Doppler and Zeeman

Doppler Imaging of stars

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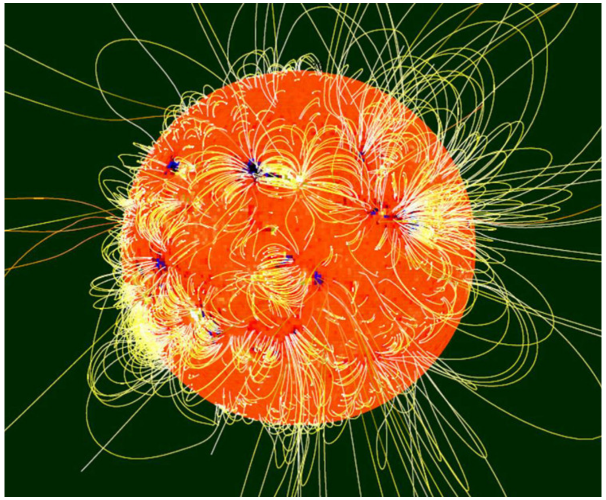
Surface cartography of the Sun and stars, Besançon, 2014

Outline

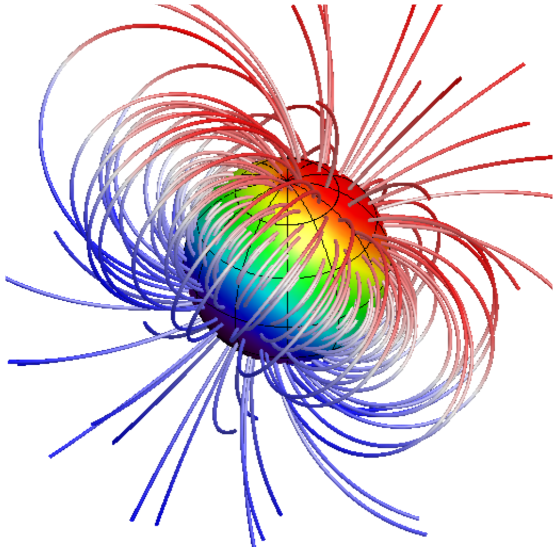
- Introduction: why map stellar surfaces?
- Doppler Imaging
  - Main principles
  - Examples
  - Open issues
- Zeeman Doppler imaging
  - Stokes parameters and magnetic field diagnostics
  - Main principles
  - Examples
  - Open issues
- Practical exercise

Stellar surface structure

- Sun and all cool stars
  - Magnetic fields are created by turbulence and rotation (dynamo)
  - **Magnetic fields** are weak, complex and rapidly evolving
  - **Cool spots** (convection suppression)



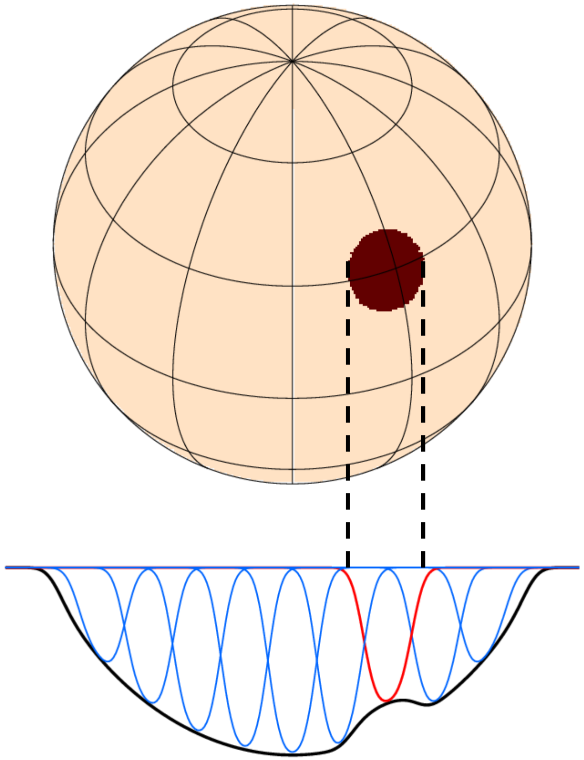
- A, B, O magnetic stars (Ap/Bp)
  - Fossil magnetic fields trapped in stellar radiative zones
  - **Magnetic fields** are strong, globally organised (dipolar?) and stable
  - **Chemical spots** (atomic diffusion)



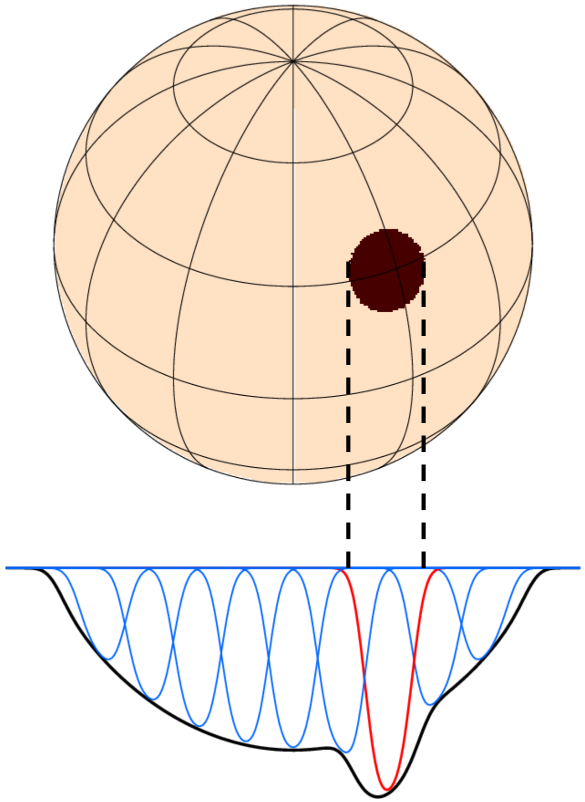
Basic principles of DI

◆ Surface feature creates a distortion in the Doppler broadened line profile

Temperature spot



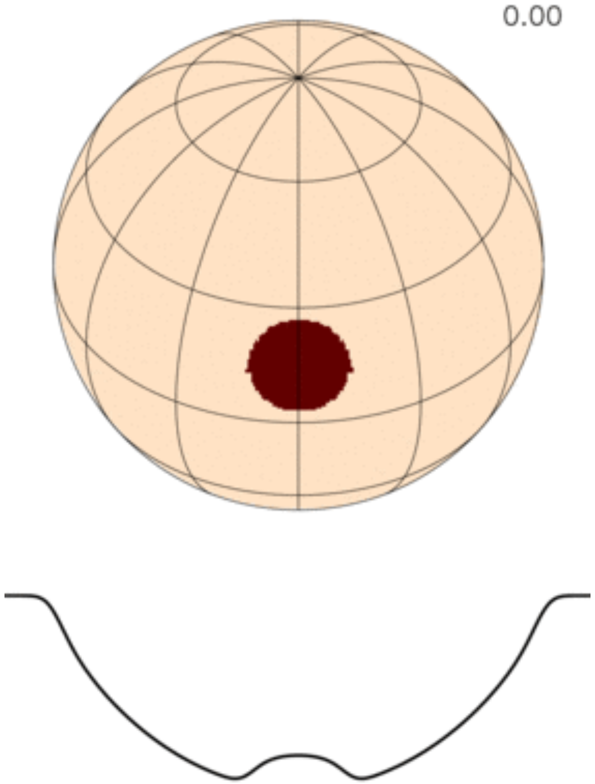
Chemical spot



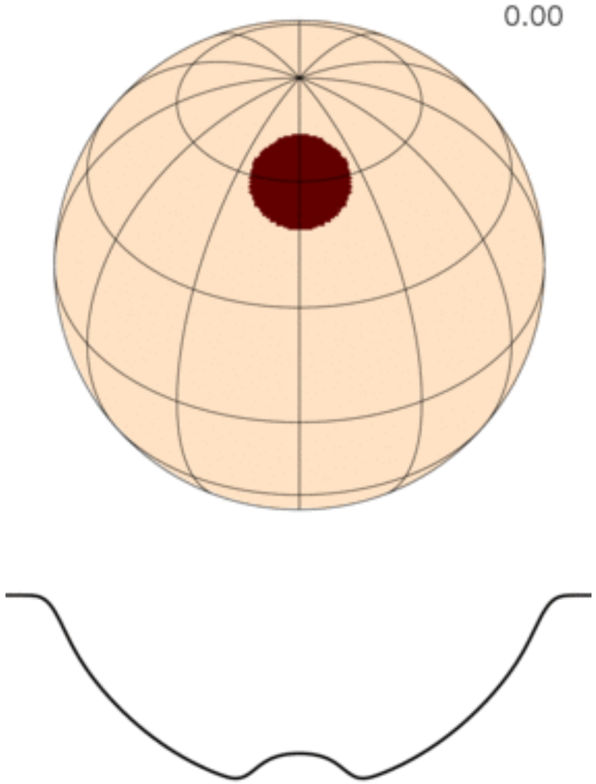
Basic principles of DI

◆ Distortion moves across the line profile as the star rotates

Low latitude



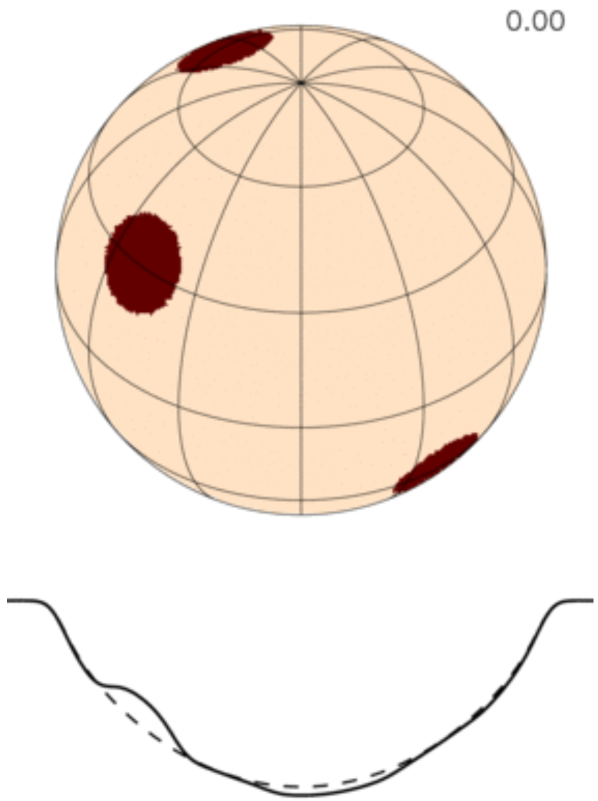
High latitude

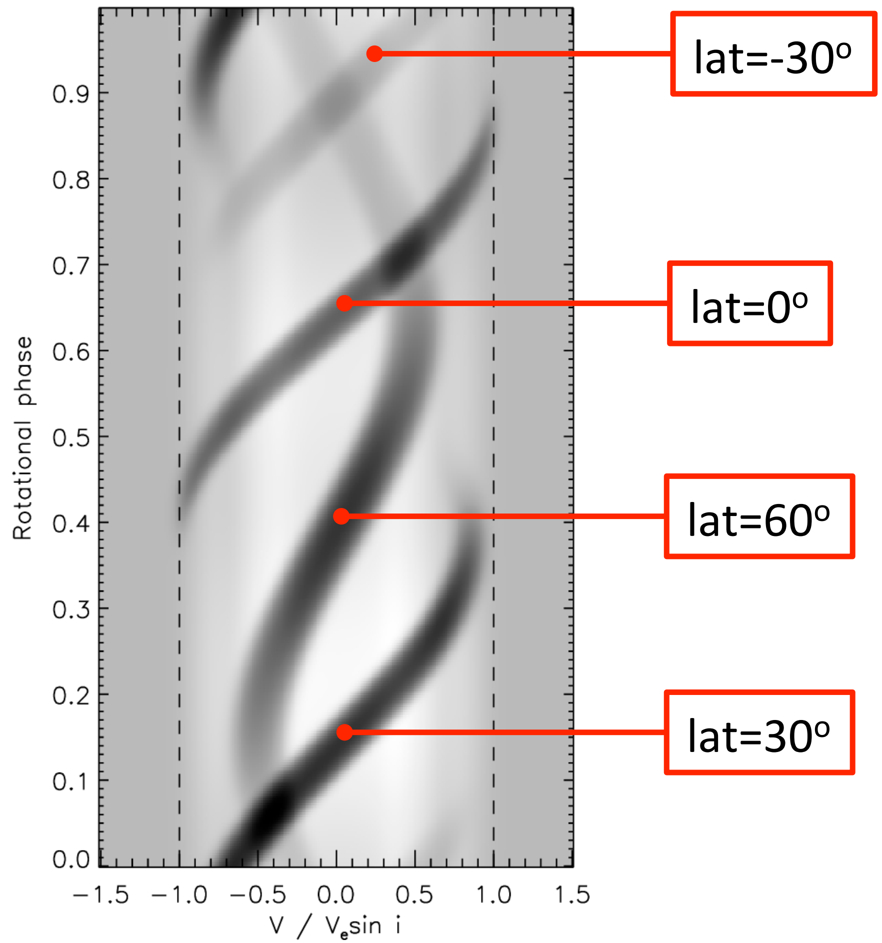


Basic principles of DI

- Distortion moves across the line profile as the star rotates

Temperature spots

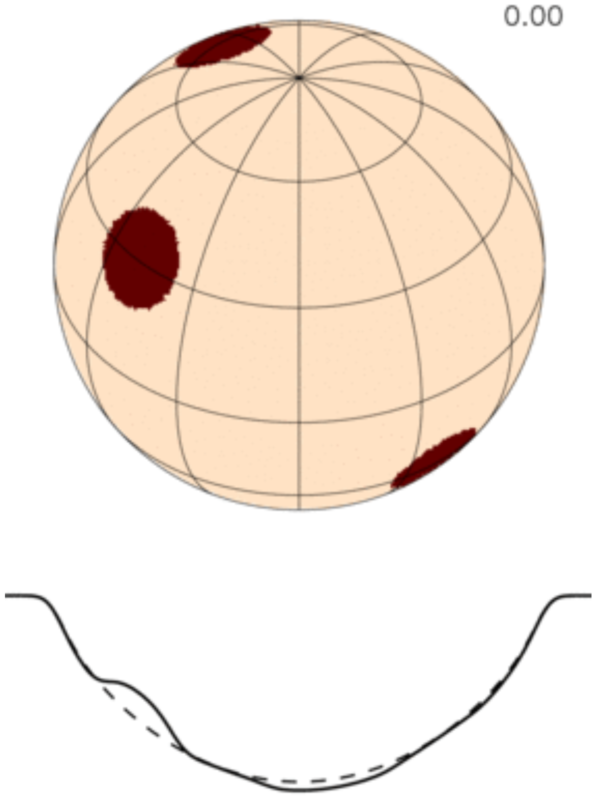




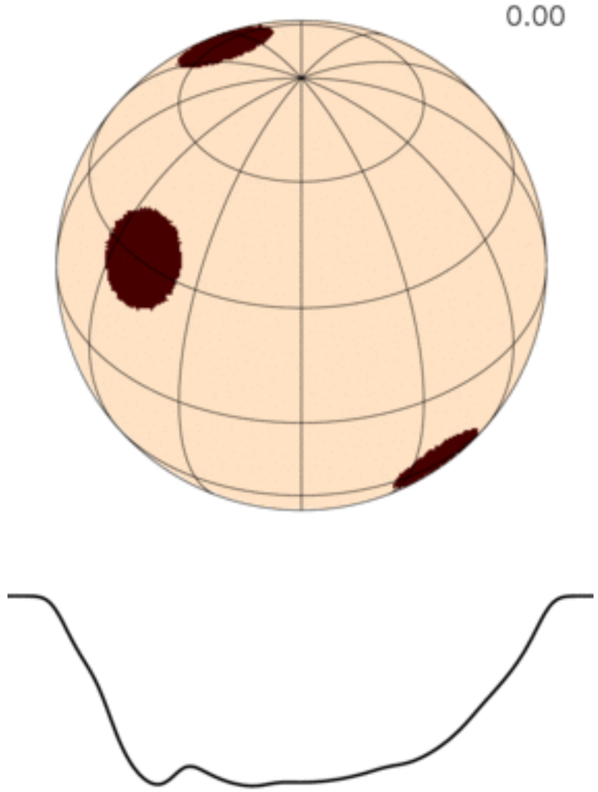
Basic principles of DI

- Distortion moves across the line profile as the star rotates

Temperature spots



Chemical spots



Spatial resolution of DI

- Longitude: from velocity position of the distortion
- Latitude: from time series behaviour
- Spatial resolution of DI
  - From a single observation $$\delta l = 90^{\rm o} \frac{\Delta\lambda}{\lambda} \frac{v_{\rm c}}{v_{\rm e} \sin i}$$

    For R = 65000, $v_e \sin i$ =150 km/s: δl = 2.7°

    Angular resolution for $R = 3R_{sun}$, d = 1 kpc: 0.3 μarcsec

  - From spectroscopic time series $$\delta l \sim 360^{\rm o} / \Delta\phi$$

Ill-posed nature of DI inversions

◆ DI reconstruction of the stellar surface maps is an *ill-posed inverse problem* (Goncharskij et al. 1977)

$$\underbrace{\sum_i [\mathrm{Obs}_i - \mathrm{Syn}(m)_i]^2/\sigma_i^2}_{\chi^2} \rightarrow \min$$

Ill-posed nature of DI inversions

- DI reconstruction of the stellar surface maps is an *ill-posed inverse problem* (Goncharskij et al. 1977)

$$\underbrace{\sum_i [\mathrm{Obs}_i - \mathrm{Syn}(m)_i]^2/\sigma_i^2}_{\chi^2} + \underbrace{\Lambda R(m)}_{\text{regularization}} \rightarrow \min$$

- Add a penalty function to
  - Ensure uniqueness and stability of the solution
  - Avoid fitting observational noise
  - Convergence to a global minimum
  - Decoupling from the surface grid

Regularization in DI

◆ "Occam razor": find the simplest solution that fits observations

– **Tikhonov regularization** = small local gradient (Tikhonov & Arsenin 1977)

$$\chi^2 + \Lambda \sum_j (m_j - m_k)^2 \rightarrow \min$$

– **Maximum entropy** = minimum "information content" (Skilling & Bryan 1984)

$$-\chi^2 - \Lambda \sum_j \frac{m_j}{m_0} \log \frac{m_j}{m_0} \rightarrow \max$$

where m_0 is the default value; e.g. $m_0 = 1/N \sum_j m_j$

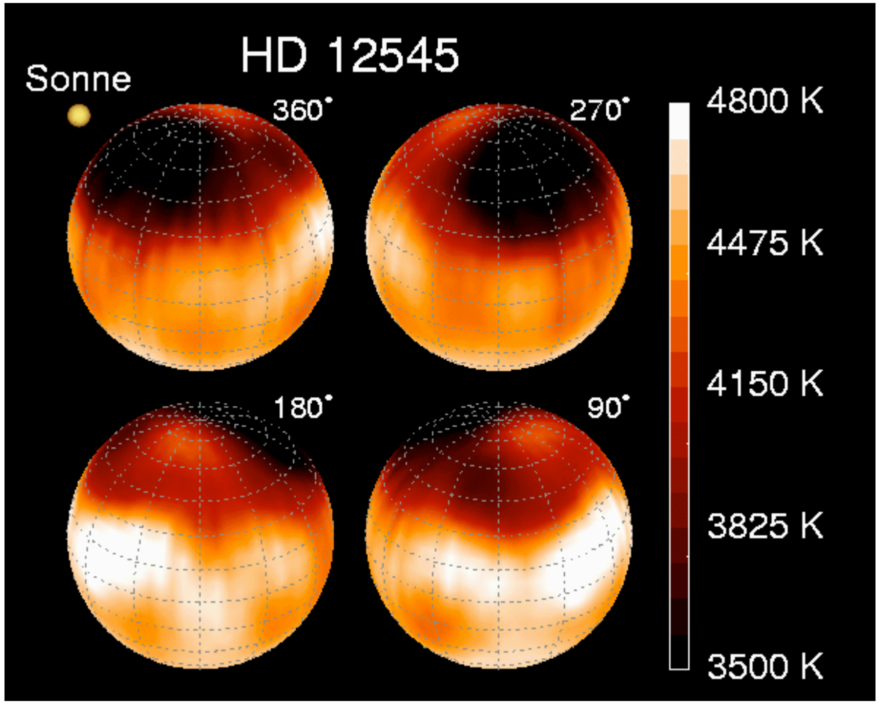
Critical auxiliary parameters

- Rotational period
- Projected rotational and radial velocity
- Inclination of stellar rotation axis $$\sin i = \frac{P_{\rm rot} v_{\rm e} \sin i}{50.613 R_\star}$$
- Azimuth angle of stellar rotation axis (Stokes *QU*)
- Local line profiles
  - Model atmosphere parameters ($T_{\rm eff}$, log *g*, [M/H]), atomic data
  - Parameters of analytical profiles (EW, FWHM, limb darkening, assumed spot contrast, etc.)

