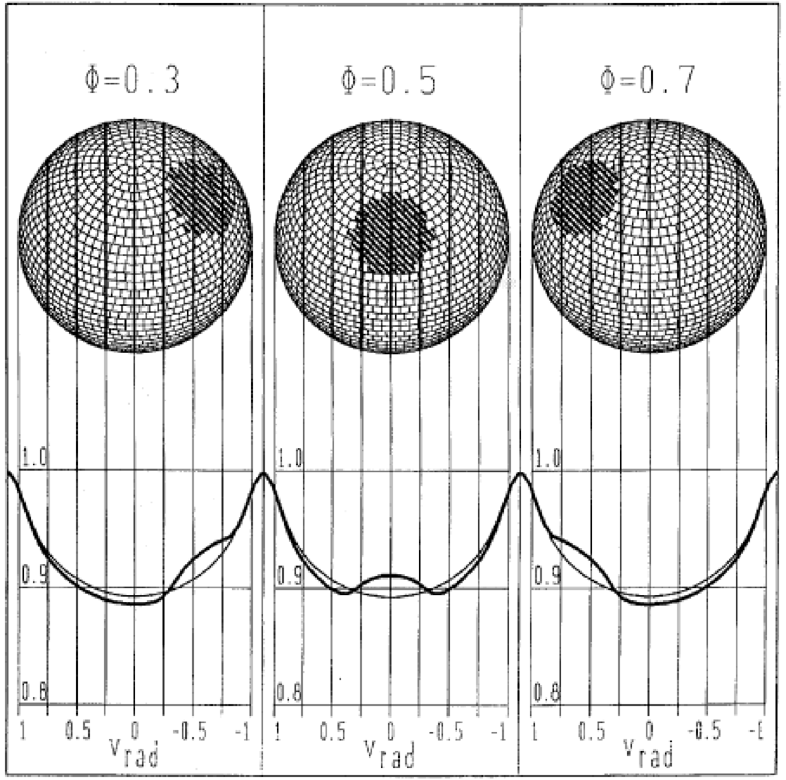
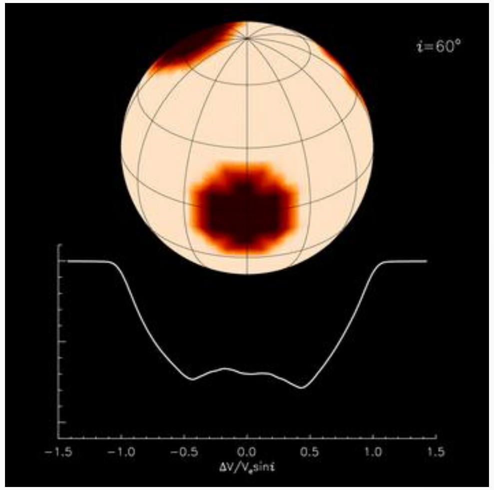


Fig. 2. Absorption line profiles of a spherical non–differentially rotating star with constant local line profile and zero limb–darkening. The spot–to–photosphere brightness ratio is I_{sp}/I_{ph} = 0.3; the inclination is i = 40°. Shown are three different phases. The observed profiles (heavy lines) are essentially a 1–D projection of the stellar surface. As a comparison, the light lines represent profiles of a spotless star

Kürster, M, 1993, A&A 274, 851

6.4. DOPPLER IMAGING (CONT.)

- Star rotates => spots cause "bumps" moving across the absorption lines.
  - Rotational Doppler effect => resolution perdendicular to the projected rotation axis.
  - Visibility of the spot => latitudinal resolution.



Animation by O. Kochukhov.

