Exploring the magnetic Hertzsprung-Russell diagram with spectropolarimetry

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Outline

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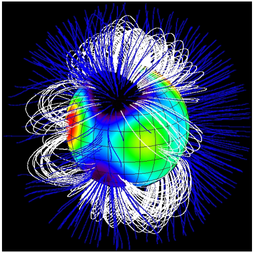
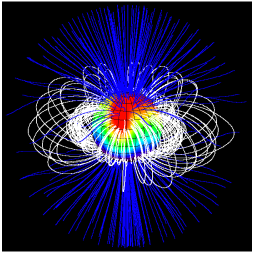
Stellar magnetic fields are ubiquitous

- Measured across H-R diagram
  - All masses
  - All evolutionary stages
- Wide variety of properties
  - Intensity/geometry/variability



τ *Sco, 15* $\mathrm{M}_\odot$ *Donati et al.(2006a)*

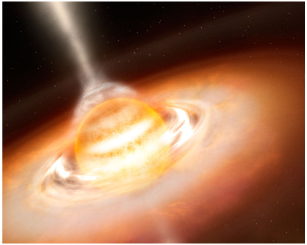


V374 Peg, 0.3 $\mathrm{M}_\odot$ *Donati et al.(2006b)*

Magnetic fields play a key role (1/2)

- Activity
  - Observable across electromagnetic spectrum
  - Impact of **B** on all atmospheric layers
- Formation
  - Phase where **B** has strongest impact
    - Jets launching
    - Magnetospheric accretion

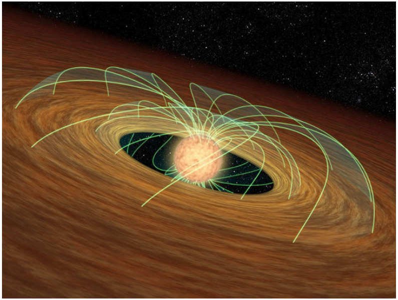
Credit: F. Espenak



Credit: ESO

Magnetic fields play a key role (2/2)

- Rotation
    - During formation
        - star–disc interaction
    - Post T Tauri
        - Magnetized winds
        - Much more efficient than non-magnetized *Schatzman (1962)*



Credit: NASA / JPL-Caltech / R. Hurt

- Star–planet interaction
    - Stellar wind
    - Coronal mass ejection

➔ Planetary magnetosphere

➔ Planetary atmosphere

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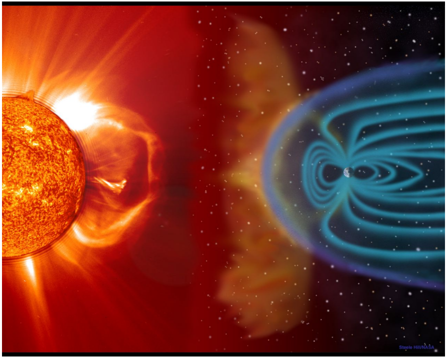
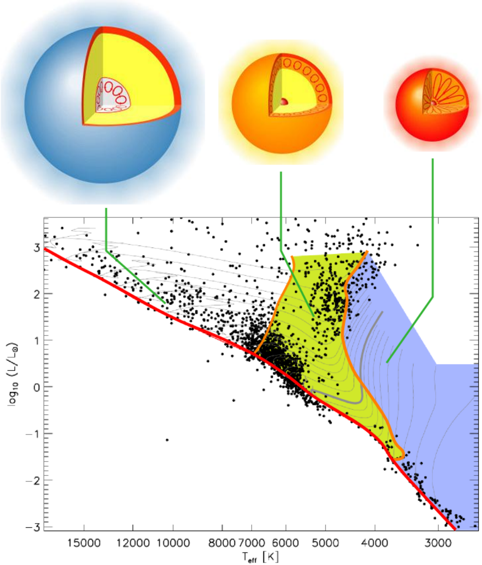


Credit: NASA / ESA

The origin of stellar magnetic fields (1/2)



Adapted from Reiners (2008)
star sketches credit J. Bennett et al.

