Public PhD defense

Magnetic fields of cool stars

from near-infrared spectropolarimetry

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Tuesday 26th May 2020 at **09:15** CEST
Polhemsalen, Ångströmlaboratoriet

Zoom livestream:
https://uu-se.zoom.us/j/4586124293

Background image adapted from *Einige Kreise*, Vasily Kandinsky, 1926. Public domain

Papers presented in this thesis

Zeeman broadening

near-ir spectroscopy

Paper I (2017)
Magnetic fields of intermediate mass T Tauri stars
Lavail, A., Kochukhov, O., Hussain, G.A.J., Alecian, E., Herczeg G.J., and Johns-Krull C.
A&A, **608**, A77

Paper II (2019)
Characterising the surface magnetic fields of T Tauri stars with high-resolution near-infrared spectroscopy
Lavail, A., Kochukhov, O., and Hussain, G.A.J.
A&A, **630**, A99

Zeeman Doppler imaging

optical spectropolarimetry

Paper III (2018)
A sudden change of the global magnetic field of the active M dwarf AD Leo revealed by full Stokes spectropolarimetric observations
Lavail, A., Kochukhov, O., and Wade, G.A.
MNRAS, **479**, 4836

Paper IV (2020)
The large-scale magnetic field of the eccentric pre-main-sequence binary system V1878 Ori
Lavail, A., Kochukhov, K., Hussain, G.A.J., Argiroffi, C., Alecian, E., Morin, J., and the BinaMIcS collaboration
Submitted to MNRAS

Observations

CRIRES at the 8-m ESO Very Large Telescope
High-resolution near-infrared spectroscopy
R=100000
Can observe from ~950 to ~5200 nm (YJHKLM bands).
Narrow spectral grasp

UVES at the 8-m ESO Very Large Telescope
High-resolution optical spectroscopy

ESPaDOnS at the 3.6-m Canada-France-Hawaii Telescope
High-resolution optical spectropolarimetry
R=65000
370 to 1000 nm
Circular (Stokes *V*) and linear (Stokes *QU*) polarization

Photos: ESO/H.H.Heyer, CC BY-NC-ND 2.0 Duane Newman

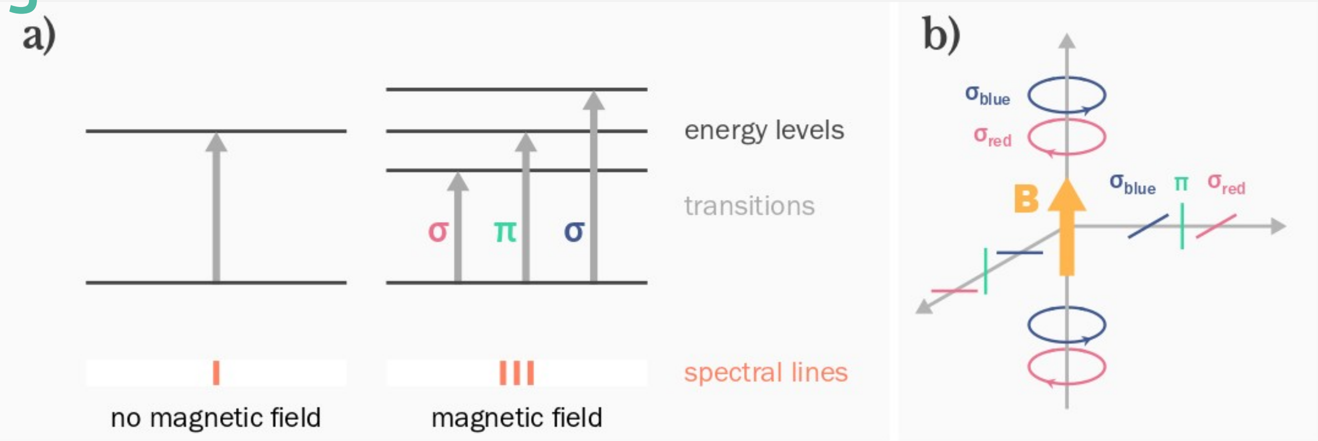
Paper I and **Paper II**

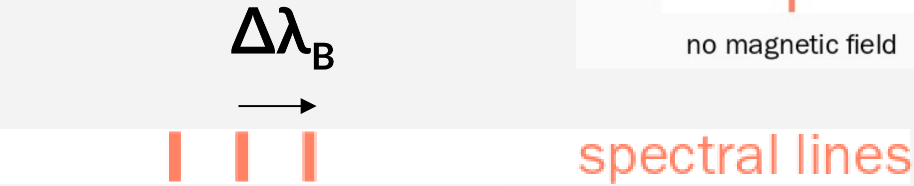
High-resolution near-infrared spectroscopic studies
of T Tauri stars
Data from the CRIRES spectrograph,
near-infrared H & K bands, R=100000

Paper I: **intermediate-mass** T Tauri stars
Paper II: **low-mass** T Tauri stars

Zeeman broadening

Intensity spectra



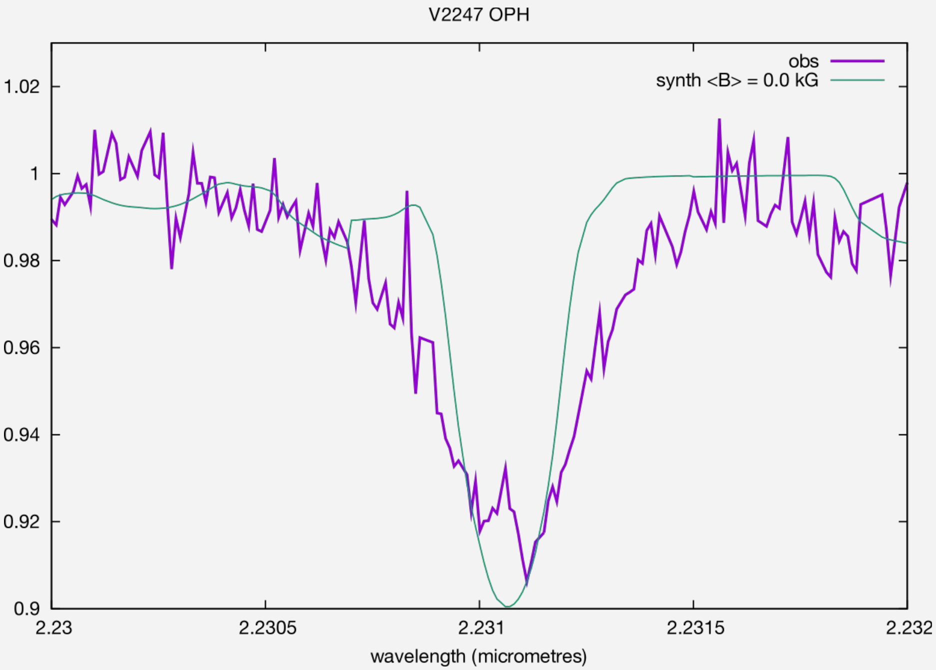


Zeeman broadening $\Delta\lambda_B$ scales with:

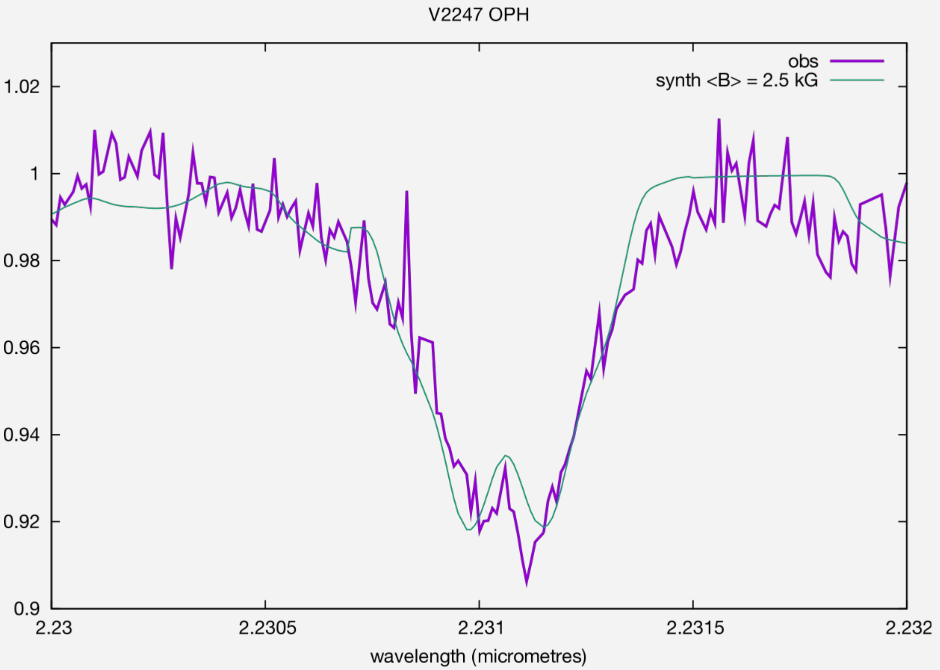
- Wavelength $\boldsymbol{\lambda^2}$
- Magnetic field strength ***B***
- Effective Landé factor ***g_eff*** [0 - 3] (unitless)

You need to know the non-magnetic case!

<*B*> = 0.0 kG



<*B*> = 2.5 kG



Paper I and II

Paper I

- 5 intermediate mass T Tauri stars (1 M ☉ <M < 4 M ☉) and 1 low-mass T Tauri star observed with CRIRES
- Determined non-magnetic broadening from the CRIRES data and archival optical spectroscopy data
- Constrained the average unsigned magnetic field <B> using Zeeman broadening

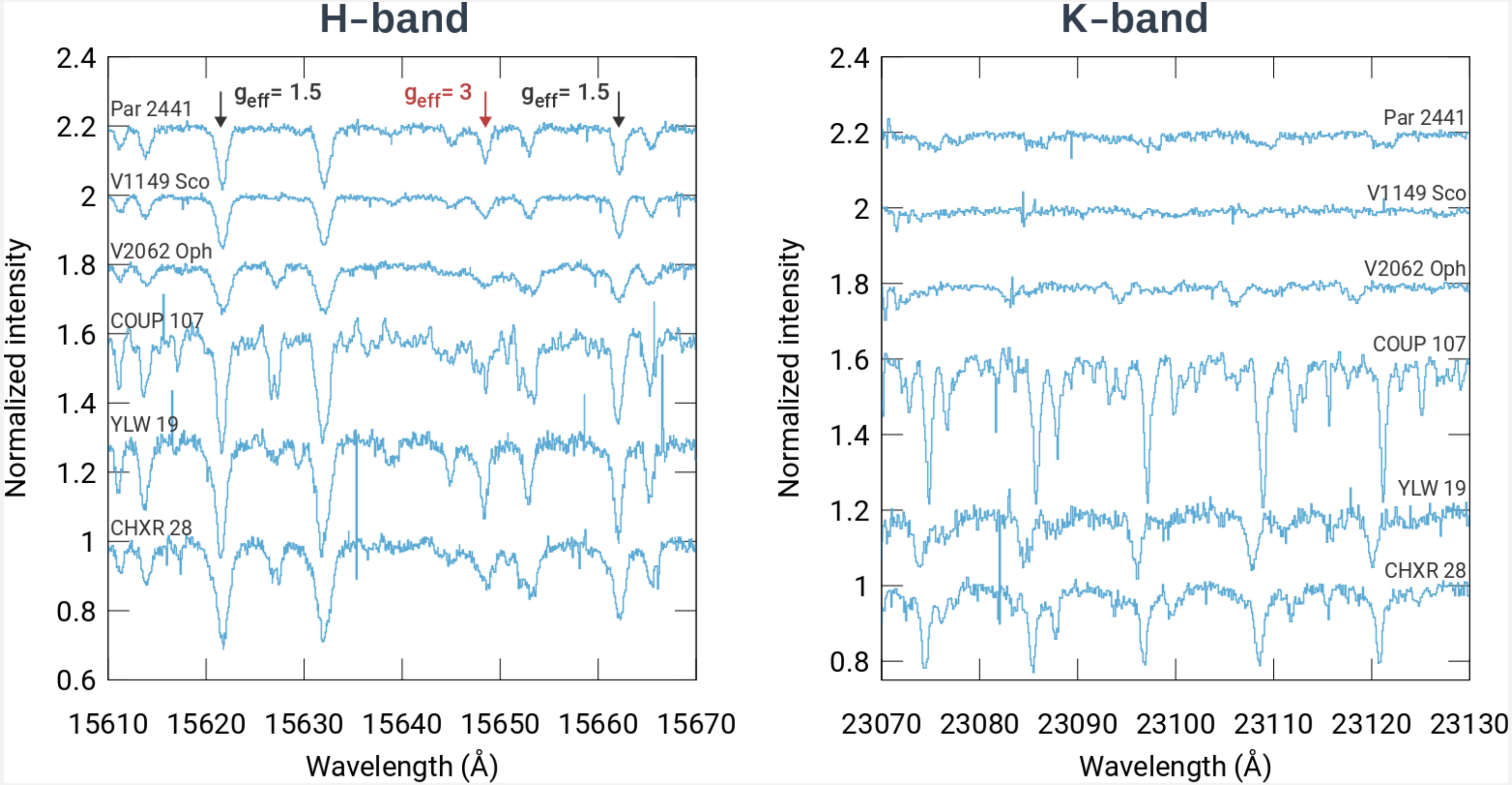
Paper II

- 8 low mass T Tauri stars observed repeatedly with CRIRES (of which 6 were previously studied with ZDI)
- Determined non-magnetic broadening
- Constrained <B> using magnetic Zeeman broadening and MCMC methods
- Investigated rotational variability
- Compared ZDI and Zeeman broadening results

