Stellar Magnetic Fields

Oleg Kochukhov

Department of Physics and Astronomy

Uppsala University

UPPSALA UNIVERSITET

Funded by the European Union

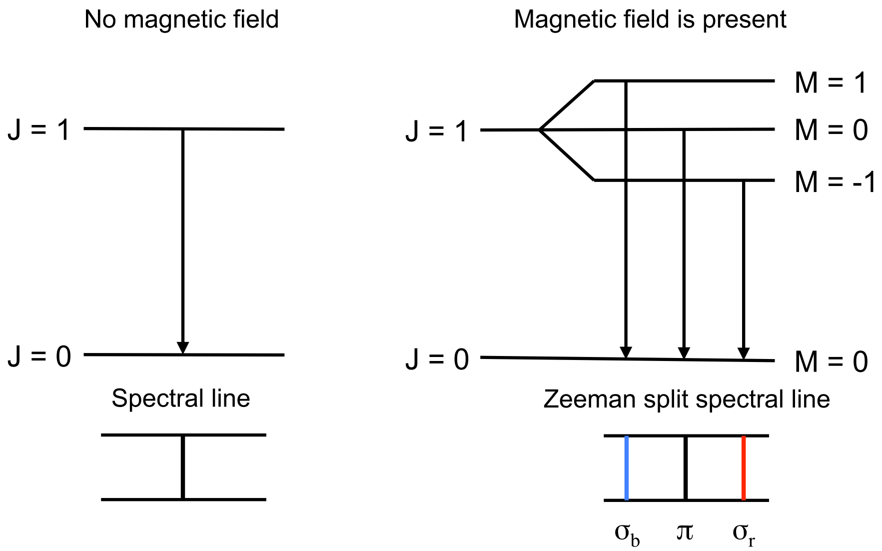
EXOHOST spectroscopy workshop, Tartu, 27-09-2023

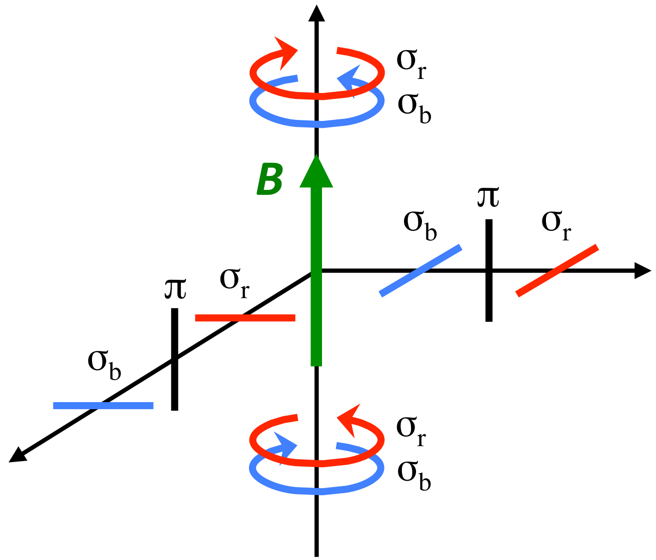
Outline

- The scope of this lecture
- Zeeman effect in stellar spectra
  - Local polarised line formation
  - Disk-integrated magnetic observables
- Stellar magnetic fields
  - Spatial structure of different types of stellar magnetic fields
  - Hot stars with fossil fields
  - Cool stars with dynamo fields
- Impact on spectroscopic analyses

Zeeman effect

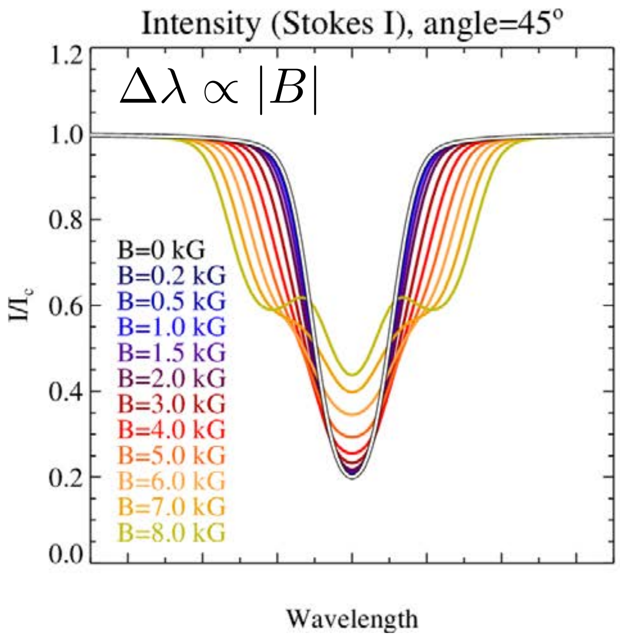
- Main tool to obtain <u>direct</u> information on stellar surface magnetic fields
  - Splitting of spectral lines => high-resolution spectroscopy
  - Polarization of spectral lines => spectropolarimetry (Stokes QUV parameters)