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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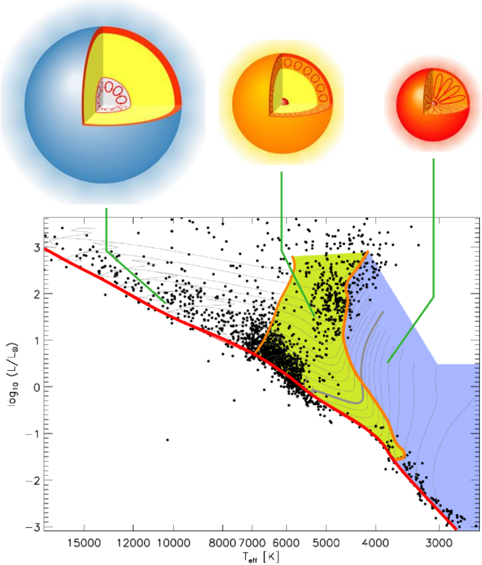

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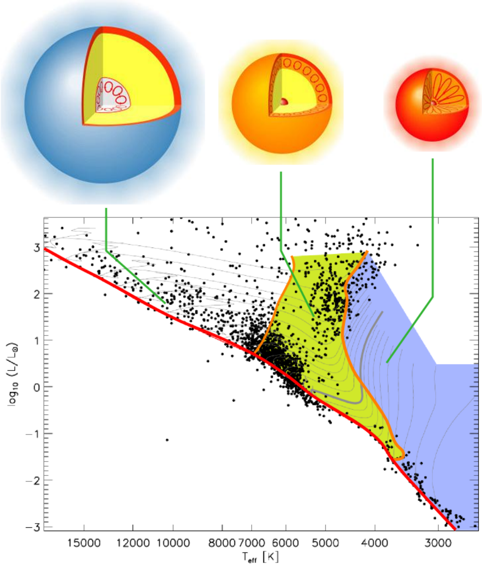

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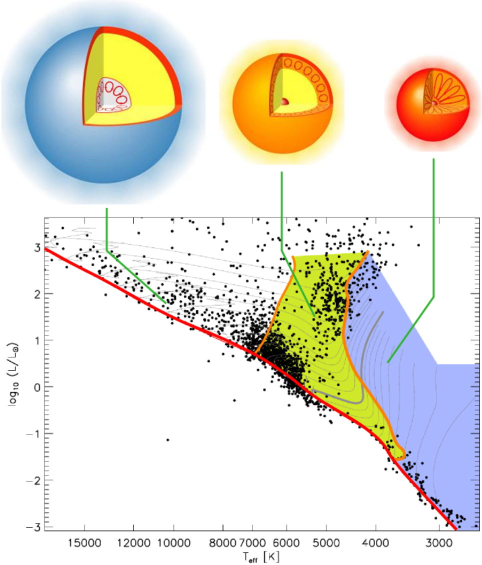

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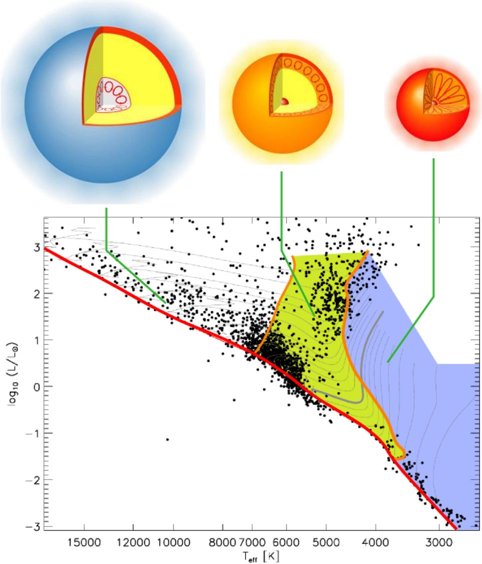

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Relation
⋆ parameters
↔ **B** properties?