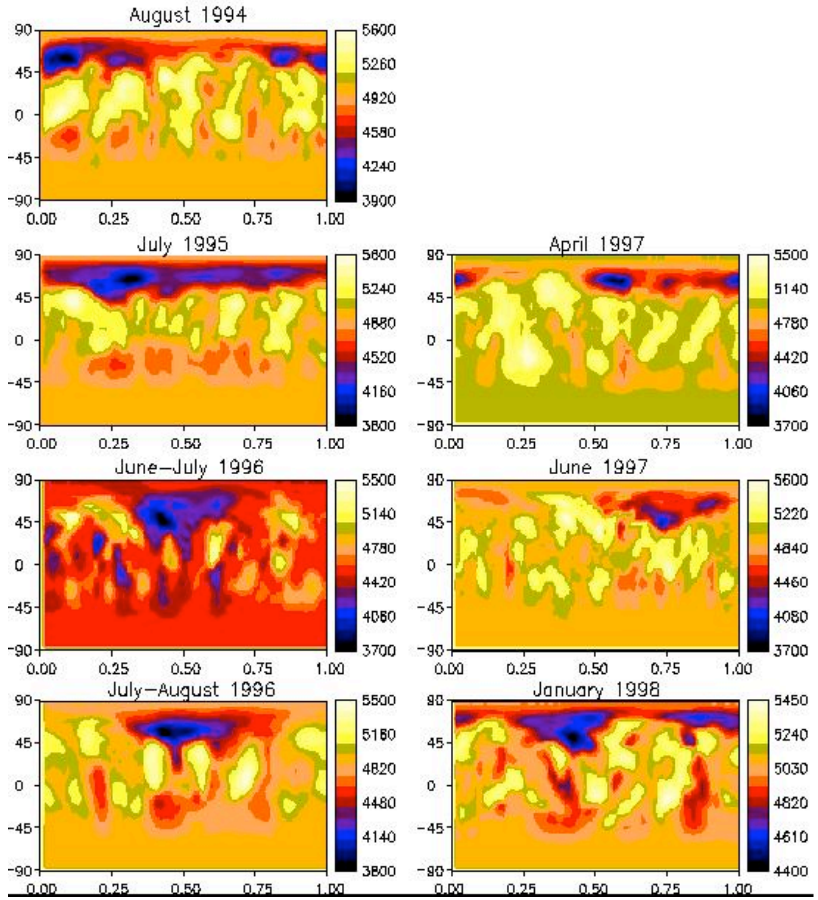
Can be constrained with DI inversions

Spot maps of cool stars

XX Tri (Strassmeier 1999)

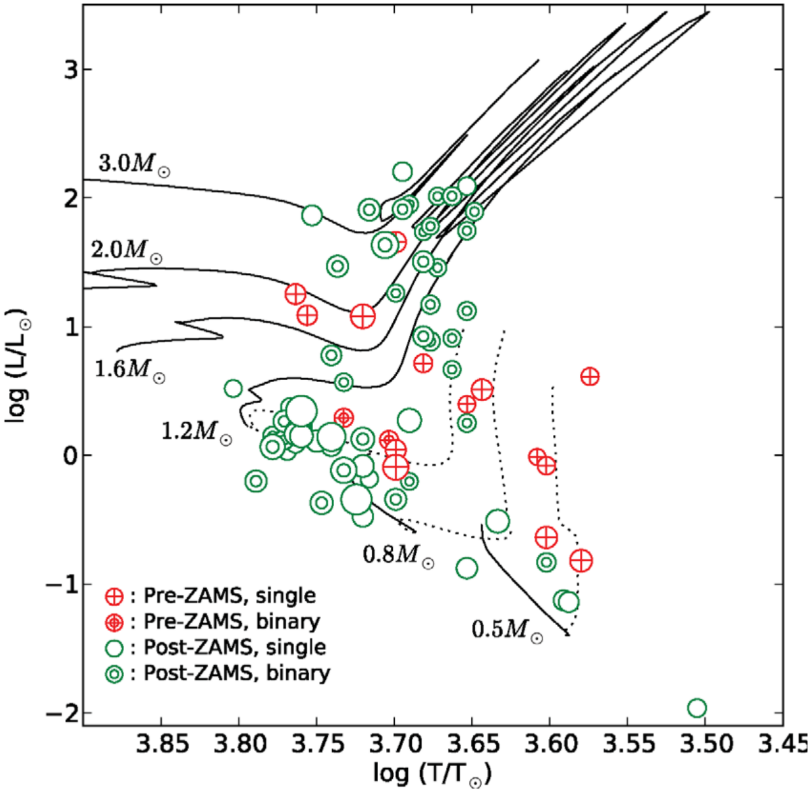


FK Com (Korhonen et al. 2010)

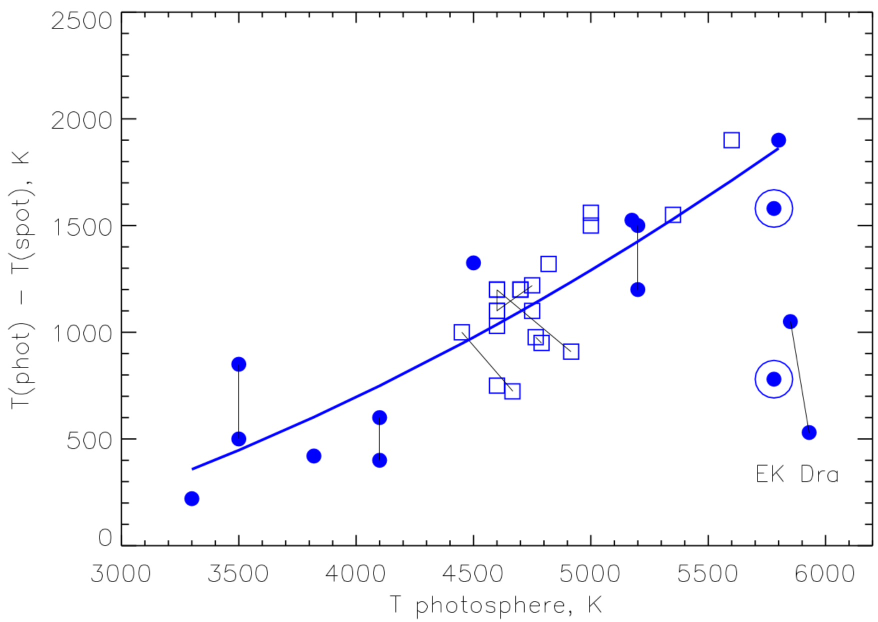


Summary of cool star DI

◆ Temperature/brightness maps for ~100 stars



Strassmeier (2010)

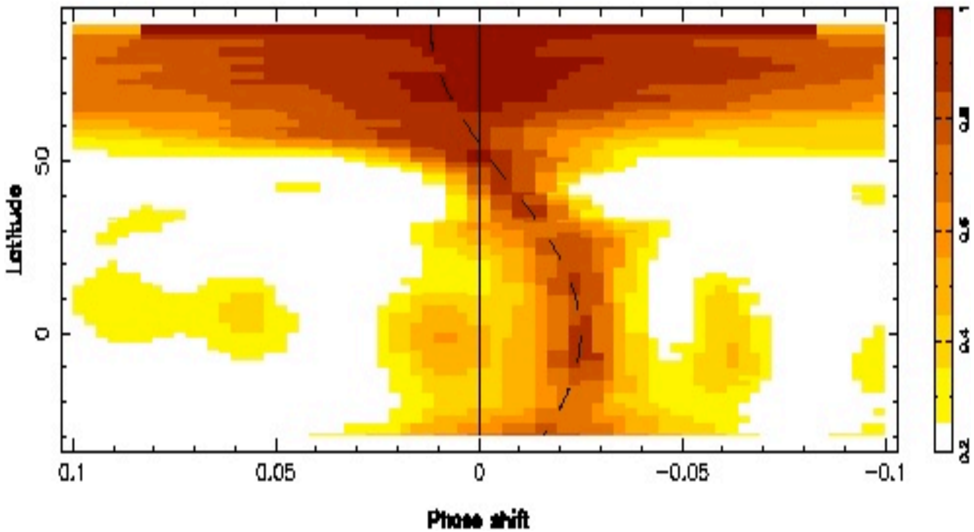


Berdyugina (2005)

Differential rotation from DI

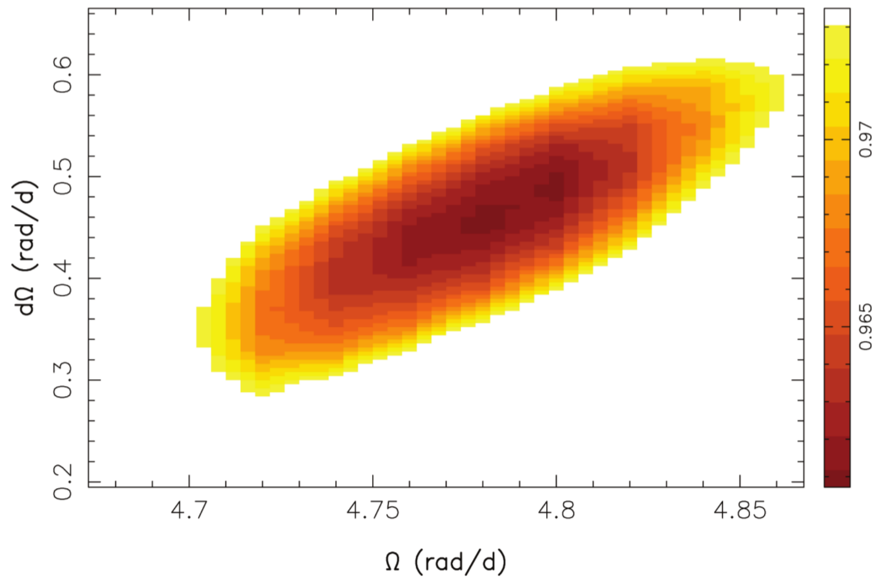
- Methodology
  - Cross-correlation of DI maps
  - Incorporated in inversions $\Omega(\theta) = \Omega_{\rm eq} - \delta\Omega \sin^2\theta$

cross-correlation



Donati & Collier Cameron (1997)

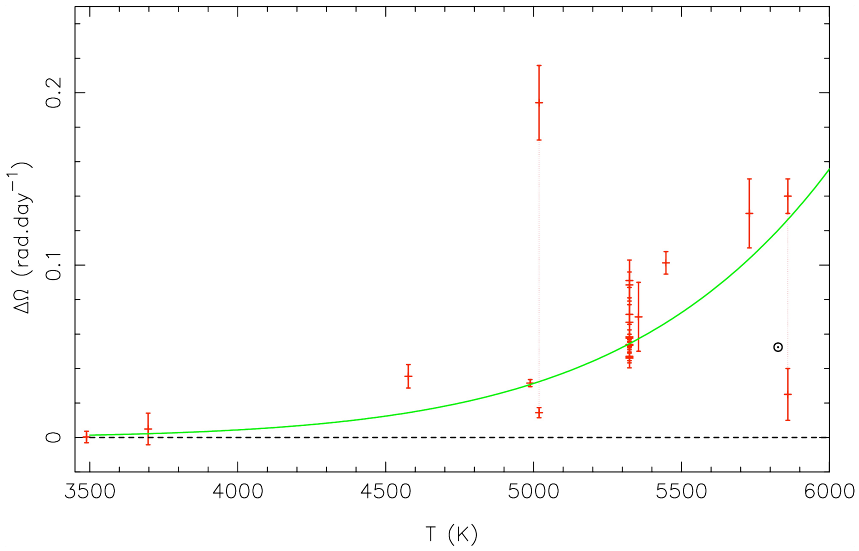
χ^2 landscape



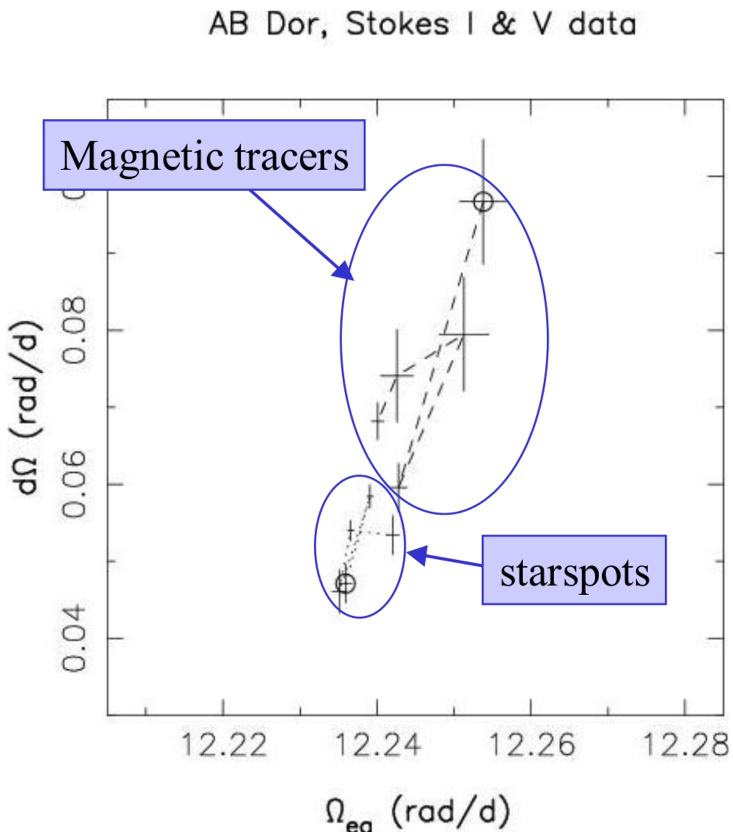
Jeffers et al. (2010)

Differential rotation from DI

- Results
  - Increase of δΩ with T_{eff}
  - Stokes *I* and *V* difference
  - Temporal variation



Barnes et al. (2005)



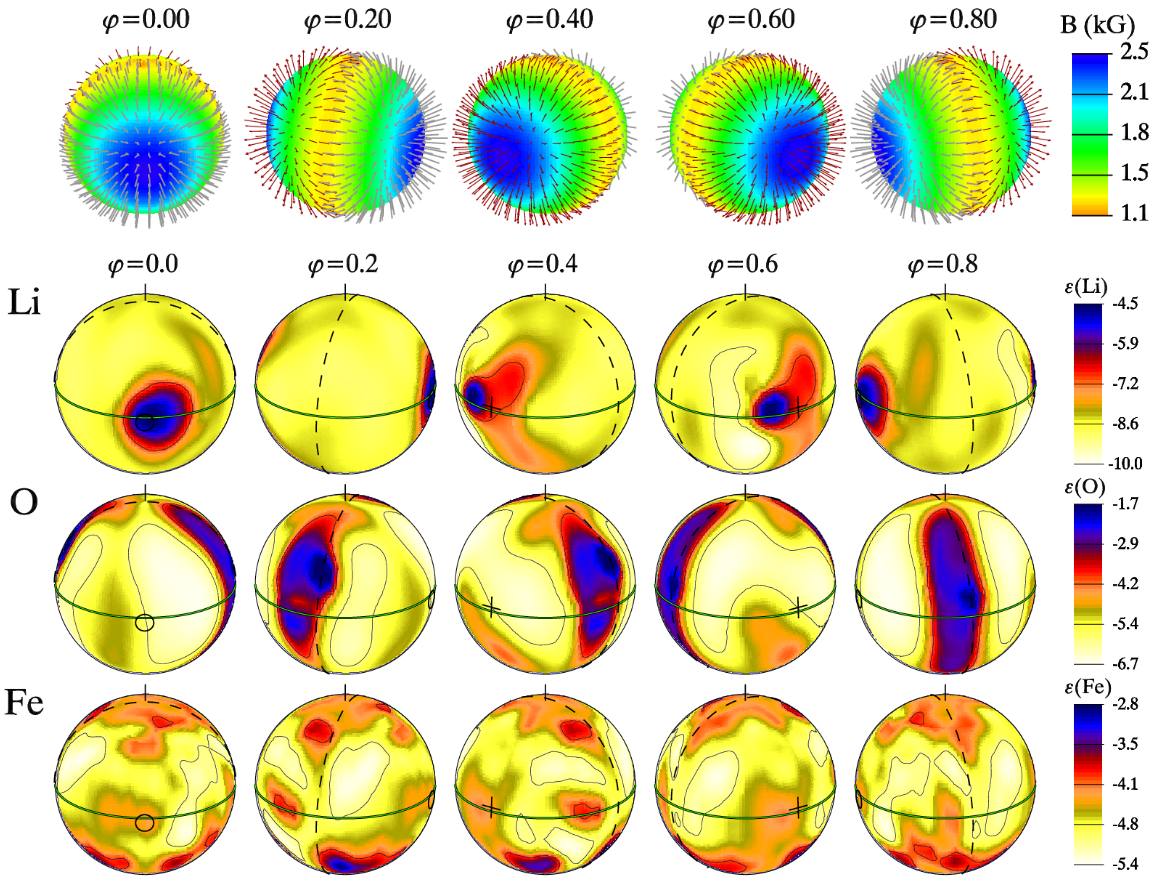
Donati et al. (2003)

Outstanding issues of cool star DI

- Spot temperatures/contrasts vs. spot sizes
  - Better constrained by DI compared to photometry
  - Molecular lines
- Polar spots
- Interpretation of brightness maps
- Unresolved small-scale spots
- Atmosphere of a starspot