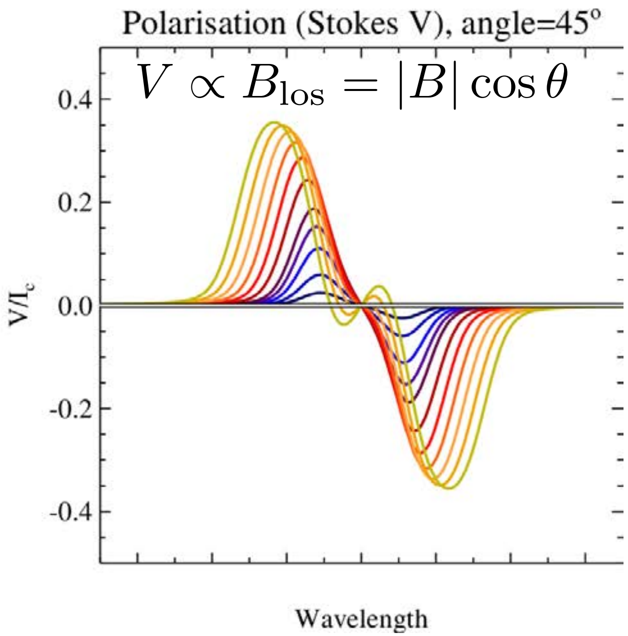
Local line profiles

Zeeman broadening



Field strength
Non-linear, 2nd order effect

Circular spectropolarimetry



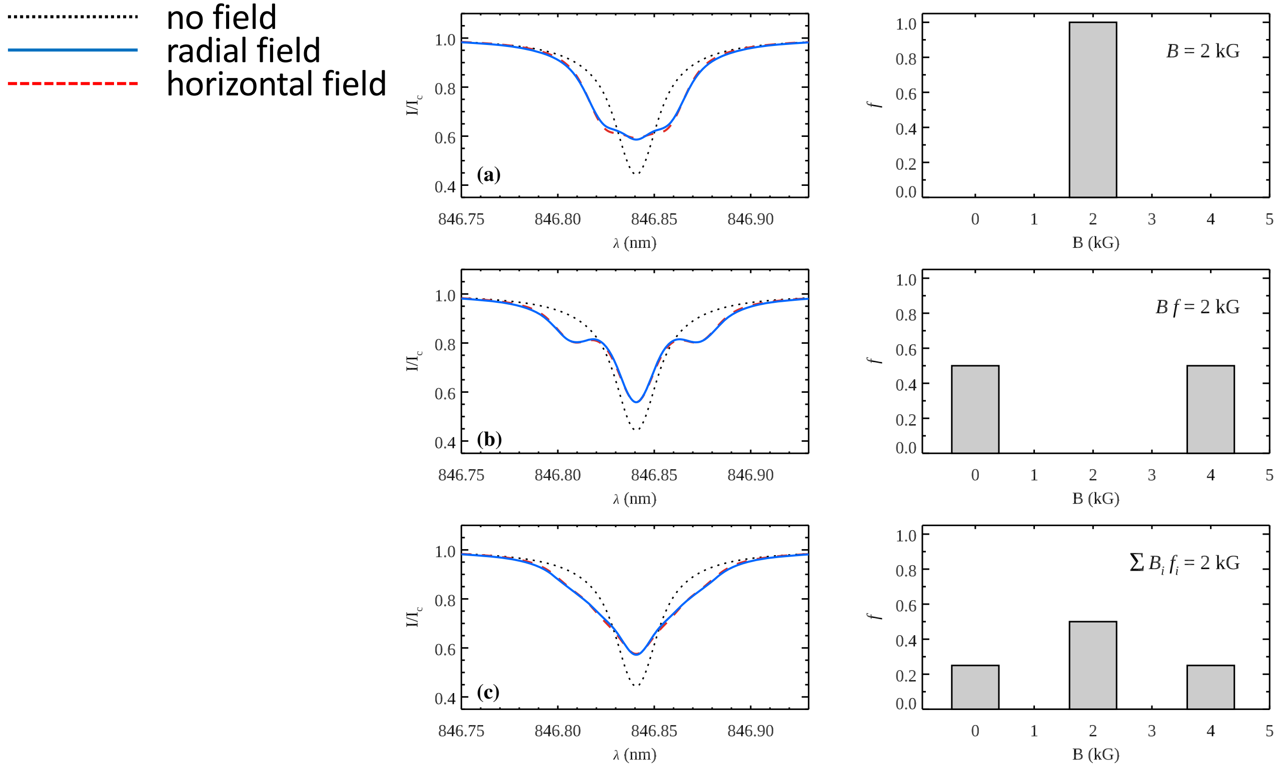
Field strength and orientation
Linear, 1st order effect

Polarised RT methods

- Weak field approximation
- Analytical solution in Milne-Eddinton atmosphere
- Detailed numerical polarised RT (e.g. *Zeeman; Synmast*)

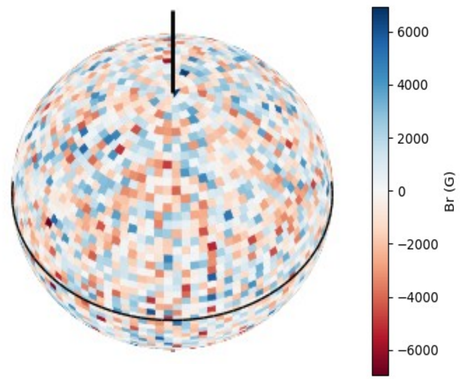
Disk-integrated line profiles

Zeeman broadening



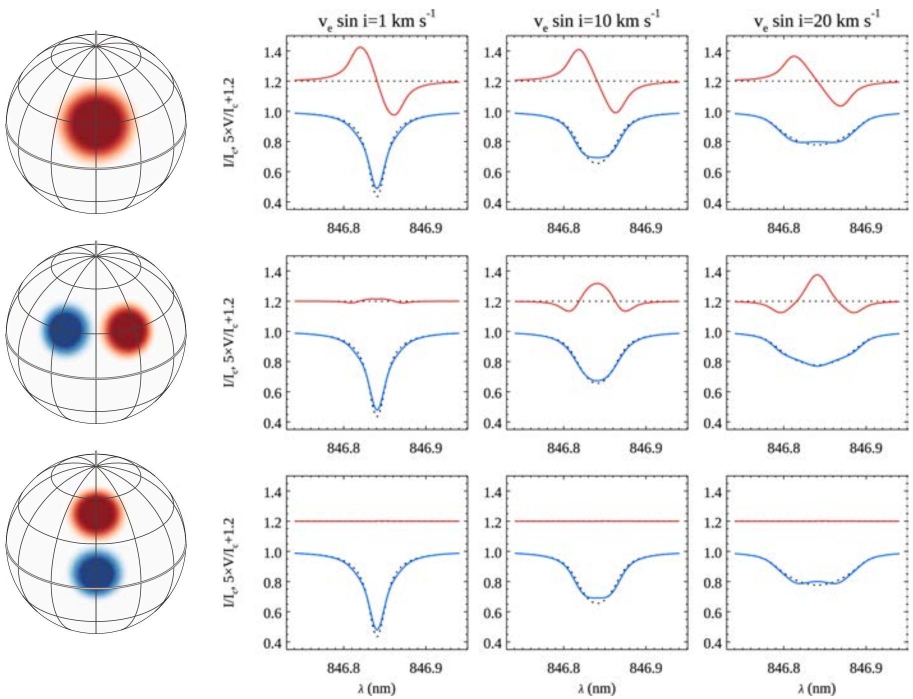
Parameters: total mean field strength, field strength distribution