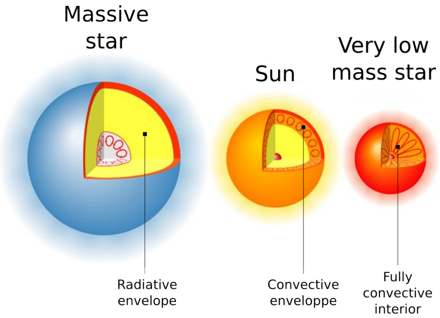
The origin of stellar magnetic fields (2/2)

Dynamo action

- Amplifies and sustains **B**
  - Conversion E_{kin} ➔ E_{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



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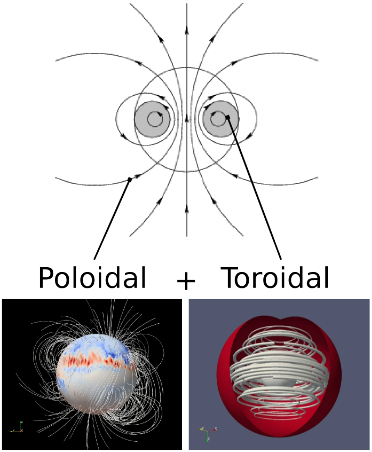

Adapted from figures by
J. Braithwaite and T. Gastine

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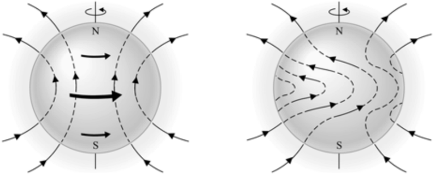

Ω-effect

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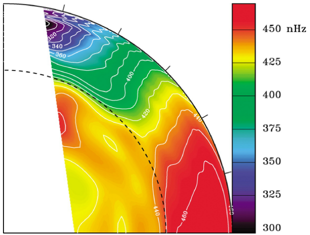
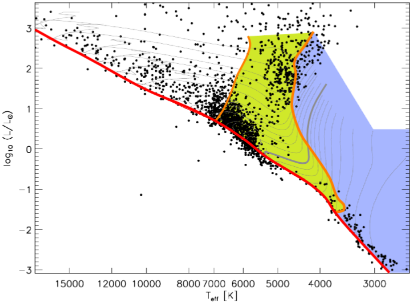


Internal angular velocity
Shu et al., 2006; from SOHO–MDI data



Outline

1 Magnetic fields: a crucial ingredient of stellar physics

2 Detection and characterization of stellar magnetic fields

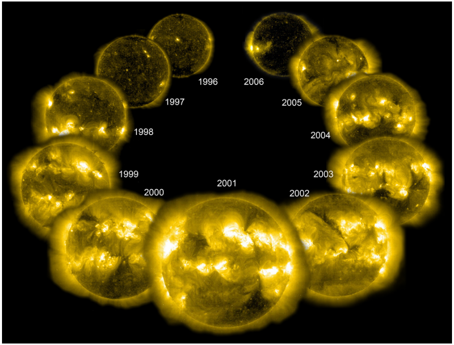
- Indirect measurements: stellar activity
- Direct measurements of photospheric magnetic fields
- Longitudinal/transverse field measurements
- High-resolution spectropolarimetry
- Zeeman-Doppler Imaging

3 A (likely biased) selection of results

4 Summary

Indirect measurements: stellar activity

- Magnetic field
  - Photospheric features
    - Visible photometry
    - HR spectroscopy
  - Chromosphere
    - UV, vis. emission lines
  - Corona
    - X-ray, radio
- Spatial + temporal correlations
- Usual proxies for stellar **B**
  - CaII H&K emission
  - Coronal X-ray emission