Multi-element DI of Ap stars

- Chemical spots are (un?)related to magnetic geometry



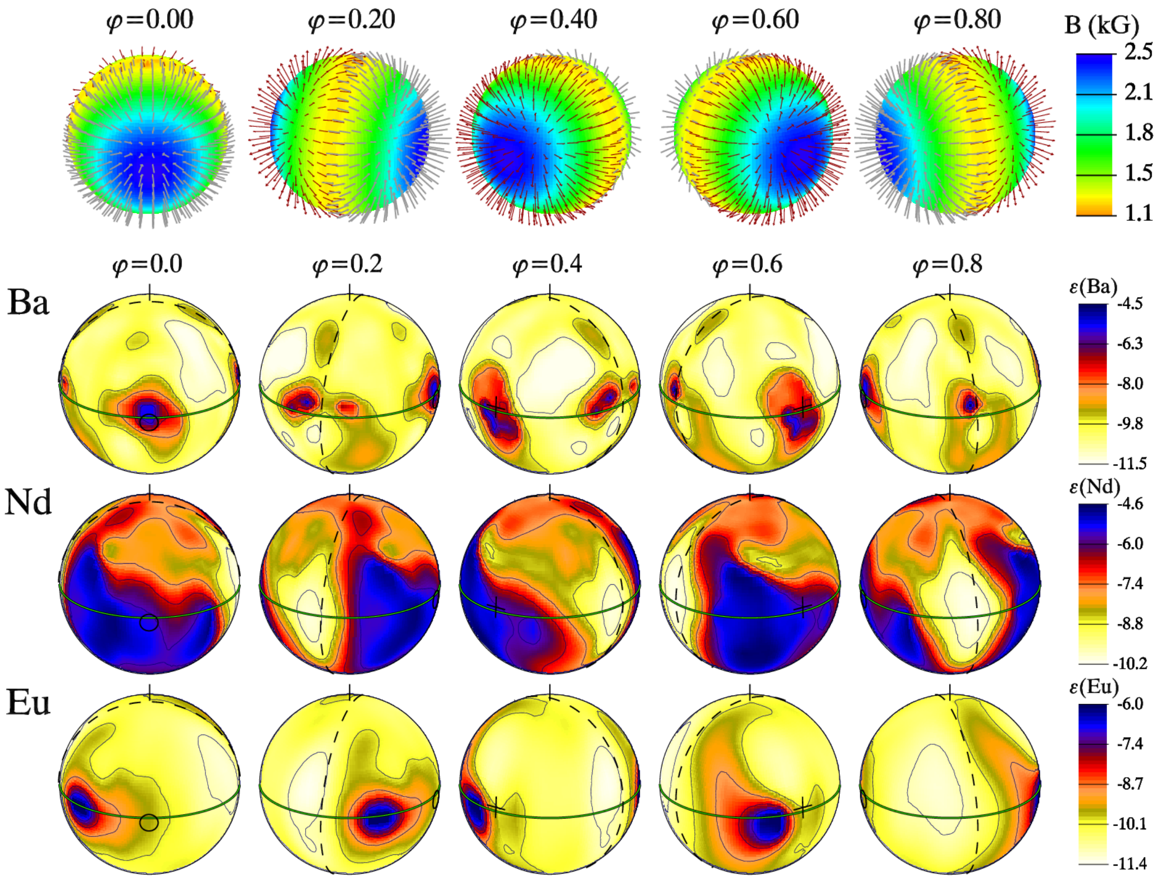
HR 3831
(Kochukhov et al. 2004)

correlation with the magnetic field geometry

no apparent correlation

Multi-element DI of Ap stars

◆ Chemical spots are (un?)related to magnetic geometry



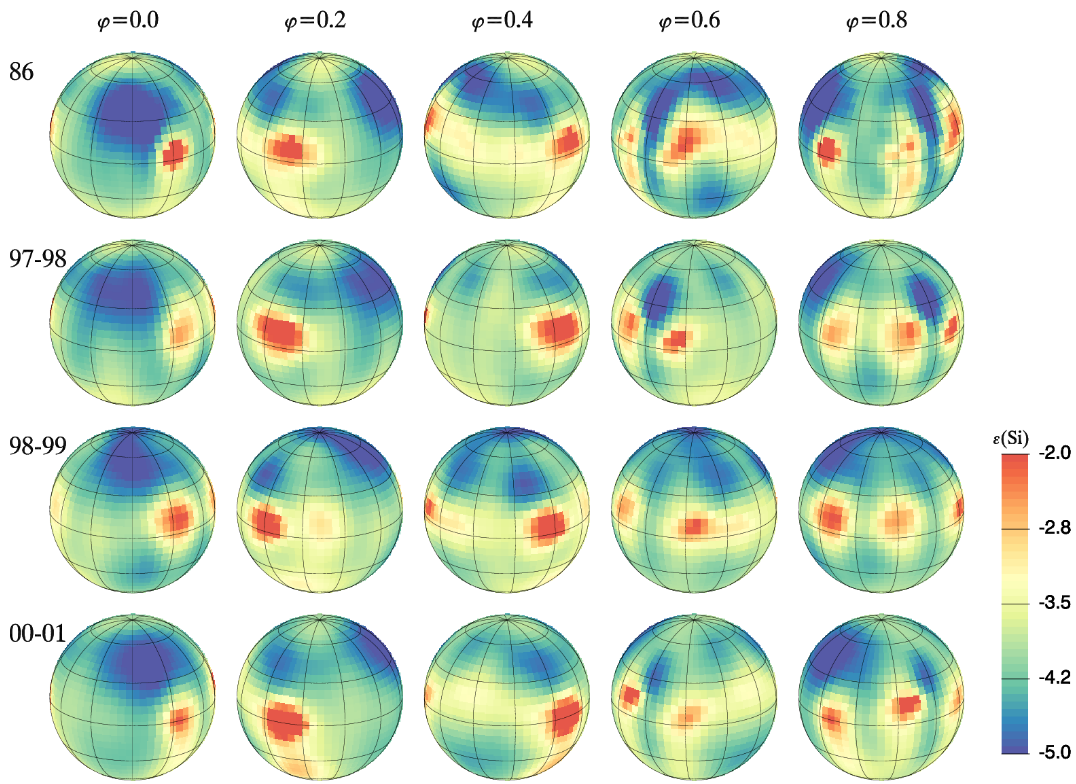
HR 3831
(Kochukhov et al. 2004)

diversity of heavy-element distributions

Stability of Ap-star spots

- No evidence of significant variability
  - Equivalent width curves: ~100 yr time scale
  - DI maps: ~20 yr time scale

Ap star 56 Ari
Si maps from
1986 to 2001



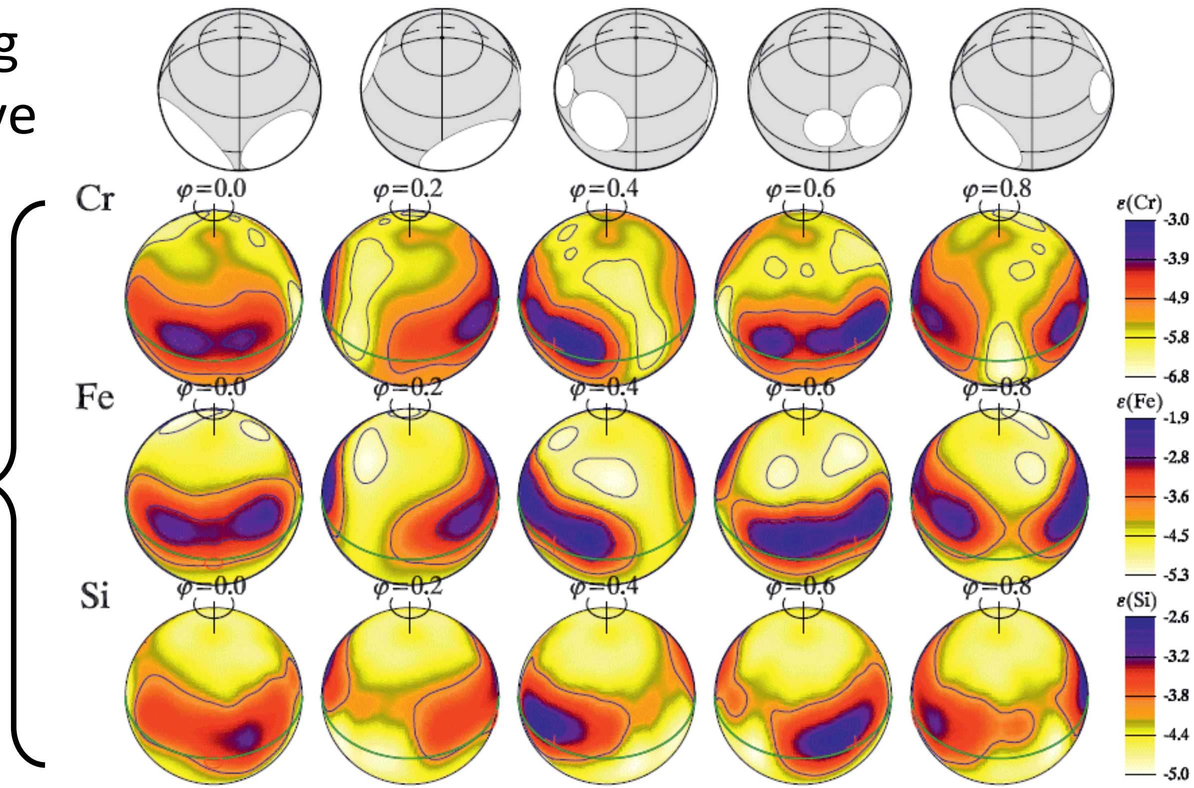
Light curves vs. DI maps

◆ SED of Ap stars: flux redistribution from UV to optical
chemical spots are bright in the optical, dark in UV

Lüftinger et al. (2010) for Ap star HD 50773

Bayesian modelling of CoRoT light curve

Doppler imaging abundance maps

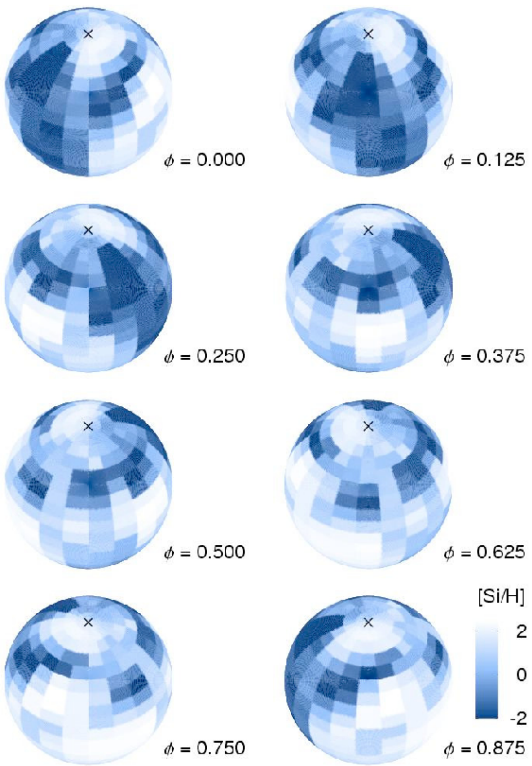


Light curves vs. DI maps

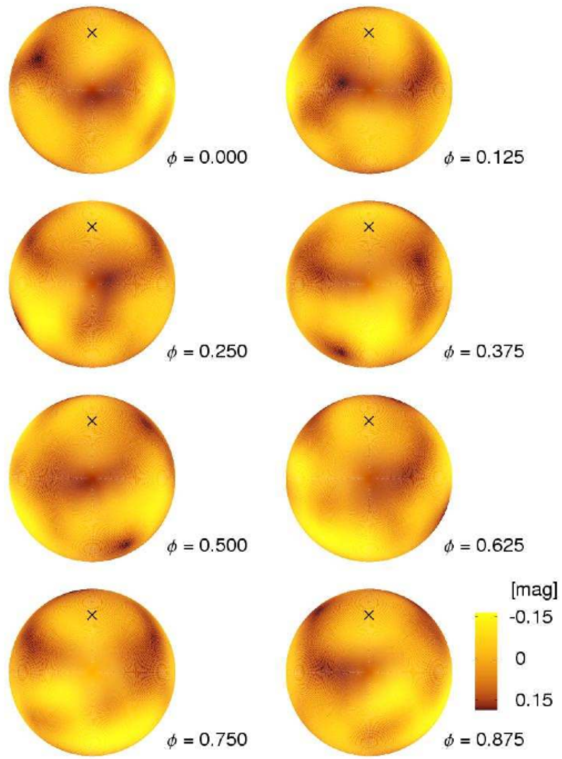
◆ DI maps explain light curve shapes

Khokhlova et al. (2000) Krticka et al. (2007)

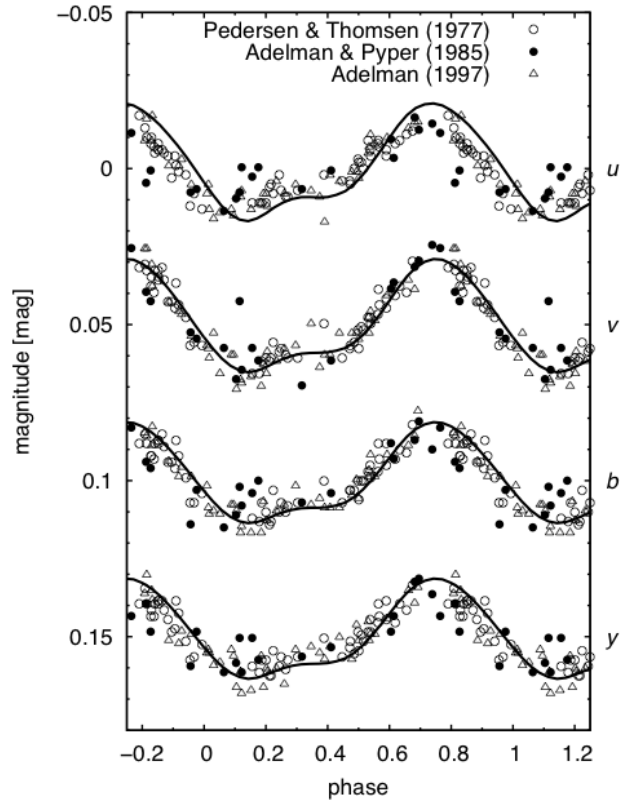
Si DI map



Brightness



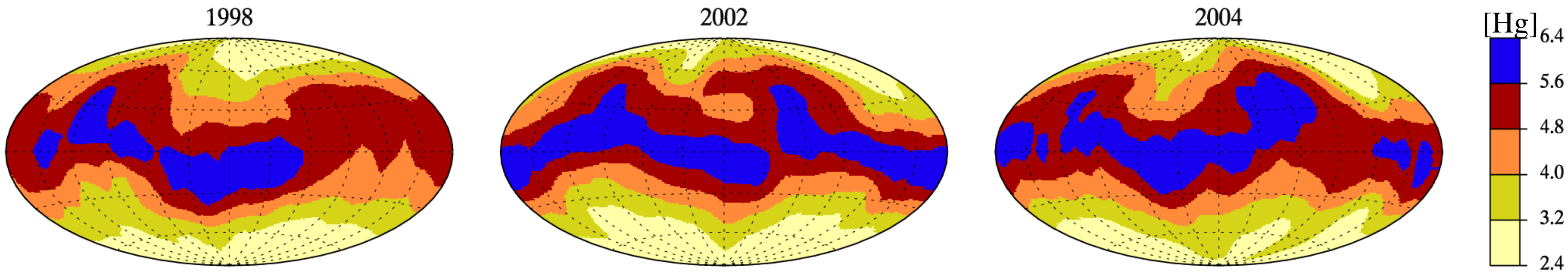
Light curves

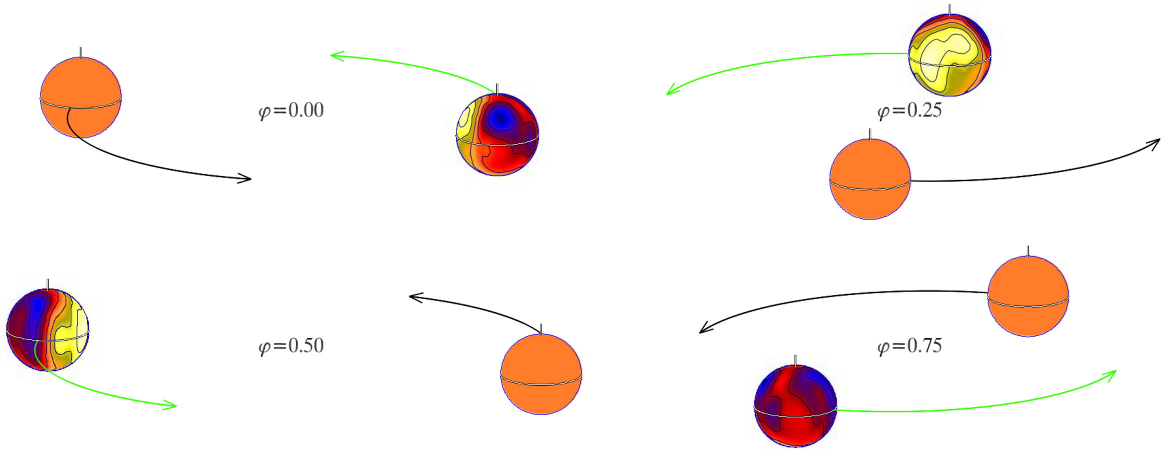


Dynamic chemical spots on HgMn stars

- Low-contrast, evolving spots of heavy elements
- **No evidence of magnetic field**

Evolution of Hg spots on α And (Kochukhov et al. 2007)



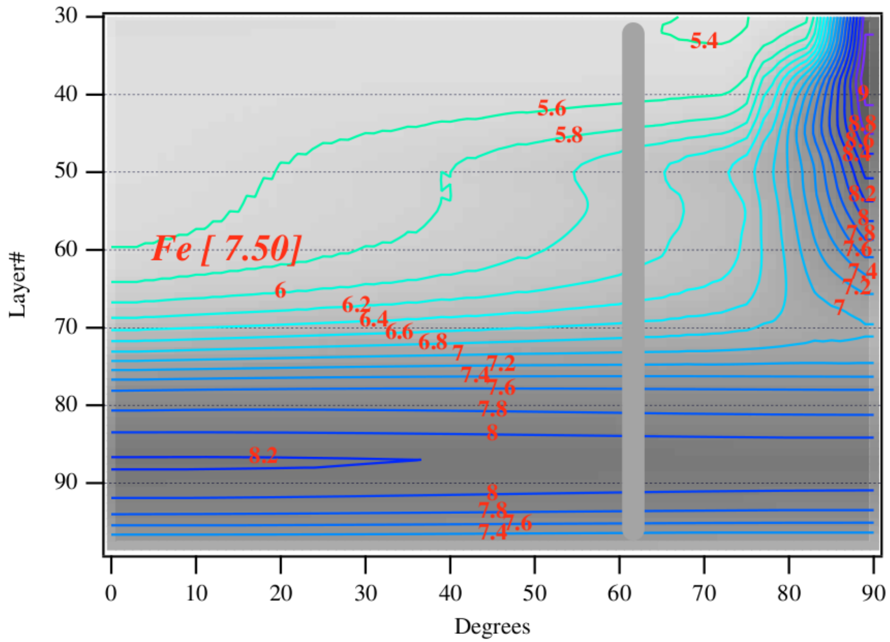


Y spots on the primary component of 66 Eri (Makaganiuk et al. 2012)

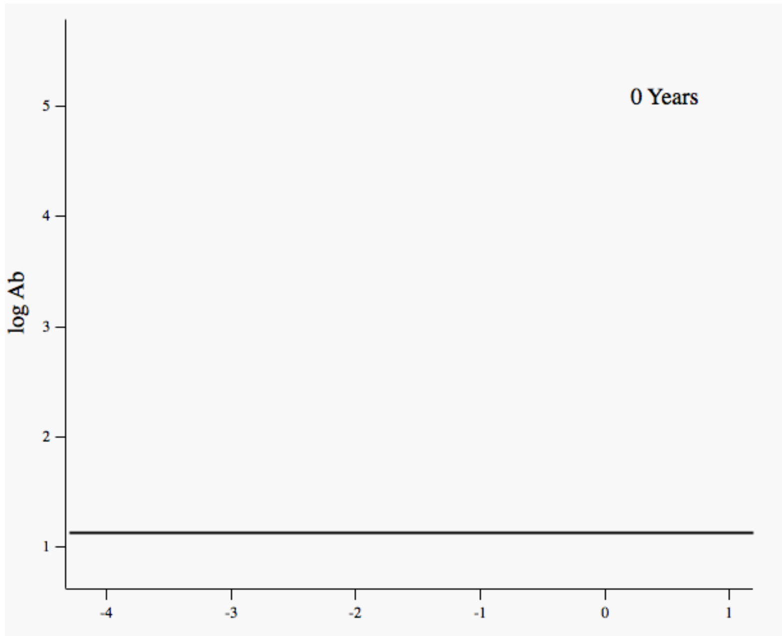
Origin of chemical spots

- Radiative diffusion in magnetic field
  - Why chemical maps are so complex and diverse?
  - How can spots exist on non-magnetic stars