Method: fitting of multiple line profiles with single spectra



Disk-integrated line profiles

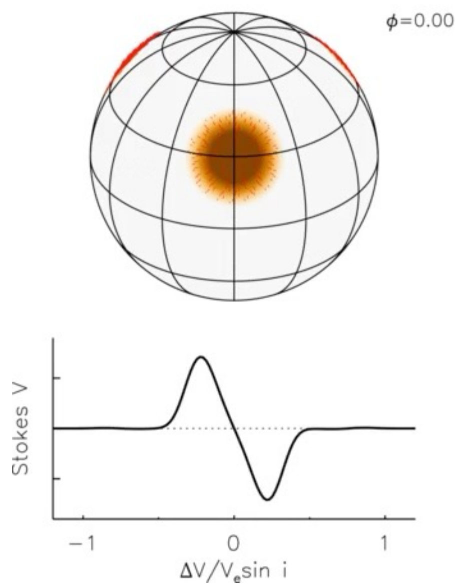
Circular spectropolarimetry



Cancellation of opposite polarities

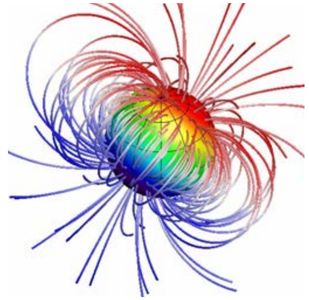
Parameters: vector map of global magnetic field

Method: inversion (ZDI) of mean polarization profile (LSD) time series

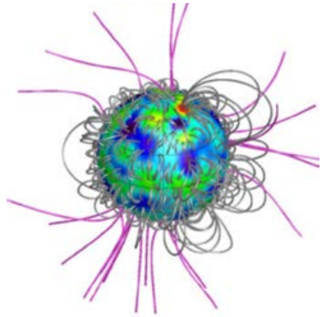


Main types of stellar magnetic fields

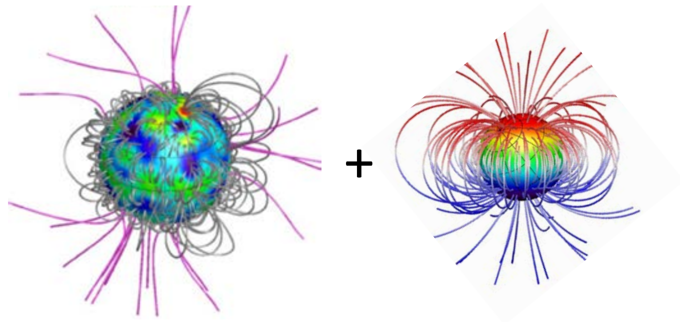
- Hot stars (mCP, early-B & O)
  - *Fossil* magnetic field trapped in radiative zone
  - Simple geometry, strong (1-10 kG), constant
  - $\sim$10% stars are magnetic; no relation to rotation



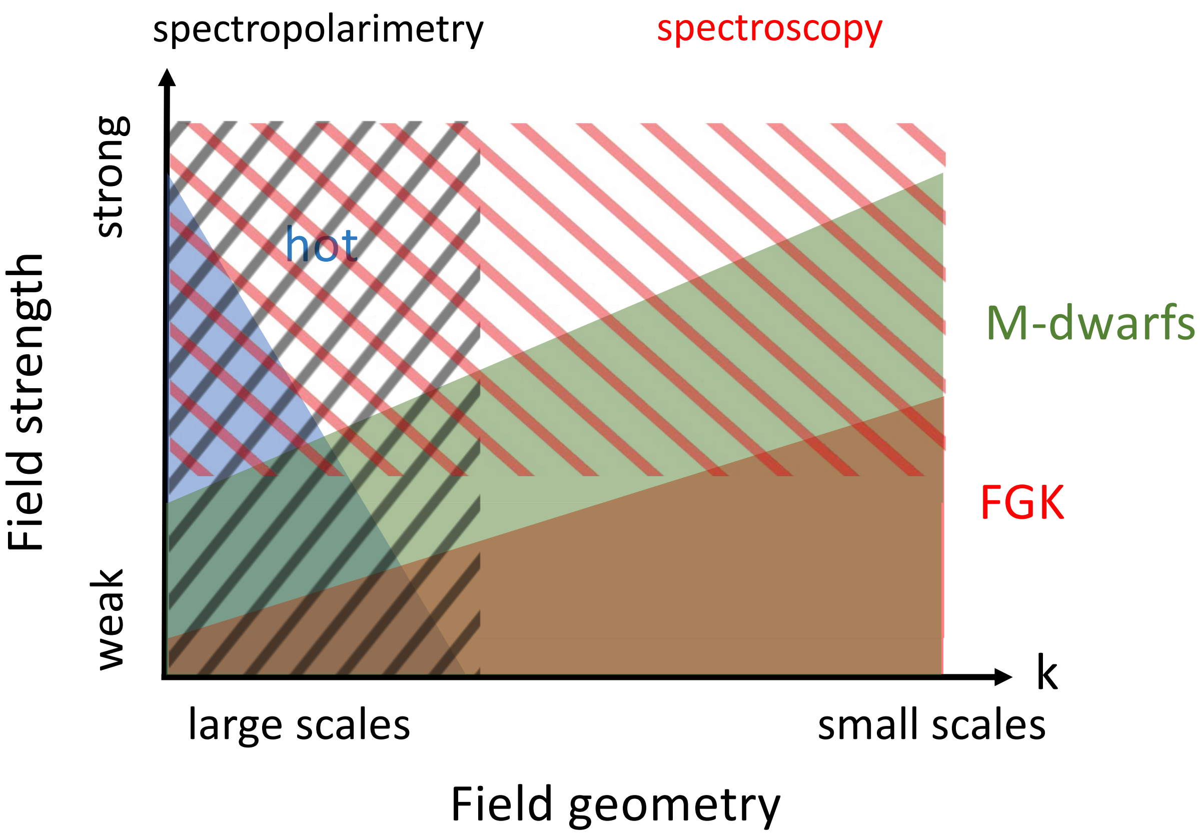
- Cool stars ($M \lesssim 1.5\ M_\odot$; FGK, early-M)
  - *Dynamo* magnetic field in convective zone
  - Complex geometry, weak (0.1-1 kG), evolving
  - All stars are magnetic; stronger fields in fast rotators