SOHO, EUV

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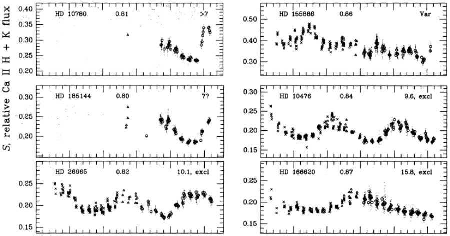
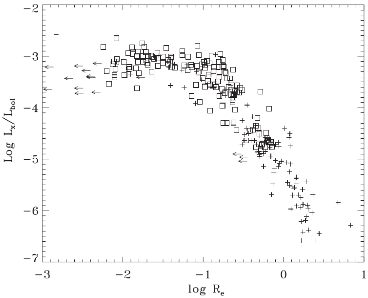


Baliunas et al. (1995)



Pizzolato et al. (2003)

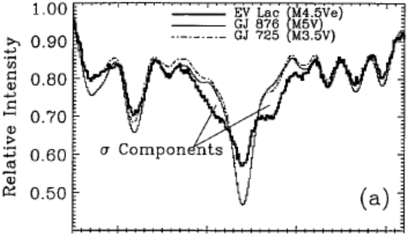
Direct measurements of photospheric fields

- Direct $\mathbf{B}_{photosph}$ measurements
  ➥ Zeeman effect

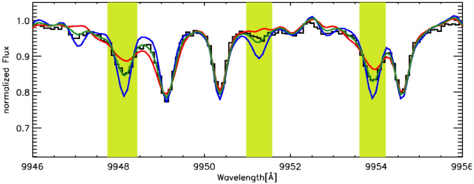
- Measure "magnetic flux": $\langle\|\mathbf{B}\|\rangle$
  - Atomic lines
  - Molecular lines

- Multi-component models
- Weakly sensitive to **B** orientation
  - Partly degenerate

- Low to moderate $v \sin i$



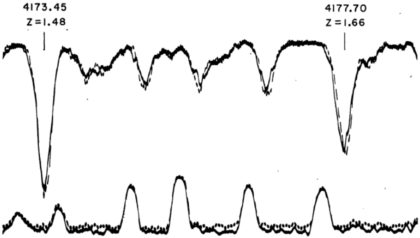
Johns-Krull & Valenti (1996)



GJ 729, FeH Wing-Ford band
Reiners & Basri (2006)

Longitudinal/transverse field measurements

- B_ℓ: longitudinal field
- Zeeman-induced circ. pol.
  - Shift RHCP/LHCP spectra
  - $B_\ell \propto \Delta\lambda_B$
- 1^{st} 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*



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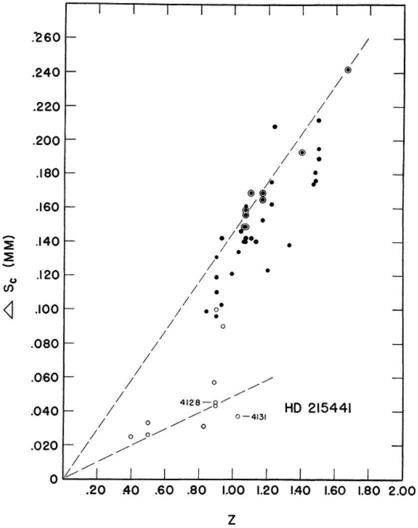

Babcock (1960)

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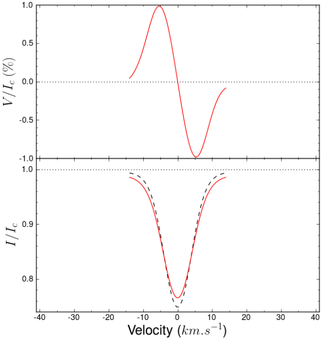