Equilibrium (Alecian et al. 2010)



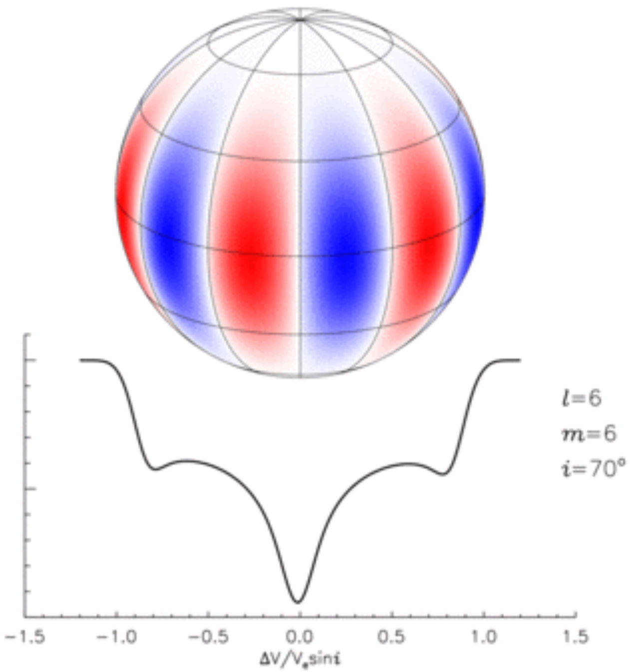
Time-dependent (Alecian et al. 2010)

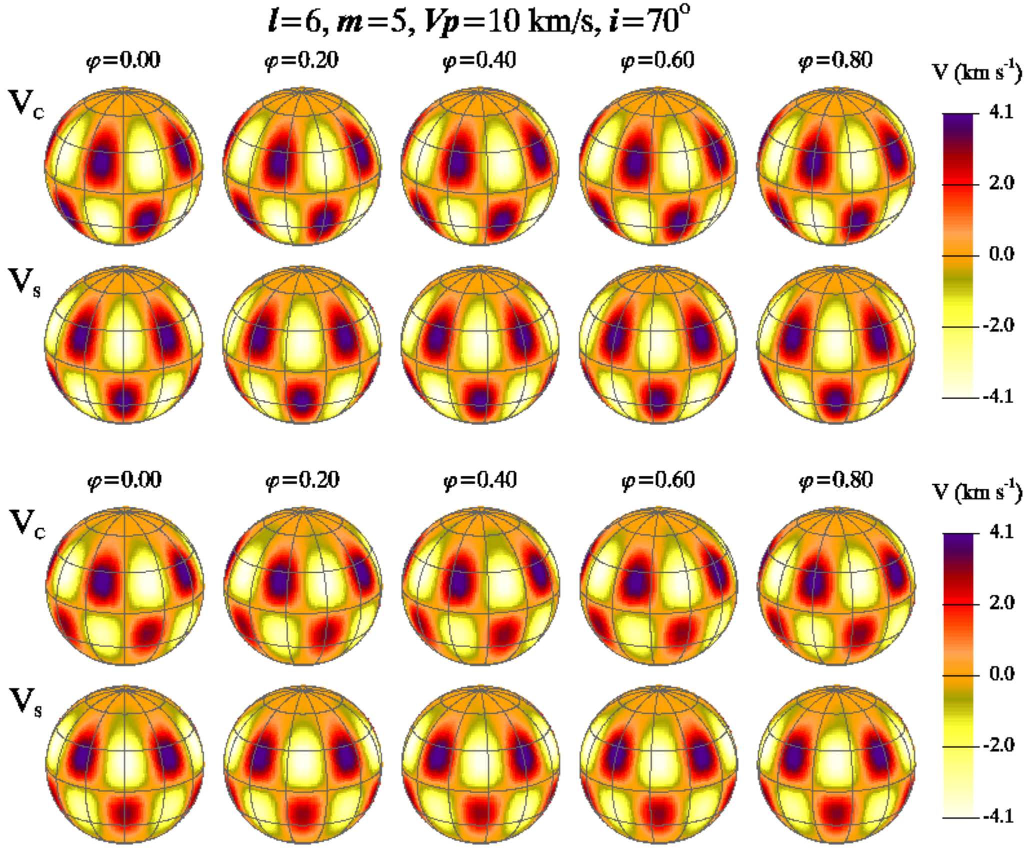


DI of non-radial pulsations

- Mapping distortions in velocity field (Kochukhov 2004)

$$V_r(\theta, \varphi, t) = V_c(\theta, \varphi) \cos \omega t + V_s(\theta, \varphi) \sin \omega t$$





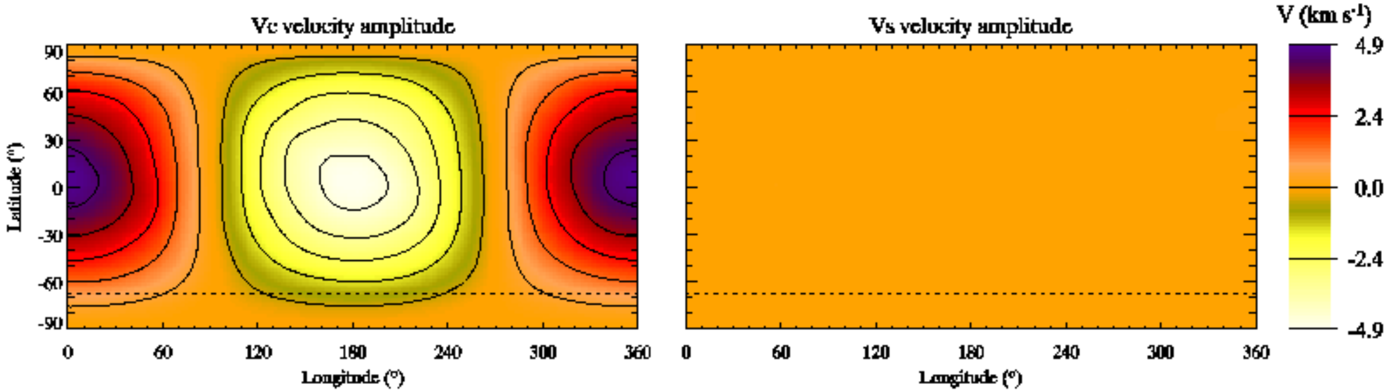
true

reconstructed

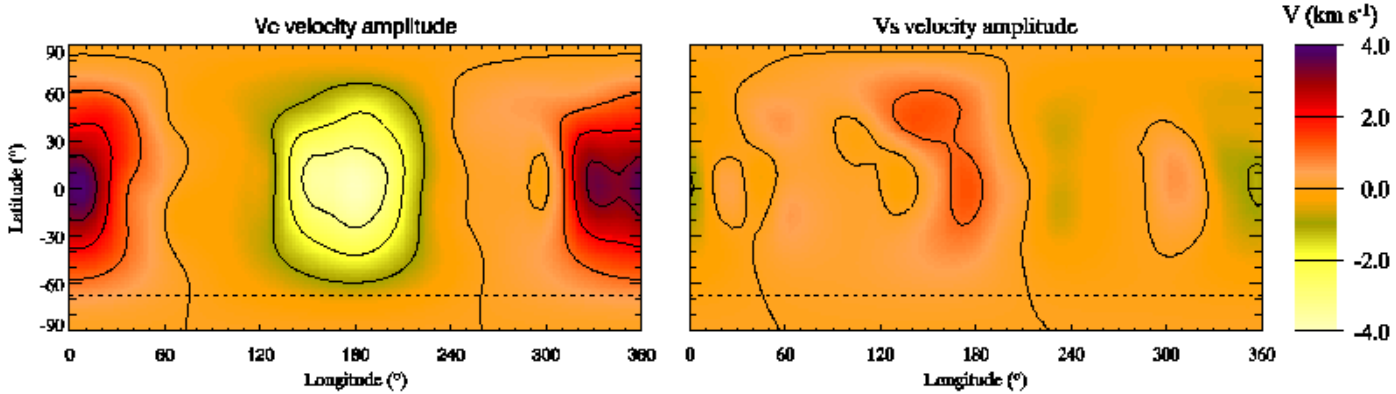
DI of non-radial pulsations

◆ Mapping pulsations in rapidly oscillating Ap stars (Kochukhov 2004)

– Reconstructed from simulated observations for *l*=1, *m*=0



– Reconstructed from actual observations of roAp star HR 3831



Cartography of stellar magnetic fields

◆ With one exception (HgMn stars) magnetic field is thought to be responsible for the star spot formation

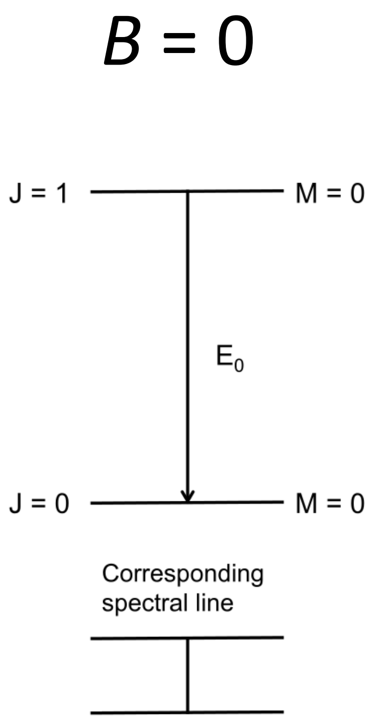
◆ The ultimate goal is to map both magnetic field geometry *and* star spot configuration

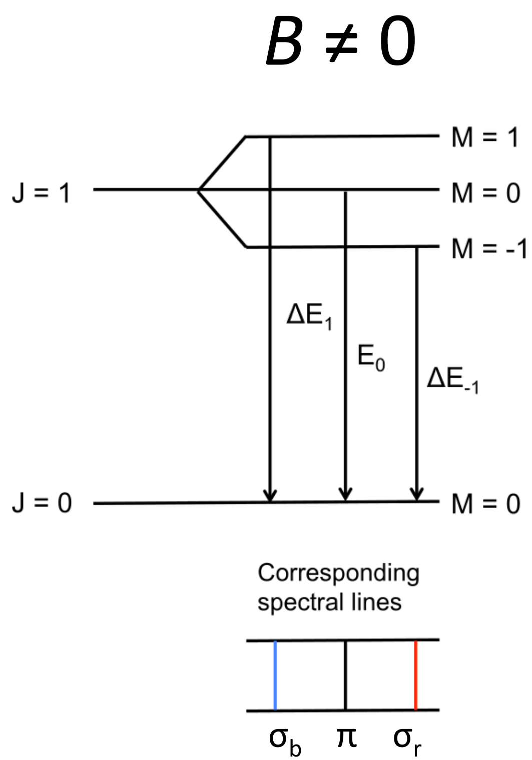
◆ How to measure magnetic field properties?

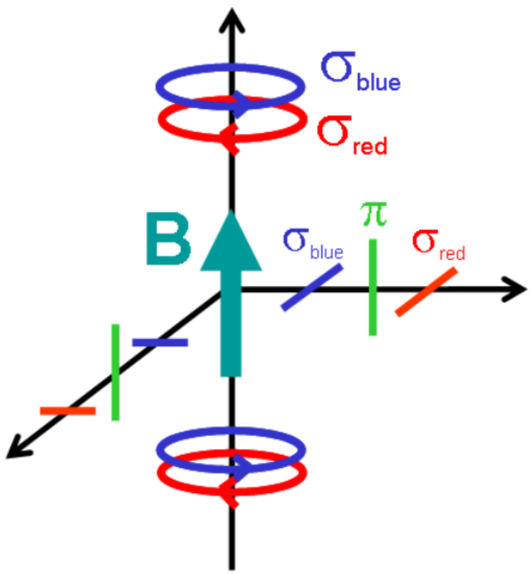
Detect magnetic fields and map their structure using spectropolarimetry

Zeeman effect

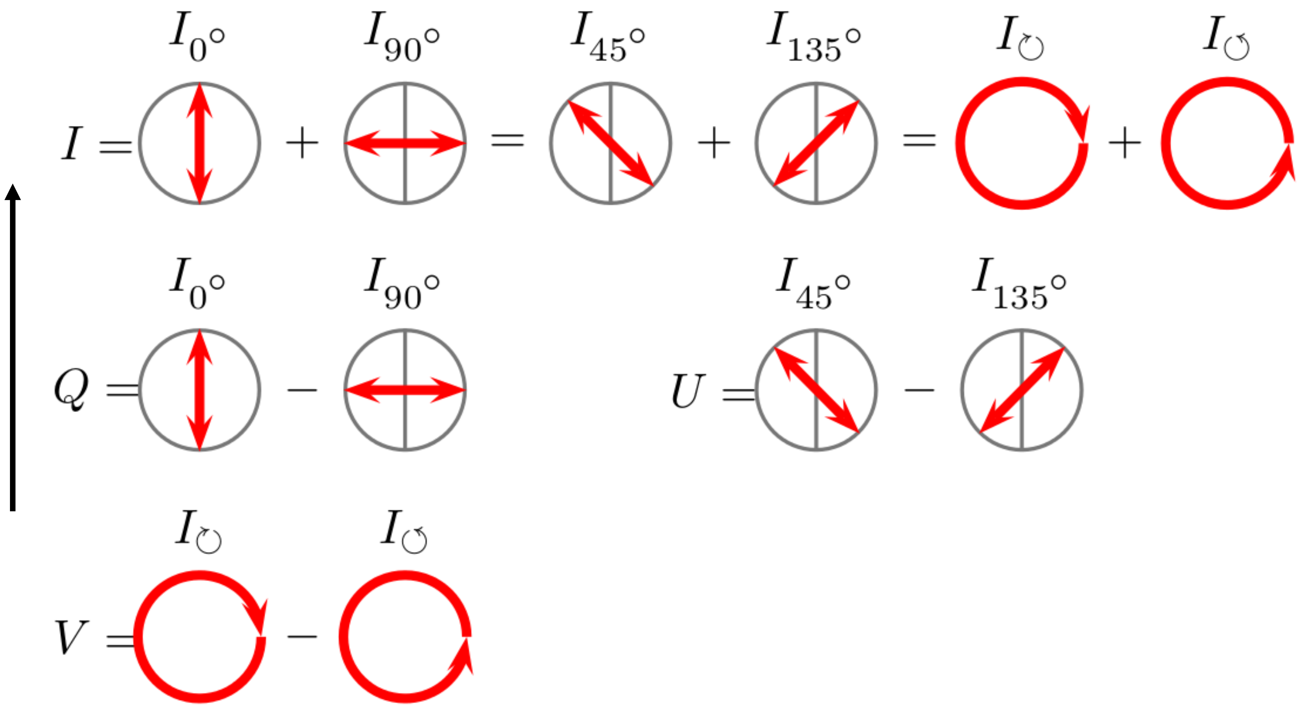
◆ Splitting of lines and polarisation in Zeeman components







Stokes parameters



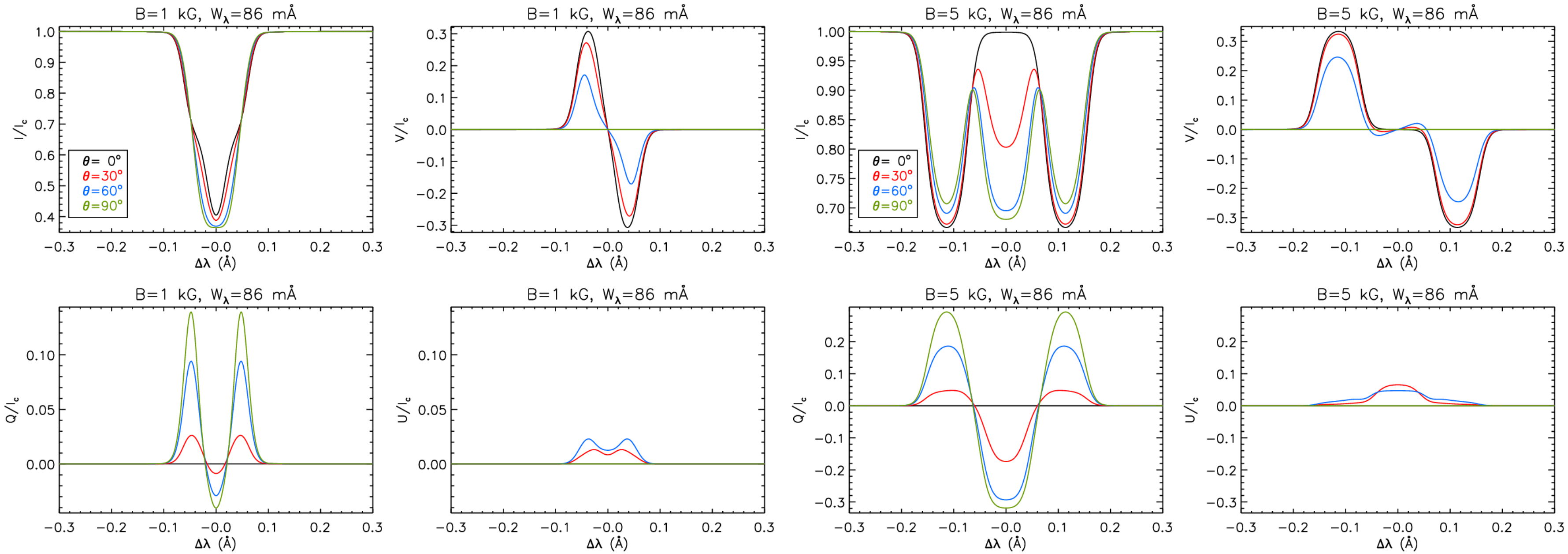
I_{α° intensity measured through perfect linear polarizer

$I_{\circlearrowright}, I_{\circlearrowleft}$ intensity measured through perfect right-hand and left-hand polarizers