CRIRES observations

Paper I

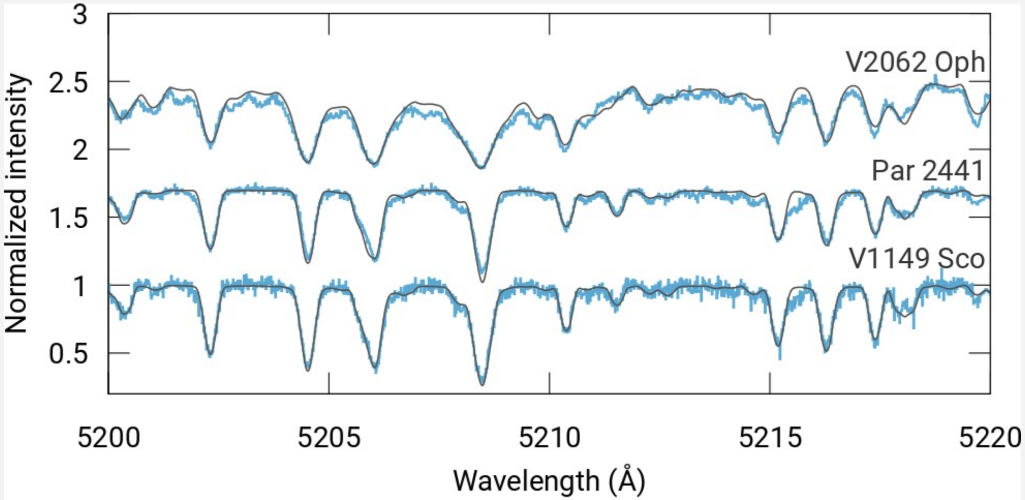
Magnetically insensitive CO lines



Non-magnetic broadening

Paper I

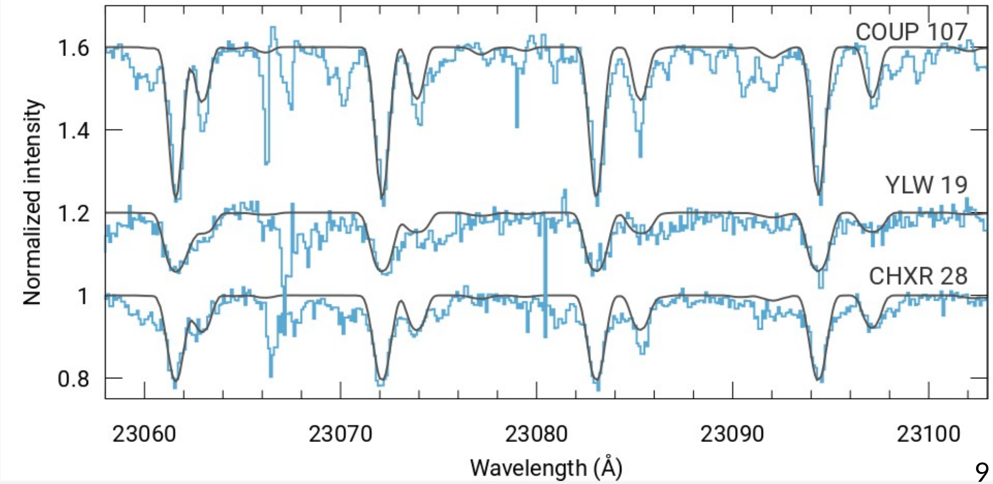
Optical UVES spectra →



Step 1

Get the non-magnetic case right

Near-IR CRIRES spectra →



Characterizing <B>

Step 2

Characterize the **mean magnetic field strength <B>** modelling the Zeeman broadening

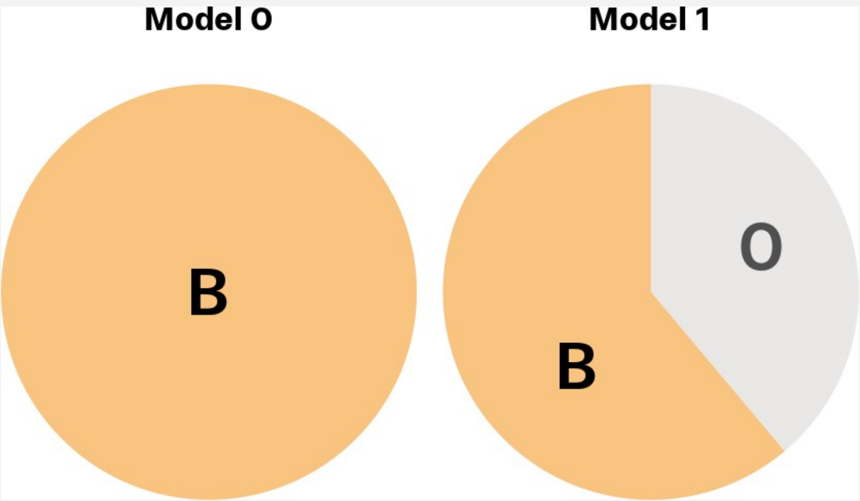
1. Compute magnetic synthetic spectra
2. Adopt a model specifying the distribution of magnetic fields on the stellar surface
3. Fit magnetically sensitive spectral lines
4. Infer the mean magnetic field strength <B>

Magnetic field distribution

Our approach

For Paper I

Trial and error approach.
Model 0 works well, except for 2 stars (for which we used Model 1)



$\langle B \rangle = B$

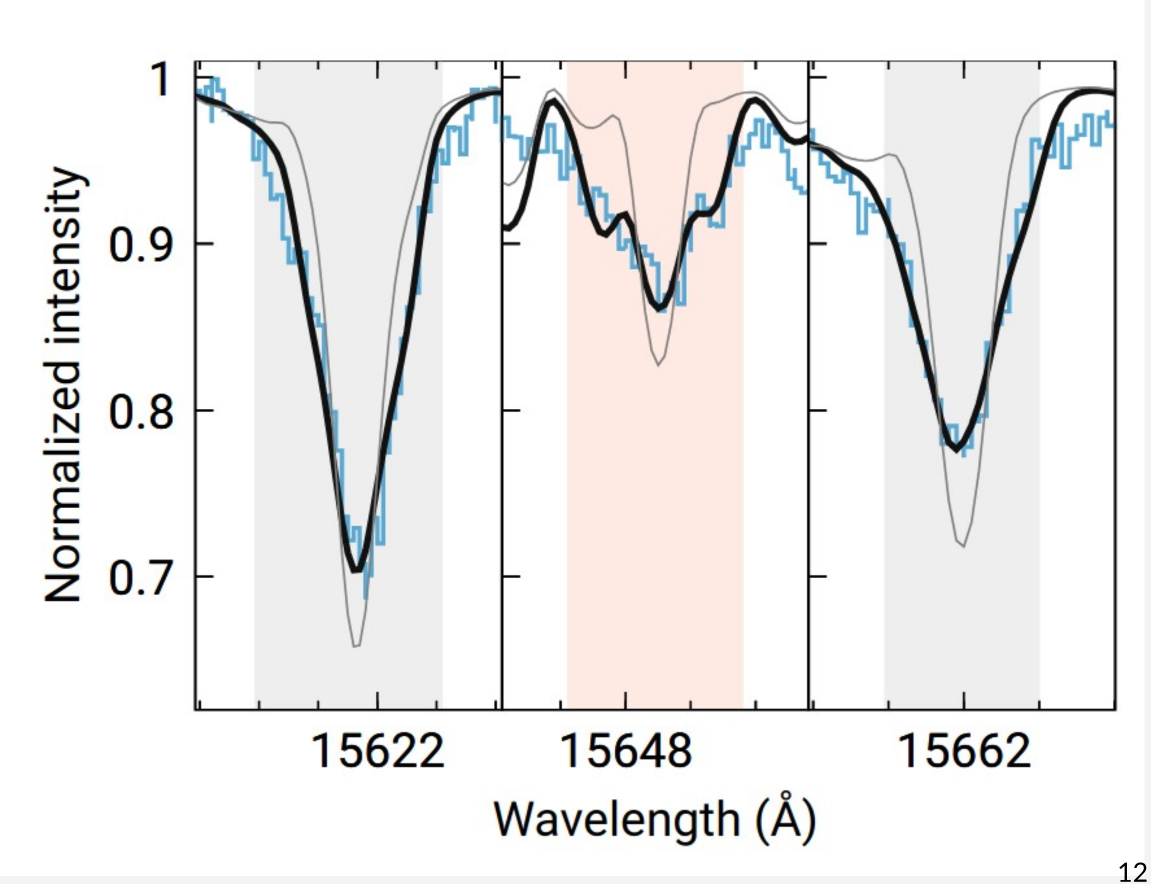
$\langle B \rangle = B \times f$

Modelling Zeeman broadening

Paper I

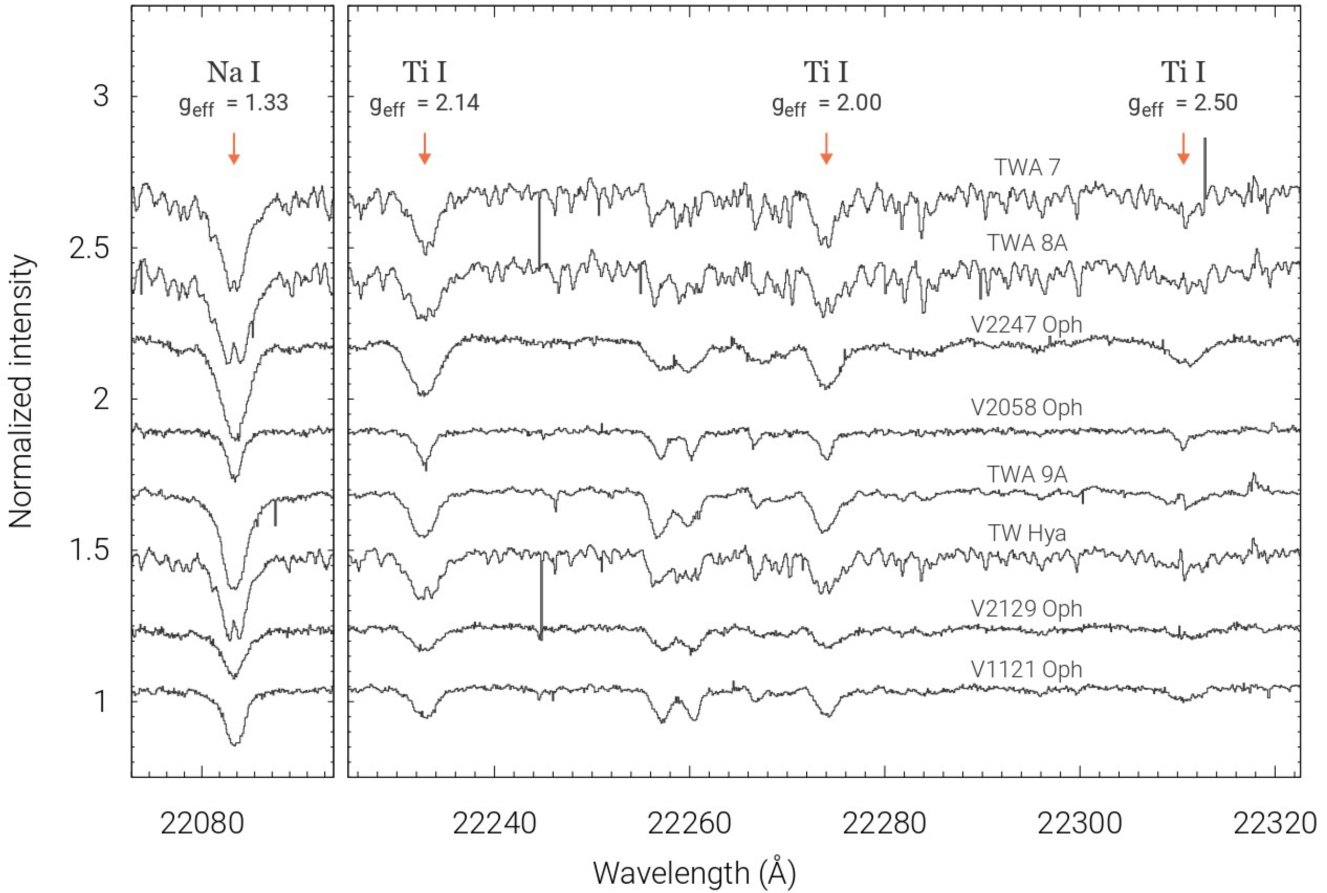
Fitting the observed →
spectrum with magnetic
synthetic spectra.