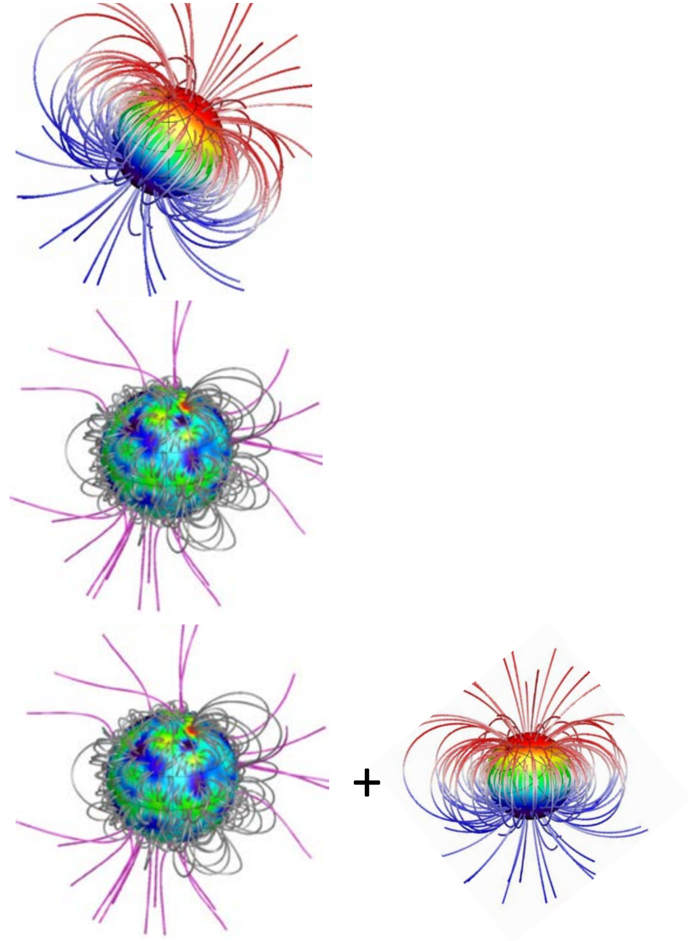


- Fully-convective M dwarfs
  - Dynamo field with a strong global component
  - Simple/complex, intermediate-strength, slowly evolving
  - Stronger fields in fast-rotating stars



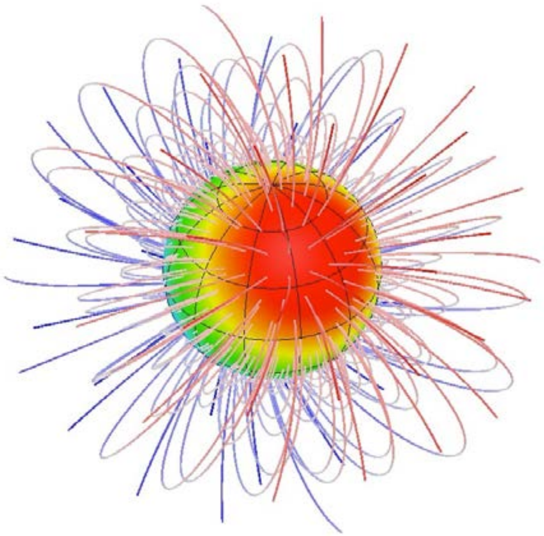
Main types of stellar magnetic fields

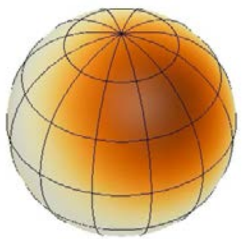




Magnetic fields in hot stars

Oblique rotator model





– Reproduceable variation of spectra and magnetic observables with rotation phase

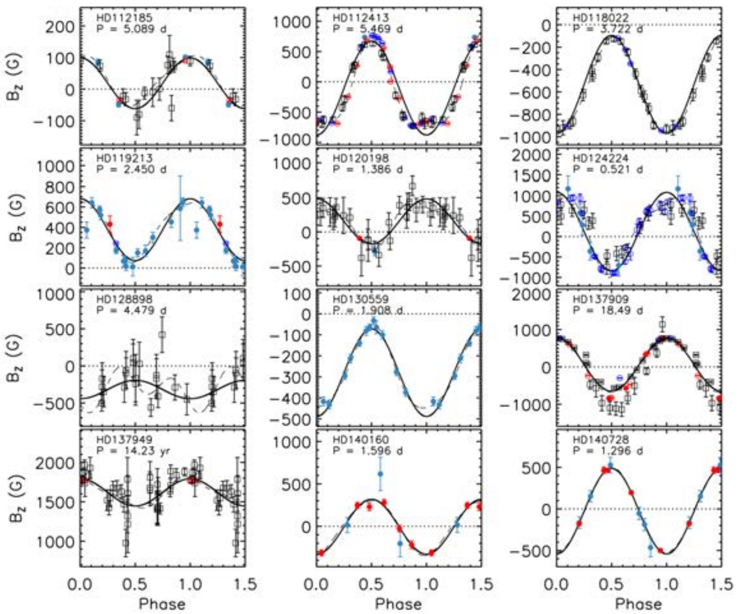
– Resolved Zeeman splitting and consistency between different observables points to the absence of small-scale fields