Local Stokes profiles

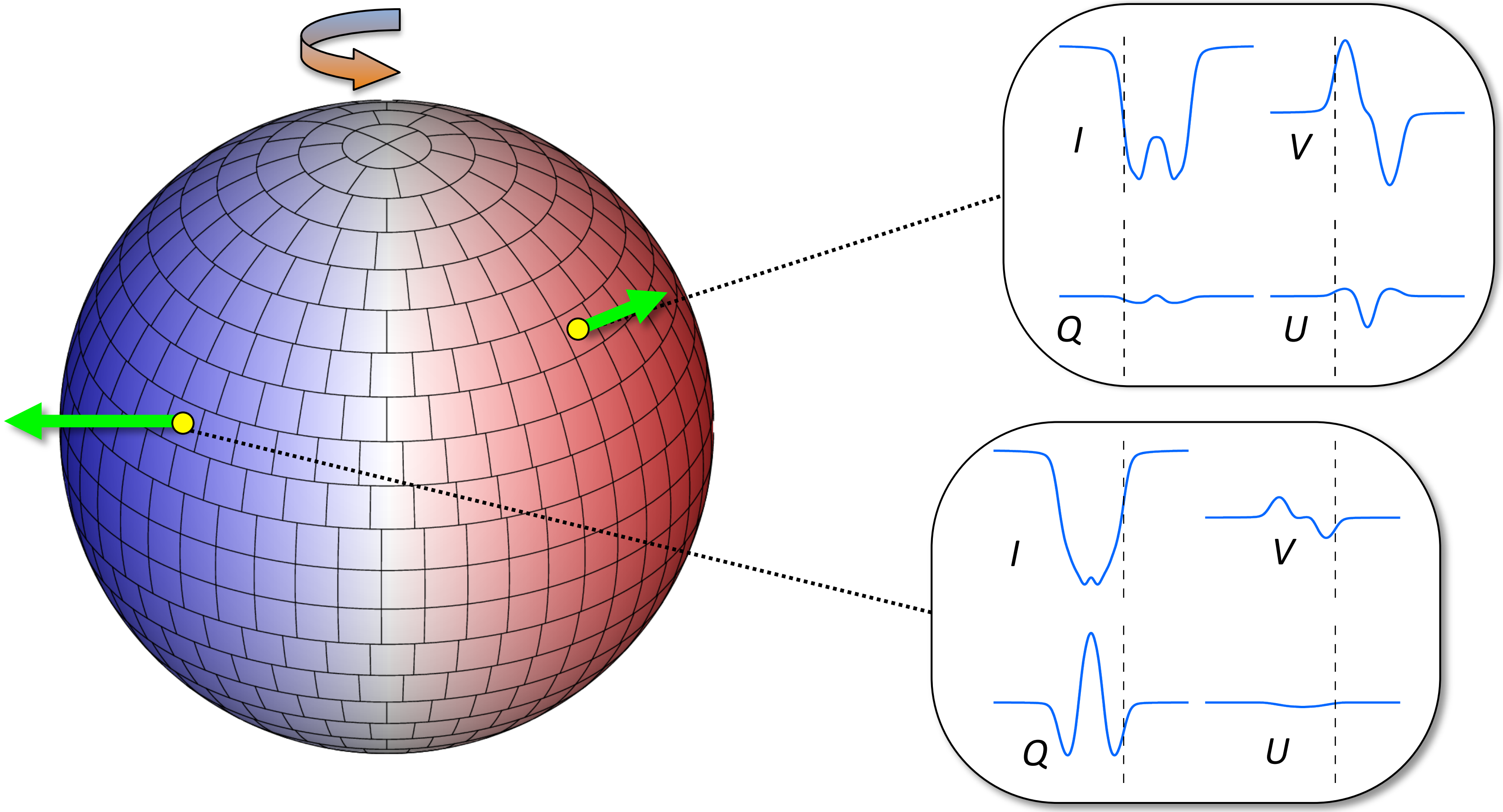
- Polarised radiative transfer based on model atmospheres
- Analytical formulas (weak-field approximation, Milne-Eddington atmosphere)

B = 1 kG　　　　*B* = 5 kG



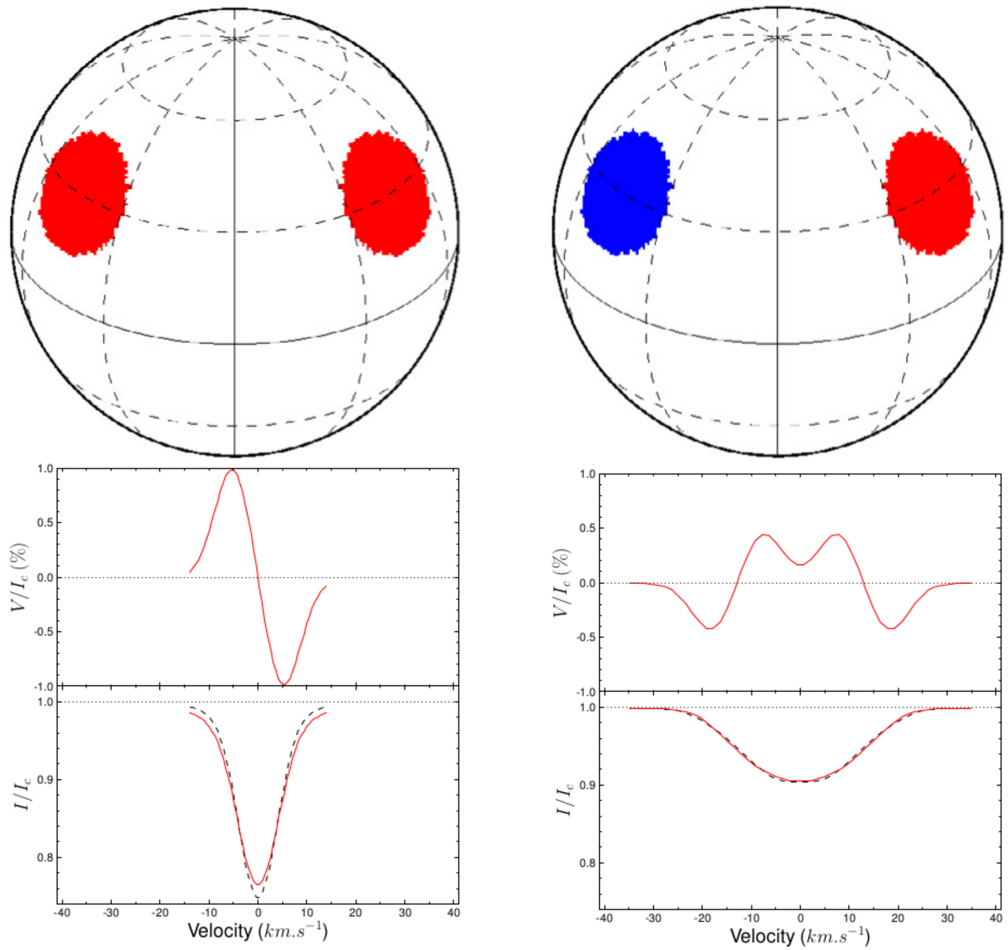
Disk-integrated Stokes profiles

Summing over ≥1000 surface zones, each with individual ***B***, μ, projected area, Doppler shift, temperature, abundance



Disk-integrated Stokes profiles

Radial field spots



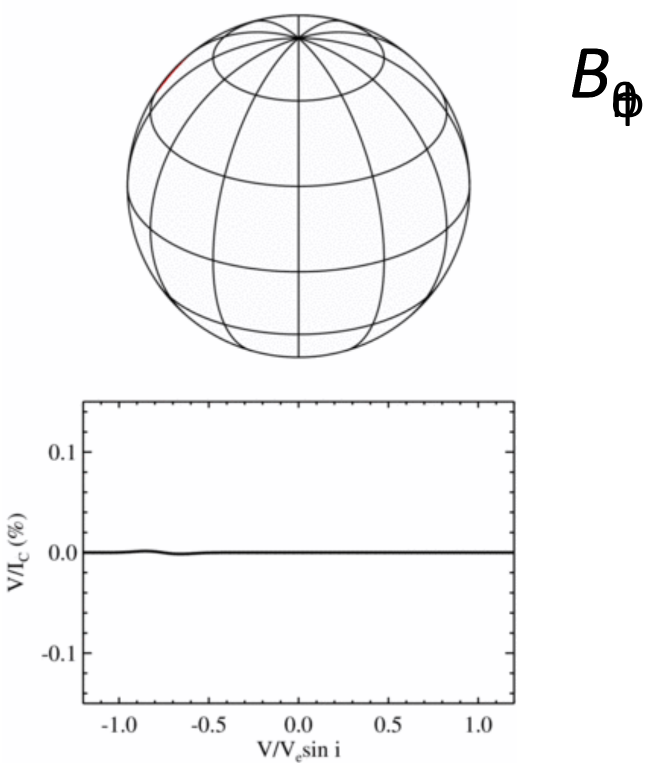
– Evidence of magnetic field comes of non-zero line polarisation signature

– Diverse and complex Stokes signatures depending on the surface field distribution and rotation velocity of the star

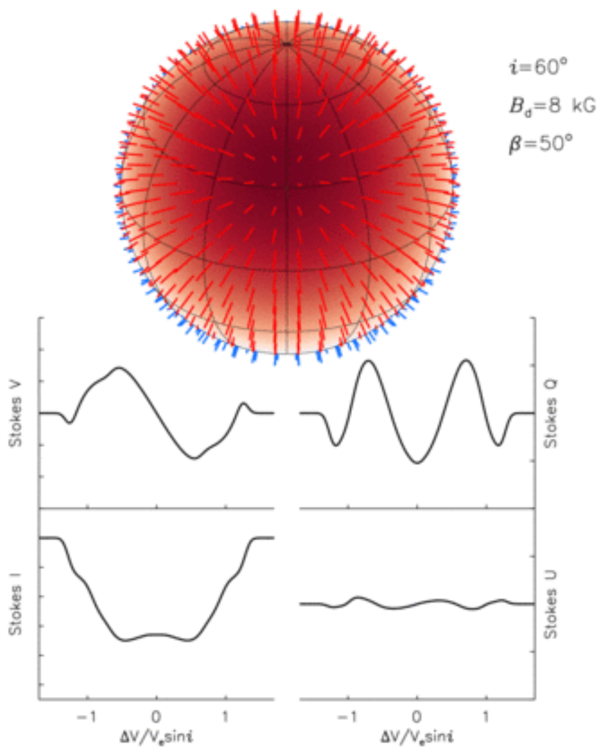
Phase variation of Stokes profiles

◆ Combined impact of Zeeman effect, Doppler effect, projection, and rotational modulation

Magnetic spots



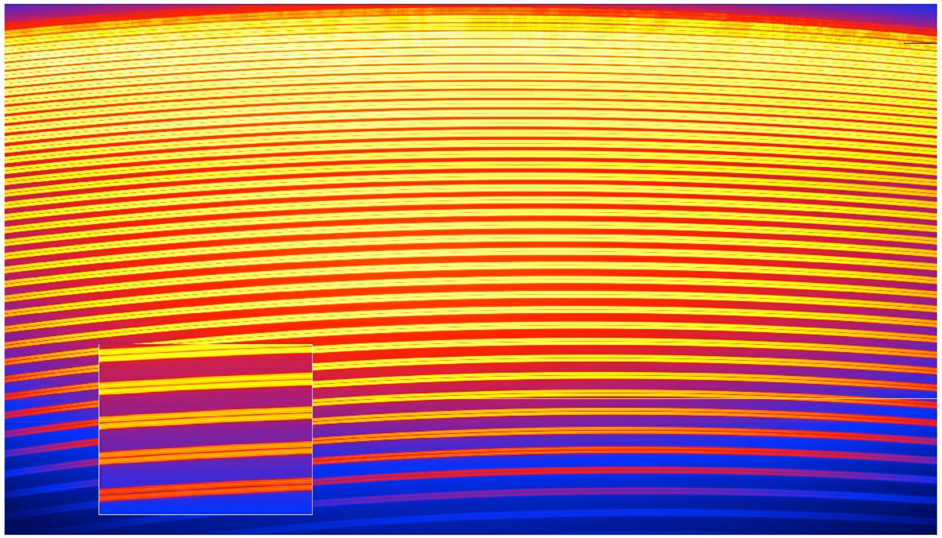
Global field

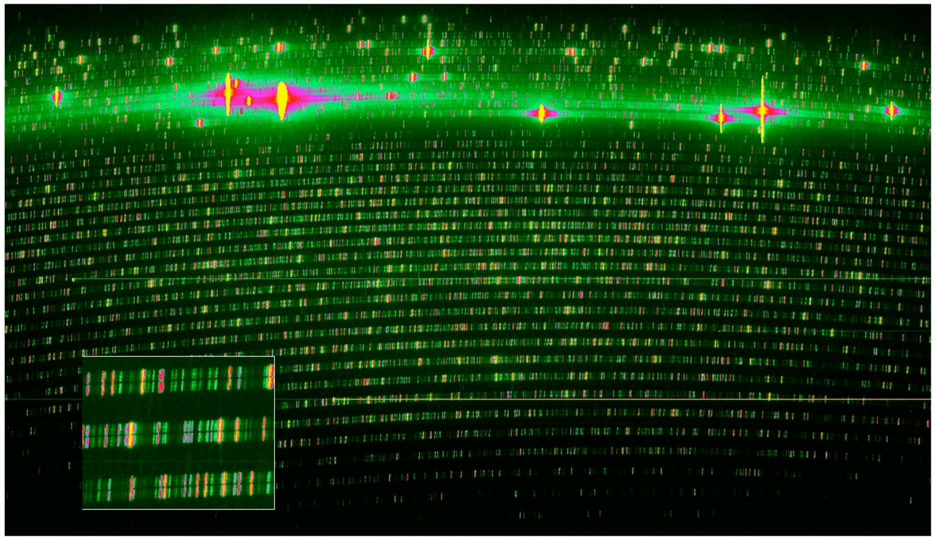


Instrumentation for spectropolarimetry

◆ Axially symmetric beam, high-resolution, (fiber-fed,) thermally stabilized, echelle spectrograph

- ESPaDOnS@CFHT and NARVAL@TBL:
  R = 65,000, 370-1050 nm, ~30 m/s stability
- HARPSpol@3.6m:
  R = 110,000, 380-690 nm, ~1 m/s stability





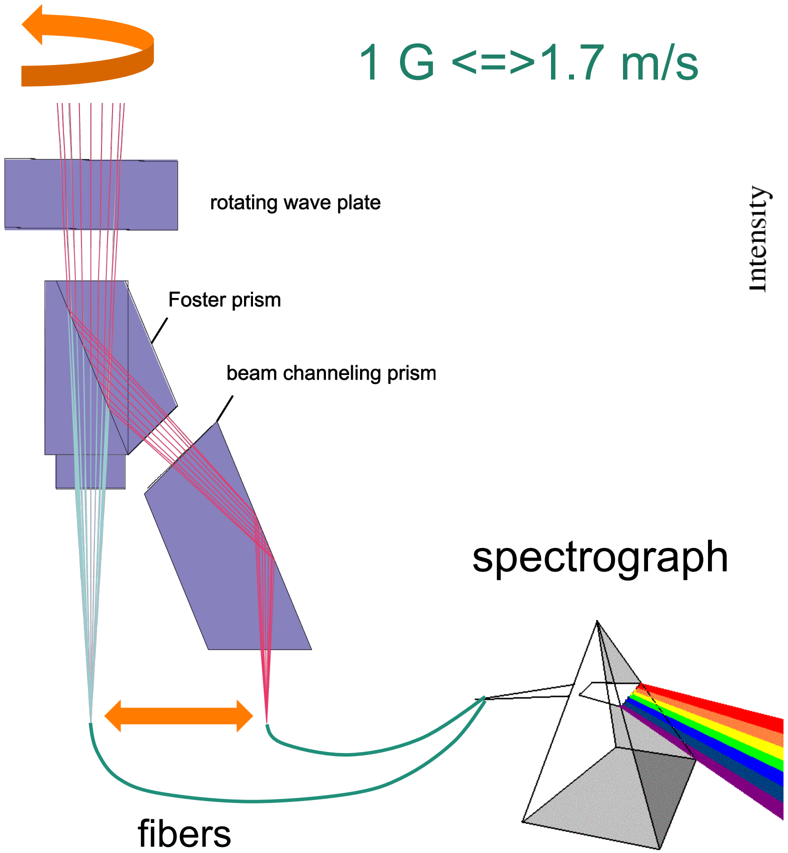
Beam exchange technique

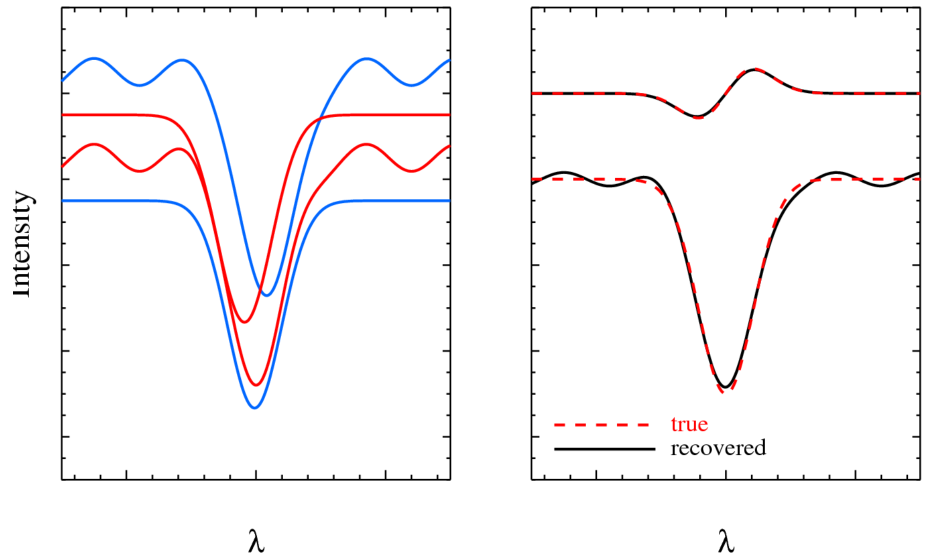
- Spectropolarimetry = differential spectral measurement

(Semel et al. 1993, Bagnulo et al. 2009)

HARPSpol @ 3.6-m

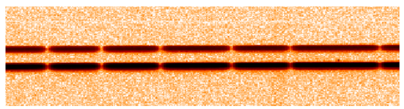
1 G <=>1.7 m/s





$$I_{\rm R} = I + V$$

$$I_{\rm L} = I - V$$

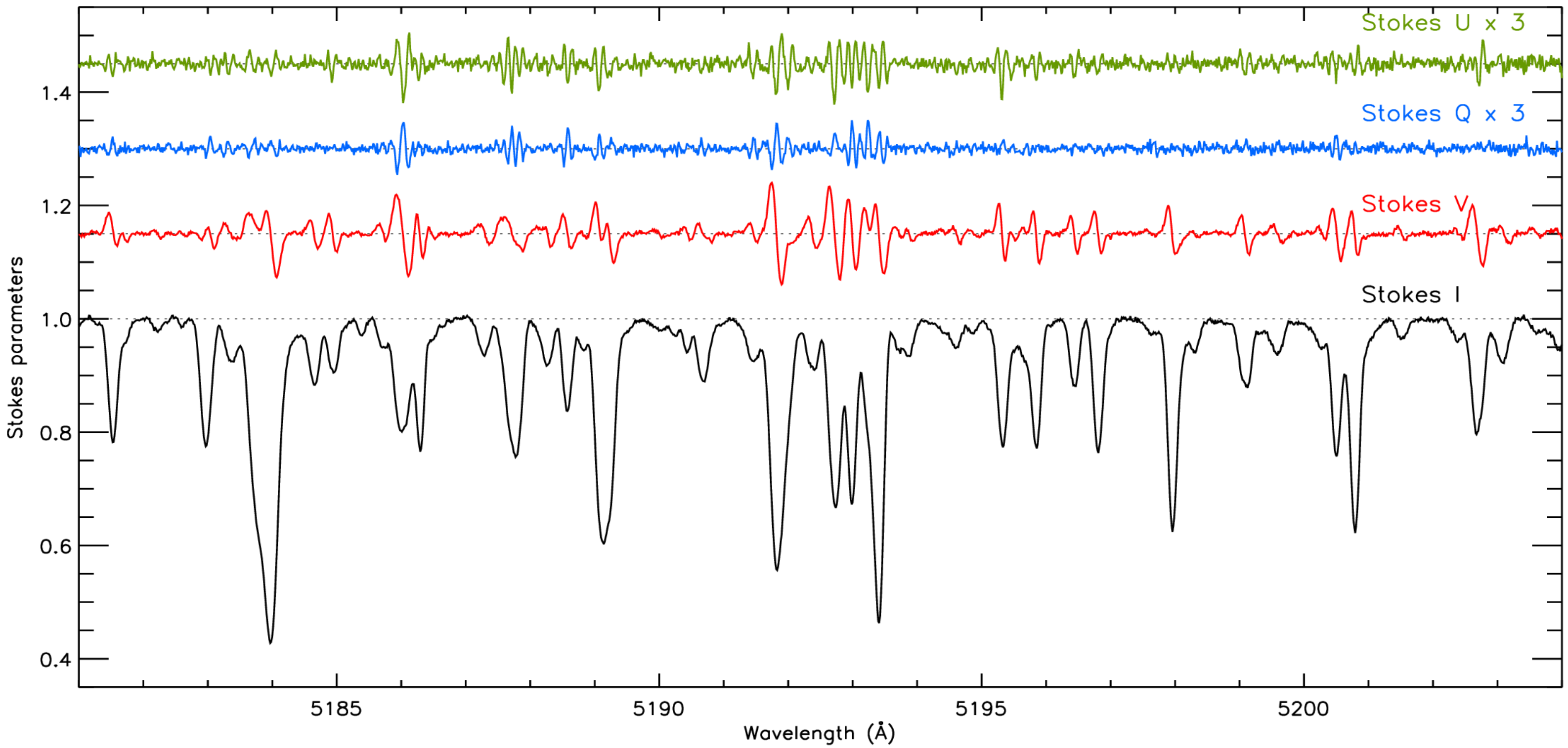


$$\frac{V}{I} = \frac{1}{2}\sum_{i=1}^{2}\frac{I_{\rm R}^{(i)} - I_{\rm L}^{(i)}}{I_{\rm R}^{(i)} + I_{\rm L}^{(i)}}$$

