Magnetic fields and activity of low-mass stars in the SPIRou context

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Outline

1. Magnetic activity of low-mass stars in the planet-search context
2. Stellar magnetometry based on spectroscopy/spectropolarimetry
3. Identifying and filtering activity in velocimetric measurements
4. Summary

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1. Magnetic activity of low-mass stars in the planet-search context
   - Detecting planets orbiting active stars
   - Effects of stellar activity on planets
   - Magnetic field generation in low-mass stars

2. Stellar magnetometry based on spectroscopy/spectropolarimetry

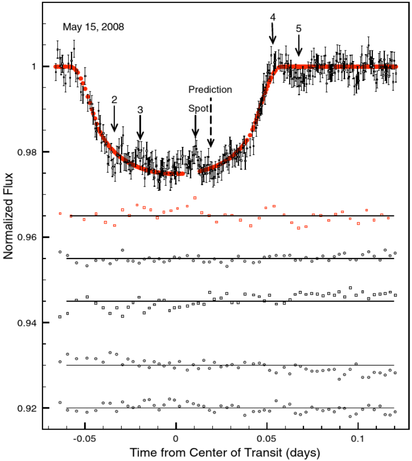
3. Identifying and filtering activity in velocimetric measurements

4. Summary

Detecting planets orbiting active stars

- Activity effect on RV/photometric measurements
  - Impede detection
  - Bias planetary parameters
  - False positives

➔ Lectures by Xavier Bonfils



Dittman et al. (2009)

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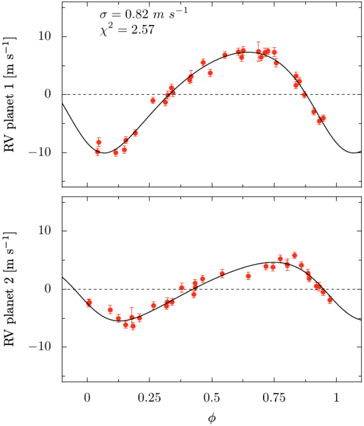
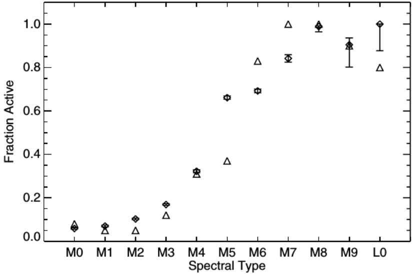


Bonfils et al. (2007)

Active stars are everywhere

- Focus on low-mass stars
  - longer activity lifetimes
  - remain fast rotator longer
  - even slow rotators display activity
- At high precision (almost) any star is active
  - Even the Sun!



West et al. (2008)

→ *cf. Lecture by Céline Reylé*

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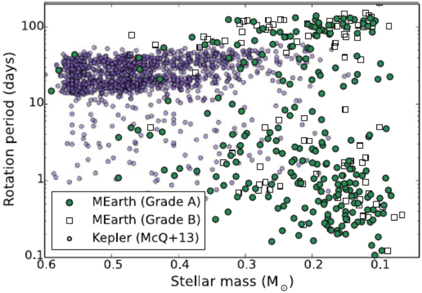

Newton et al. (2016)

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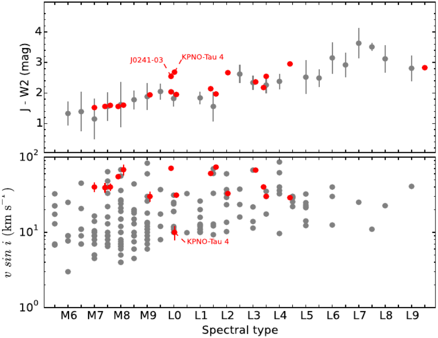

Miles-Páez et al. (2017)

$v \sin i = 10\ km\,s^{-1} \leftrightarrow P_{\rm rot} < 0.5\ d$

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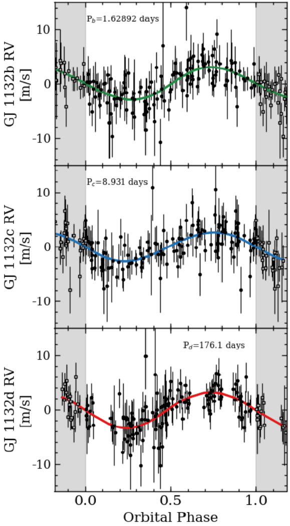

Bonfils et al. (2018)

GJ 1132 $P \sim 125\ d$

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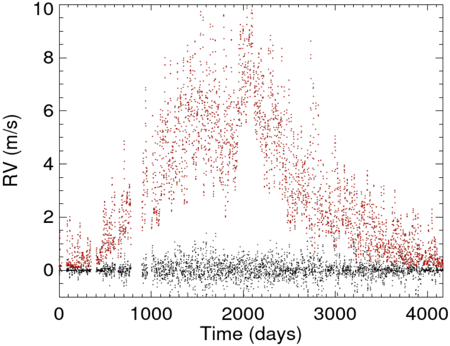
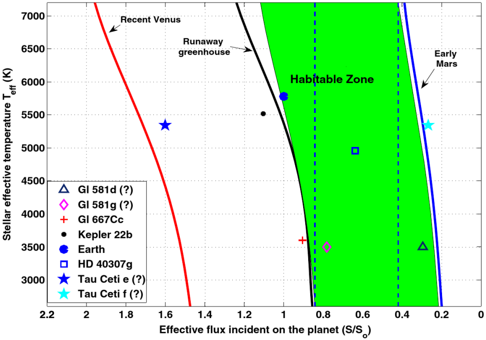


Photometric (black) vs convective blueshift (red) RV jitter on the Sun
Meunier et al. (2010)

Effects of activity on planets: HZ definition

- Insolation HZ based on stellar flux
- Role of magnetic field/activity
  - XUV radiation
  - Stellar wind + magnetic pressure
  - ➥ planetary magnetosphere balance
  - ➥ erosion of planetary atmosphere
- Need for evolutionary perspective
  - Water loss vs reservoir
  - Specific case of BD
    - No main sequence
    - → cf. Lecture by Céline Reylé



Kopparapu et al. (2013)

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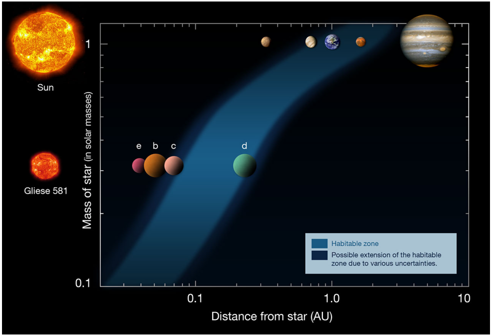

Credit: ESO/F. Selsis
PR for Mayor et al. (2009)

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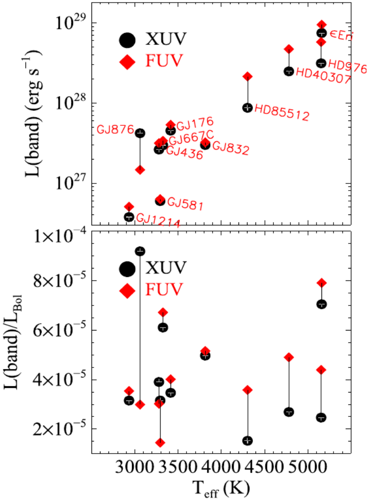

France et al. (2016)

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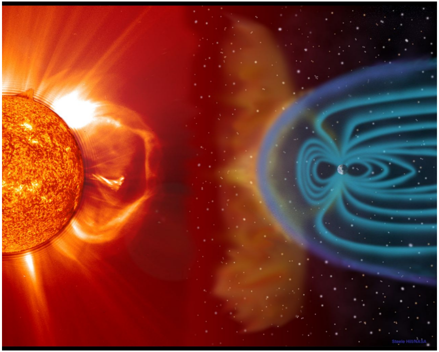

Credit: NASA

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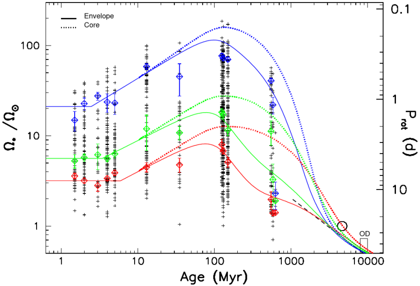

(c) 0.5 $M_\odot$

Gallet & Bouvier (2015)