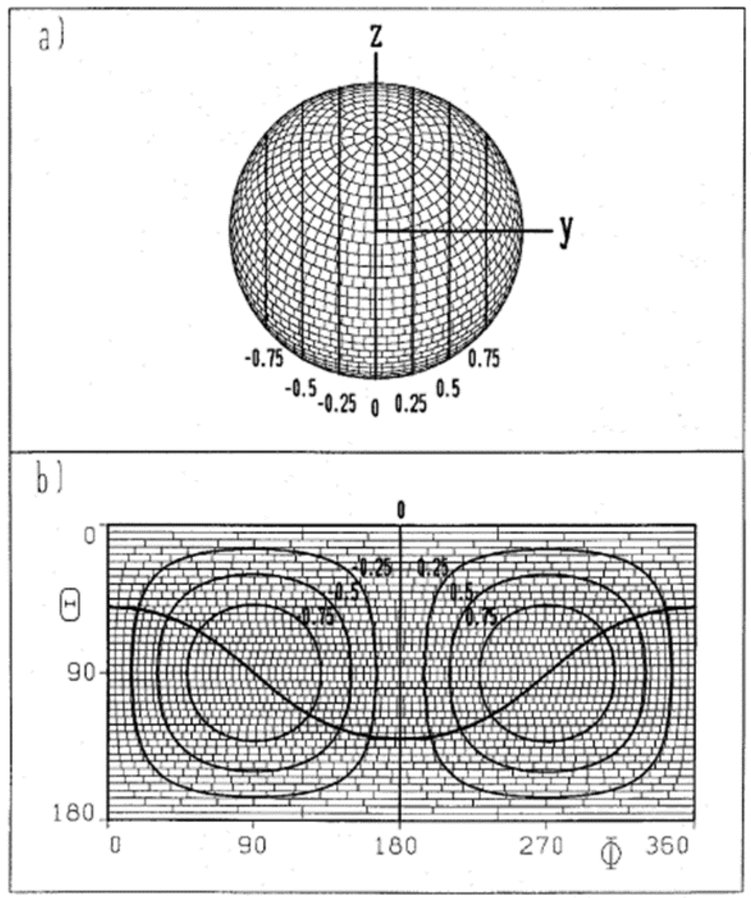


Fig. 1. a and b. Equidistant iso–RV lines on a spherical non–differentially rotating star with inclination $i = 40°$. **a** Projection onto the plane of the sky. **b** Plot of stellar co–latitude θ (90° minus latitude) vs. longitude ϕ. Iso–RV lines are given by Eqs. (10) and (11). At the current rotation phase the area below the heavy cosine line is invisible

6.4.1 FORMULATION OF THE DOPPLER IMAGING PROBLEM

- Search for the solution that minimizes:

$$D(X) = \sum_{\phi_{\mathrm{sp}},\lambda} \omega_{\phi_{\mathrm{sp}},\lambda} \frac{\left(r_{\phi_{\mathrm{sp}}}(\lambda) - r^{\mathrm{obs}}_{\phi_{\mathrm{sp}}}(\lambda)\right)^2}{N_{\phi_{\mathrm{sp}}} N_{\lambda}},$$

where X is the surface distribution of e.g. the temperature and $r_{\phi_{\mathrm{sp}}}$ can be calculated solving radiative transfer in numerical stellar atmosphere.

- D is an operator => solution from D^{-1}.

6.4.2 REGULARISATION

- The problem is ill-posed: The solution is unstable to distortions in the data.
- Solution: An additional constraint:

$\Phi(X) = D(X) + \Lambda R(X)$, where Λ is the *regularisation* parameter.

- Different options for the regularisation:

Tikhonov-regularisation (Piskunov et al. 1990): $R(X) = \iint \|\nabla X\|^2 d\sigma,$

Maximum entropy method (Vogt et al. 1987): $R(X) = \iint X \lg X d\sigma$

$d\sigma$ denotes integration over the surface elements.

6.4.3 CALCULATION OF LINE PROFILES

- Errors in $r_{\phi_{sp}}(\lambda)$ => systematic errors in the image.
- The line profile $r_{\phi_{sp}}(\lambda)$ is calculated using numerical stellar model atmospheres:
  - Local line profiles are calculated for different values of x and different limb angles on the stellar disk.
  - Using the line profiles table, we can calculate $r_{\phi_{sp}}(\lambda)$ for a given distribution X.

6.4.3 CALCULATION OF LINE PROFILES

- The stellar flux at wavelength λ:

$$F_\lambda(X) = \iint I(x, \lambda + \Delta\lambda)\mu d\sigma,$$

- μ is the cos of the limb angle, $\Delta\lambda$ is the Doppler shift (stellar rotation + radial velocity).
-
- For a realistic profile, F_λ is convoluted with
  - macro turbulence and
  - instrumental profile

6.4.3 LINE PROFILES …

- The integrated line profile is normalised: $r_\lambda = \frac{F_\lambda}{F_{\text{cont}}}.$
- The radiative transfer eq. is solved:

$$I_\lambda(\tau_\lambda) = I_\lambda(0)e^{-\tau_\lambda} + \int_0^{\tau_\lambda} S_\lambda(t_\lambda)e^{-(\tau_\lambda - t_\lambda)}dt_\lambda$$