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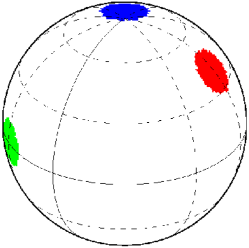
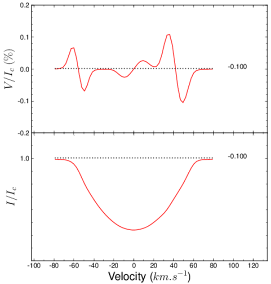
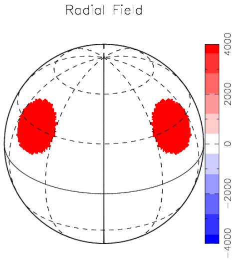
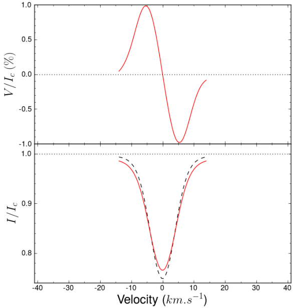




High-resolution spectropolarimetry

- 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 $\sim 10^3 - 10^4$
- Mutli-line extraction
  - Self-similar signal in all lines
  - Least-Square Deconvolution
    Donati et al. (1997)
  - Behaves as real line up to a few kG
    Kochukhov et al. (2010)
- Efficient instruments:
  CFHT/ESPaDOnS, TBL/NARVAL, LaSilla3.6m/HARPSpol





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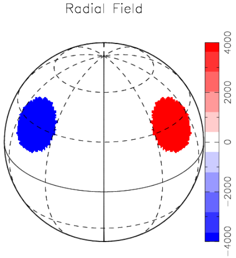

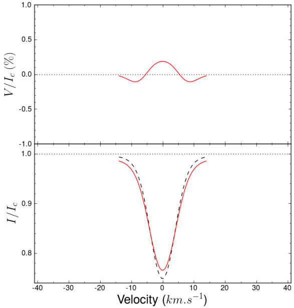

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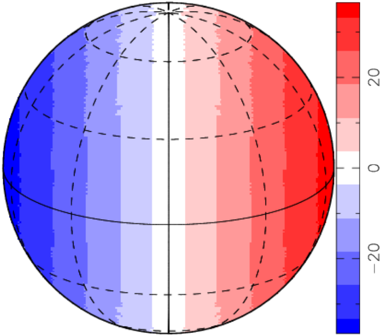

Equal RV stripes

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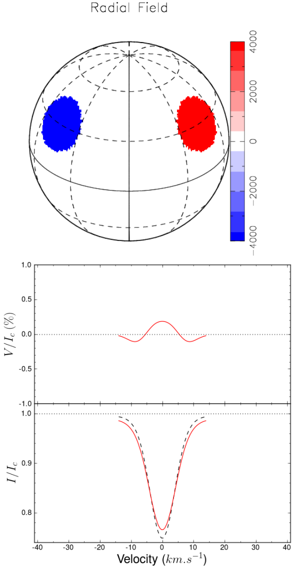

$v \sin i = 1\ km\, s^{-1}$

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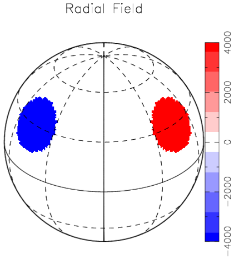

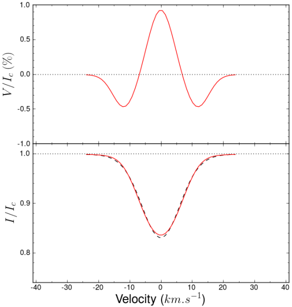

$v \sin i = 10\ km\, s^{-1}$

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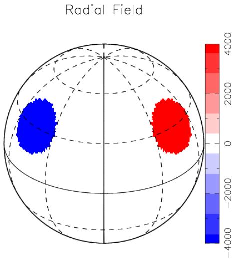