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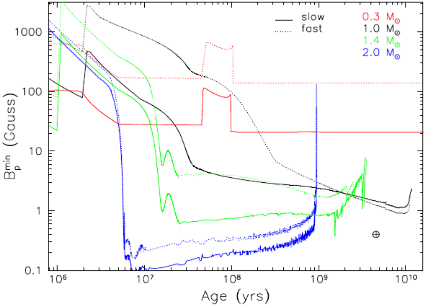

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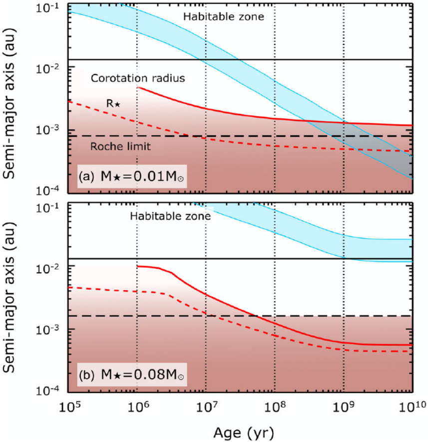
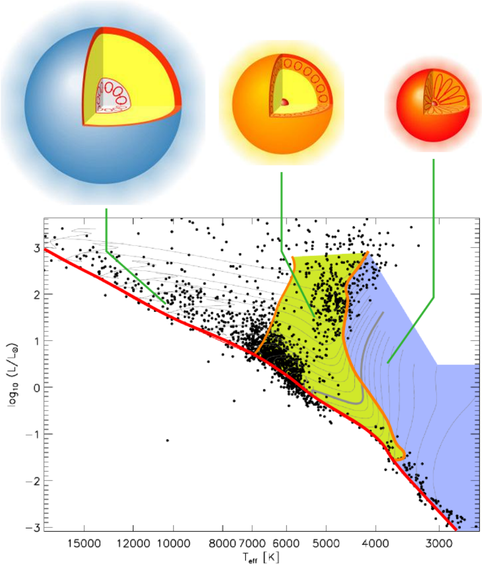


Bolmont et al. (2017)

The origin of stellar magnetic fields (1/2)



Adapted from Reiners (2008)

High-mass star:
Simple steady field

➡ Fossil field ?

Partly convective star:
Complex **B**
temporal evolutions

➡ Solar-type dynamo

Fully convective star:
No tachocline

➡ Non-solar dynamo

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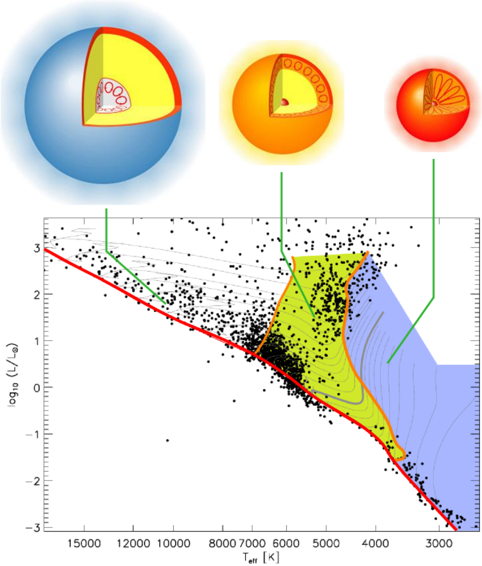

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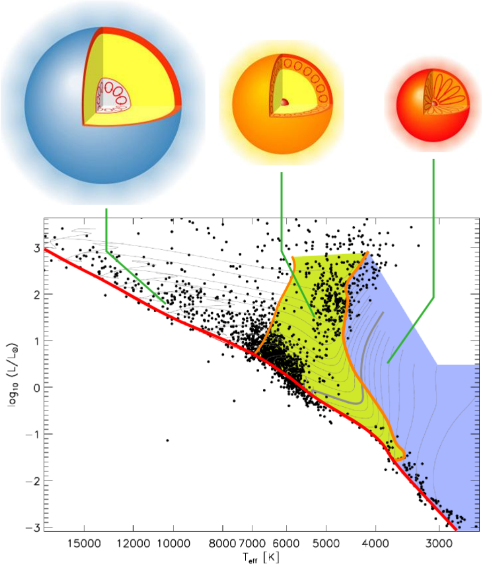

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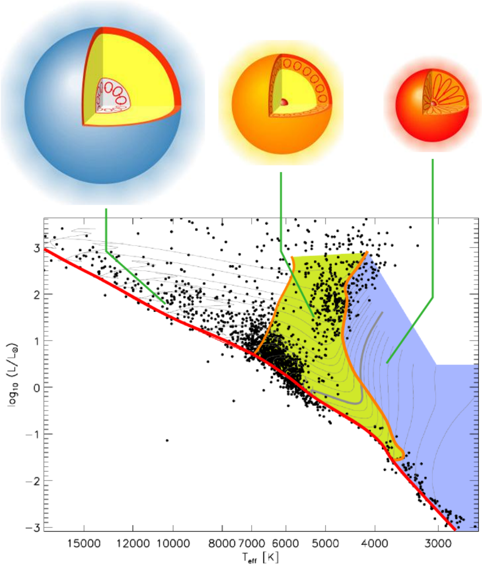

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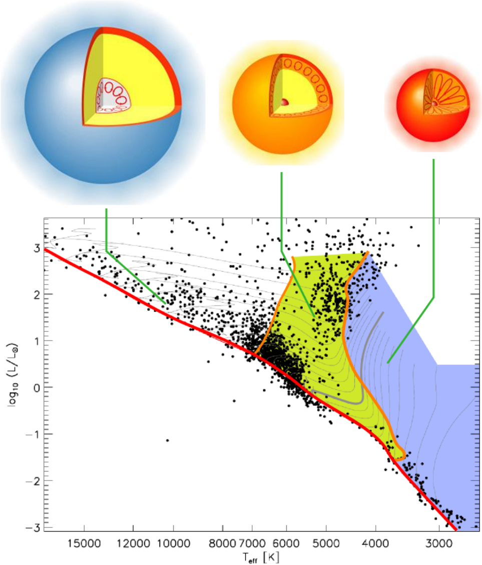

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→ cf. Lecture by Silvia Alencar

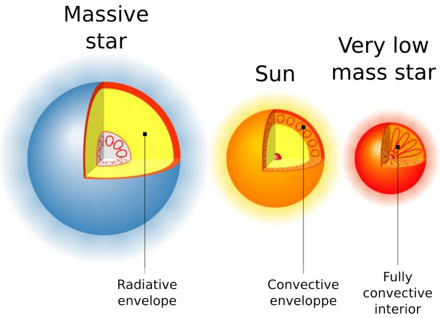
The origin of stellar magnetic fields (2/2)

Dynamo action

- Amplifies and sustains **B**
  - Conversion $E_{\mathrm{kin}} \rightarrow E_{\mathrm{mag}}$
  - Induction effect

$$\frac{\partial \mathbf{B}}{\partial t} = \underbrace{\nabla \times (\mathbf{u} \times \mathbf{B})}_{\textit{induction}} + \underbrace{\eta \Delta \mathbf{B}}_{\textit{dissipation}}$$

- Solar dynamo
  - Ω-effect: poloidal ➔ toroidal
  - Poloidal field regeneration?
  - Role of tachocline
- Stellar magnetic fields
  - Different regime of parameters
  - Non-solar dynamo
- *Rincon (2019)*



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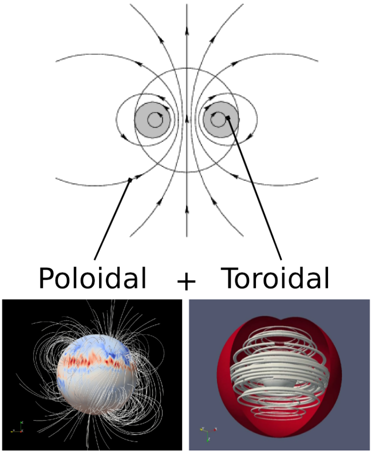

Adapted from figures by
J. Braithwaite and T. Gastine

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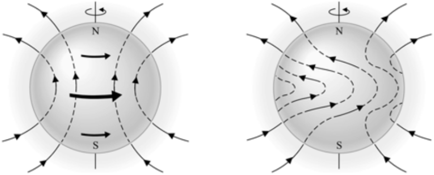