- The line absorption coefficient: $\kappa_\nu^l = \frac{\pi e^2}{m_e c} f_{ij} N_i g_i \phi(\nu) \frac{e^{-h\nu/kT}}{U(T)} (1 - e^{-h\nu/kT})$
- Continuum absorption:
    - bound-free absorption
    - free-free absorption
    - scattering

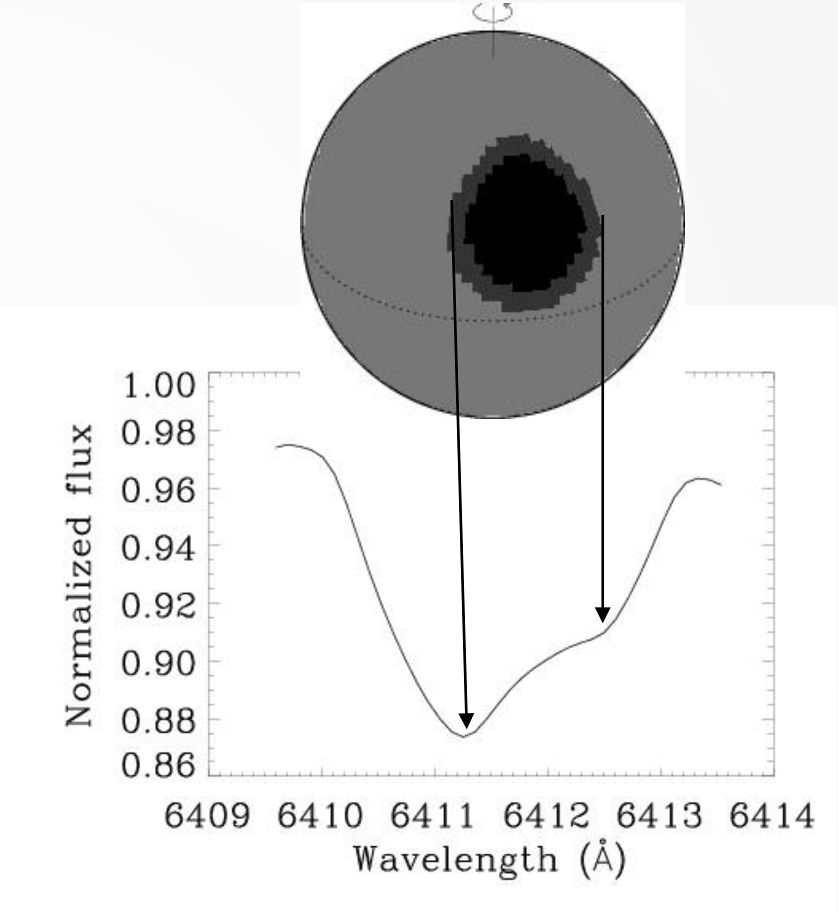
6.4.3 CALCULATION OF LINE PROFILES

- Spectral broadening mechanisms
  - ”Micro level” $\mapsto$ influences the amount of absorption:
    – Radiation damping
    – Collisional broadening
    – Thermal Doppler broadening
    – Micro turbulence
    – Zeeman effect

    } *Voigt*-profile
  - ”Macro level” $\mapsto$ no effect on the amount of absorption:
    – Macro turbulence
    – Stellar rotation

6.4.4 INTEGRATED LINE PROFILE

- The effect of a spot:
  - Line absorption changes:
    - Typically, absorption is stronger in a cool spot
  - The continuum radiation changes
    - Continuum is weaker in the spot.
  - Continuum usually dominates ↦ *”emission bump”.*



6.4.5 OTHER ADDITIONAL CONSTRAINTS

- Line profiles are calculated from a limited temperature interval $[T_{\text{min}}, T_{\text{max}}]$
- … but the solution is not necessarily constrained to this interval
- $\mapsto$ can be useful to constraint the solution: $T_{\text{min}} \leq T \leq T_{\text{max}}$
- This can be done with a penalty function

6.4.6 REQUIREMENTS FOR DOPPLER IMAGING ON STELLAR PARAMETERS

- Rapid rotation:
  - The projected rotation velocity much larger than other line broadening.
  - $\mapsto v \sin i > 15$ km/s
- An estimate of the resolution along the stellar equator:

$$N_{\mathrm{res}} \sim \frac{4 v \sin i}{w_{\mathrm{fwh}}},$$

w_{fwh} is the FWHM of the spectral line without rotation.