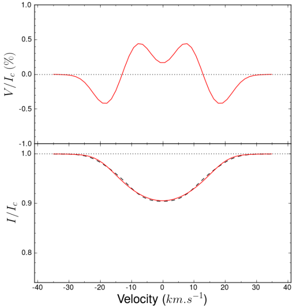

$v \sin i = 20\ km\, s^{-1}$

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
  - Diagnostic

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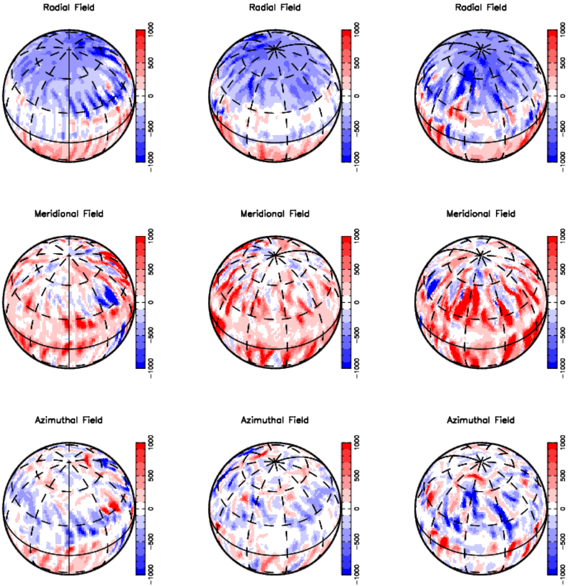
ZDI: performances and limitations (1/2)

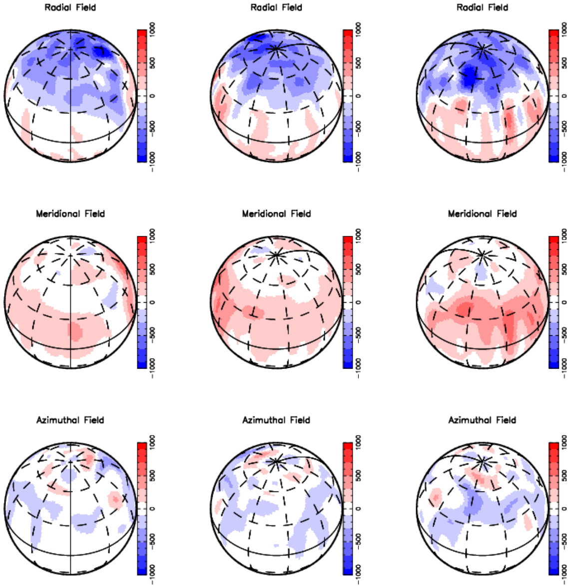


Input numerical simulation

Credit: T. Gastine

MagIC code

ZDI: performances and limitations (1/2)



ZDI reconstruction

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

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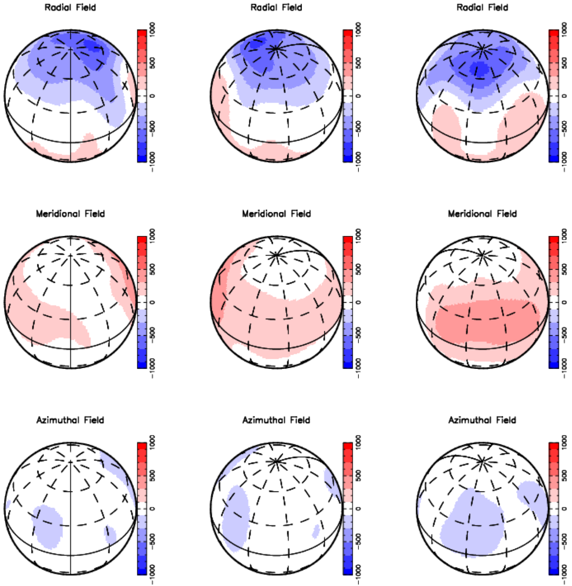