Ω-effect

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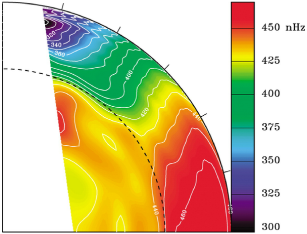
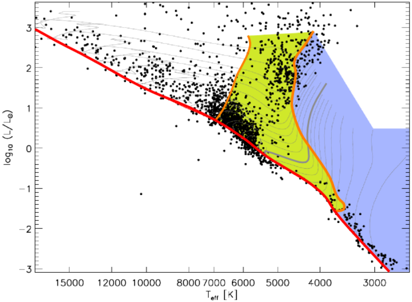


Internal angular velocity
Shu et al., 2006; from SOHO–MDI data



Stellar magnetism in the SPIRou/SLS context

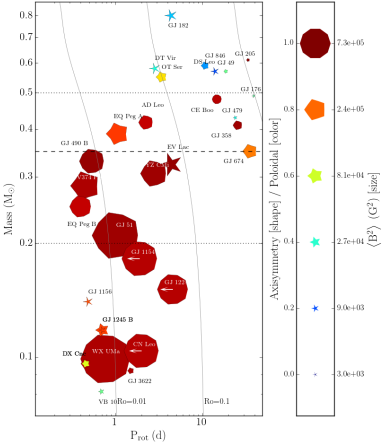
- Strong synergy

  planet search ↔ stellar magnetism
  - stellar dynamos
  - magnetic cycles
  - angular momentum evolution

→ large sample

→ moderate-low activity regime

→ baseline > 4 yr



Donati et al. (2006,2008), Phan-Bao et al. (2009), Morin et al. (2008-2010), Hébrard et al. (2016), Moutou et al. (2018)

Outline

1 Magnetic activity of low-mass stars in the planet-search context

2 Stellar magnetometry based on spectroscopy/spectropolarimetry
- Indirect measurements: stellar activity
- Direct magnetic field measurement: Zeeman effect
- Spectroscopy vs spectropolarimetry
- Overview of M dwarfs magnetism

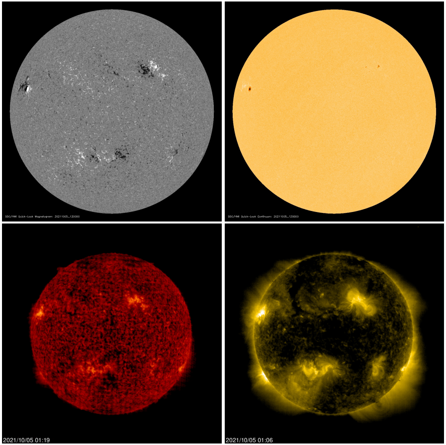
3 Identifying and filtering activity in velocimetric measurements

4 Summary

Indirect measurements: stellar activity

- Magnetic activity
  - Photospheric features
    - photometry
    - HR spectroscopy
  - Chromosphere
    - UV, Vis., nIR emission lines
  - Corona
    - EUV/X-ray, radio
- Spatial + temporal correlations
- "Historical" proxies for stellar **B**
  - Chromospheric Ca II H&K / Hα
  - Coronal X-ray emission
- nIR indicators
  - HeI, Paβ, γ, δ
  - weaker emission wrt optical
  - J-band metallic lines

→ *Cortes-Zuleta & Boisse (2021)*



ESA/NASA SOHO images
magnetogram | continuum
He II 304 Å| Fe XV 284 Å

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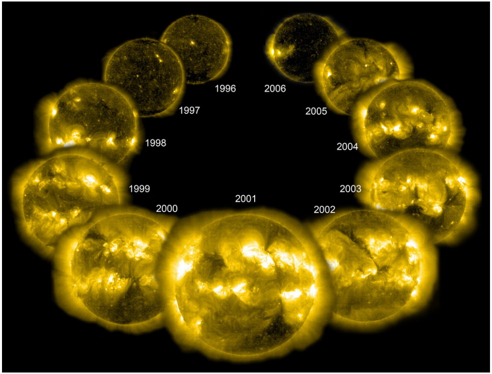

SOHO, EUV

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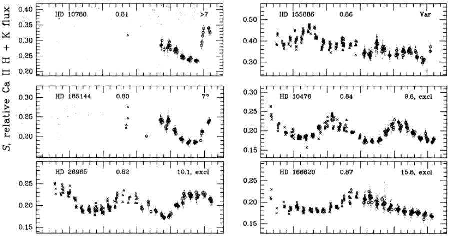
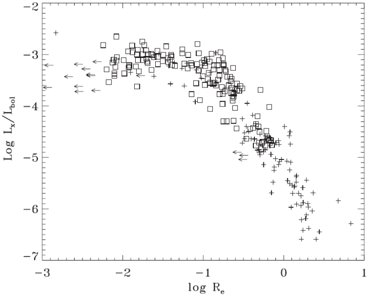


Baliunas et al. (1995)



Pizzolato et al. (2003)

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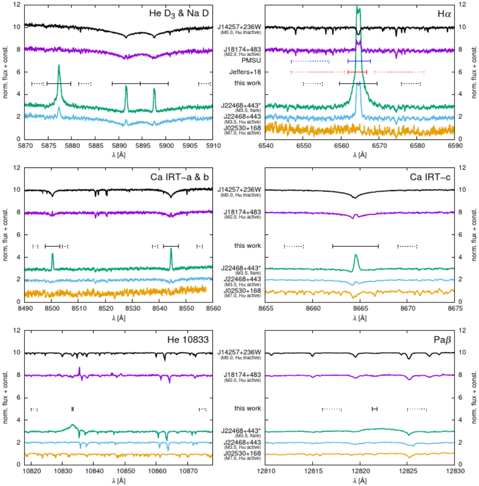
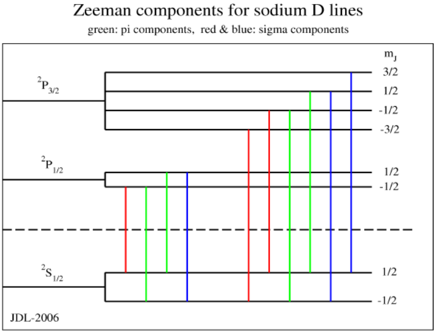


Shöffer et al. (2019)

Direct magnetic field measurement: Zeeman effect

- Zeeman effect
  - **B** breaks J-degeneracy
  - Selection rules
    - 3 components σ_b, π, σ_r
  - Zeeman π-to-σ splitting
    - $\Delta\lambda_B = \frac{e}{4\pi m_e c}\lambda_0^2 g_{eff} B$ $= 4,67\times10^{-12}\,\lambda_0^2 g_{eff} B$ $B(\mathrm{G})\ ;\ \lambda(\mathrm{nm})$
  - Polarization
    - Information on vector properties of **B**
    - Circ. pol. ➔ longitudinal
    - Lin. pol. ➔ transverse
- Cool MS stars
  - atomic lines ➔ Zeeman
  - molecular can be in Paschen-Back regime



Credit: J. Landstreet

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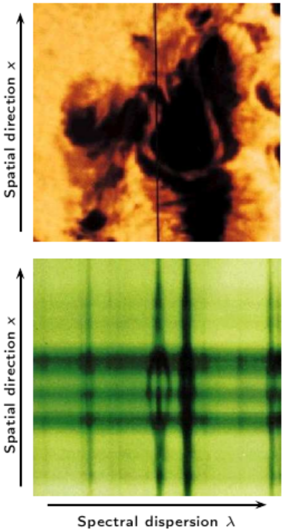

Credit: NOAO

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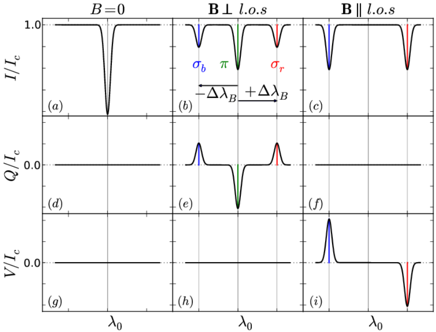
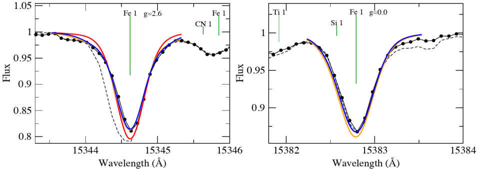


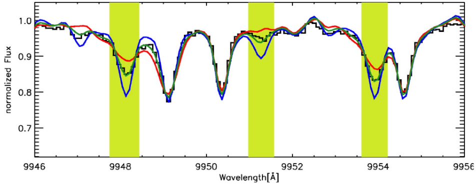
Schematic view of the observed Stokes parameters as a function of the field orientation w.r.t the line of sight