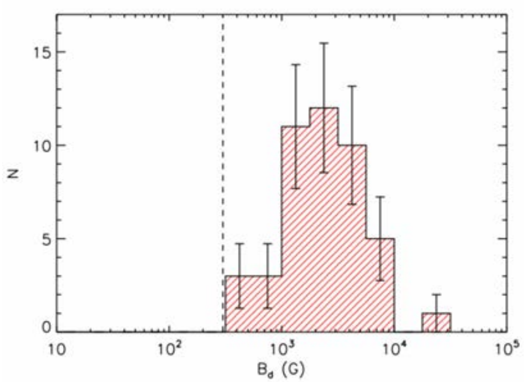
– Smooth variation of magnetic observables suggests dipole-dominated topologies

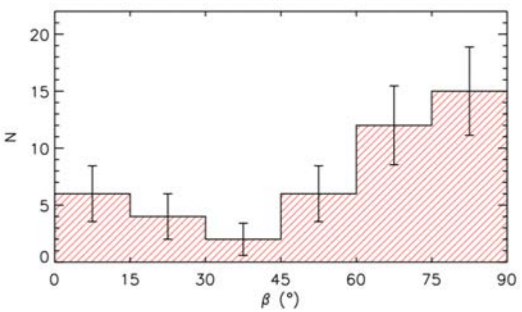
– No relation to stellar rotation except existence of ultra-slow rotators

Multipolar fits of magnetic observables

- Fitting phase curves of quantities derived from line profiles (longitudinal field, mean field modulus, quadratic field, etc.)
- Low-order multipolar expansion or pure dipolar field







Auriere et al. (2007); Sikora et al. (2019)

Threshold dipolar field strength of ~100-300 G

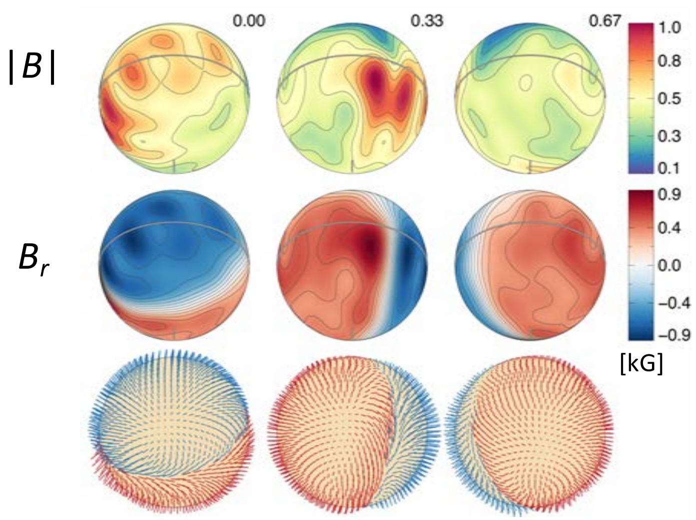
No evidence of preferred field obliquity

Zeeman Doppler imaging

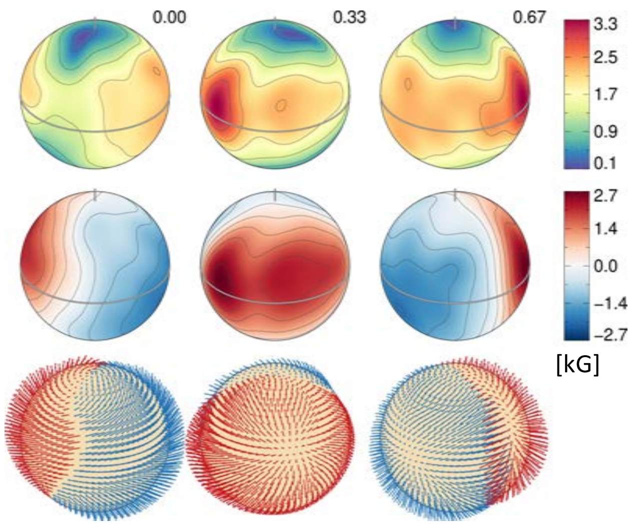
- Direct modelling of intensity and polarisation in individual lines or LSD profiles
- General high-order multipolar expansion

Distorted dipolar fields are common

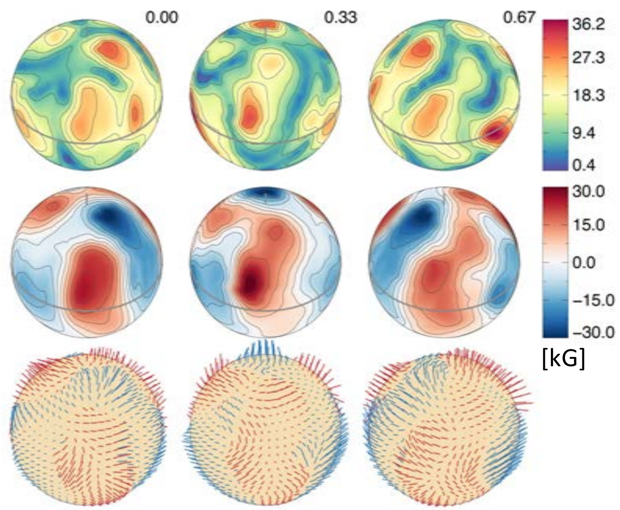
Toroidal or complex non-dipolar fields are rare