Observed spectrum —
Best-fit with magnetic fields —
non-magnetic spectrum —

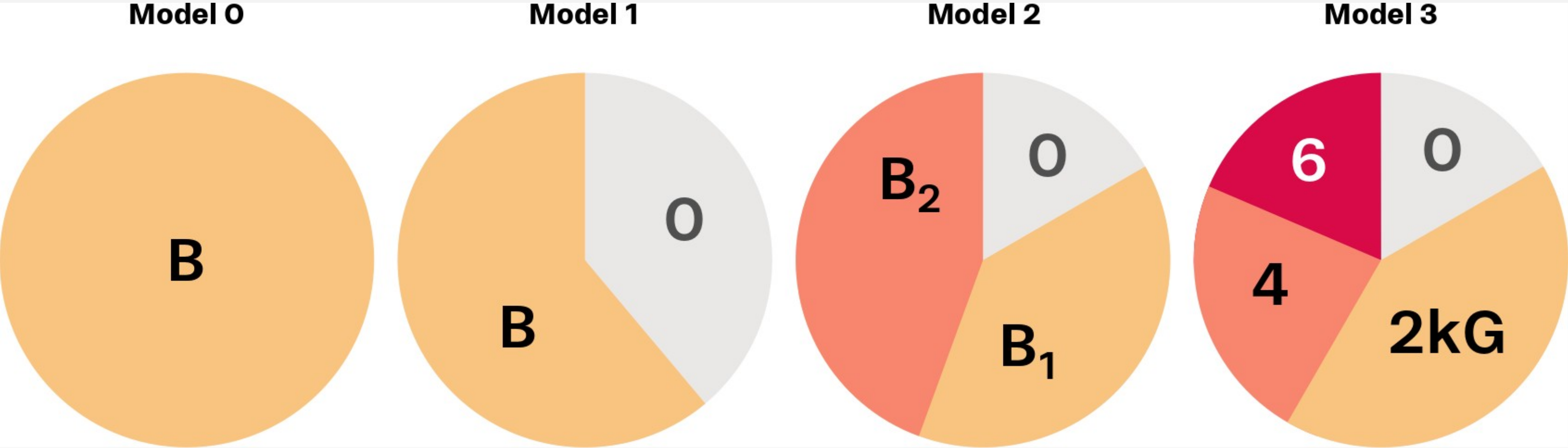


CRIRES observations

Paper II



Magnetic field distribution



$\langle B \rangle = B$

Sokal et al. 2020
Flores et al. 2019
Sokal et al. 2018
Lavail et al. 2017

$\langle B \rangle = B \times f$

Lavail et al. 2019
Hill et al. 2019
Lavail et al. 2017
Yang et al. 2011
Yang et al. 2008
Yang et al. 2005

$\langle B \rangle = B_1 f_1 + B_2 f_2$

Hill et al. 2019
Yang et al. 2005

$\langle B \rangle = 2f_2 + 4f_4 + 6f_6$

Lavail et al. 2019
Lavail et al .2017
Yang et al. 2011
Yang et al. 2008
Johns-Krull 2007
Yang et al. 2005
Johns-Krull et al. 2004

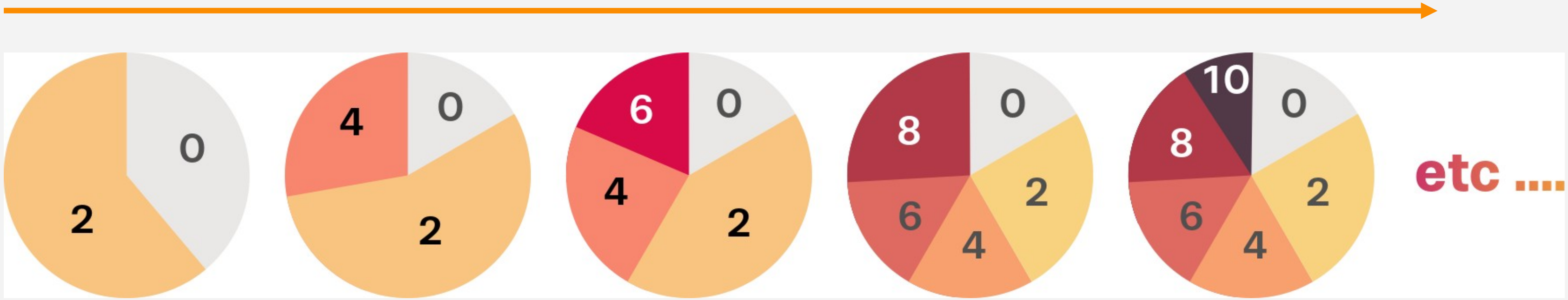
Magnetic field distribution

Our approach

For Paper II
Strong fields: need a more advanced model

Solution:

- Generalize Model 3 to include more components and stronger fields
- Penalize complex models to avoid overfitting the data



Modelling Zeeman broadening

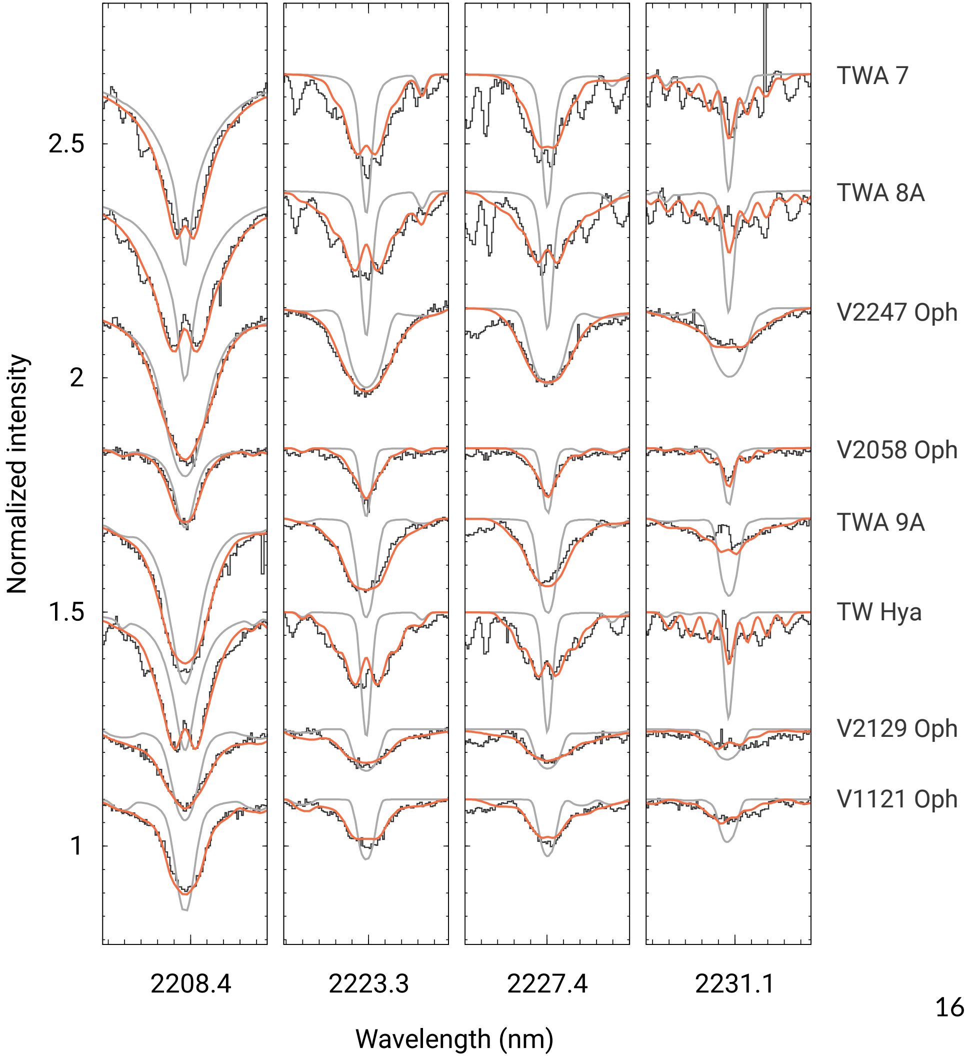
Paper II

Fitting the observed → spectrum with magnetic synthetic spectra.

Observed spectrum —

Best-fit with magnetic fields —

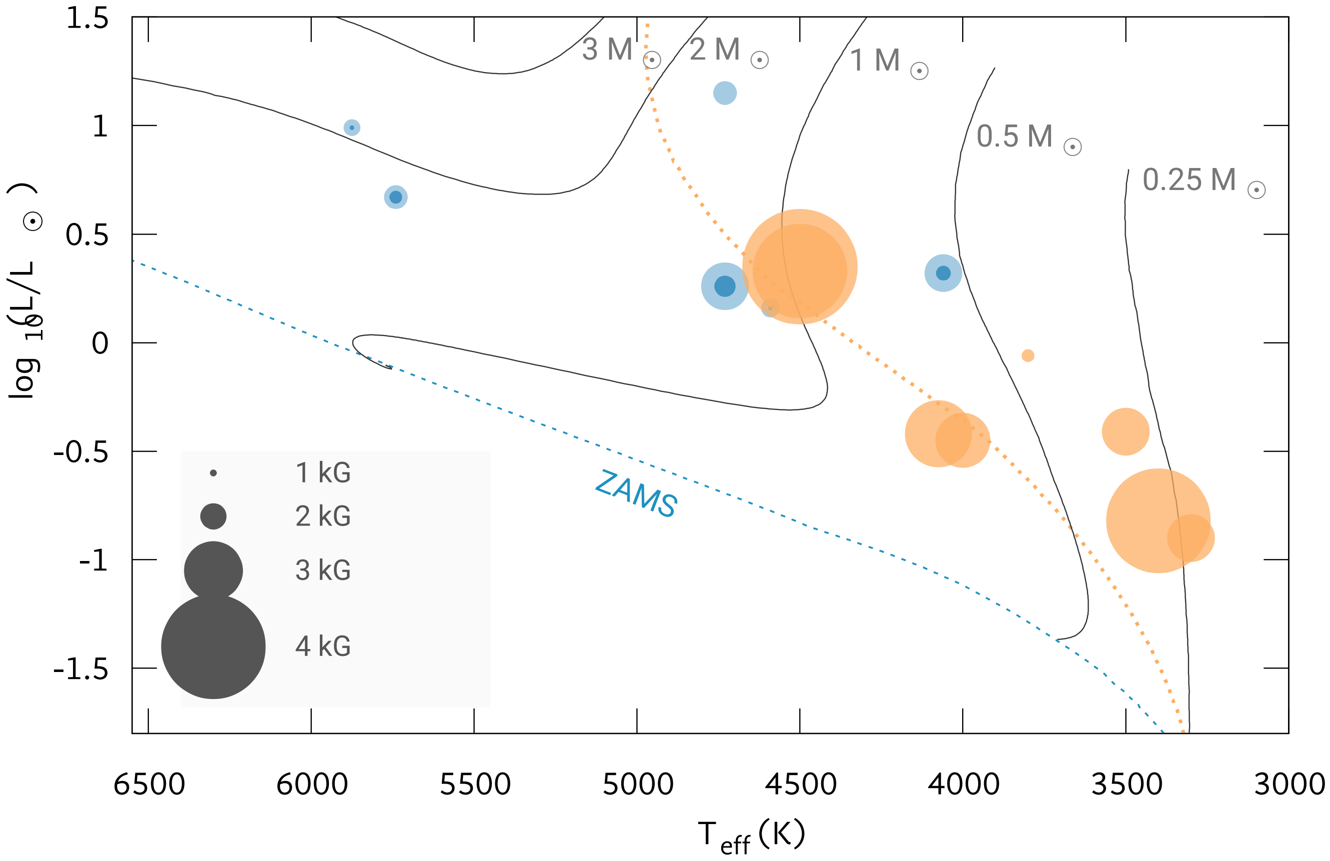
non-magnetic spectrum —



Results

● Paper I

● Paper II

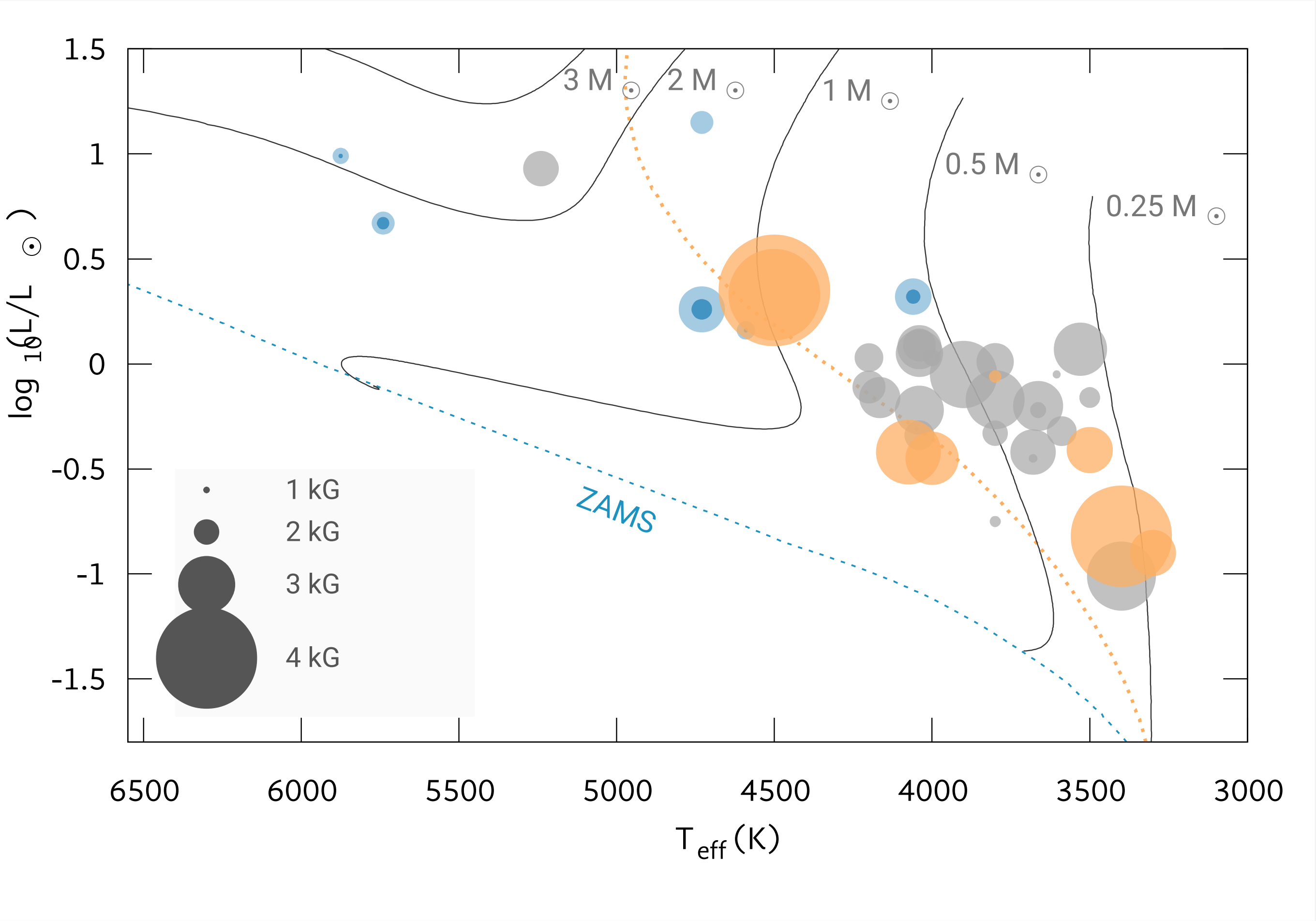


Results

● Paper I

● Paper II

● literature



Take away messages

- Measured <B> on 6 + 8 T Tauri stars of intermediate and low mass
- Developed new methodology that works for wide range of <B> values
- We do not measure very strong field (< 3 kG) on IMTTS. This could mean that there is a transition in how dynamos operate between LMTTS and IMTTS.
- Wide range of magnetic field measured in LMTTS, and <B> is not a simple function of stellar parameters
- The proportion of the magnetic field recovered by ZDI varies greatly (2-50%) and seems to depend on the field complexity
- No strong rotational variability of <B> is observed which hints that the magnetic field is rather uniformly distributed over the stellar surface