Magnetometry with unpolarised spectroscopy

- Zeeman components not resolved
  - when $\Delta v_B < \Delta v_0 \simeq 8\ \mathrm{km\,s^{-1}}$
  - natural, thermal, pressure, turbulent width
  - instrumental profile
- Measure "magnetic flux":
  - $\langle \|\mathbf{B}\| \rangle = B \times f$
- Multi-component models
  - $\langle \|\mathbf{B}\| \rangle = \sum_i B_i \times f_i$
- Weakly sensitive to **B** orientation
  - Partly degenerate
- Low to moderate $v \sin i$...
  - except w/ magnetic intensification
- Paschen-Back effect in CrH
  - *Kuzmychov et al. (2017)*



ϵ Eri (K2V), H-band atomic lines
Petit et al. (2021)



GJ 729 (M3.5V), FeH Wing-Ford band
Reiners & Basri (2006)

Magnetometry with unpolarised spectroscopy

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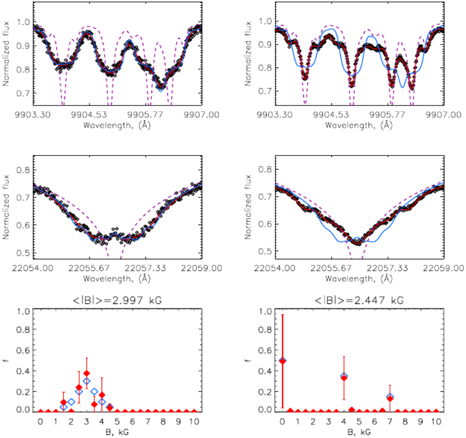

Simulation of FeH and Na I *lines for multi-component model*
Shulyak et al. (2014)

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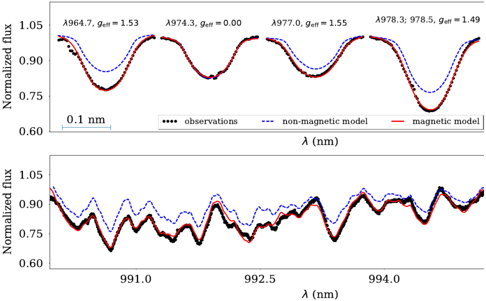

V374 Peg ($v \sin i \sim 37\ \mathrm{km\,s^{-1}}$) magnetic intensification of FeH and Ti I lines
Shulyak et al. (2017)

Magnetometry with unpolarised spectroscopy

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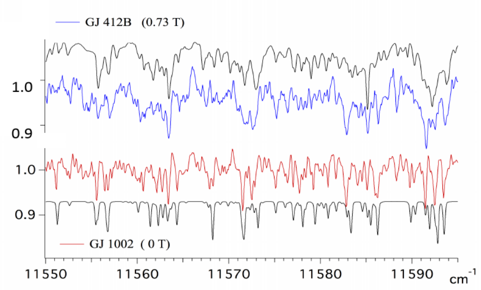
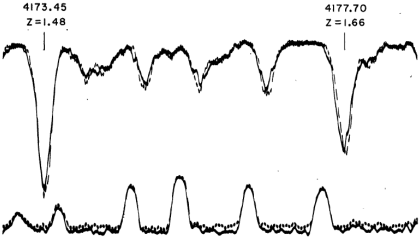


Paschen-Back effect on CrH lines of WX UMa (M6V) and GJ 1002 (M5.5V)
Crozet et al. (2021)

Spectropolarimetry: B_ℓ measurements

- B_ℓ: longitudinal field
- Zeeman-induced circ. pol.
  - Shift RHCP/LHCP spectra
  - $B_\ell \propto \Delta\lambda_B$
- 1st detection on another star than the Sun: *Babcock (1947)*
- Differential measurement / weakly affected by modelling error
- Requires high S/N ($\sim 10^4$)
- Similarly linear polarisation ➔ transverse field
- Limited information: 1st moment of Stokes V

$$B_\ell(\mathrm{G}) = -2.14 \times 10^{11} \frac{\int v\, V(v)\, \mathrm{d}v}{\lambda_0\, g_{\mathrm{eff}}\, c \int [I_c - I(v)] \mathrm{d}v}$$



78 Vir (A2p)
Babcock (1947)

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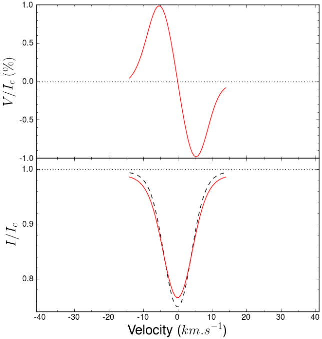

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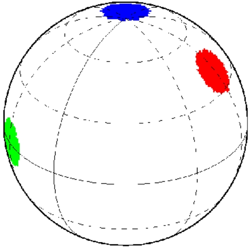

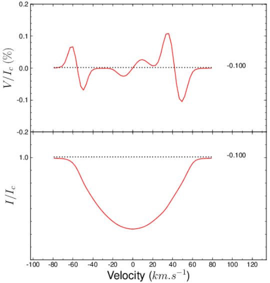

High-resolution spectropolarimetry

- Zeeman polarisation sensitive to vector properties
- Partial cancellation
  - Blind to small-scale field
- "Weak-field regime"
  - V: typically $10^{-3} - 10^{-2} \times I_c$
  - Q, U: typically $0.1 \times V$

→ Requires S/N $\sim 10^3 - 10^4$

- Multi-line extraction
  - Self-similar signal in all lines
  - Least-Square Deconvolution
    Donati et al. (1997)
  - Behaves as real line up to a few kG
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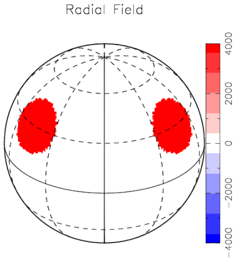

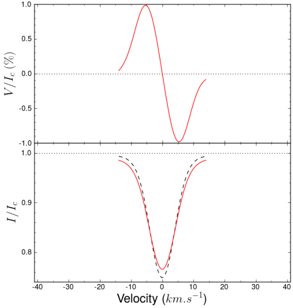

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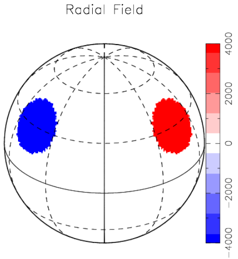

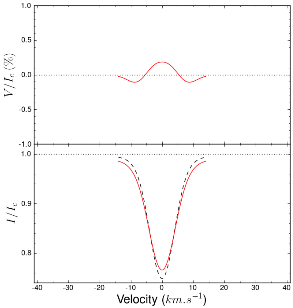

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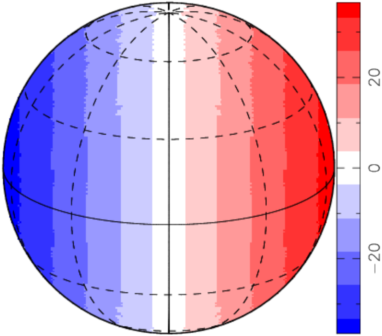

Equal RV stripes

High-resolution spectropolarimetry

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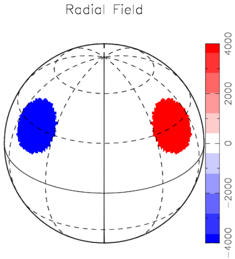

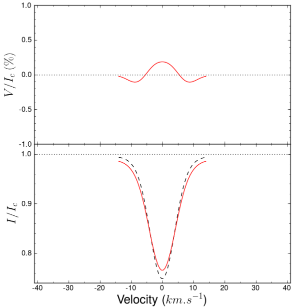

$v \sin i = 1 \ km\,s^{-1}$

High-resolution spectropolarimetry

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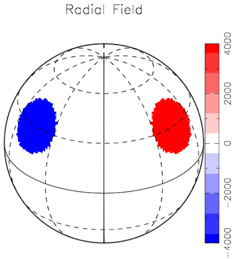

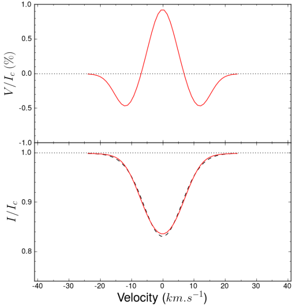

$v \sin i = 10 \; km \, s^{-1}$

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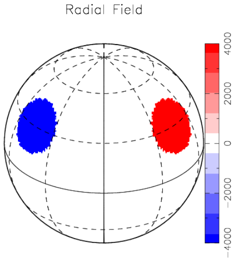