θ Aur (Kochukhov et al. 2019)



36 Lyn (Oksala et al. 2017)

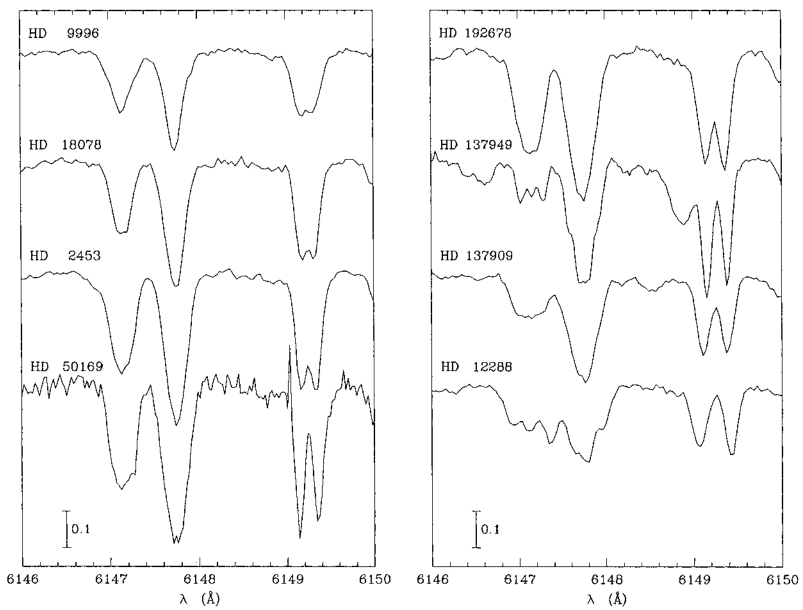


HD 37776 (Kochukhov et al. 2011)

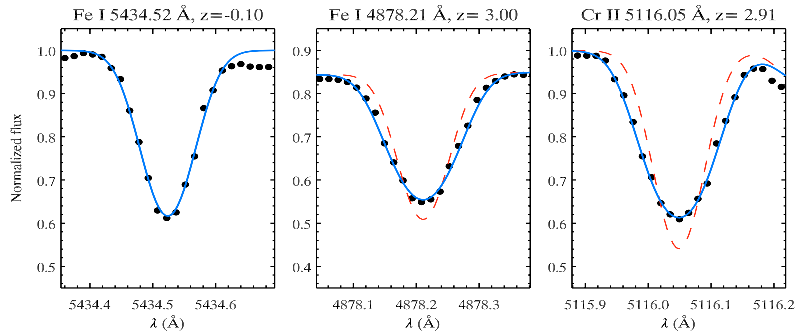
Magnetic signatures in intensity spectra

mCP stars: large splitting and intensification due to kG-strength fields; large scatter of abundances derived from lines with different magnetic sensitivity

<B>=2.2-7.6 kG

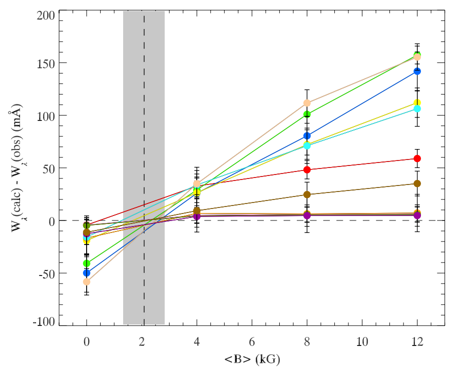


Mathys & Lanz (1992)



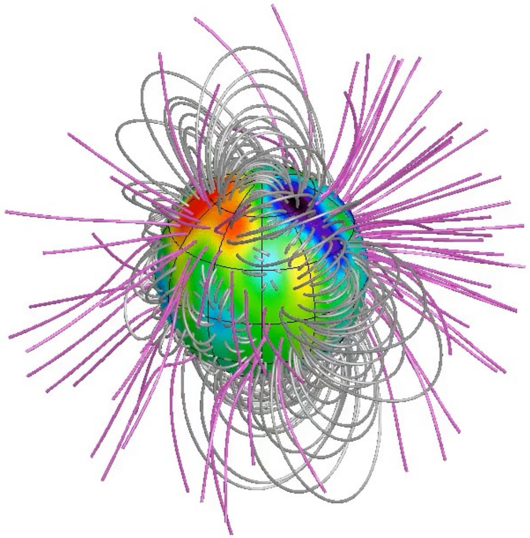
<B>=1.1 kG

Kochukhov et al. (2006)



Kochukhov et al. (2004)

Magnetic fields in cool stars



– Non-reproduceable variation of intensity and polarization spectra with rotation phase

– Inconsistency between magnetic signatures in polarization and intensity points to the presence of small-scale fields

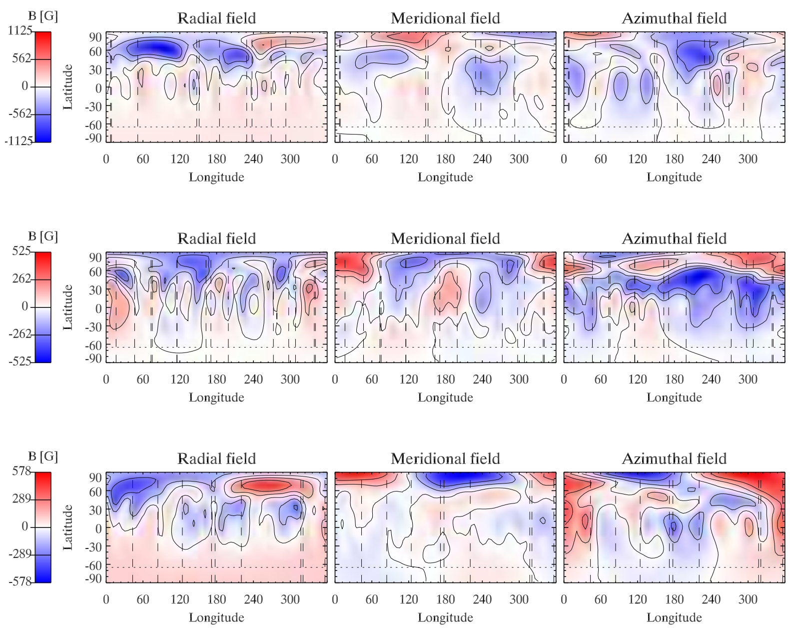
– Complex shapes of Stokes V profiles suggest non-dipolar field topologies