Zeeman effect in stellar spectra

◆ Early-type magnetic stars: amplitude ~10^{-2} for Stokes *V*, ~10^{-3} for Stokes *QU*; analysis of individual lines at S/N~10^3

Cool Ap star HD 24712 with HARPSpol (Rusomarov et al. 2013)



Multi-line polarisation analysis

- Late-type stars: amplitudes ~10^{-3} to 10^{-5} for Stokes *V*; need to use a multi-line technique for the field analysis
- Least-squares deconvolution (LSD)
  - spectrum = superposition of shifted and scaled profile
  - weak-field and weak-line approximations
  - linear least-squares problem

$$I(v) = 1 - \sum_i w_I^i Z_I(v - v^i), \quad w_I^i = d_i$$

$$V(v) = \sum_i w_V^i Z_V(v - v^i), \quad w_V^i = \bar{g}\lambda_i d_i$$

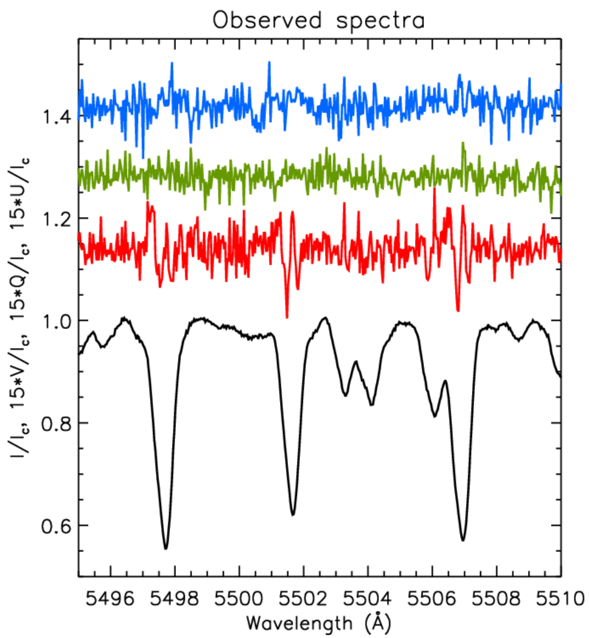
$$Q(v) = \sum_i w_Q^i Z_Q(v - v^i), \quad w_Q^i = \bar{G}\lambda_i^2 d_i$$

Donati et al. (1997)
Kochukhov et al. (2010)

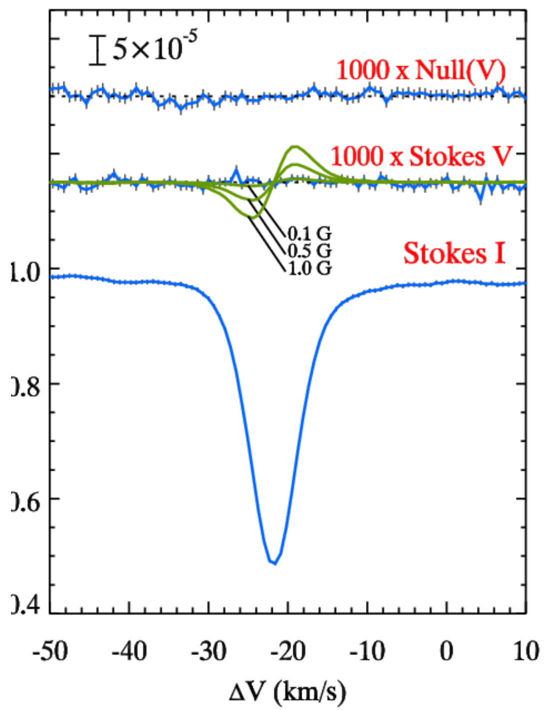
Multi-line polarisation analysis

- Widely used in stellar spectropolarimetry
- Enables sensitivity $<10^{-5}$ for Stokes V of bright stars

Stokes *IQUV* for II Peg
(Rosén et al. 2012)



α Cen A



Zeeman (Magnetic) Doppler imaging

- Restricted ZDI inversion (Brown et al. 1991)

$$\chi^2_V(\boldsymbol{B}) + \Lambda R(\boldsymbol{B}) \rightarrow \min$$

- General ZDI inversion (Piskunov & Kochukhov 2002)

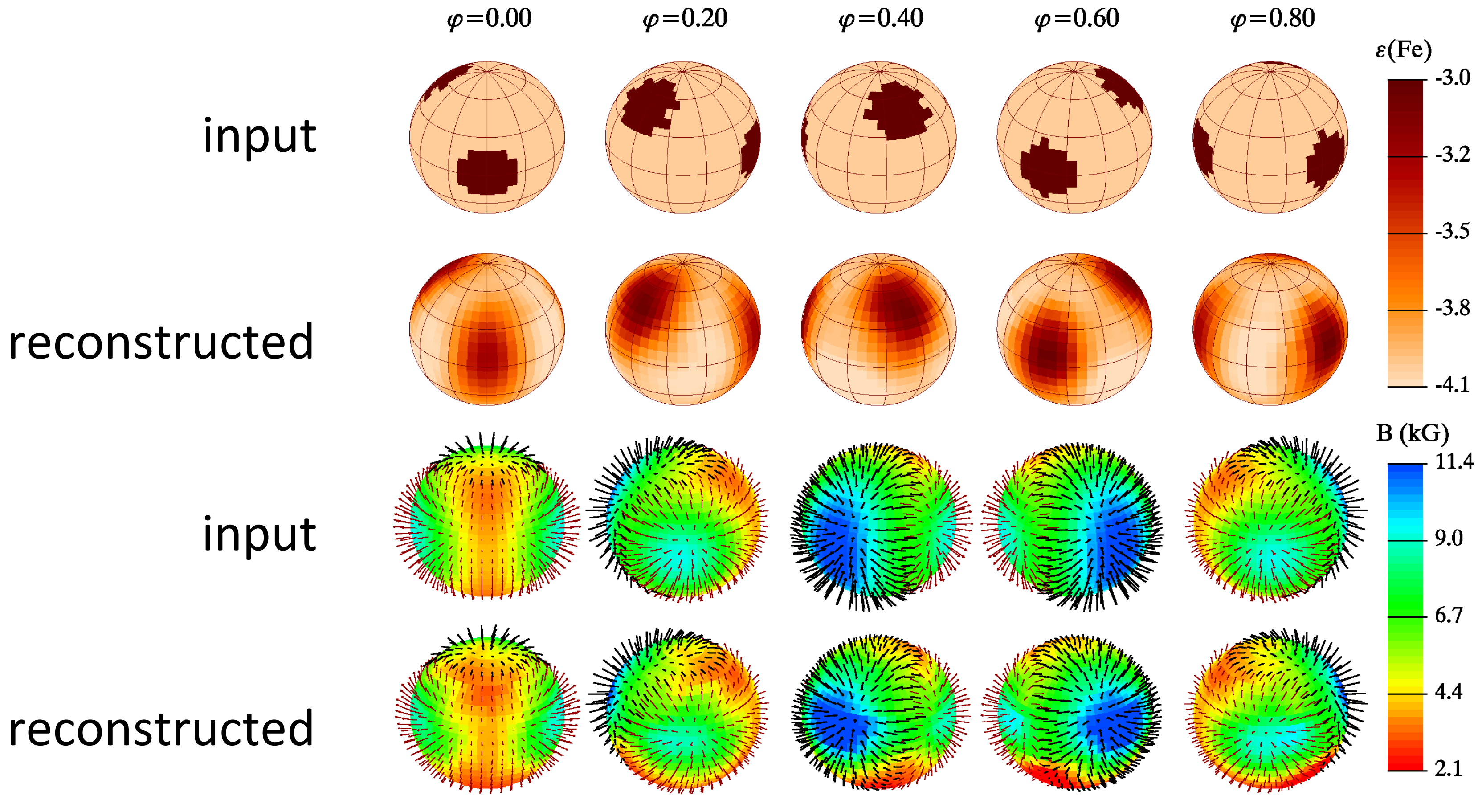
$$\sum_k w_k \chi^2_k(\boldsymbol{B}, T) + \Lambda_1 R(\boldsymbol{B}) + \Lambda R(T) \rightarrow \min$$

- Regularization in ZDI
  - Tikhonov regularization applied to individual field components
  - ME regularization not applicable to global field geometries
  - Multipolar expansion

$$\boldsymbol{B} = F(\alpha_{\ell,m}, \beta_{\ell,m}, \gamma_{\ell,m}), \quad R(\boldsymbol{B}) = \sum_\ell \ell^2(\alpha^2_{\ell,m} + \beta^2_{\ell,m} + \gamma^2_{\ell,m})$$

Tests of ZDI inversions

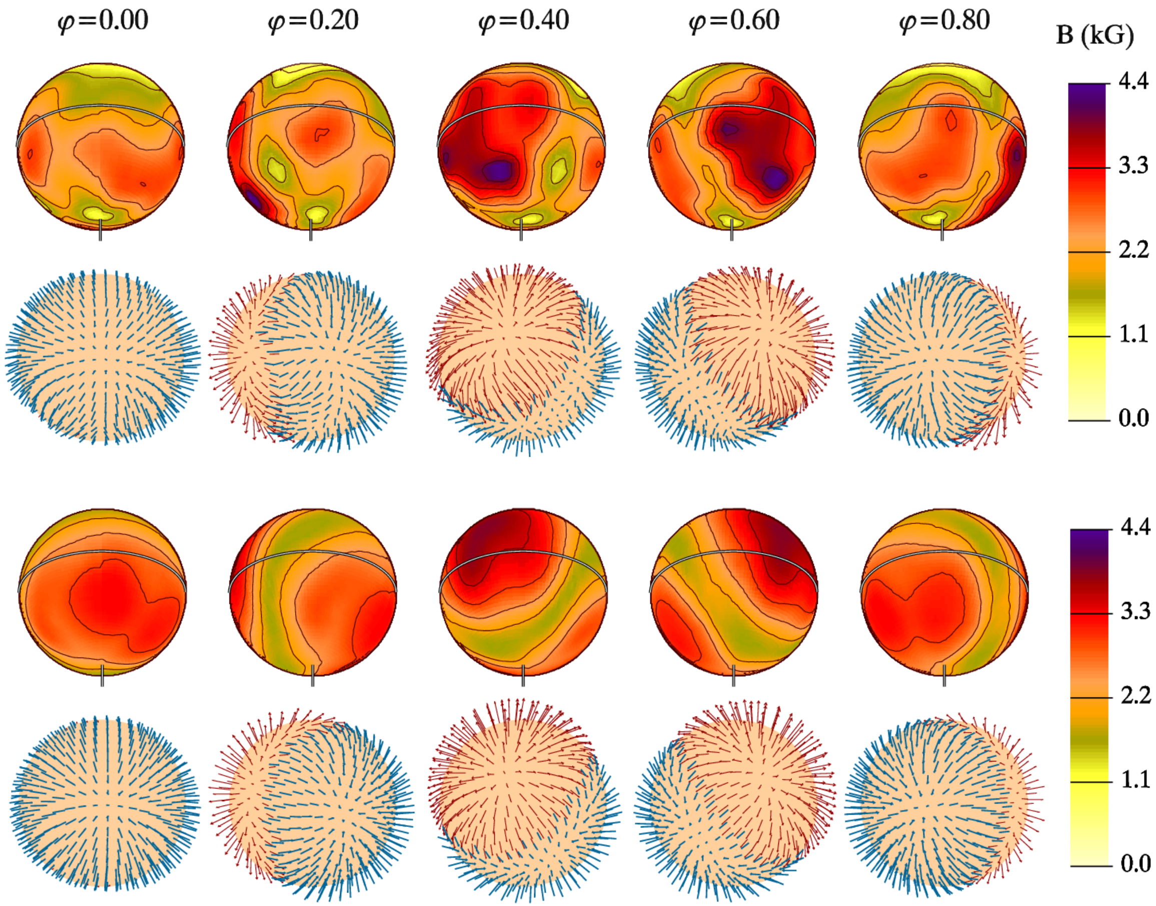
◆ Verification of ZDI code with numerical experiments



Kochukhov & Piskunov (2002)

ZDI results: Ap/Bp stars

- Full Stokes inversions reveal deviations from dipolar fields



Inversion using *IQUV*

Inversion using *IV*

α^2 CVn=HD 112413
(Kochukhov & Wade 2010)

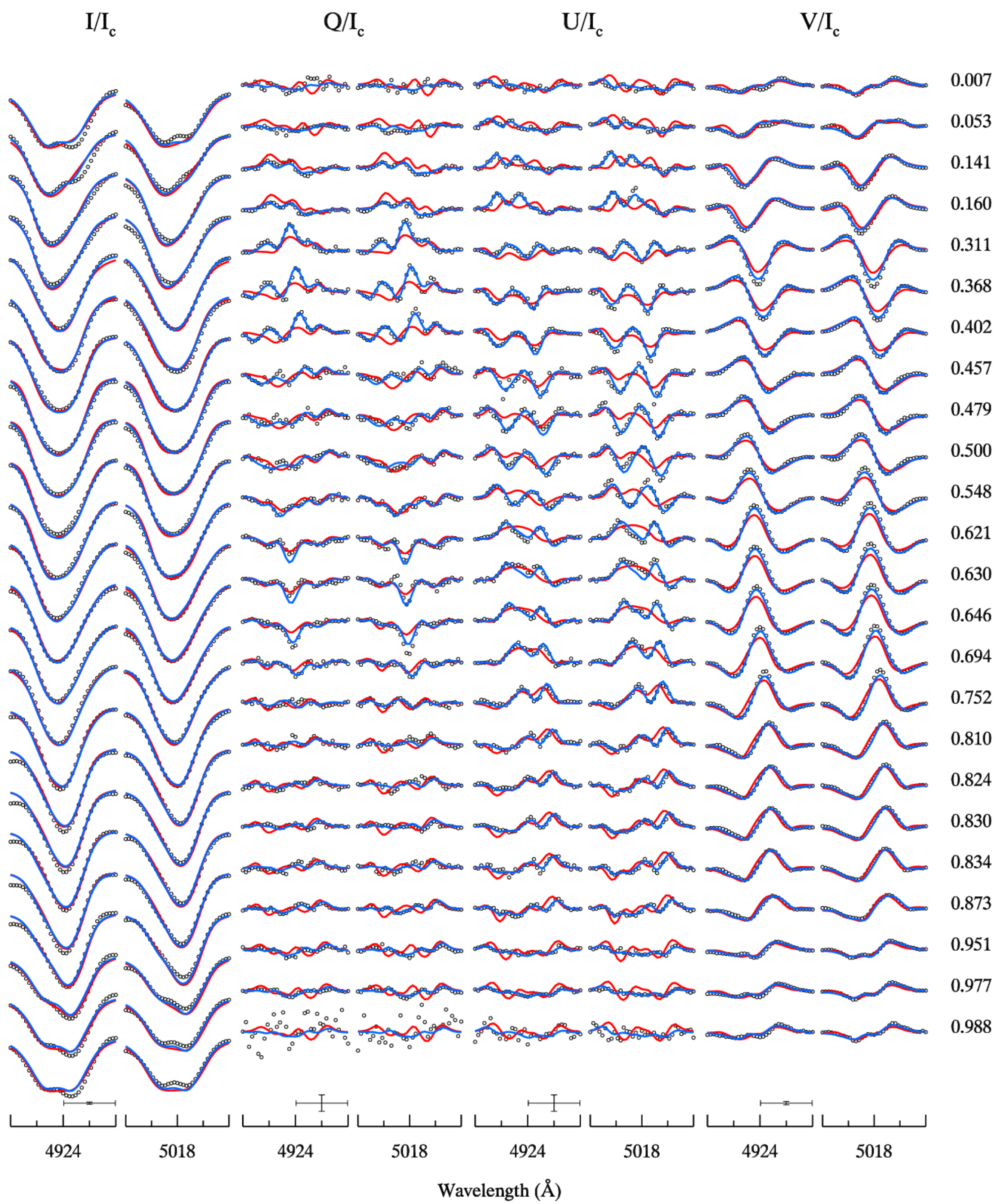
ZDI results: Ap/Bp stars

Observed and computed Stokes profiles of α^2 CVn

observations

best ZDI fit

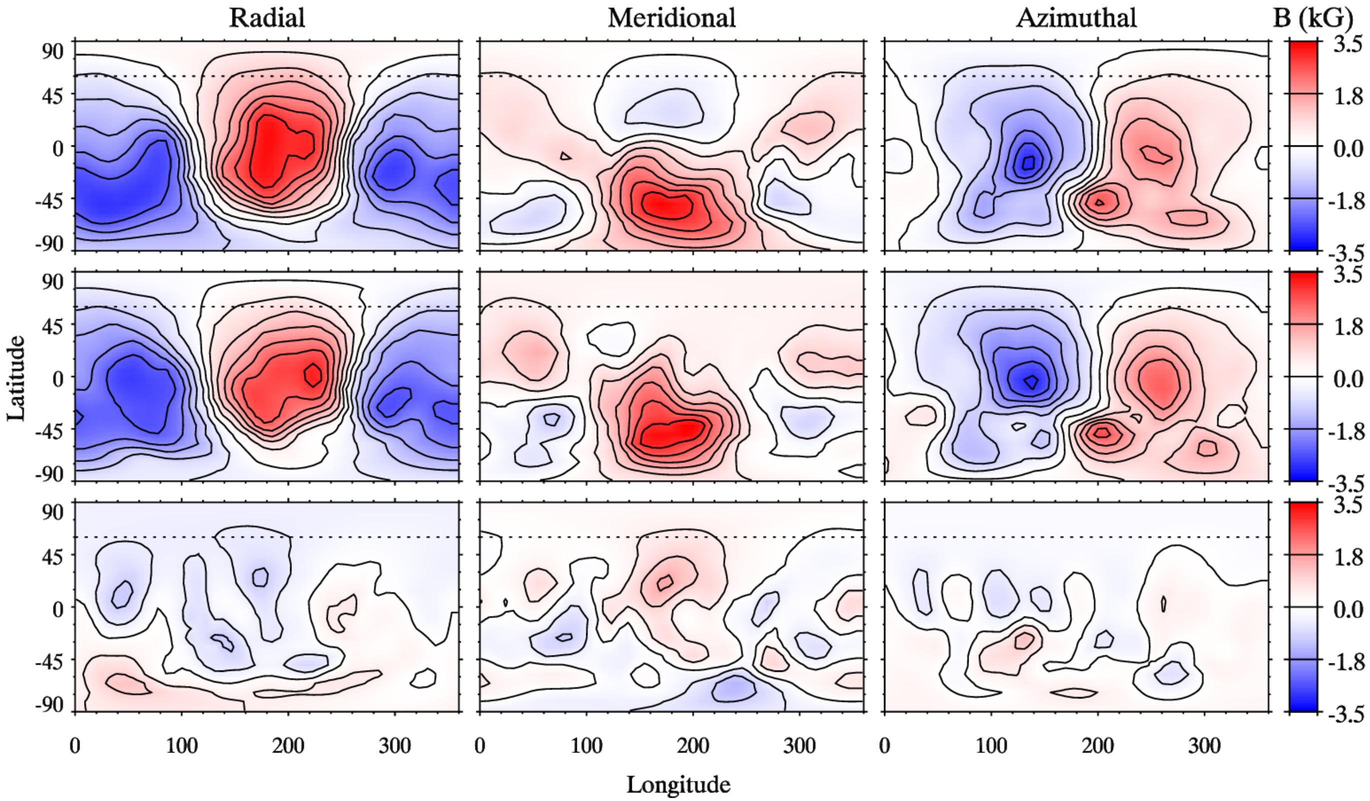
dipolar fit



ZDI results: Ap/Bp stars

- No field evolution on the time scale of ~10 yr

α^2 CVn (Silvester et al. 2012)