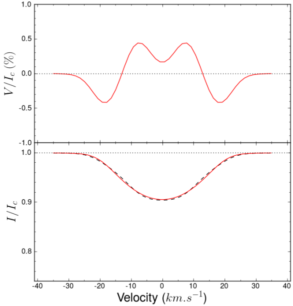

$v \sin i = 20\ km\, s^{-1}$

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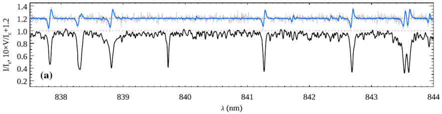

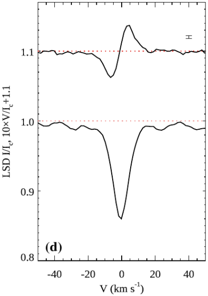

Portion of spectrum and LSD profiles of AD Leo (M3V) Kochukhov (2020)

Zeeman-Doppler Imaging: principles

- ZDI: principle *Semel (1989)*
  - Properties Zeeman effect
  - Doppler effect
  - Rotational modulation
  - ➥ Vector **B**
- Ambiguity/degeneracy
  - Regularization required
    - e.g. maximum entropy *Donati & Brown (1997)*
- Spherical harmonics decomposition *Donati et al. (2006)*
  - Solenoidal field
  - Limit reconstruction scale
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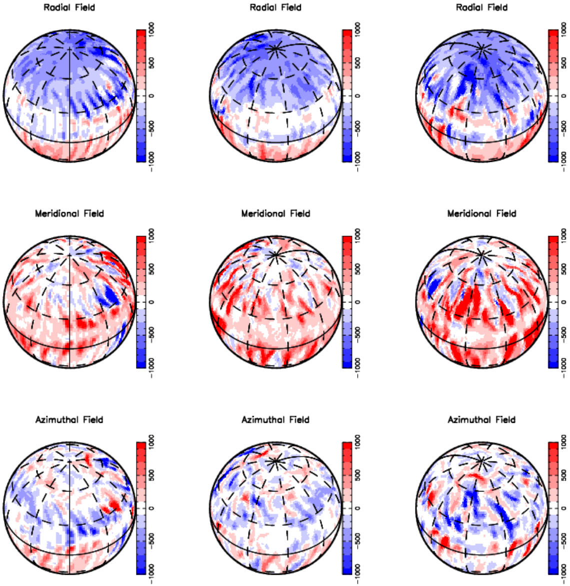
ZDI: performances and limitations (1/2)

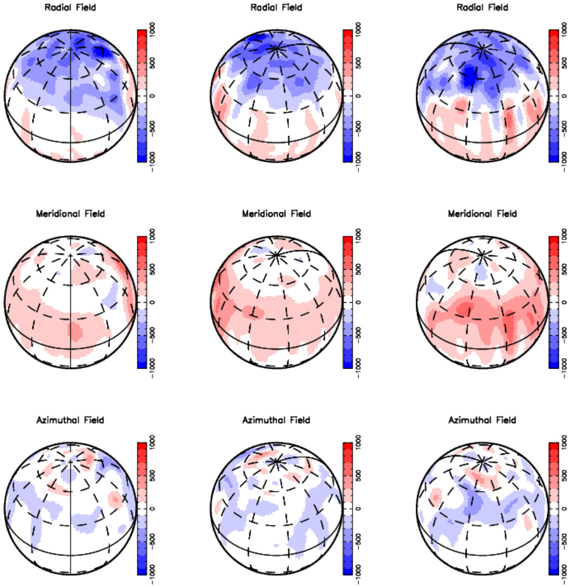


Input numerical simulation

Credit: T. Gastine
MagIC code

See also: Yadav et al. (2015)
Lehmann et al. (2019, 2021)

ZDI: performances and limitations (1/2)



ZDI reconstruction

- *$v \sin i = 40$ km/s*
- *20 spectra*
- *$S/N = 6{,}000$*
- *$\ell_{max} = 20$*
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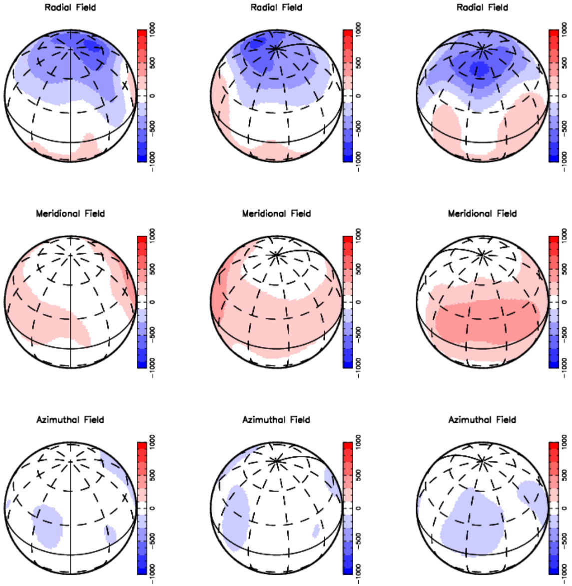

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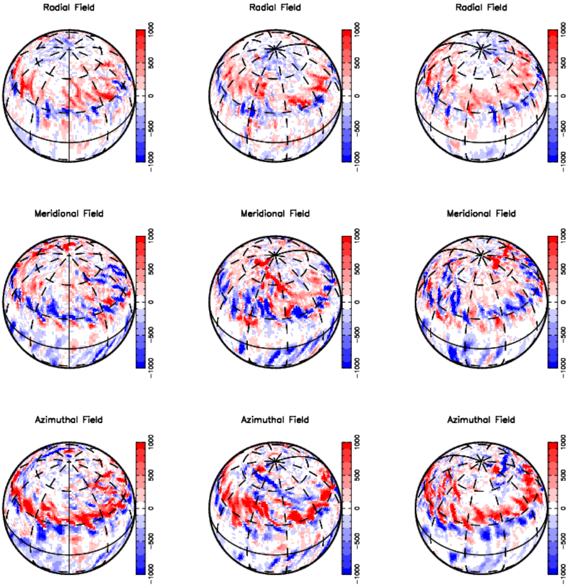

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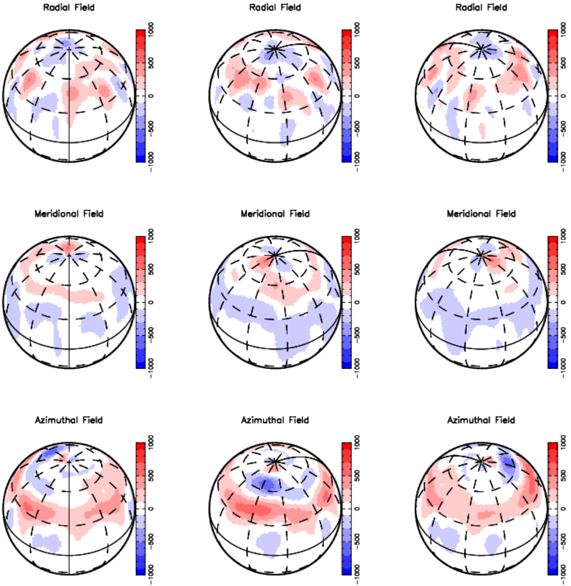

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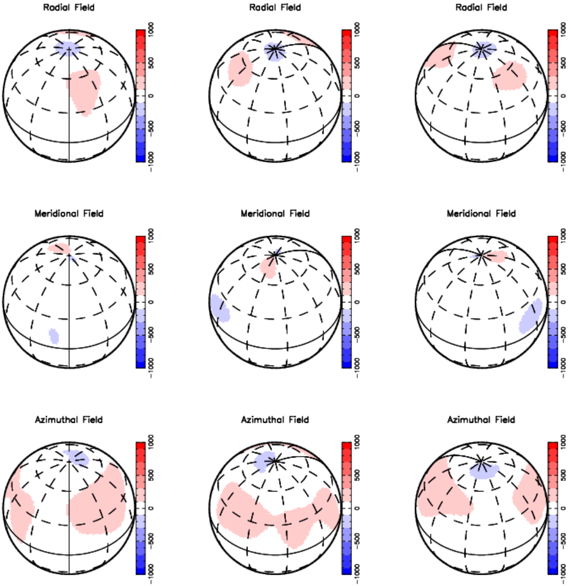

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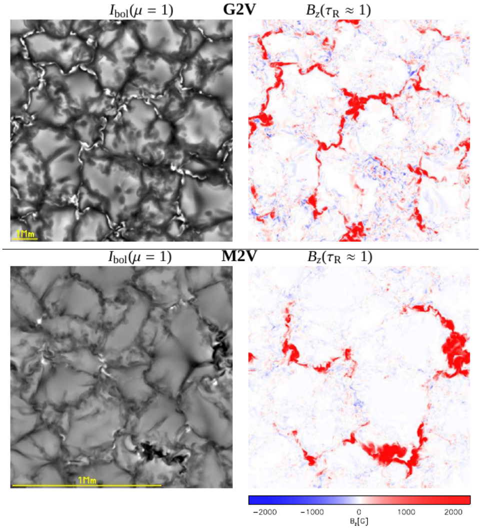
ZDI: performances and limitations (2/2)



Beeck et al. (2011)

- Magnetic models assume
  - No velocity field
  - Homogeneous brightness
- How can we take them into account?