Paper III

A sudden change of the global magnetic field of the active M dwarf AD Leo revealed by full Stokes spectropolarimetric observations

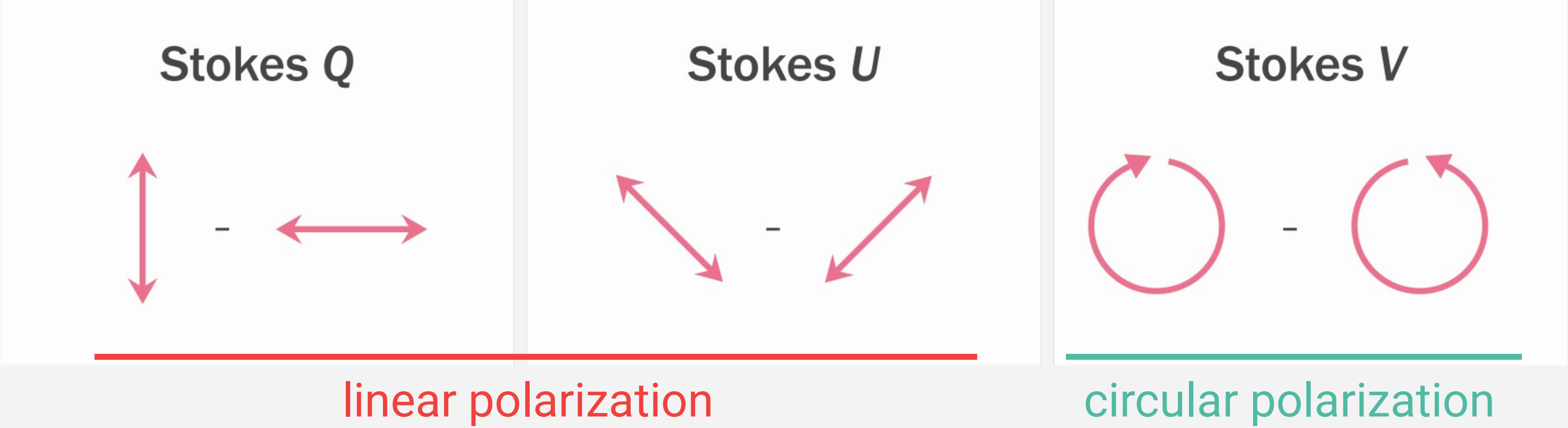
Data from the ESPaDOnS spectropolarimeter at CFHT, optical up to ~1000 nm, *R*=65000

Observing proposal:

Lavail, Wade, and Kochukhov. **23 hours**, *A search for Zeeman linear polarization in spectral lines of active M dwarfs.*

Polarization

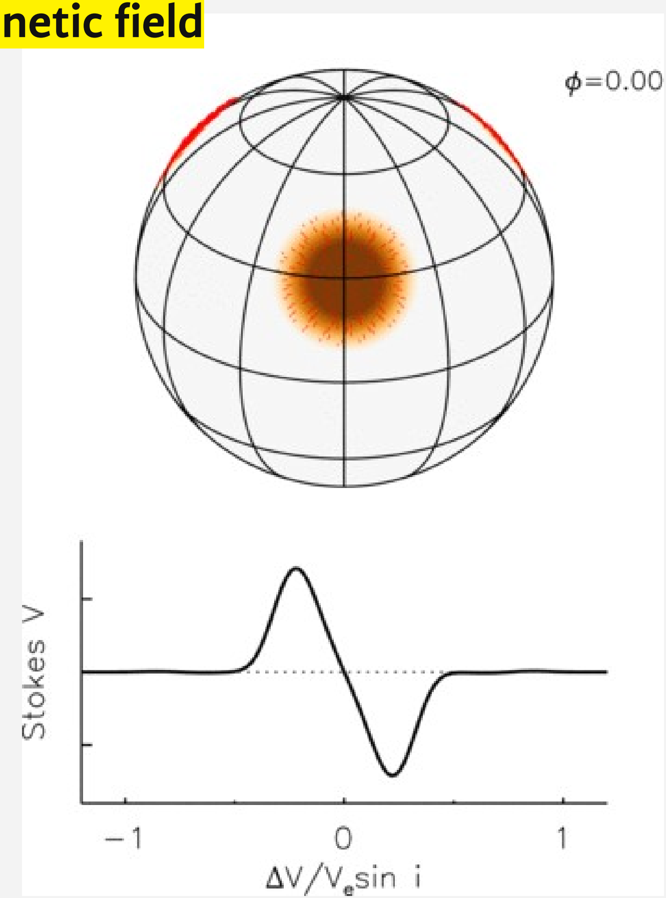
Stokes parameters

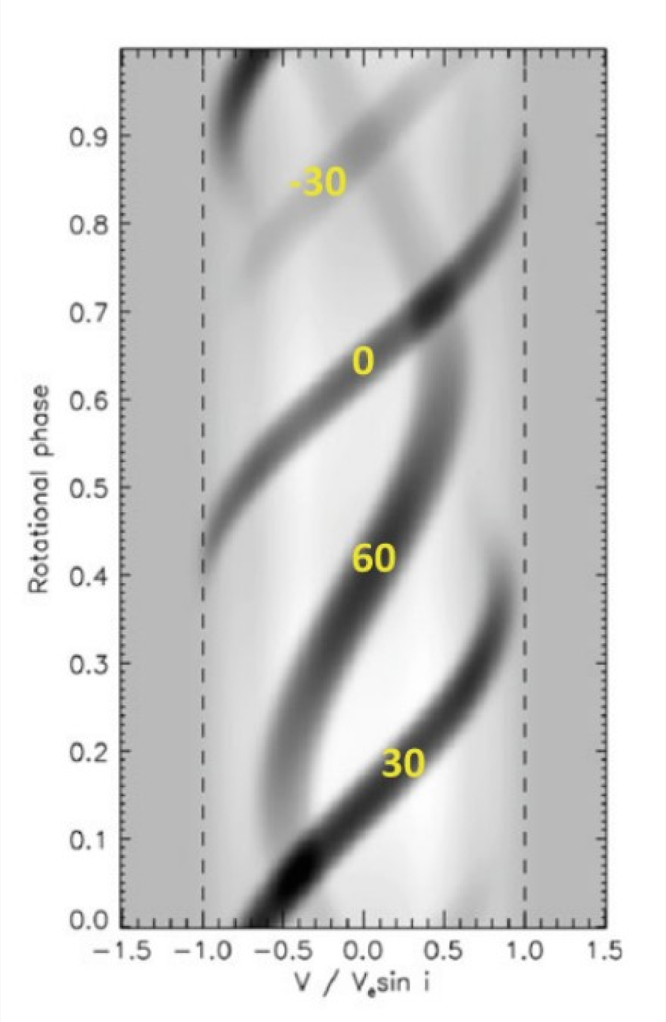


→ Linear polarization is ~10x weaker than circular polarization in cool stars
→ All cool stars (but one: II Peg; Rosén et al. 2015) studied with only circular polarization
→ Linear polarization gives more information, higher spatial resolution, and stronger magnetic fields