ZDI reconstruction

$v \sin i$=10 km/s

10 spectra

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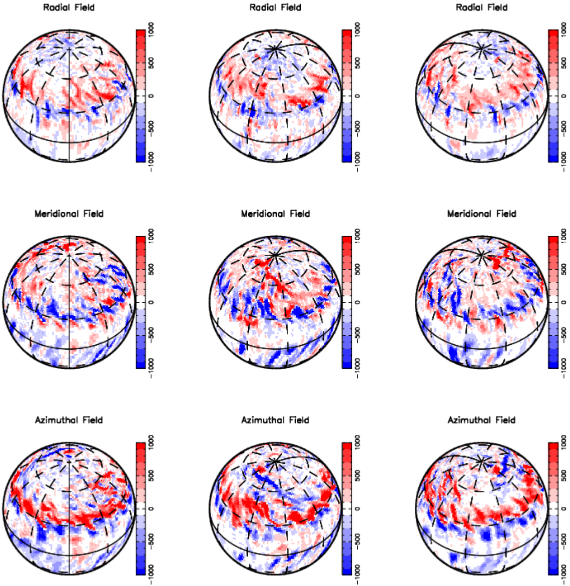

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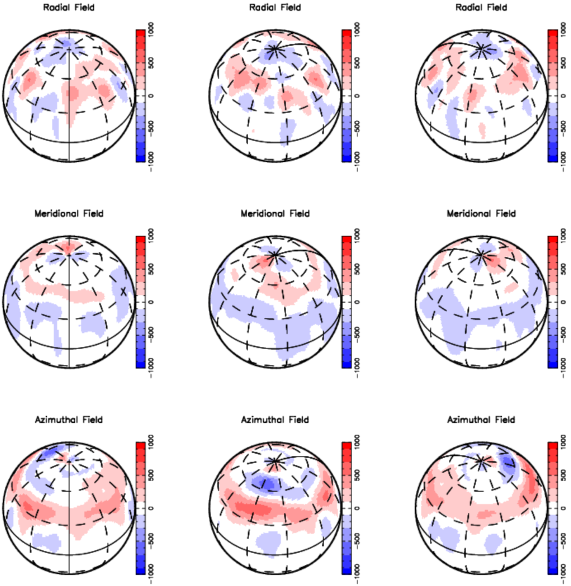

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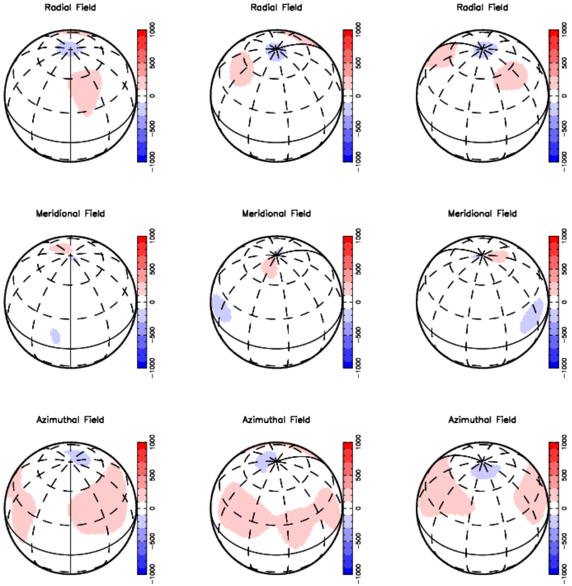

ZDI reconstruction

v sin *i*=*10 km/s*

10 spectra

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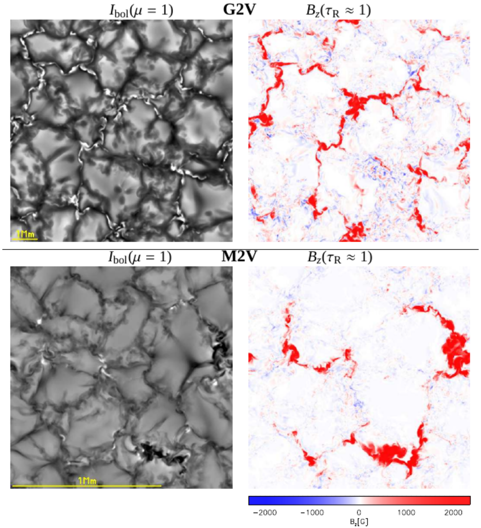
ℓ_{max}=*10*