ZDI: performances and limitations (2/2)

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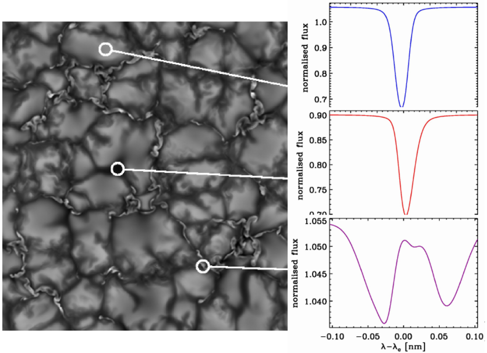

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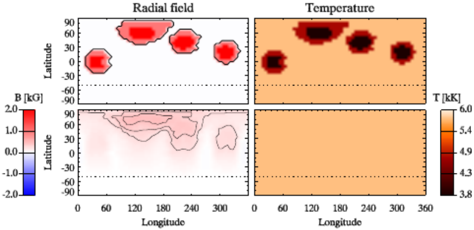
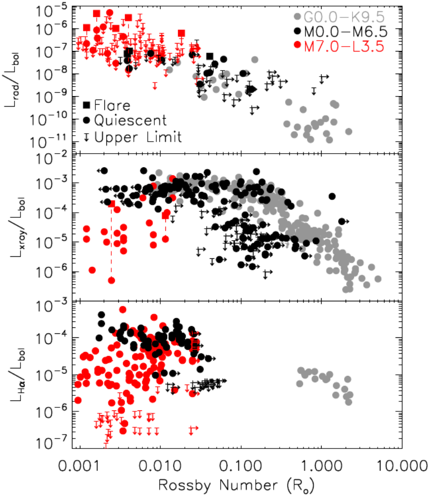


Rosen &Kochukhov (2012)

Overview of M dwarfs magnetism: activity

- Rotation–activity relation
  - Early-mid M dwarfs: similar G-K
    - High Ro: anti-correlated
    - Low Ro: plateau
    - No break at FCL
  - Late M dwarfs
    - ∃ low activity at low Ro
    - No L_{rad}/L_{bol} saturation

- Activity cycles
  - Evidence for long-term variability
  - Hints of cycles
    - Spectroscopic indices
    - Radio polarity flips? *Route (2016)*



McLean et al. (2011)

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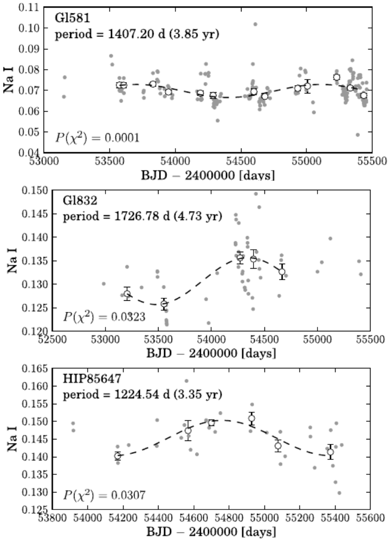

Gomes da Silva et al. (2012)

Magnetic fields of M dwarfs in unpolarised light

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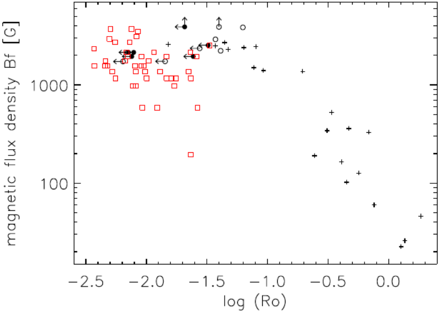
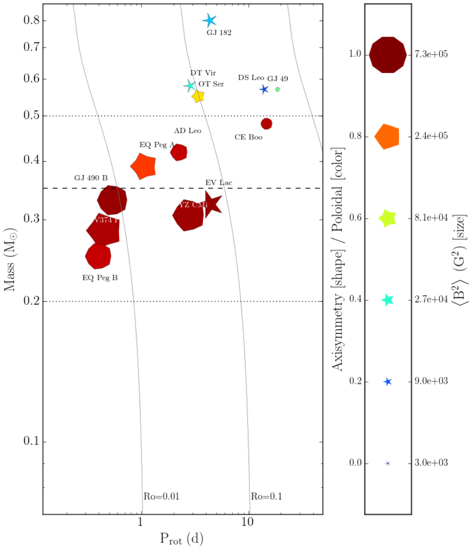


Reiners (2012)

Spectropolarimetric survey: fully convective stars

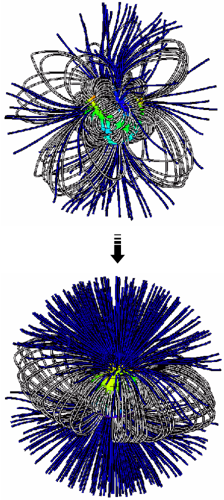


- Sharp transition $\sim 0.5\ M_\odot$
  - Magnetic topology
  - Differential rotation
- *Morin et al. (2008a,b)*
  Donati et al. (2006,2008)
  Phan-Bao et al. (2009)
- Similar transition observed between fully/partly convective T Tauri stars

➔ Silvia Alencar's lecture

- Numerical/theoretical studies
  - Conditions for strong dipole w/ density stratification?
  - *Gastine et al. (2012)*
    Raynaud et al. (2015)
    Zaire et al. (2021)

Spectropolarimetric survey: fully convective stars



Coronal extrapolations by M. Jardine from surface magnetic fields reconstructed by Donati et al. (2008), Morin et al. (2008a)

- Sharp transition $\sim 0.5\ M_\odot$
  - Magnetic topology
  - Differential rotation
- *Morin et al. (2008a,b)*
Donati et al. (2006,2008)
Phan-Bao et al. (2009)
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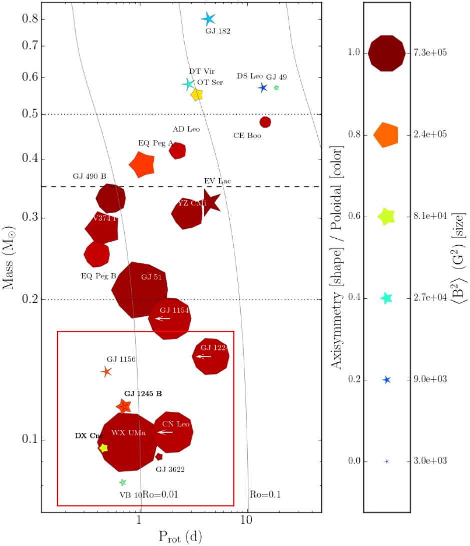
Spectropolarimetric survey: very low mass stars



- 2 groups of stars $\lesssim 0.2\ \mathrm{M}_\odot$
  - Similar stellar params
  - Radically $\neq$ magnetisms
- *Morin et al. (2010)*

- Variability / cycles?
  - No switch in 3 yr
  - *Kitchatinov et al. (2014)*
- Effect of age?
- Dynamo bistability?
  Morin et al. (2011)
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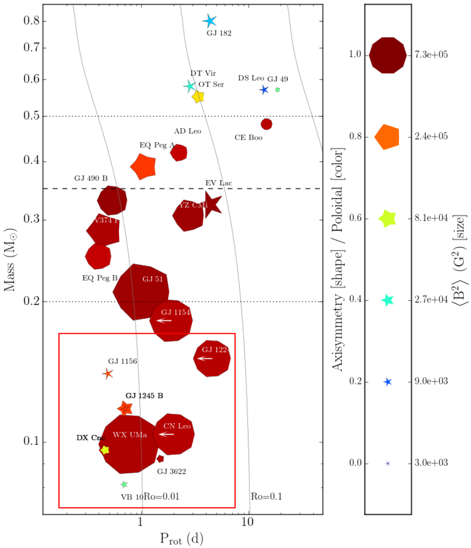