Zeeman Doppler Imaging

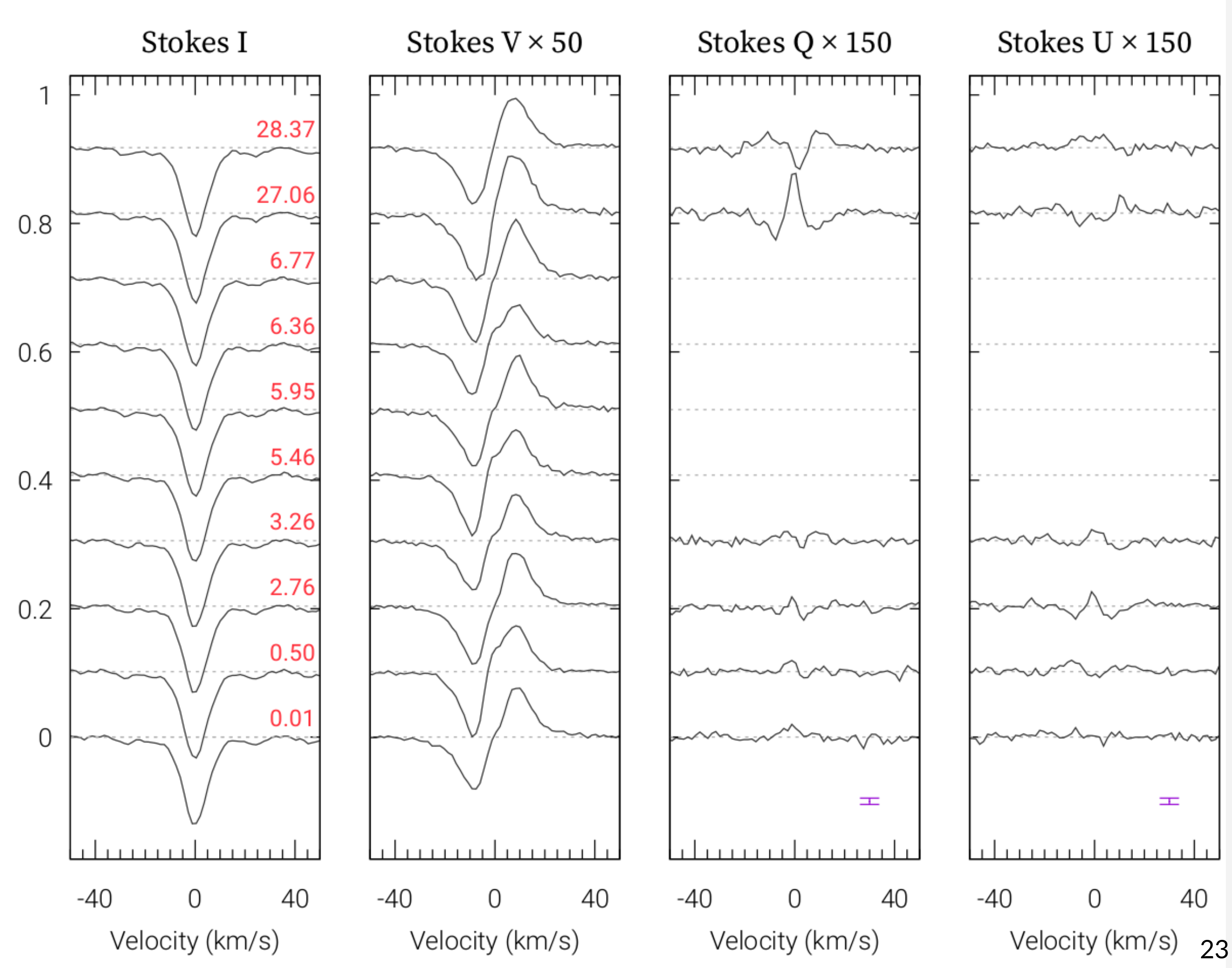
Magnetic field

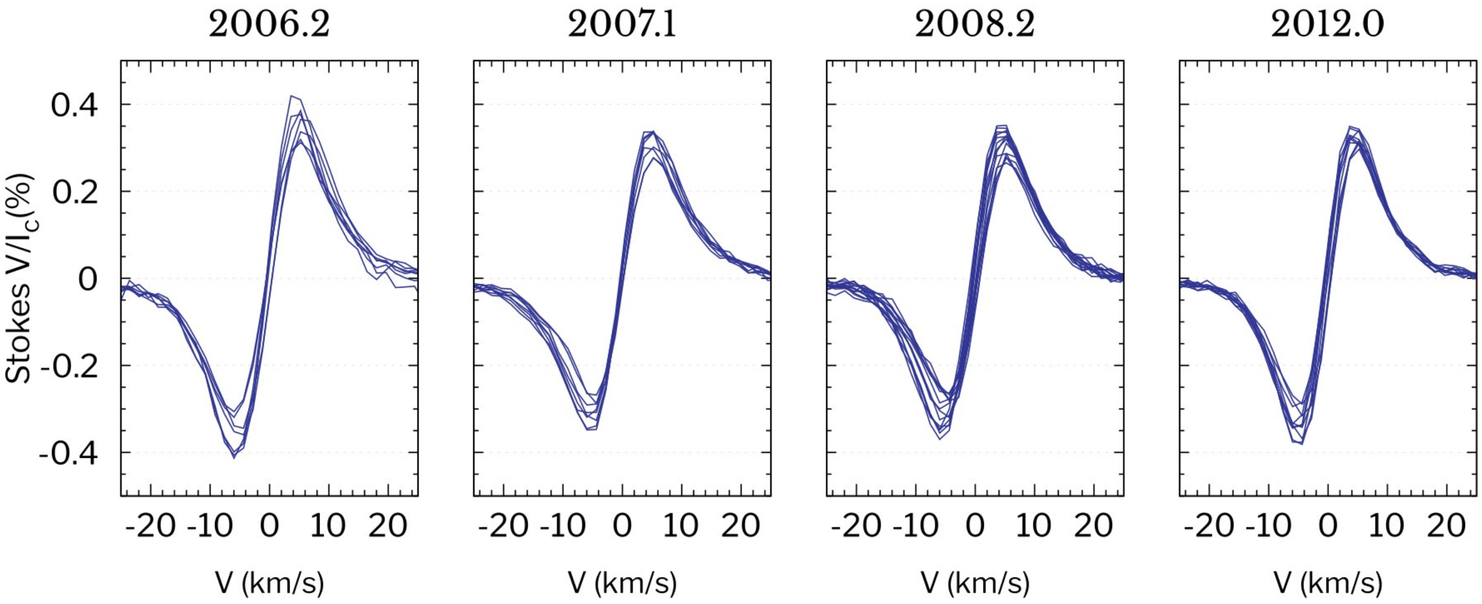


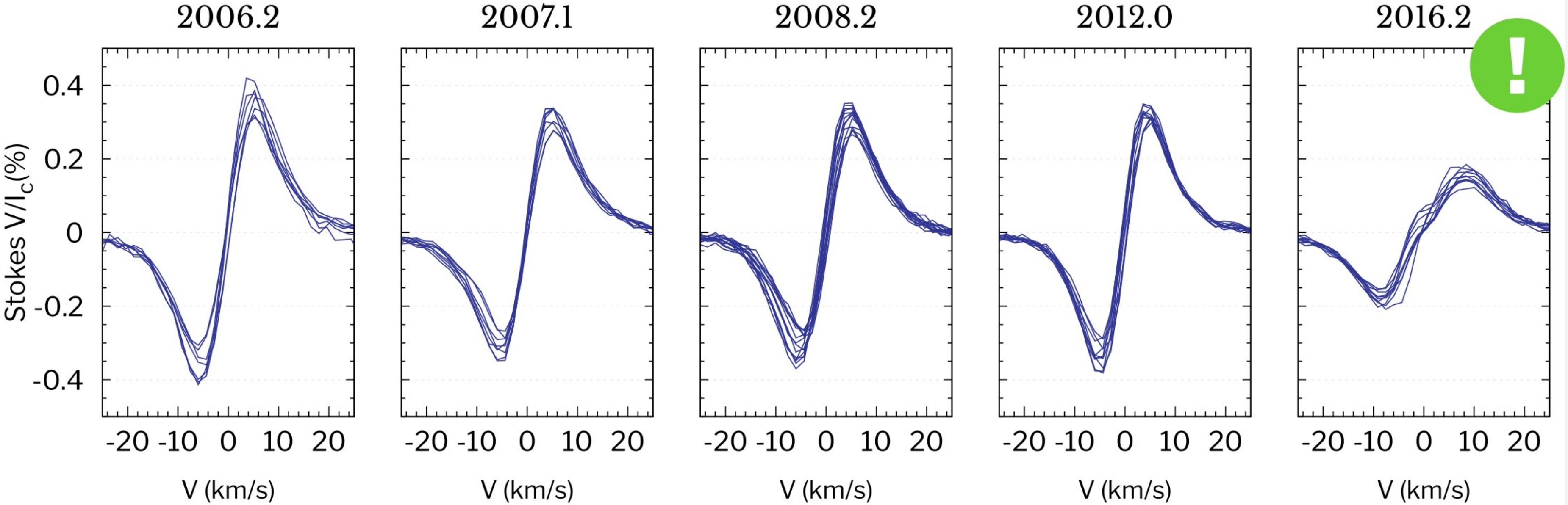


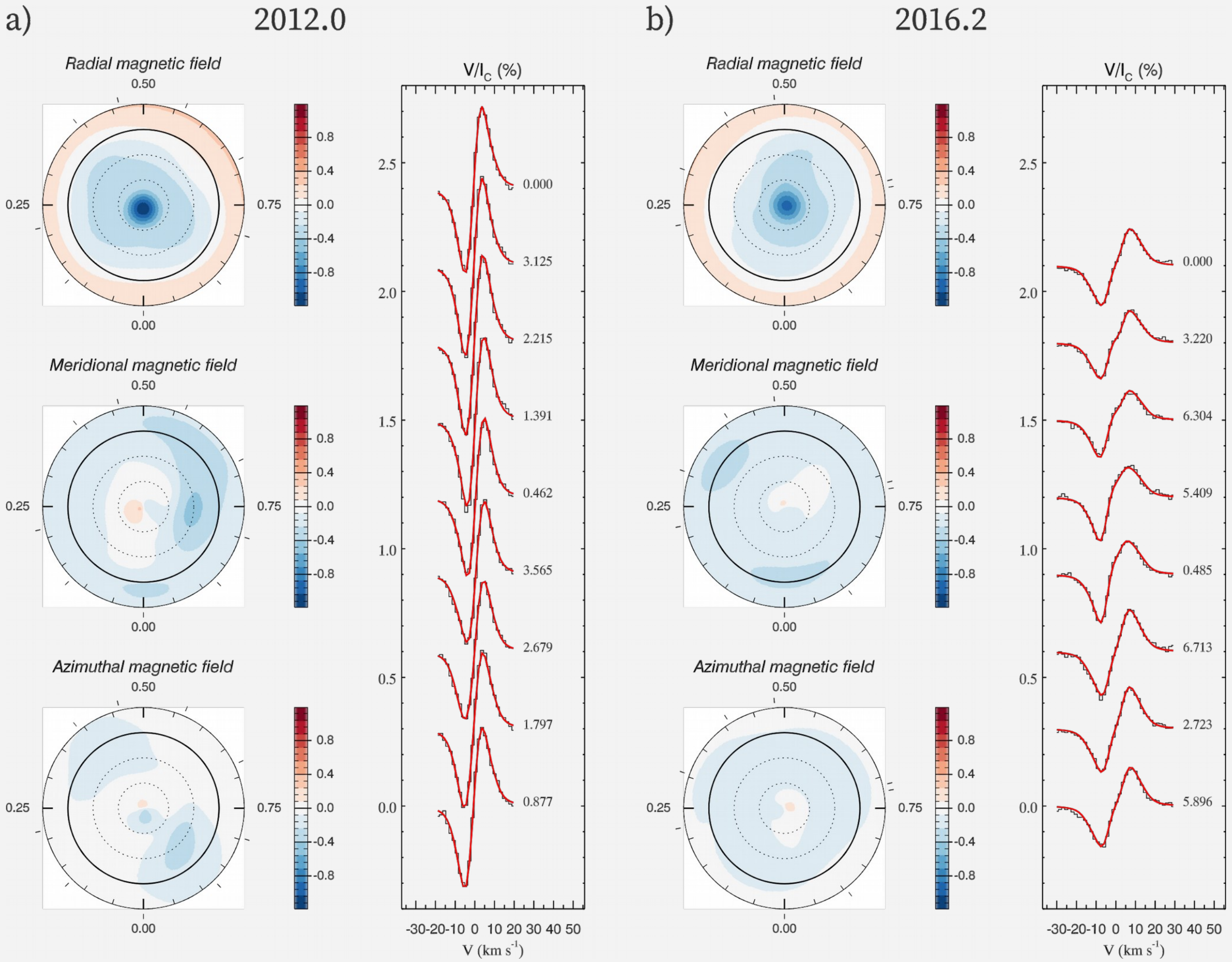
We observed AD Leo repeatedly in four Stokes parameters: *IQUV*.

We computed Stokes *IQUV* LSD profiles for each observation.



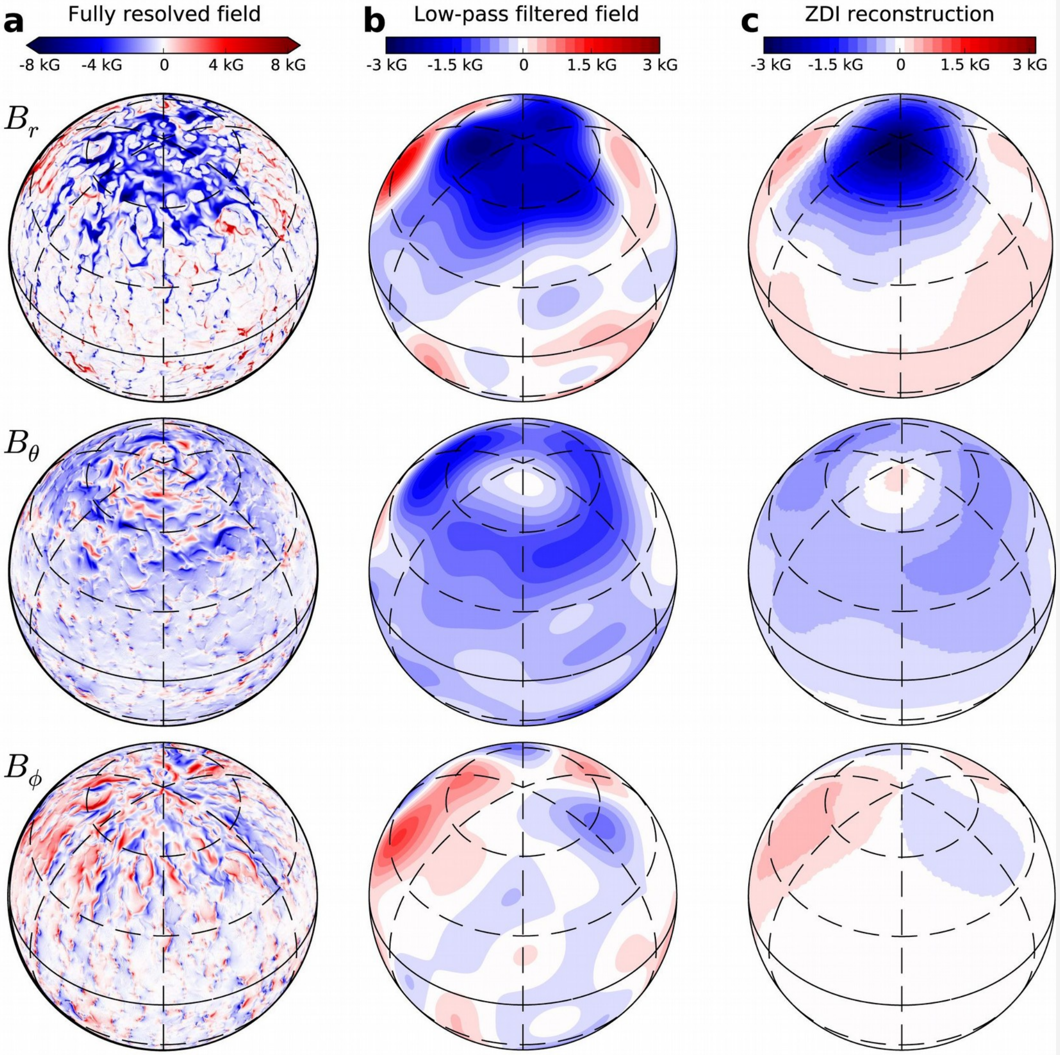

2006.2
2007.1
2008.2
2012.0
Stokes V/I$_c$(%)
0.4
0.2
0
-0.2
-0.4
-20 -10 0 10 20
V (km/s)


2006.2
2007.1
2008.2
2012.0
2016.2
!
Stokes V/I$_c$(%)
0.4
0.2
0
-0.2
-0.4
-20 -10 0 10 20
V (km/s)


a)
2012.0
Radial magnetic field
Meridional magnetic field
Azimuthal magnetic field
0.50
0.25
0.75
0.00
0.8
0.4
0.0
-0.4
-0.8
V/I_C (%)
2.5
2.0
1.5
1.0
0.5
0.0
0.000
3.125
2.215
1.391
0.462
3.565
2.679
1.797
0.877
-30-20-10 0 10 20 30 40 50
V (km s⁻¹)
b)
2016.2
Radial magnetic field
Meridional magnetic field
Azimuthal magnetic field
0.000
3.220
6.304
5.409
0.485
6.713
2.723
5.896

f_V = 13%

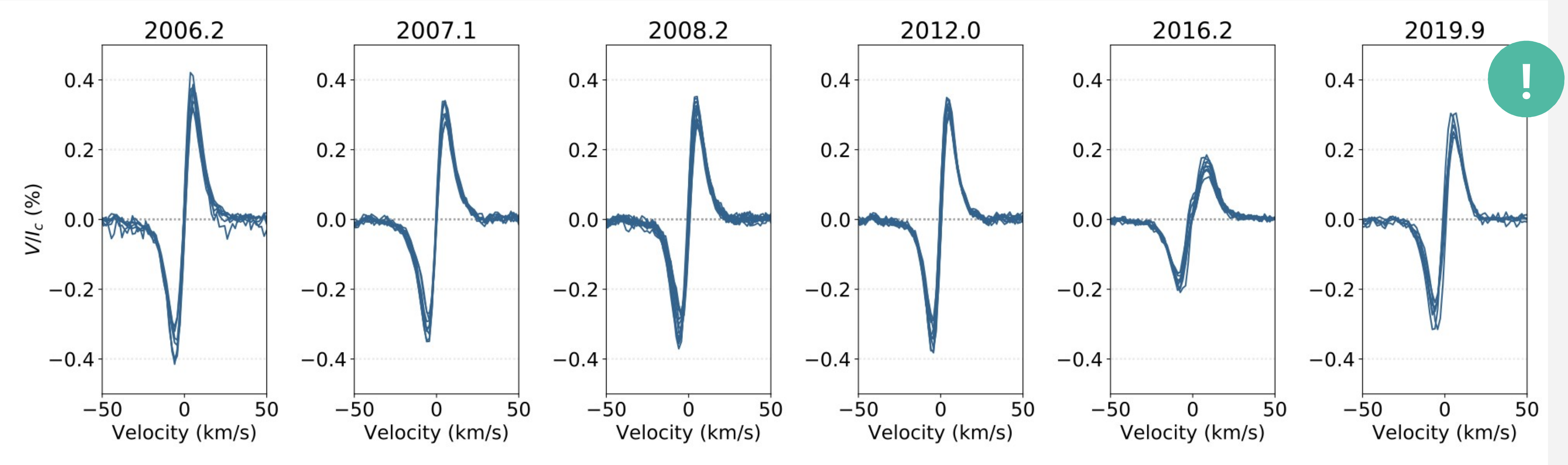
f_V = 7%



This could be what we see: **a global dipolar field but sprinkled on small unresolved scales.**

Figure from **Yadav et al. 2015**

New data from 2019!