– Field is stronger in faster rotators; correlates with other activity diagnostics

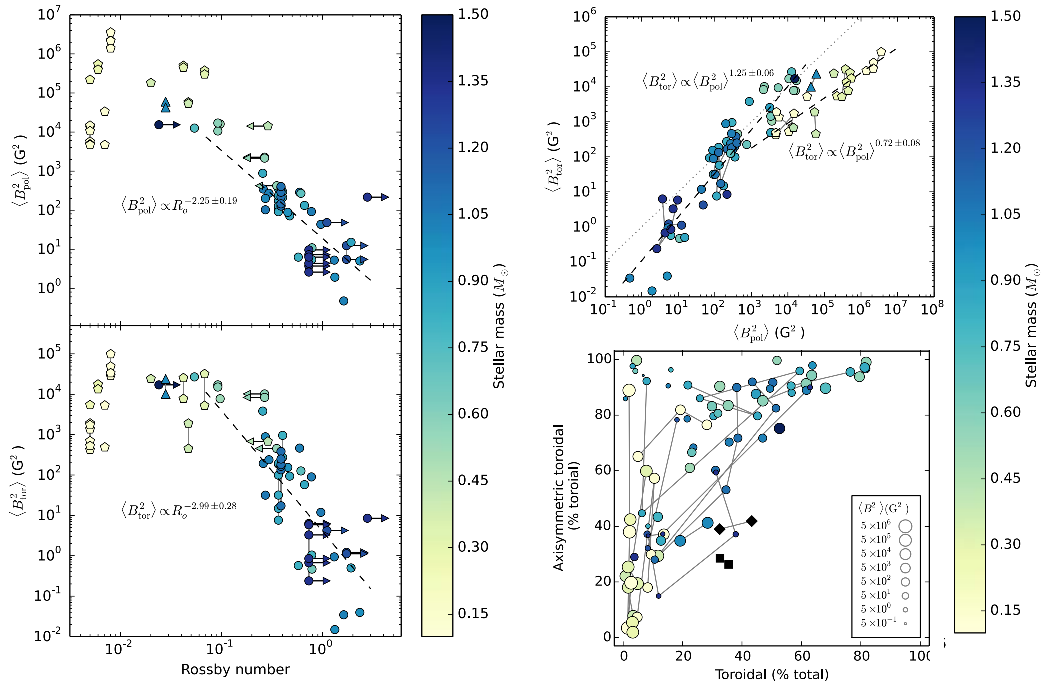
Zeeman Doppler imaging

- Direct modelling of circularly polarised (Stokes *V*) LSD profiles
- General high-order multipolar expansion; weak-field approximation

LQ Hya in 2010, 2011, 2016



Lehtinen et al. (2022)

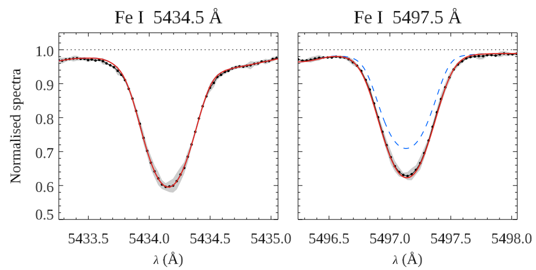


See et al. (2015)

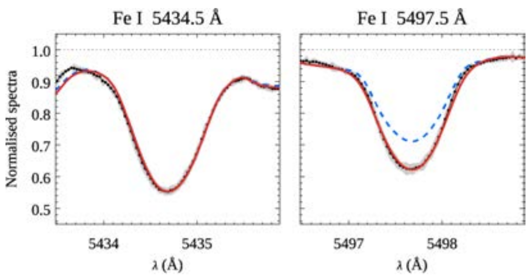
Magnetic signatures in intensity spectra

- The most active GK stars and moderately to strongly active M dwarfs: differential Zeeman broadening and intensification of spectral lines

EK Dra, G1.5V, <B>=1.5 kG

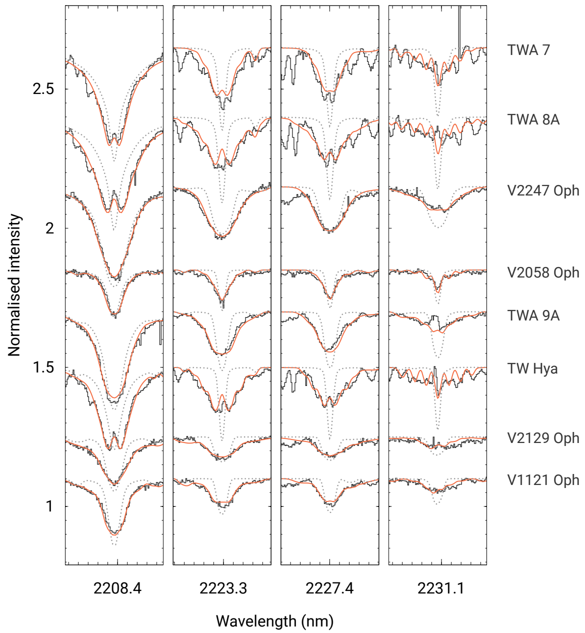


LQ Hya, K1V, <B>=2.0 kG



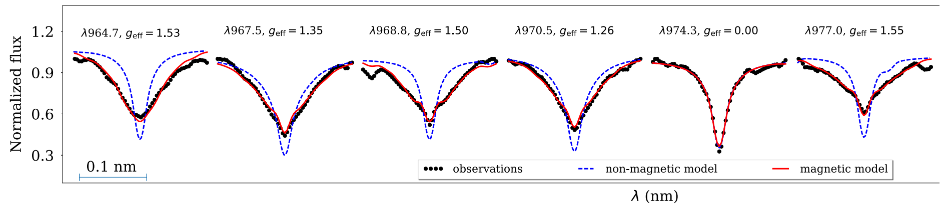
Kochukhov et al. (2020)