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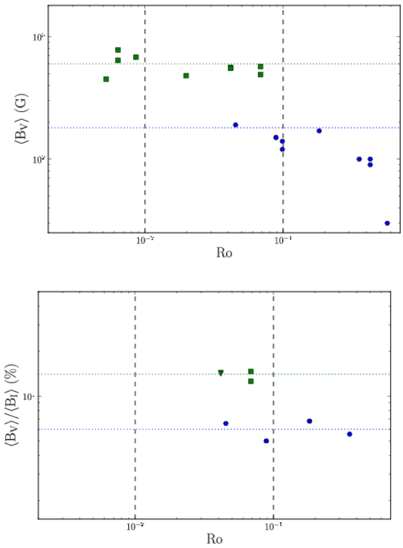
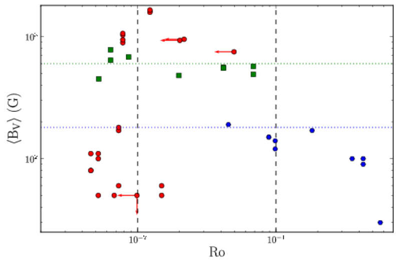
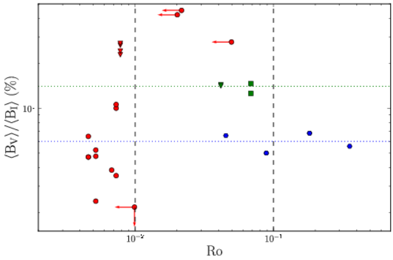
Understanding both (un)polarised measurements



- $\langle B_V \rangle = 2 - 30\% \, \langle B_I \rangle$
  - Apparent jump FC/PC
  - Large spread for VLMS
  - *Morin et al. (2008b,2010), Reiner & Basri (2009)*
- New Stokes I measurements
  - “Supersaturation” fields
  - Link w/ large-scale topology?
  - *Shulyak et al. (2017, 2019)*

Understanding both (un)polarised measurements





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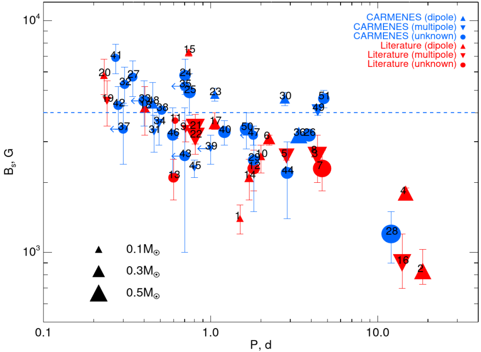
Understanding both (un)polarised measurements



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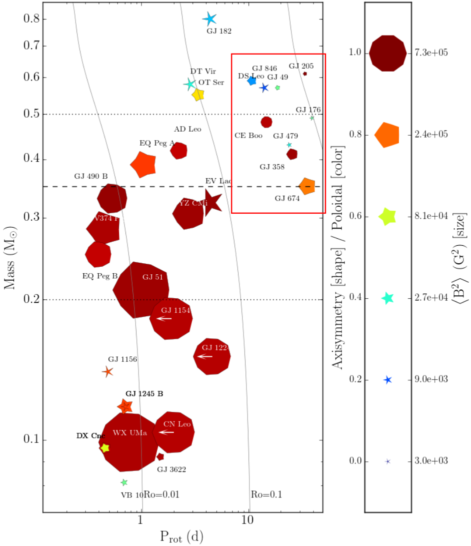
Spectropolarimetric survey: moderate rotators



- dipole-dominated Ro>1
  - similar to Sun-like
- Dipole-dominated 0.1<Ro<1
  - similar to more active FC
- Multipolar+toroidal 0.1<Ro<1
  - bistability?
- *É. Hébrard et al. (2016), Moutou et al. (2018)*

Outline

1. Magnetic activity of low-mass stars in the planet-search context

2. Stellar magnetometry based on spectroscopy/spectropolarimetry

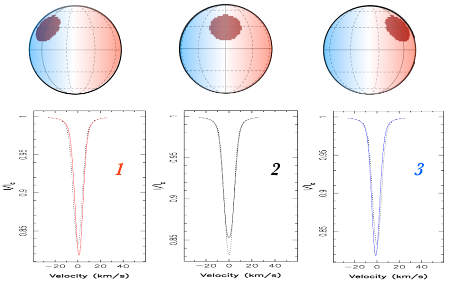
3. Identifying and filtering activity in velocimetric measurements
    - Velocimetry of active stars: multiple effects
    - Chromaticity and other line selection methods
    - Methods based on Doppler Imaging

4. Summary

Velocimetry of active stars: multiple effects

- Cool/magnetic spots and plages
  - spectral line distortion
  - chromatic effect
  - timescales: P_{rot}, spot evolution
- Convective blueshift inhibition
  - attenuation of convective blueshifts
  - depends on line depth
  - timescales: P_{rot}, activity cycle
- Flares
  - enhanced emission for lines w/ chromospheric component
  - timescales: sporadic, hour

→ Lectures by Xavier Bonfils



Effect of a cool spot on the spectral line shape for an equator-on slowly-rotating star

E. Hébrard (2015)

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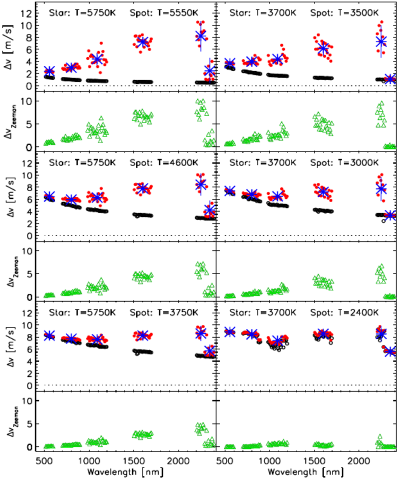

RV jitter chromaticity of a cool magnetic spot
Reiners et al. (2013)

Velocimetry of active stars: multiple effects

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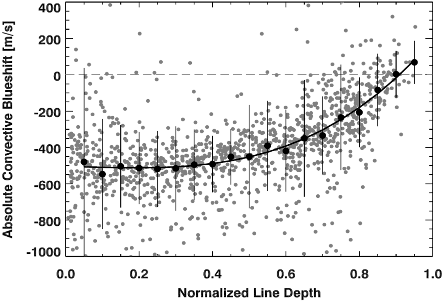

Reiners et al. (2016)

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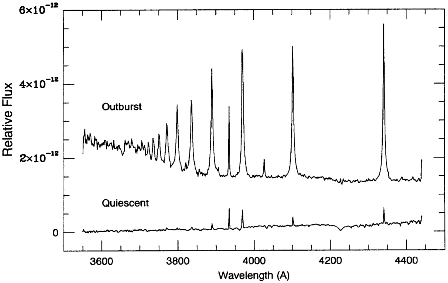
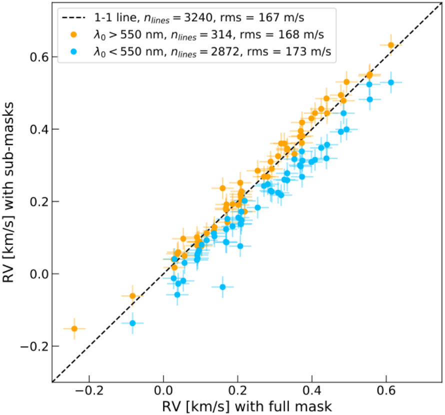


Flaring vs quiescent blue spectrum of AD Leo (M3V) Hawley & Pettersen (1991)

Chromaticity and other line selection methods

- Photometric jitter chromaticity
- Zeeman jitter chromaticity
- Conv. blueshift depth-dependent
- ➥ Can we mitigate activity jitter w/ parametric line selection?
- ➥ Empirical selection based on random draws of line groups provides significant improvement
  - Extension to the nIR ongoing
- Similar approaches
  - *Dumusque et al. (2018)*
  - *Meunier et al. (2017)*



Line selection tests on EV Lac (M3.5V)

ESPaDOnS/NARVAL data set

Bellotti et al. (2021)