Observing proposal:
Lavail, Wade, and Kochukhov. Instrument: ESPaDOnS at CFHT (Hawaii), 8 hours.
Tracking the unprecedented magnetic evolution of the magnetic field of the active M dwarf AD Leo.

Take away messages

- Linear polarization in spectral lines was detected for an M dwarf for the first time
- The global magnetic field changed and became concentrated into smaller areas on the surface between 2012-2016
- This secular change is not expected by numerical simulations. Could it be oscillatory dynamo, magnetic cycle?
- We obtained more observations in 2019, it seems that the Stokes *V* profiles are back at previous levels.

Paper IV

The large-scale magnetic field of the eccentric pre-main sequence binary system V1878 Ori

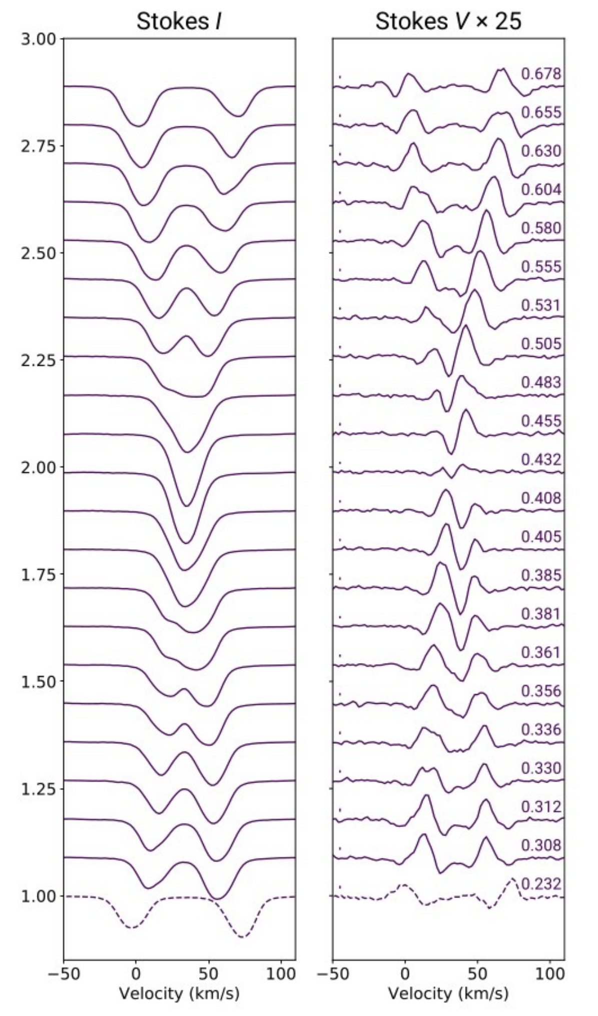
Data from the ESPaDOnS spectropolarimeter, optical up to ~1000 nm, *R*=65000

The V1878 Ori binary system

- V1878 Ori is a young double-lined spectroscopic binary.
- Both components are IMTTS ($M > 1.5M_{sun}$)
- A and B have near-equal masses and luminosities
- Eccentric orbit and asynchronous rotation
- Multi-wavelength observing campaign: **optical spectropolarimetry**, X-rays, radio, photometry.

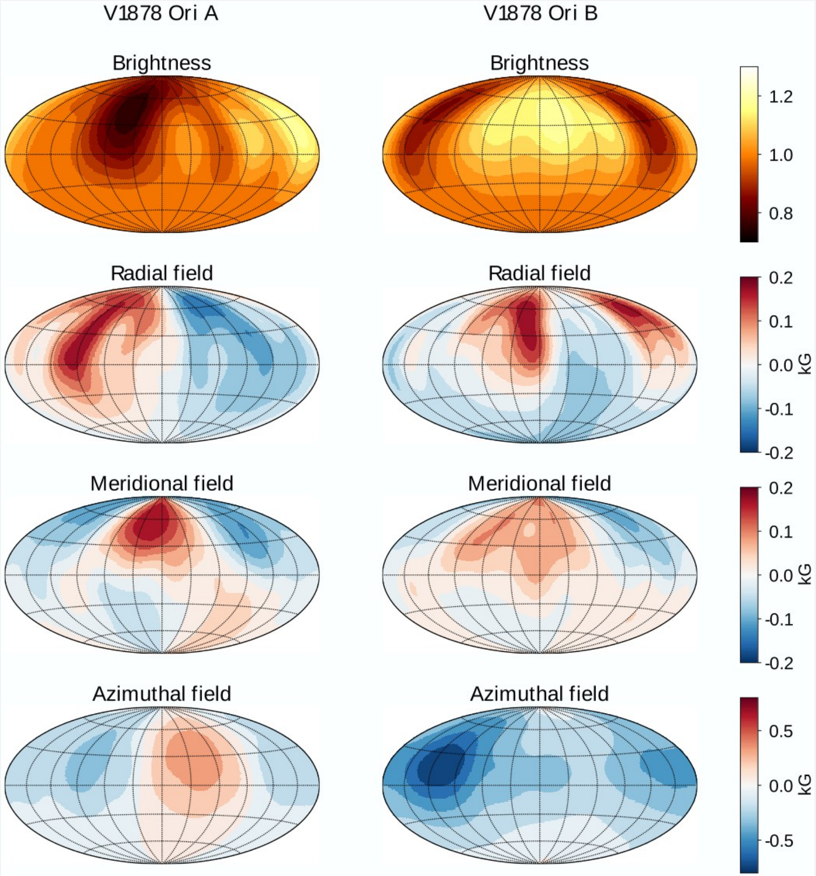
V1878 Ori

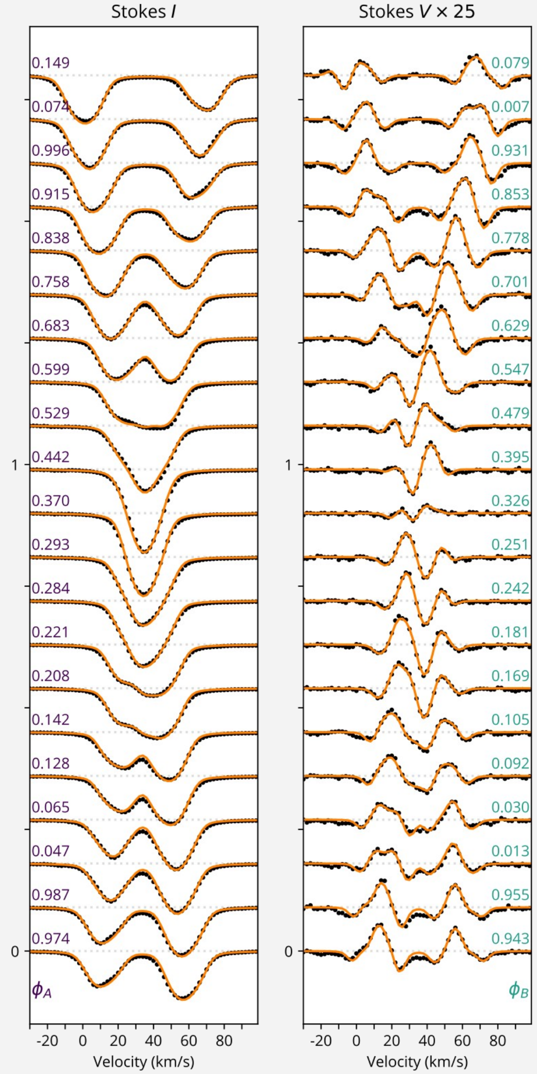
LSD profiles



V1878 Ori

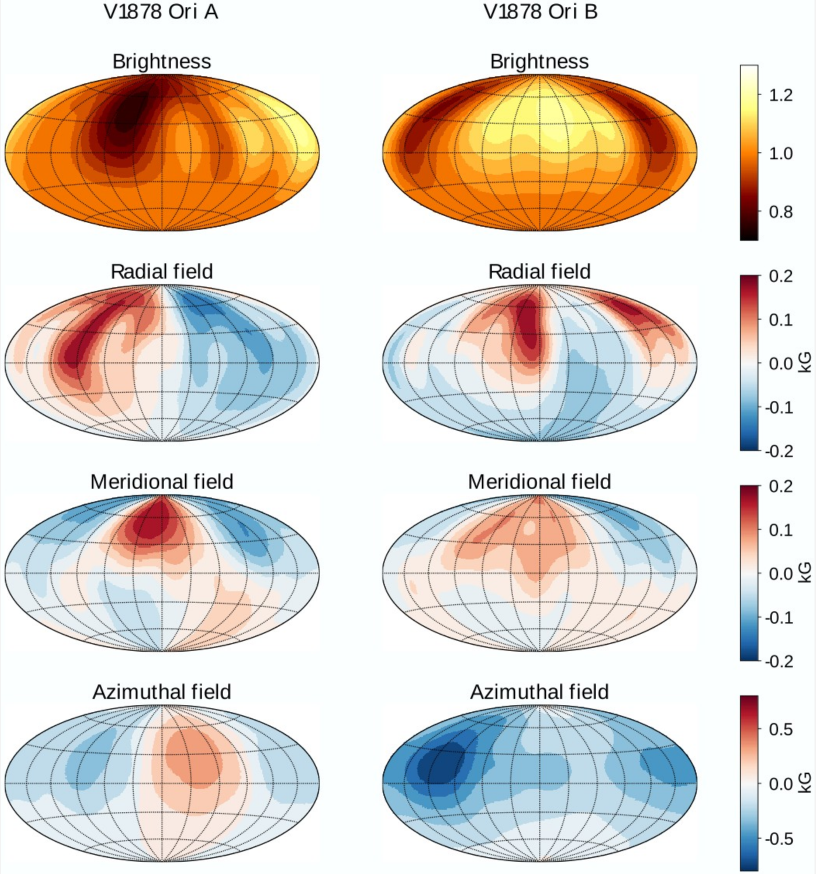
Brightness and magnetic field mapping

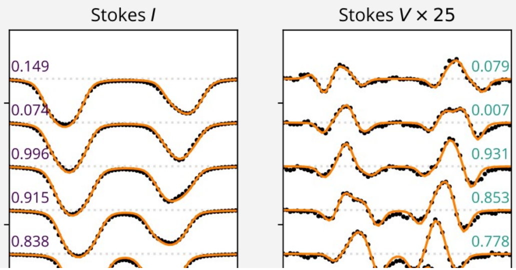




V1878 Ori

Brightness and magnetic field mapping





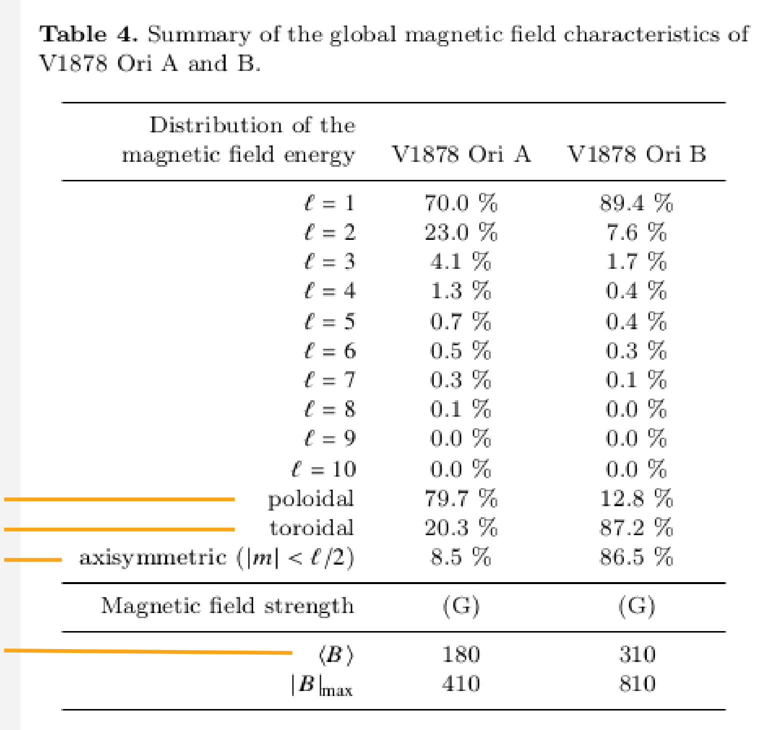


Table 4. Summary of the global magnetic field characteristics of V1878 Ori A and B.