CTTS, <B>=1.5-4 kG



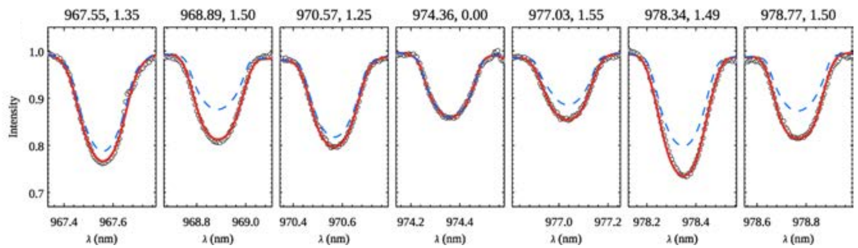
Lavail et al. (2019)

WX UMa, M6V, <B>=7.5 kG



Shulyak et al. (2017)

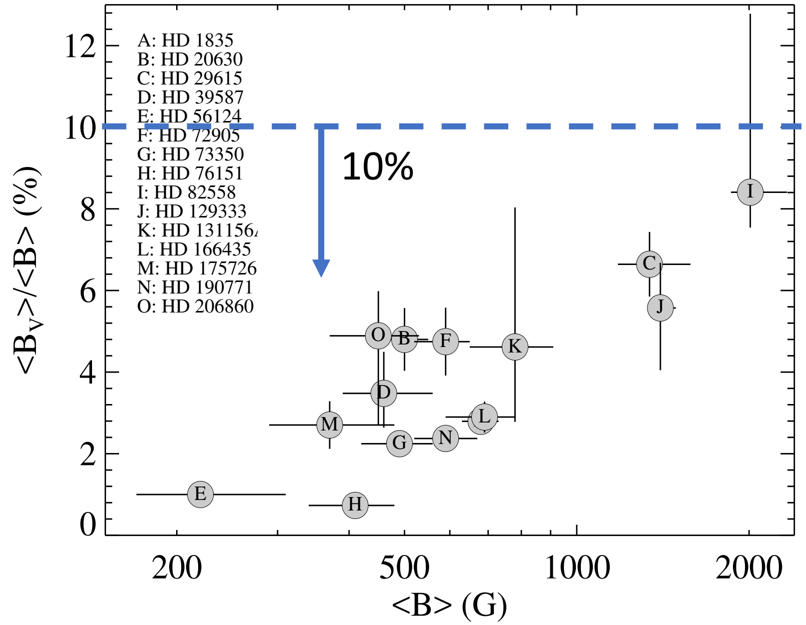
YY Gem, M0.5V, <B>=3.3 kG



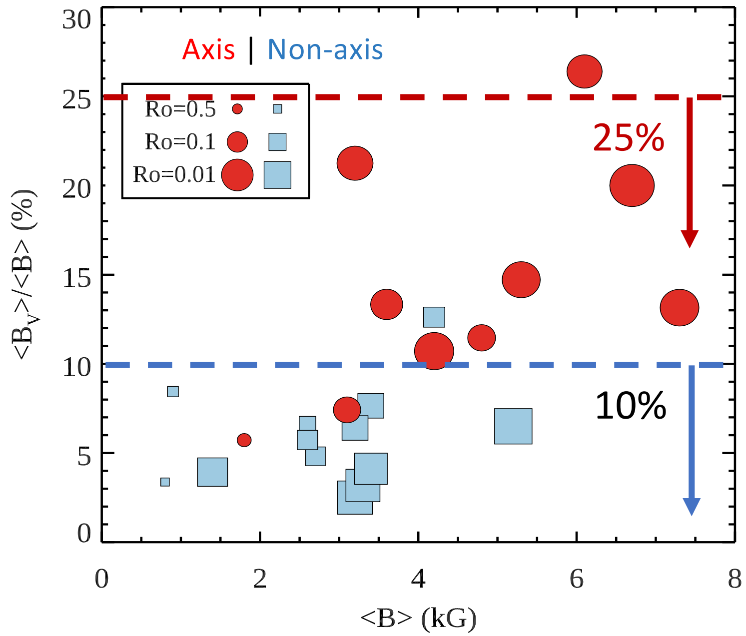
Kochukhov & Shulyak et al. (2019)

Discrepancy between intensity and polarisation

- Small-scale fields are dominant contributors to cool-star magnetism



Young Sun-like stars (Kochukhov et al. 2020)



Active M dwarfs (Kochukhov 2021)

Recommendations for spectroscopic analysis

- When one should be concerned about magnetic field effects?
  - Hot star
    - spectroscopically classified as a CP2/CP4 star or exhibits an abundance signature consistent with this type of stars
    - shows Zeeman splitting of spectral lines (in particular, Fe II 6149.2 Å)
  - Cool star
    - known to be chromospherically active (Ca H&K or/and X-ray emission)
    - displays measurable rotational broadening or/and has $P_{\mathrm{rot}} \lesssim 10$ d
  - Cool & hot star
    - shows rotational modulation in photometry
    - scatter in line-by-line abundances correlates with Lande factor
- What to do?
  - Avoid lines with average (strong field) or large (moderate field) Lande factors
  - Perform analysis taking magnetic field into account