6.4.7 OBSERVATIONAL REQUIREMENTS

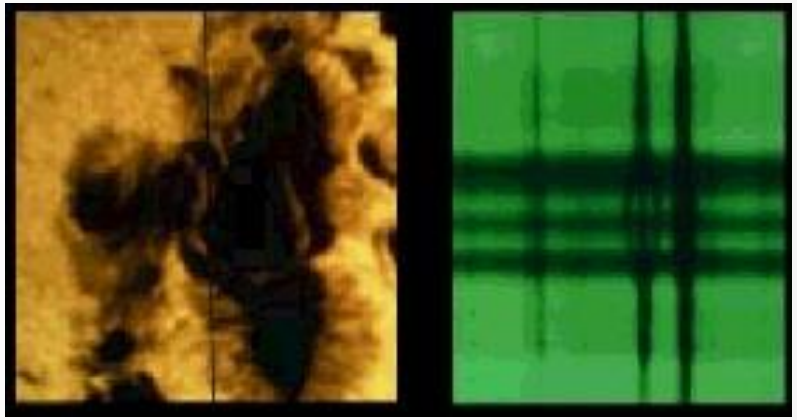
- High quality spectral observations:
  - At 6400 Å we need resolution $R > 40000$.
  - Signal-to-noise ratio $S/N > 200$.
  - Exposure times shorter than $P_{\text{rot}} / N_{\text{res}}$.
  - At least 10 spectra, evenly distributed over rotation phases.
  - Observation set shorter than timescale of changes in starspot structure.

6.4.8 PRACTICAL PROBLEMS

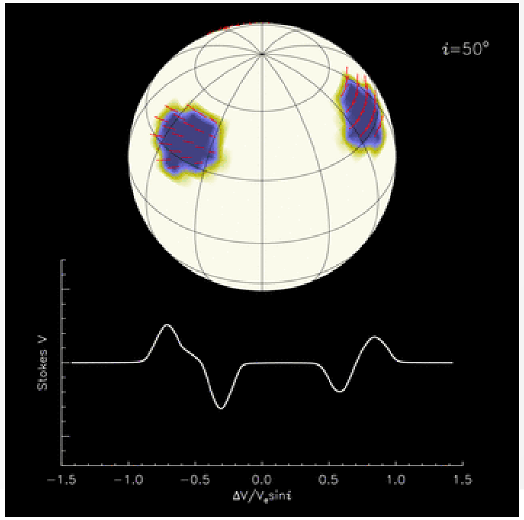
- Rapid rotation and binarity may change the stars geometry.
- Timescale of spot evolution?
- Possible differential rotation.
- Strong spectral lines $\mapsto$ Is the LTE-approximation valid?
- Uncertain parameters $\mapsto$ systematic errors.
- How does the magnetic fields effect the atmosphere?

6.5 ZEEMAN-DOPPLER IMAGING (ZDI)

- Magnetic field ↦ Zeeman effect.
- Z-D –imaging => map the magnetic vector at the stellar surface.
- Spectropolarimetric observations: Stokes parameters ***I(λ), Q(λ), U(λ), V(λ).***



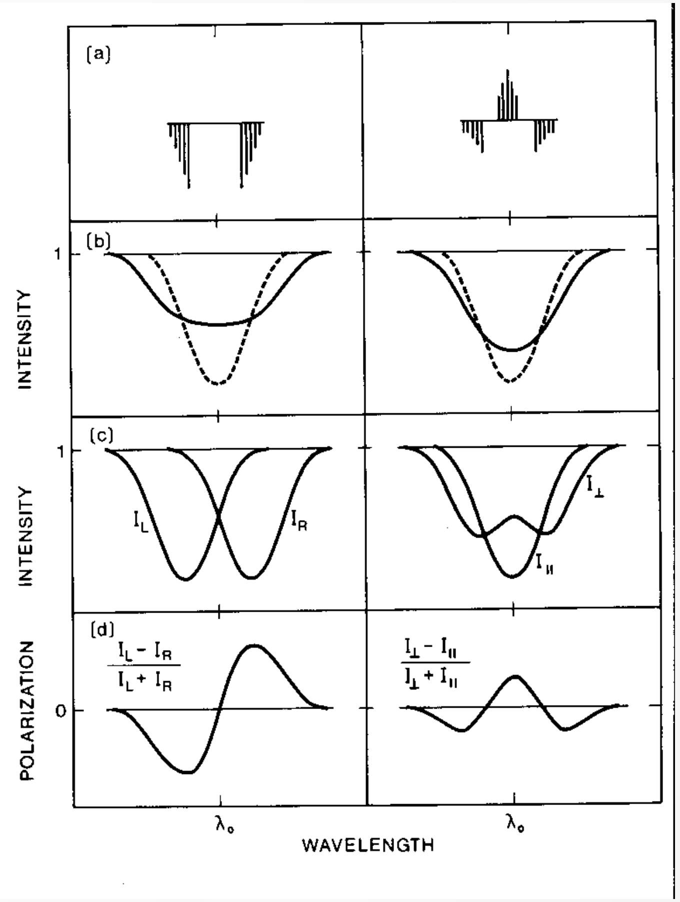
Zeeman effect splits lines into separate components.