Distribution of the magnetic field energy	V1878 Ori A	V1878 Ori B
$\ell = 1$	70.0 %	89.4 %
$\ell = 2$	23.0 %	7.6 %
$\ell = 3$	4.1 %	1.7 %
$\ell = 4$	1.3 %	0.4 %
$\ell = 5$	0.7 %	0.4 %
$\ell = 6$	0.5 %	0.3 %
$\ell = 7$	0.3 %	0.1 %
$\ell = 8$	0.1 %	0.0 %
$\ell = 9$	0.0 %	0.0 %
$\ell = 10$	0.0 %	0.0 %
poloidal	79.7 %	12.8 %
toroidal	20.3 %	87.2 %
axisymmetric ($\lvert m \rvert < \ell/2$)	8.5 %	86.5 %
Magnetic field strength	(G)	(G)
$\langle B \rangle$	180	310
$\lvert B \rvert_{\max}$	410	810

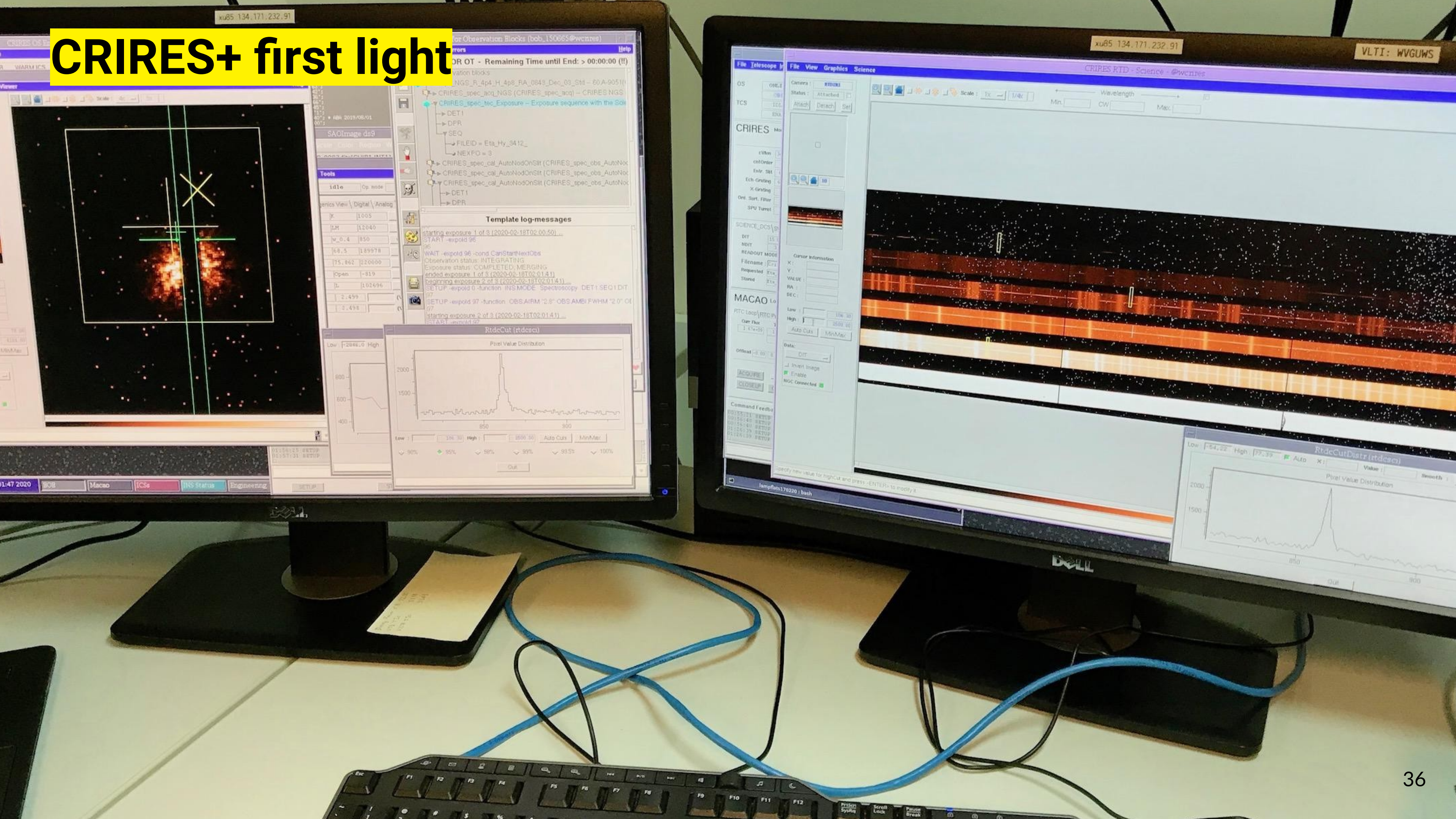
Outlook

New instrumentation is here or around the corner: **near-infrared spectropolarimeters** such as CRIRES+@VLT and SPIRou @CFHT.

It becomes possible to do **Zeeman broadening** and **ZDI simultaneously on the same data**! This will systematically gives us a more complete picture of the magnetic field: small scales and large scales at the same time.

We'll be able to observe more T Tauri stars, and younger objects such as Class I stars. The larger spectral grasp will also mean that we'll be able to determine magnetic field and stellar parameter simultaneously.

CRIRES+ first light



Template log-messages

```
starting exposure 1 of 3 (2020-02-18T02:00:50) ...
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96
WAIT -expoId 96 -cond CanStartNextObs
Observation status: INTEGRATING
Exposure status: COMPLETED; MERGING
ended exposure 1 of 3 (2020-02-18T02:01:41)
beginning exposure 2 of 3 (2020-02-18T02:01:41) ...
SETUP -expoId 0 -function  INS.MODE  Spectroscopy  DET1.SEQ1.DIT
97
SETUP -expoId 97 -function  OBS.AIRM "2.8" OBS.AMBI.FWHM "2.0" OE
97
starting exposure 2 of 3 (2020-02-18T02:01:41) ...
START -expoId 97
```
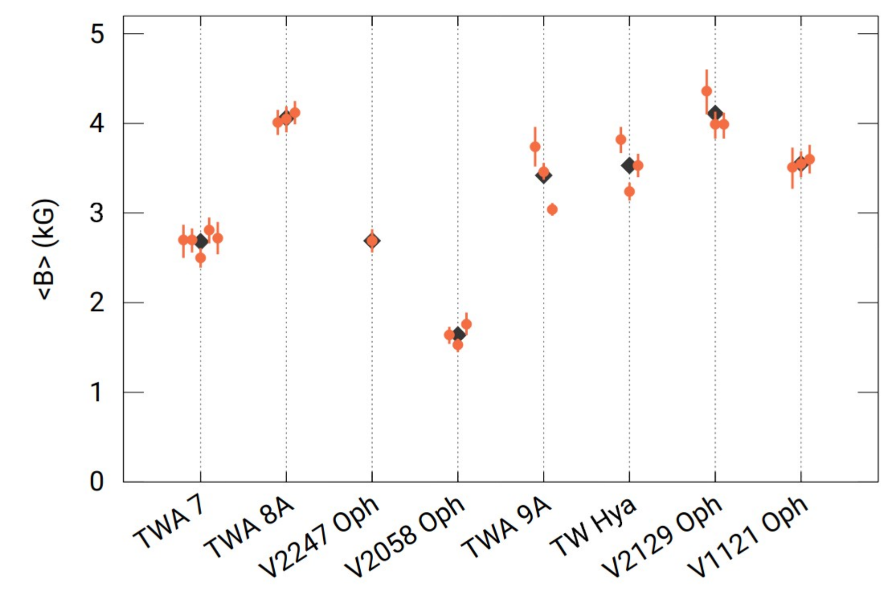
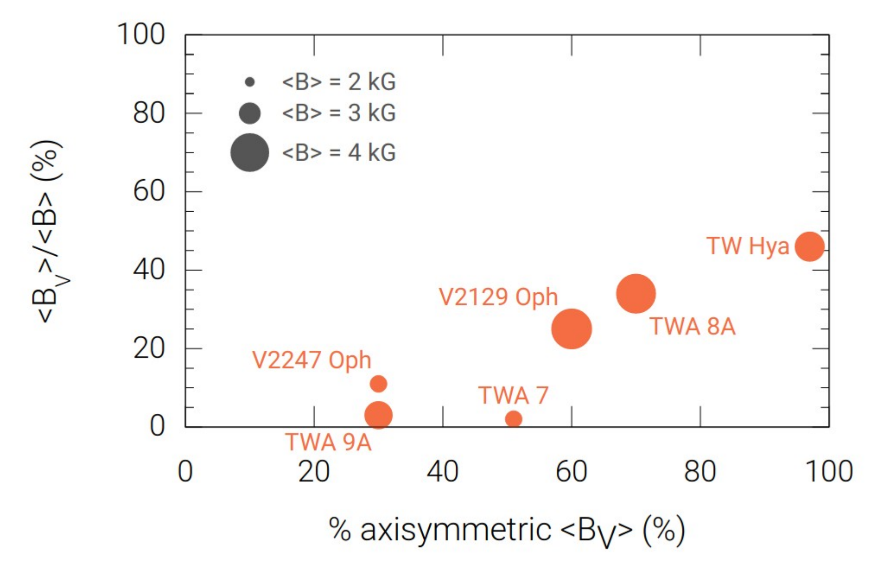

Extra slides, danger zone.

Results from Paper II

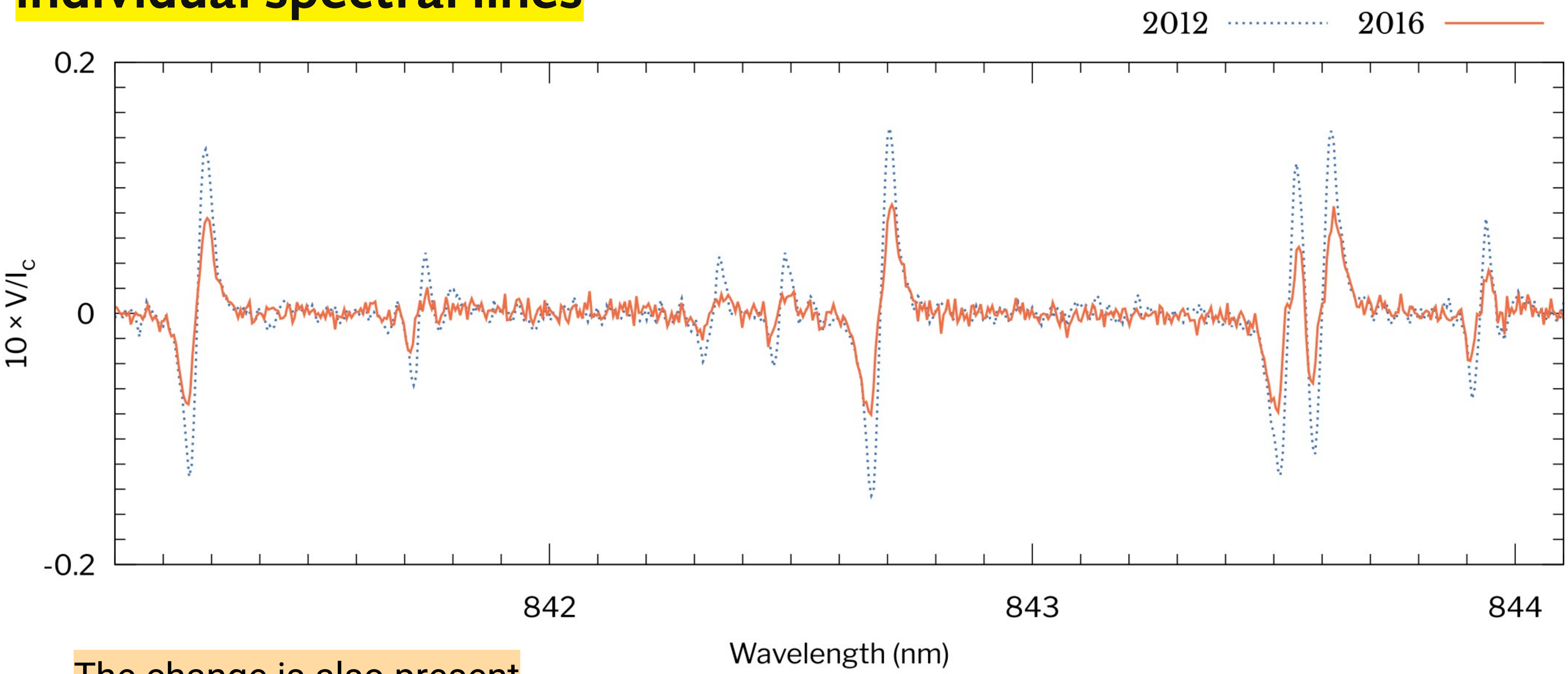


▲ Very little variability of the mean field strength <B>



▲ ZDI seems to recover a larger fraction of the magnetic field strength if the magnetic field is more axisymmetric.

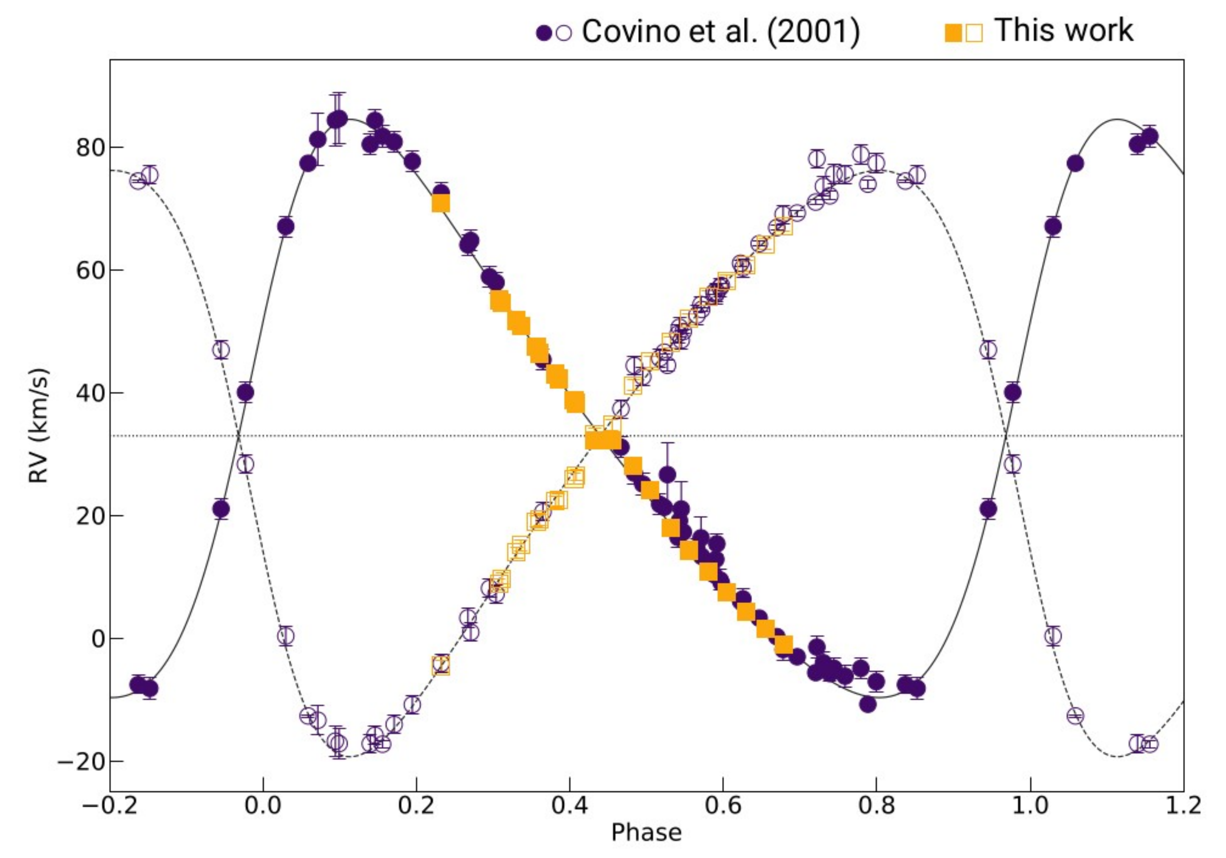
Paper III: Stokes *V* change in individual spectral lines



The change is also present in individual spectral lines.