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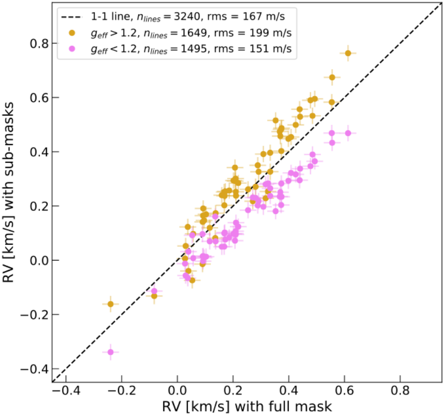

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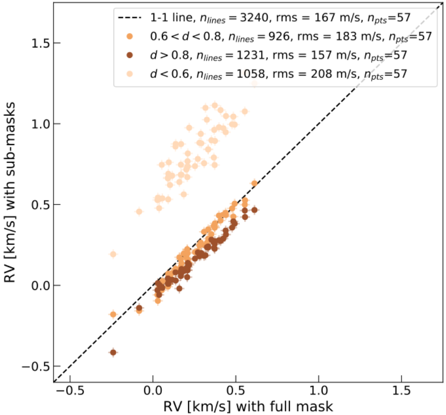

Line selection tests on EV Lac (M3.5V)

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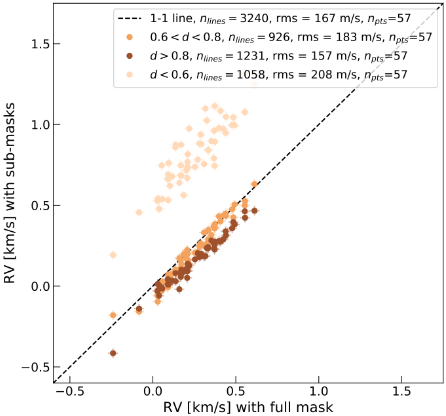

Line selection tests on EV Lac (M3.5V)

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Bellotti et al. (2021)

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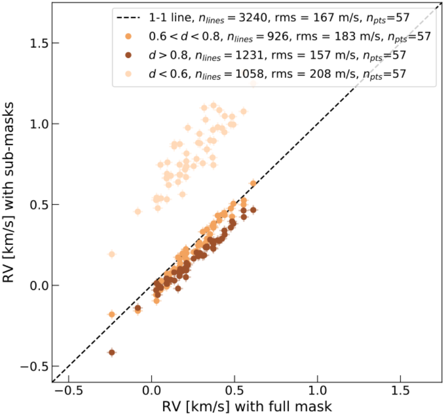


Line selection tests on EV Lac (M3.5V)

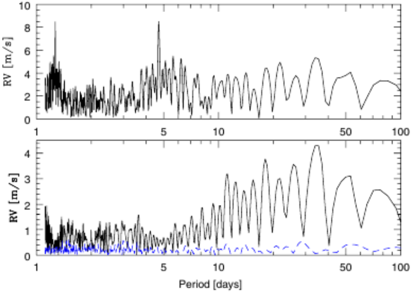
ESPaDOnS/NARVAL data set

Bellotti et al. (2021)

Methods based on Doppler Imaging

- Filtering activity jitter in RV curves

➔ Model and subtract activity signal
- Identify activity/periodicities in RV
- Use additional activity measurements
  - photometric variability
  - chromospheric variability
- directly model line profiles



Boisse et al. (2011)

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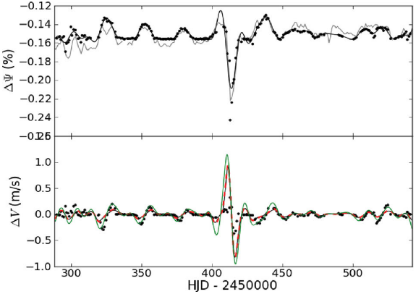
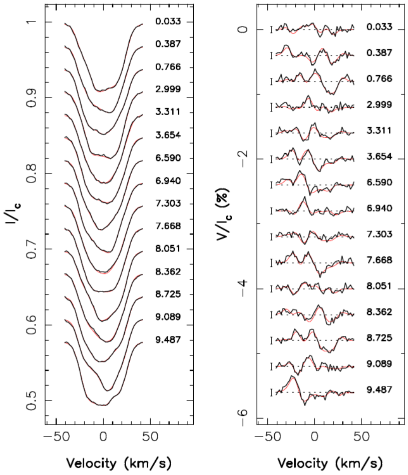


Aigrain et al. (2012)

ZDI + DI on fast rotators



Donati et al. (2015, 2016)

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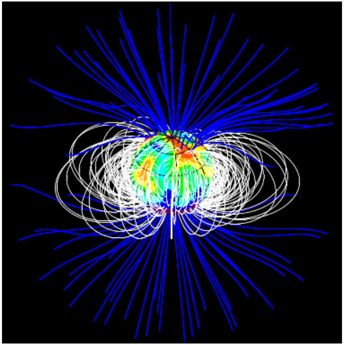
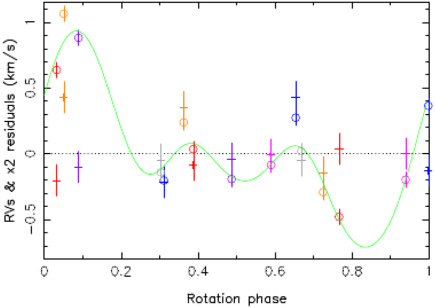
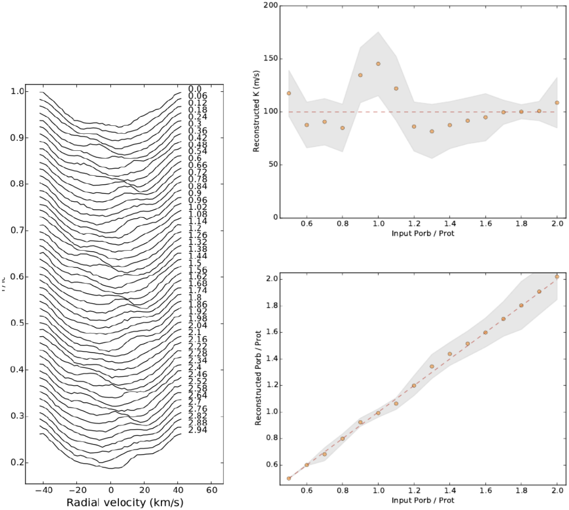




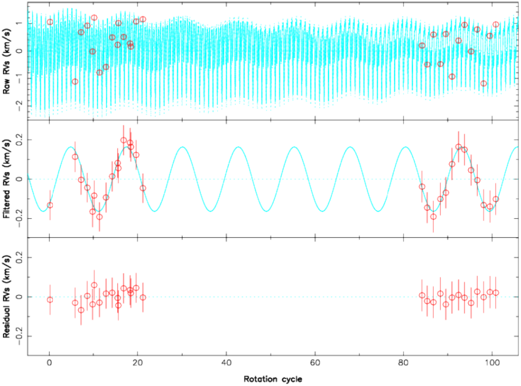
Donati et al. (2015, 2016)

A maximum entropy approach to detect close-in giant planets around active stars



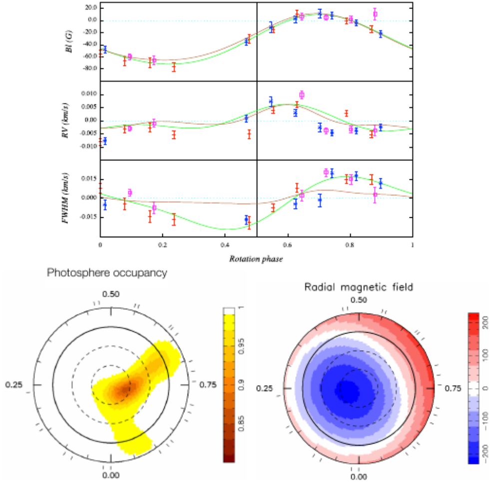
Petit et al. (2015)

Comparison w/ gaussian-process regression



Yu et al. (2017)

ZDI + DI-residuals on slow rotators



É. Hébrard et al. (2016)

Outline

Summary

- Magnetic fields
  - Crucial for stellar physics and for planetary systems
- SPIRou/SLS
  - Huge potential for stellar science
  - Extended to very active / late SpT
  - Long temporal baseline
  - → Build unique magnetic survey
  - → Include molecular lines in RV/magnetometry analysis
- Simultaneous ESPaDOnS/SPIRou and NeoNARVAL/SPIP?