Stokes V-signal of rotating star with magnetic spots (Kochukhov).

6.5.1 INFLUENCE OF MAGNETIC FIELD ON SPECTRAL LINE

- Magnetic field causes polarisation and Zeeman splitting:
  - (a): Zeeman components in longitudinal (left) and transverse (right) field.
  - (b): Observed spectral line intensity profile I without (·······) and with magnetic field (——).
  - (c): Polarisation components: Circular (left panel) and linear polarisation (right panel).
  - (d): Observed Stokes parameters: V (left) and Q or U (right).

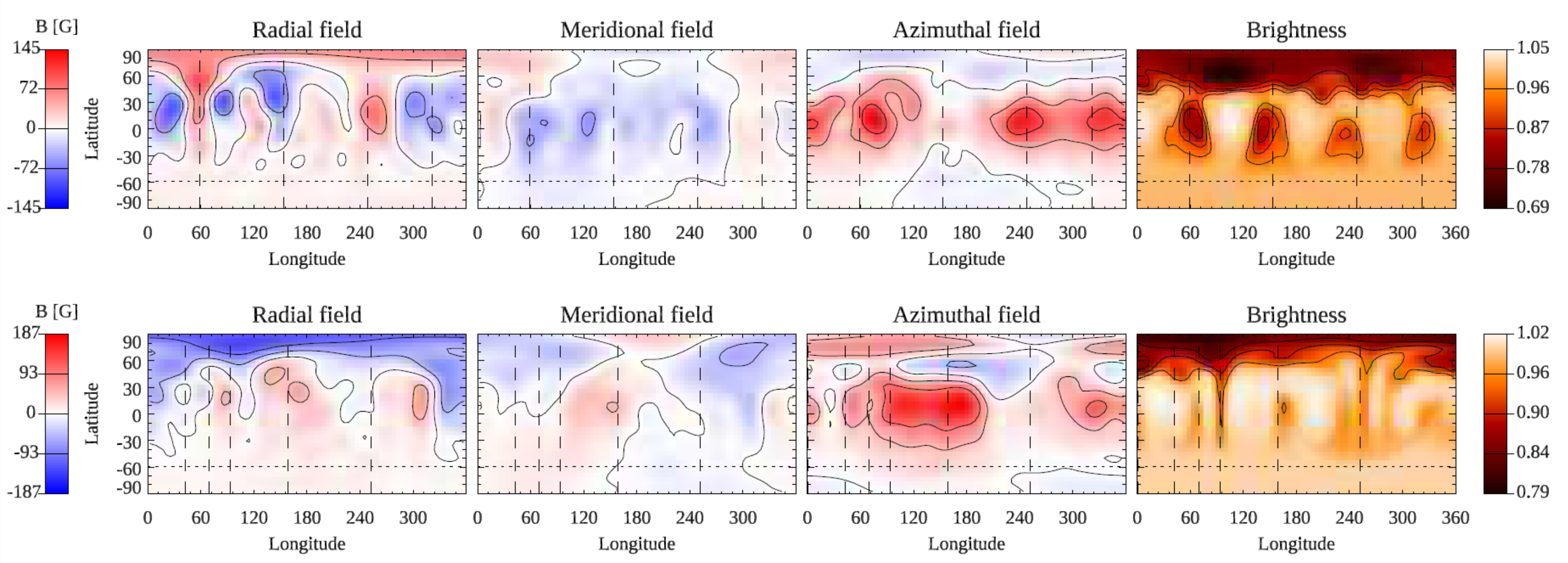


Landstreet, 2008, Univ. of Western Ontario, Kanada

6.5.2 ZDI METHOD

- A further development of Doppler imaging (Semel 1989; Brown et al. 1991; Kochukhov et al. 2014).
- Instead of just intensity spectra ($r_{\phi_{\mathrm{sp}}}$), Stokes I&V or full Stokes IVQ&U are used as observations.
- Usually based on spherical harmonics expansion:
  - Easier to employ constraint of source free magnetic field.
  - Easier to derive topology of solution; axisymmetric/non-axisymmetric, poloidal/toroidal field.
- Polarisation signal in single line weak => combination of thousands of lines necessary (e.g., Least Squares Deconvolution, Donati et al. 1997; Kochukhov et al. 2010).