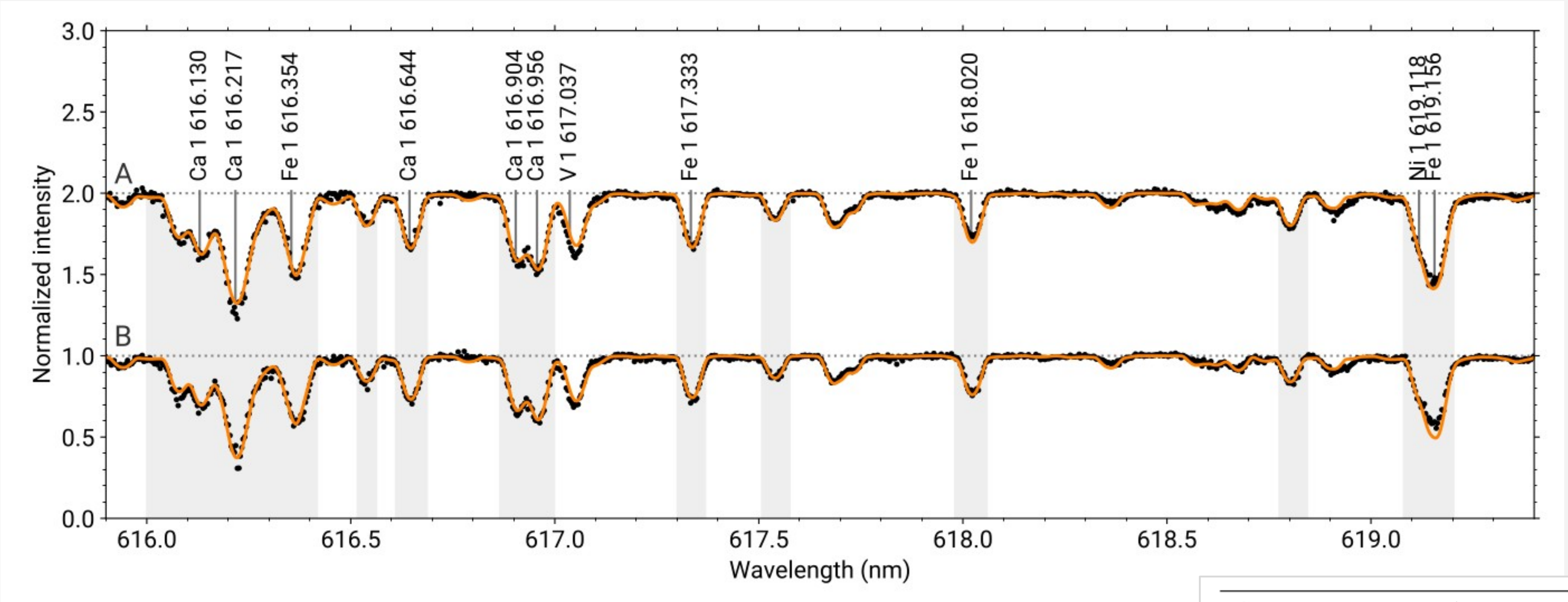
Paper IV

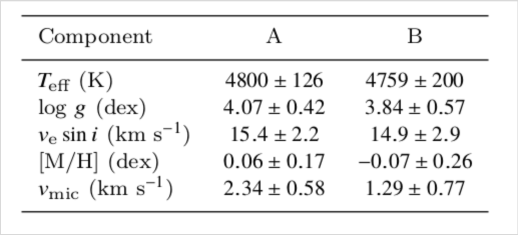
Radial velocities and orbit fitting



Paper IV

Spectrum synthesis

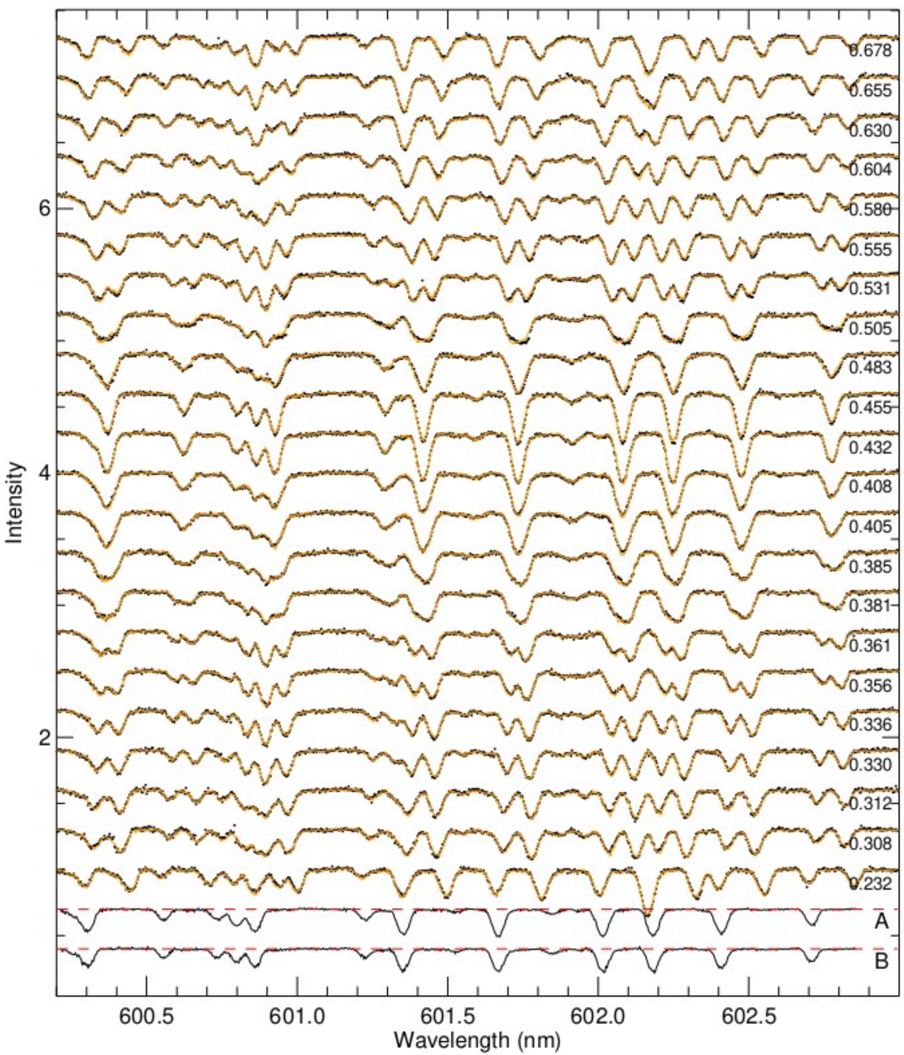




Component	A	B
$T_{\rm eff}$ (K)	4800 ± 126	4759 ± 200
log g (dex)	4.07 ± 0.42	3.84 ± 0.57
$v_{\rm e} \sin i$ (km s^{-1})	15.4 ± 2.2	14.9 ± 2.9
[M/H] (dex)	0.06 ± 0.17	−0.07 ± 0.26
$v_{\rm mic}$ (km s^{-1})	2.34 ± 0.58	1.29 ± 0.77

Paper IV

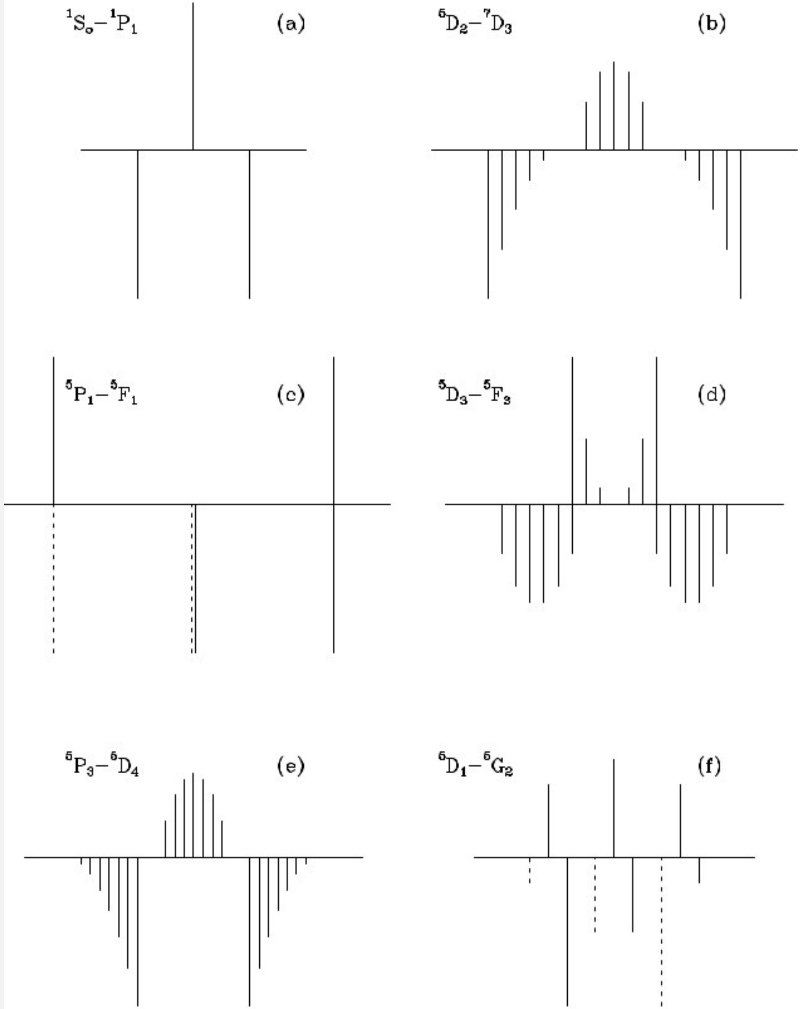
Spectrum disentangling



Zeeman splitting patterns

Fig.3.2. Characteristic Zeeman patterns for different transitions. The Landé factors are computed according to the L-S coupling scheme. Following the usual convention, the π components are drawn upward and the σ components downward. The σblue components in panels (c) and (f) are dashed for clarity; the σred and σblue components at line center in panel (c) are drawn somewhat apart but they actually coincide. From left to right, top to bottom, we have patterns of Type 0 (a), Type II (b), Type III (c,d), and Type I (e,f) (see Sect. 3.3 for the definition of Type).

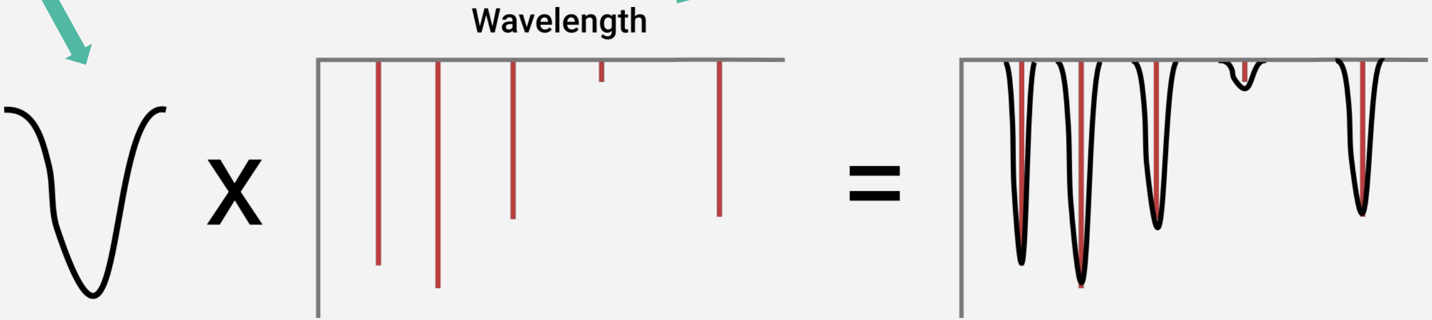
Polarization in spectral lines.
Landi degl'Innocenti & Landolfi, 2004



Least squares deconvolution (LSD)

LSD: Donati et al. 1997
iLSD: Kochukhov et al. 2010

We can retrieve from online databases:
e.g VALD at http://vald.astro.uu.se/



LSD profile
Mean spectral line profile

Line mask
Information on line wavelengths, depths, and Landé factor

Observed spectrum

what we are after

what we have

Doppler imaging

Temperature spots