MuSiCoS (1997-1999)

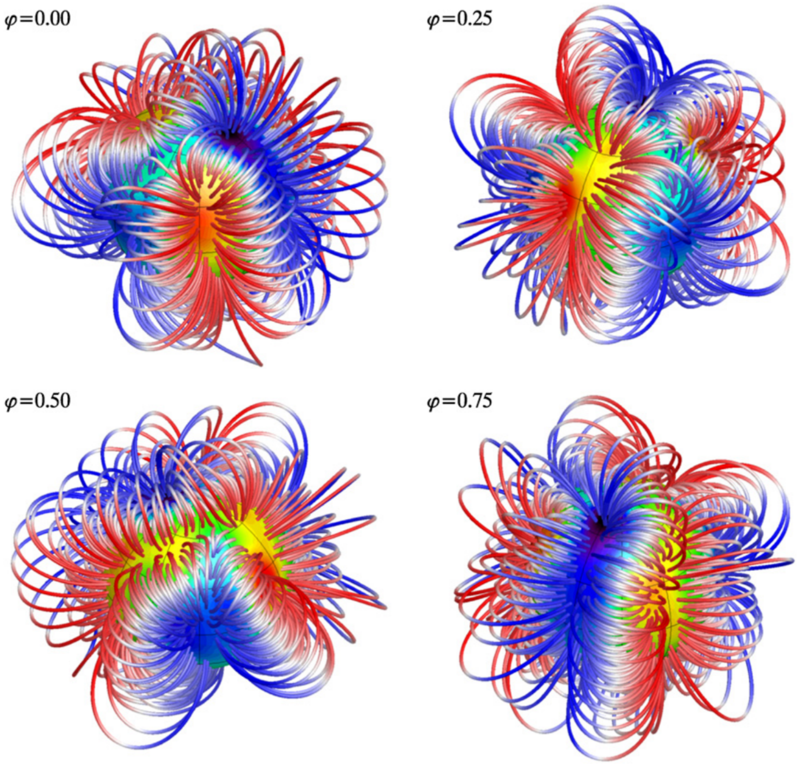
ESPaDOnS/NARVAL (2006-2010)

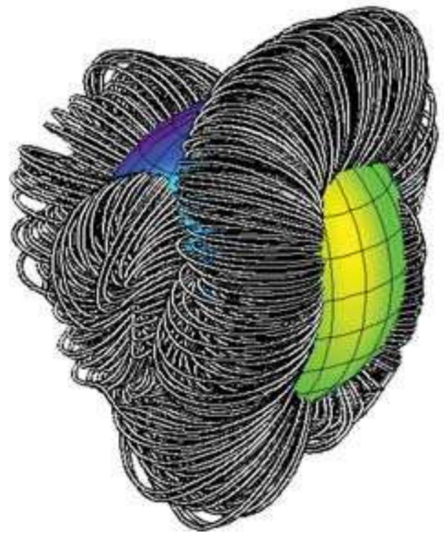
difference

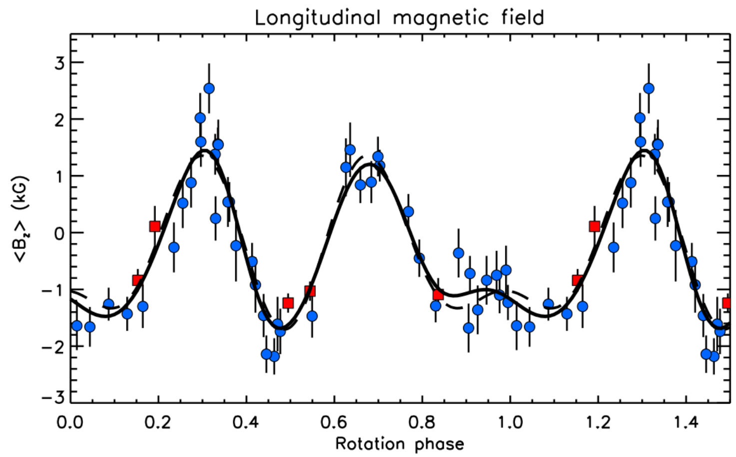
ZDI results: Ap/Bp stars

◆ Complex fields in early-B stars

τ Sco (B0V) and HD 37776 (B2V)
(Donati et al. 2006, Kochukhov et al. 2011)

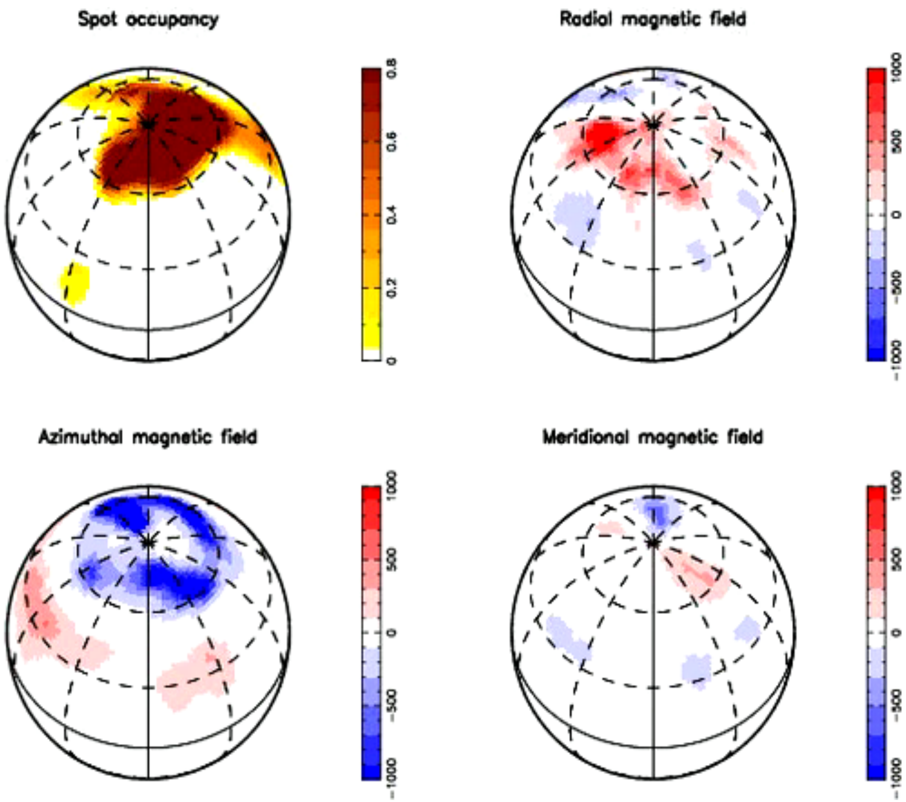






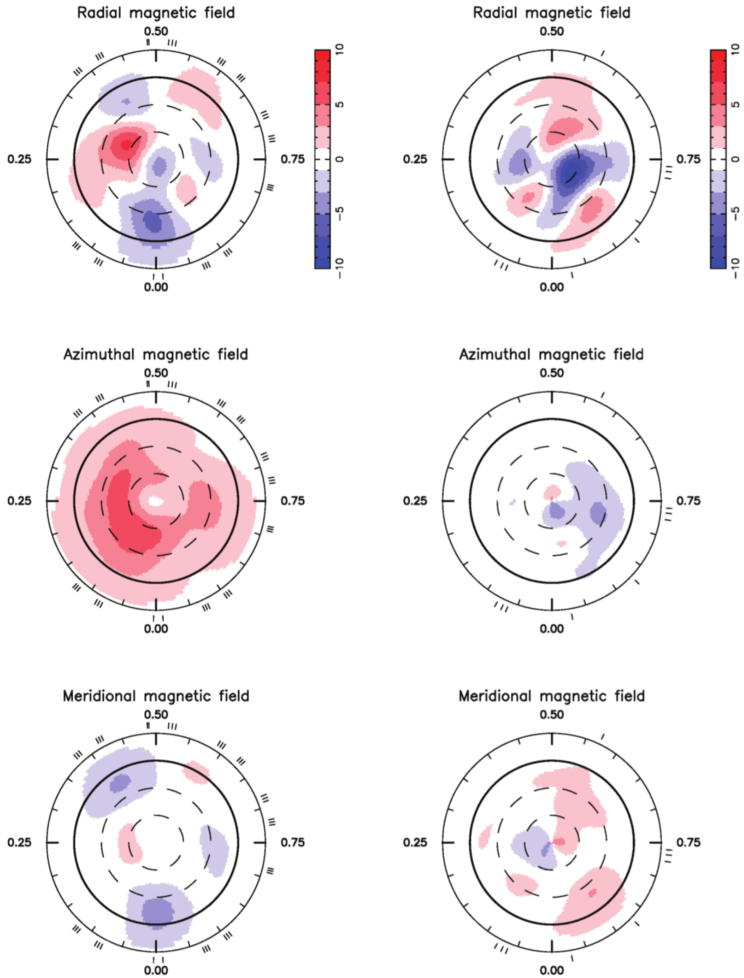
ZDI results: cool active stars

Prominent azimuthal field



HR 1099 (Petit et al. 2004)

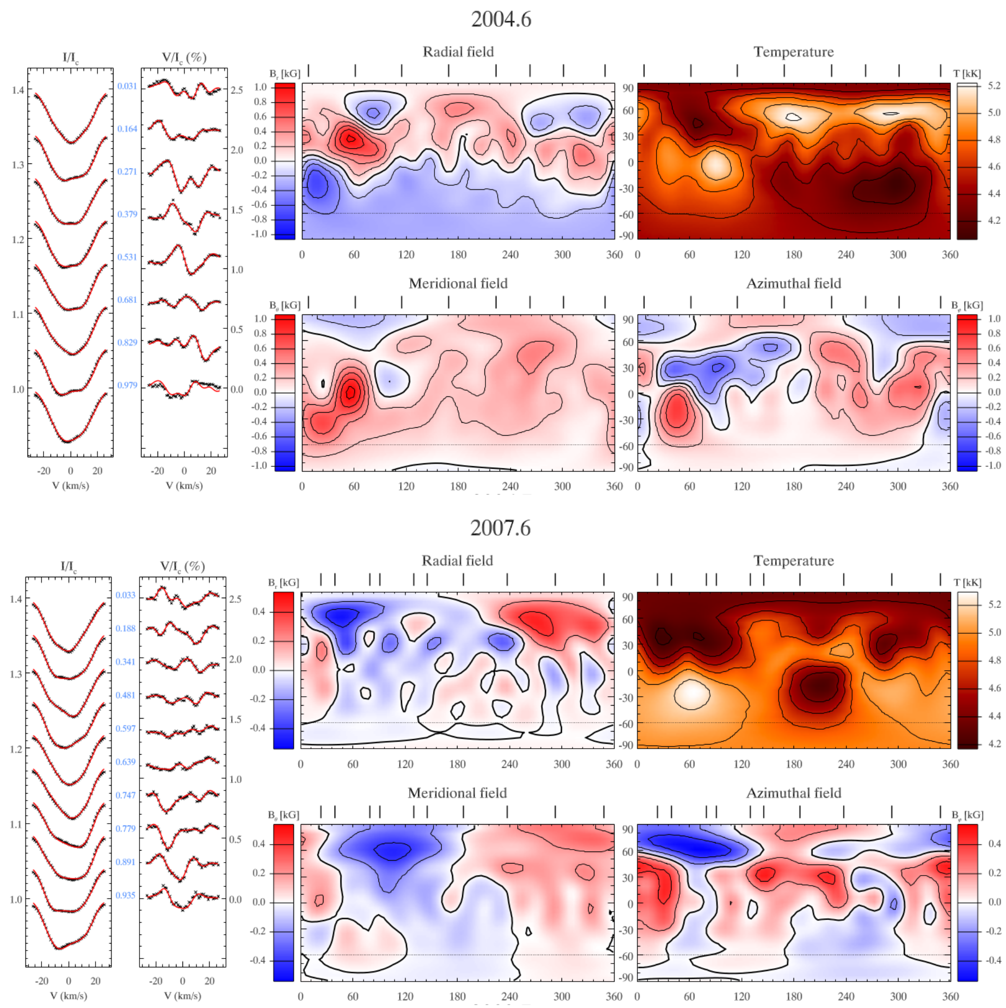
Jan 2008 June 2008



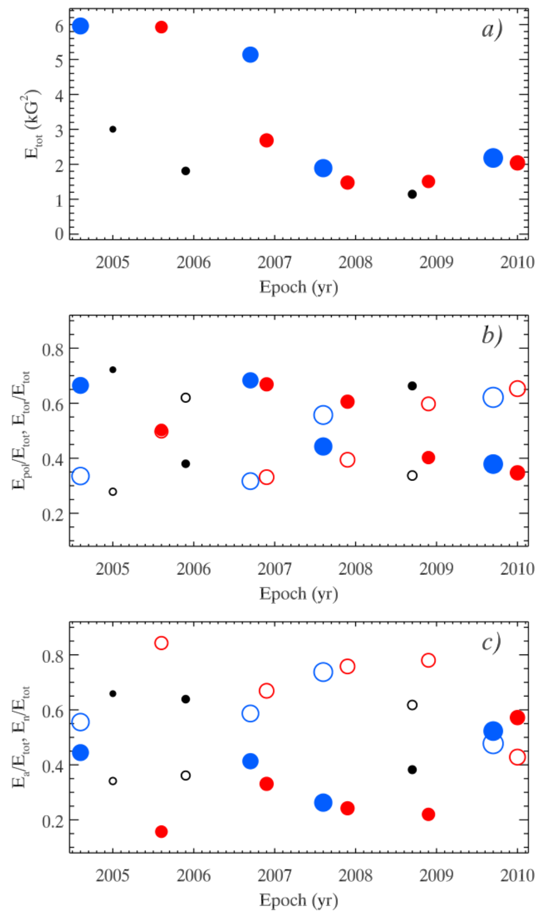
τ Boo (Fares et al. 2010)

ZDI results: cool active stars

◆ Long-term observations are to study the field evolution



II Peg (Kochukhov et al. 2013)

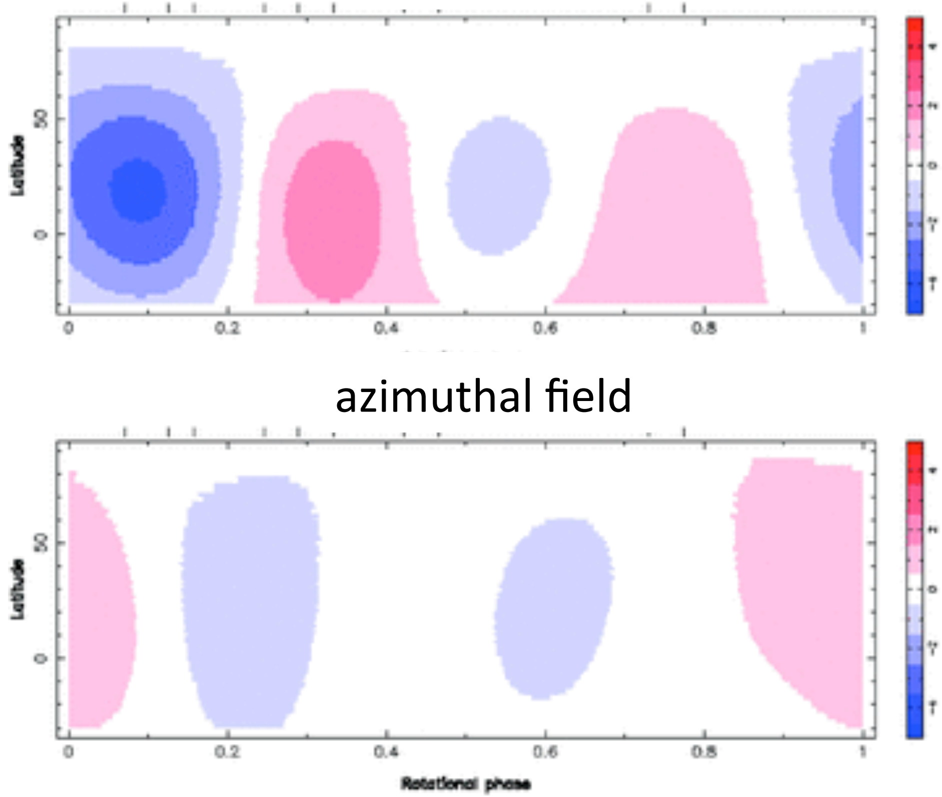


ZDI results: solar twins

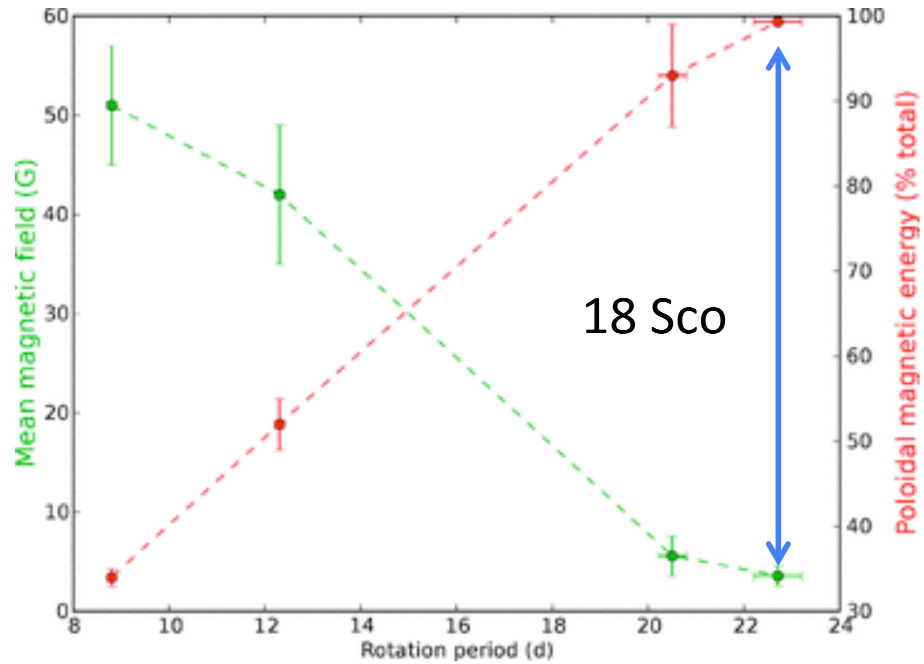
- Global magnetic field geometry depends on rotation rate

radial field ±5 G

azimuthal field



Petit et al. (2008)