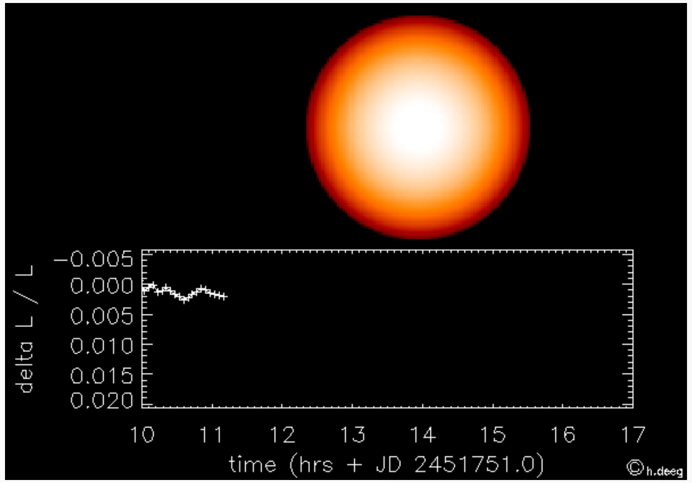
6.5.3 ZDI MAPS OF YOUNG SOLAR ANALOGUE

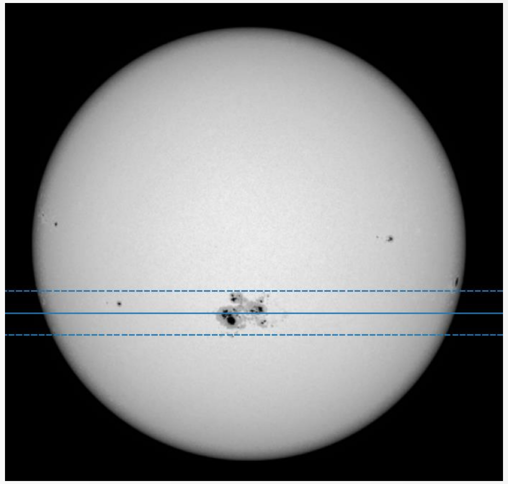


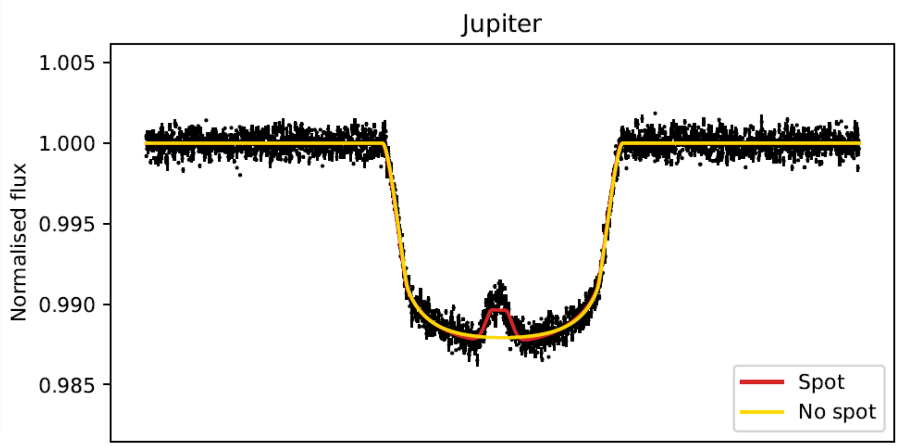
V1358 Ori, spectral class F9V, P_{rot}≈1.36d, age ~ 30 Myr. ZDI maps from 2013 and 2017 (Willamo et al. 2022).

6.6 EXOPLANETARY TRANSIT MAPPING

- Planetary transits over spots => model of spot size/temperature.







Light curve of HD 209458 with planetary transit (IAA, Deeg & Garrido).
Simulation of Jupiter transiting over the Sun (Haris-Kiss, 2023).