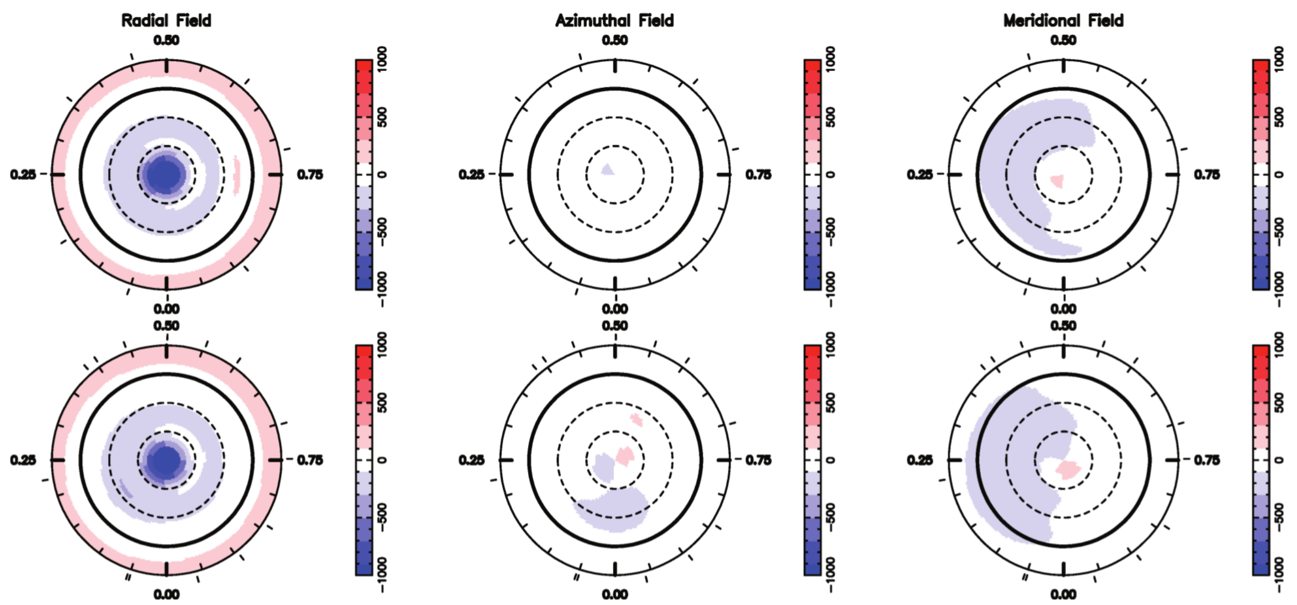


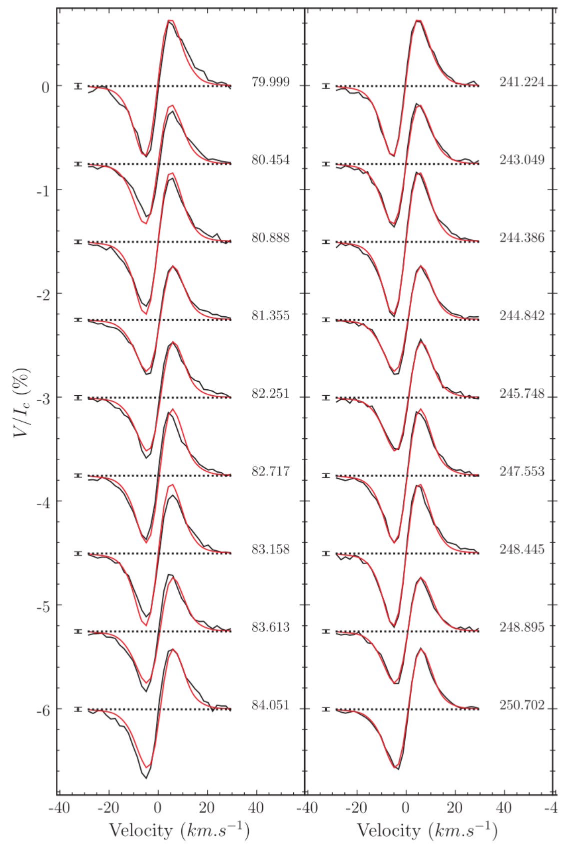
ZDI results: low-mass stars

◆ Global, strong, mostly axisymmetric fields, inconsistent with |B| inferred from line broadening

<B_I>=2.9 kG (Reiners & Basri 2007)

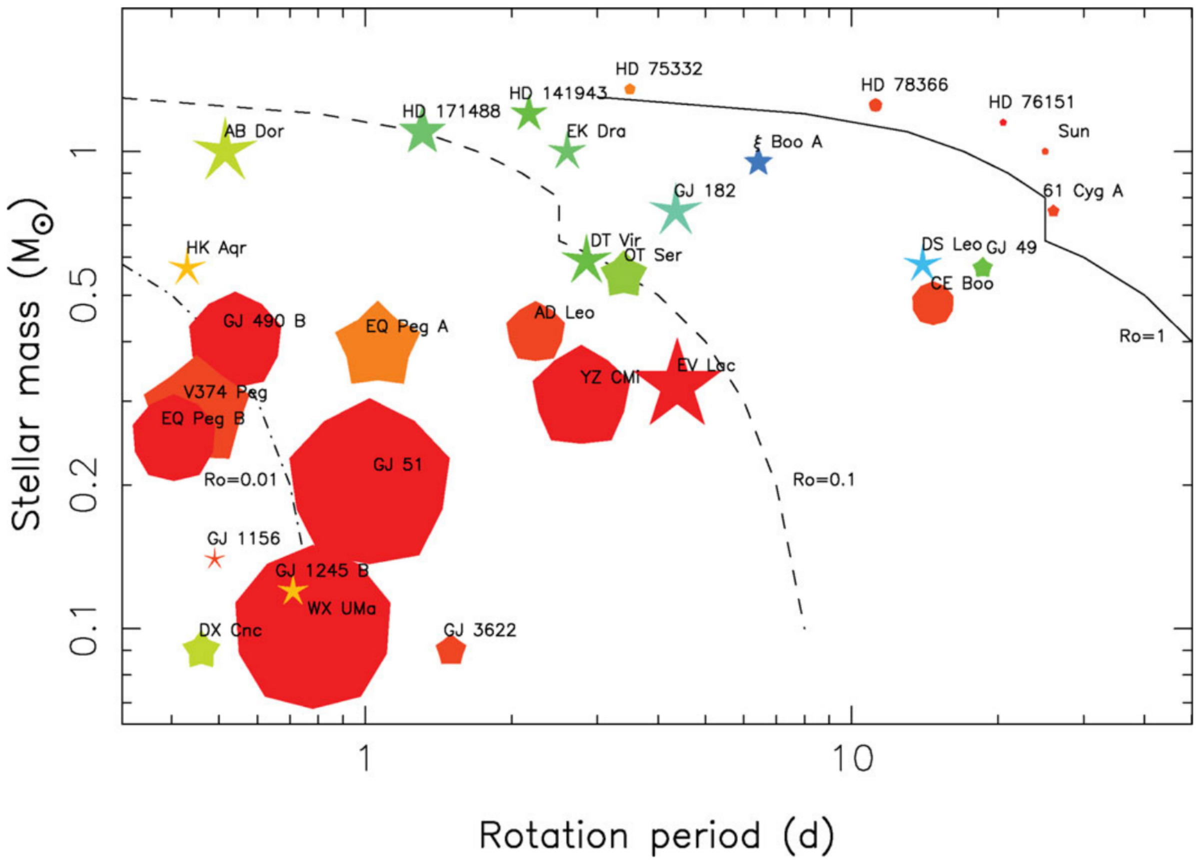
AD Leo: f_V=0.14, <B_V>=0.19 kG (Morin et al. 2008)





ZDI cool stars: overview

◆ Systematic change across H-R diagram



Size:

field strength

Shape:

● axisymmetric

★ non-axisymmetric

Color:

toroidal

poloidal

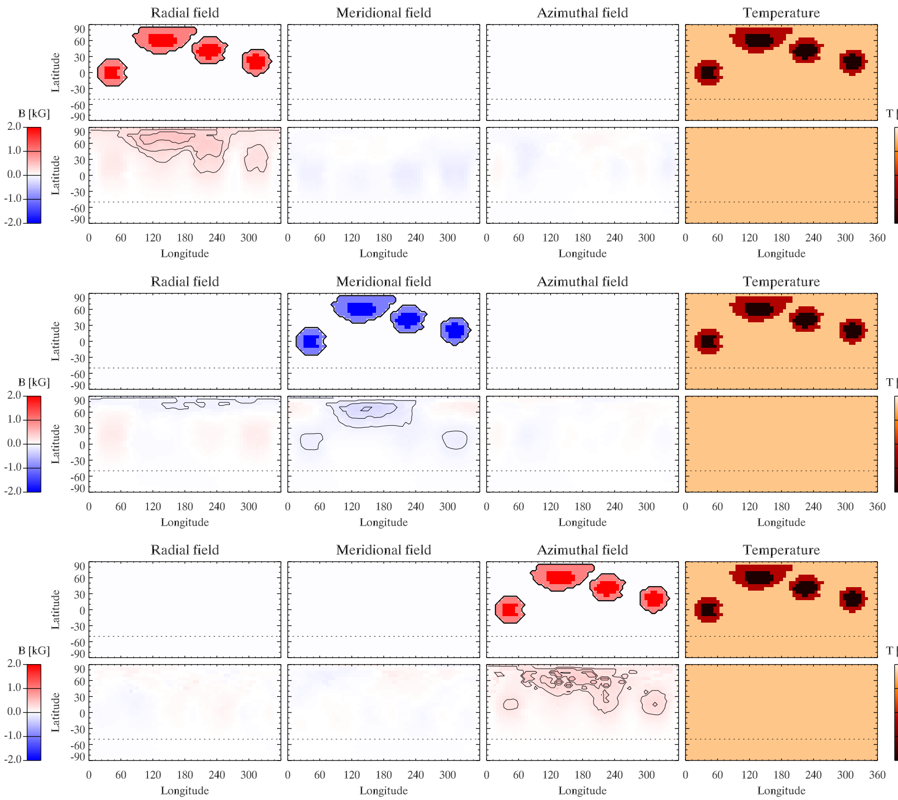
Donati (2011)

Outstanding issues of ZDI

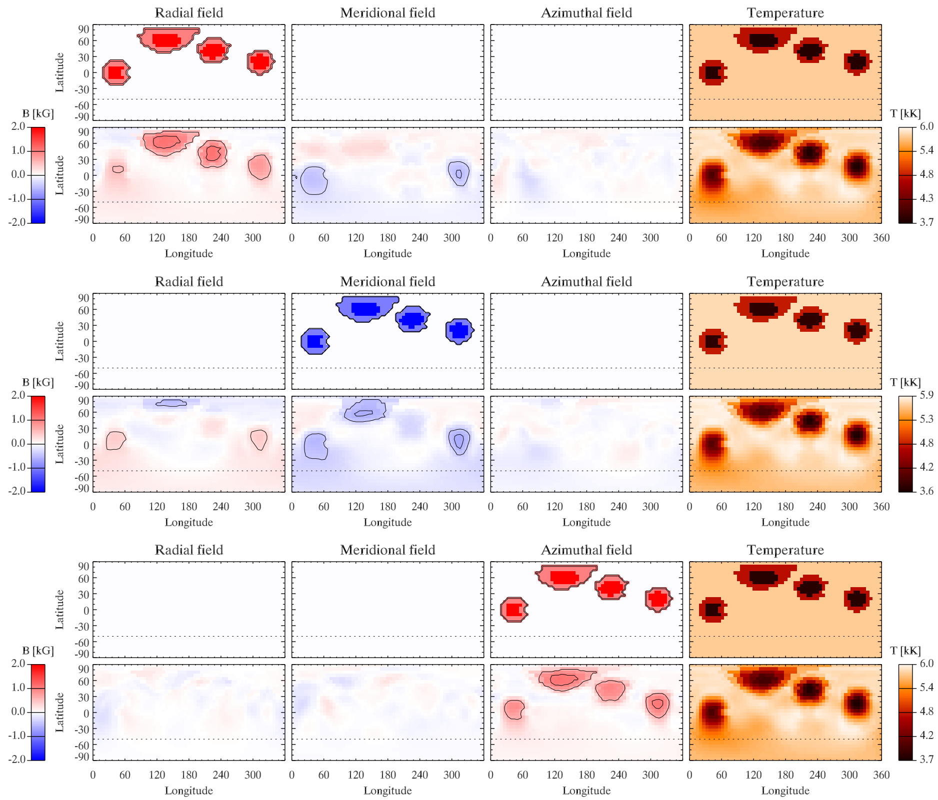
- Simultaneous reconstruction of
  - magnetic field and temperature for cool active stars
  - magnetic field and abundance for Ap stars
- Intrinsic non-uniqueness of Stokes *IV* inversions
- Simplified methods of line profile calculation
- Interpretation of LSD profiles
  - single line with mean parameters
  - theoretical LSD profiles from polarised spectrum synthesis

Lack of consistency between magnetic and temperature inversions

Constant temperature



Variable temperature

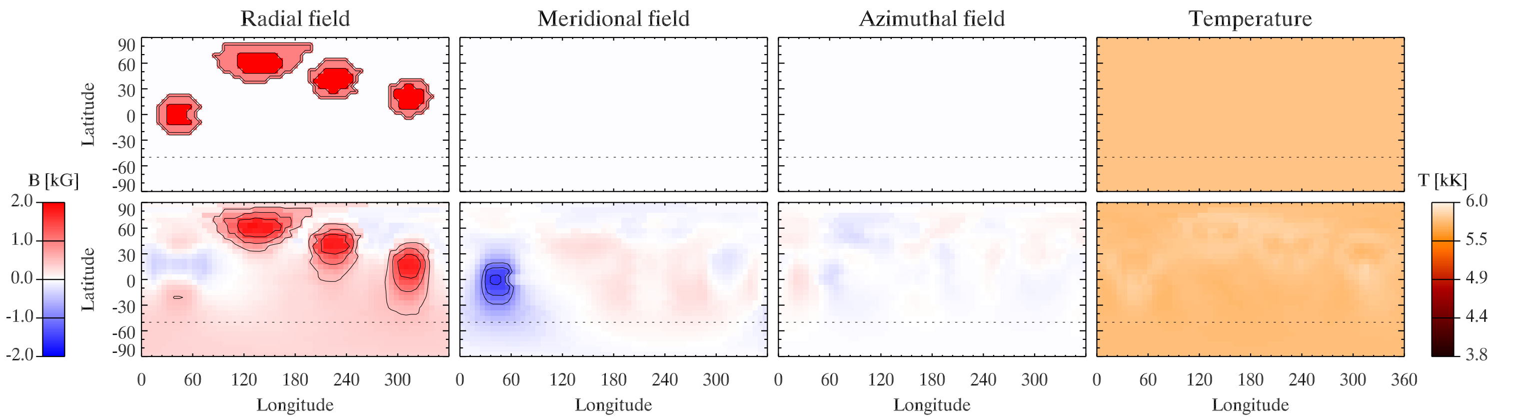


Rosén & Kochukhov (2012)

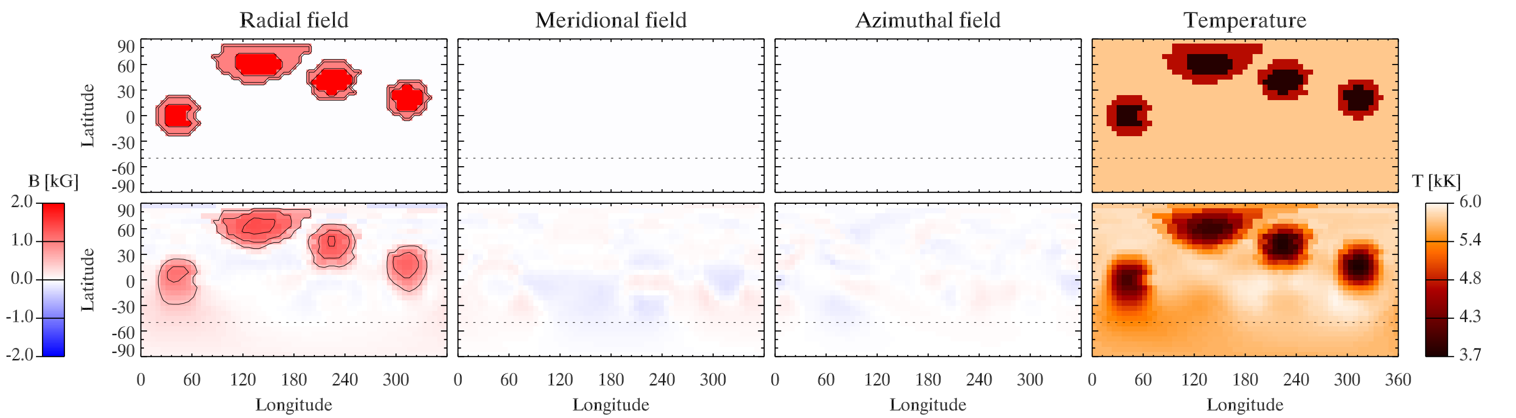
Cross-talks in Stokes *IV* inversions

◆ Low-latitude radial and meridional field features cannot be distinguished without Stokes *QU*

Rosén & Kochukhov (2012)



Stokes *IV*

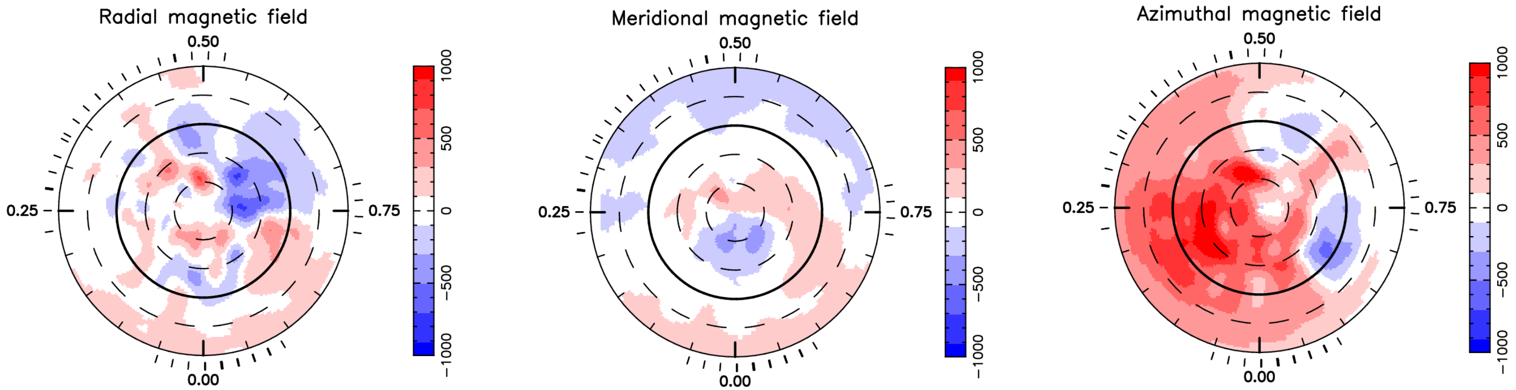


Stokes *IQUV*

Non-uniqueness of cool-star ZDI

- Independent inversions of the same objects do not agree

V410 Tau: ZDI ignoring *T* spots (Skelly et al. 2010)



V410 Tau: Self-consistent *T* and ***B*** mapping (Carroll et al. 2012)