ZDI: performances and limitations (2/2)

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



Beeck et al. (2011)

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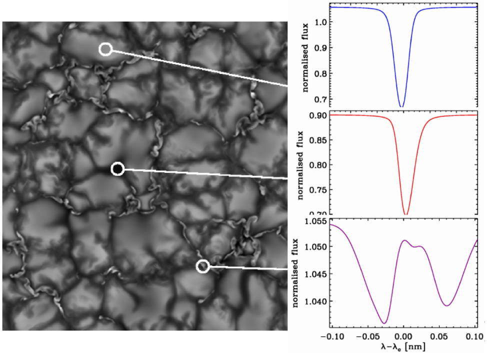

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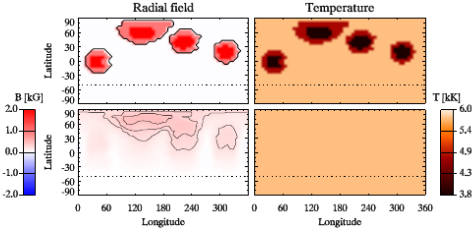


Rosen &Kochukhov (2012)

Outline

1 Magnetic fields: a crucial ingredient of stellar physics

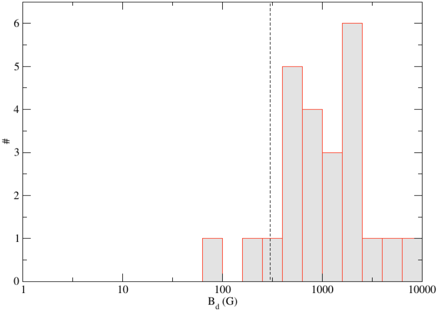
2 Detection and characterization of stellar magnetic fields

3 A (likely biased) selection of results
- Chemically peculiar stars
- Fully-convective stars
- Young low-mass stars
- And much more...

4 Summary

Chemically peculiar Ap/Bp stars

- Detailed studies
  - **B** can be more complex
  - *Kochukhov & Wade (2010)*
- *Aurière et al. (2007)*
  - 100 % detection rate on Ap stars
  - $B_{dip} > 300$ G
  - Consistent w/ fossil scenario



Aurière et al. (2007)

Fully-convective stars

Dynamo action in FC stars

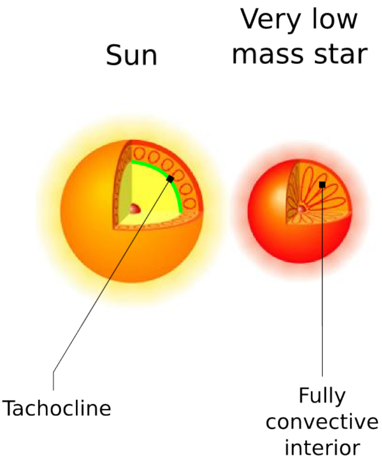
- Solar dynamo
  - Tachocline: crucial role?
- Fully convective stars
  - ~~Tachocline → solar dynamo~~

➥ observable effects?

- Activity
- **B** from Zeeman broadening

➥ No change at the fully-convective boundary

- 1st spectropolarimetric survey
  - Sharp transition ~ 0.5 $M_\odot$
  - Multipolar → Dipolar **B**
  - Significant $d\Omega$ → ~ solid-body



Internal structure of cool main sequence stars

Fully-convective stars

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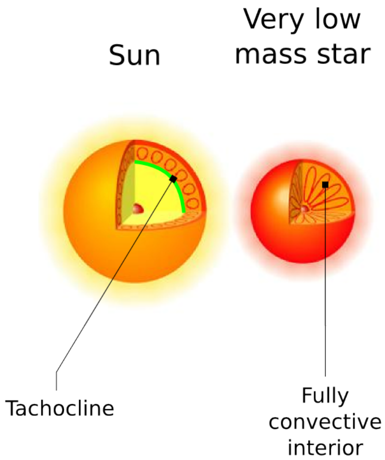

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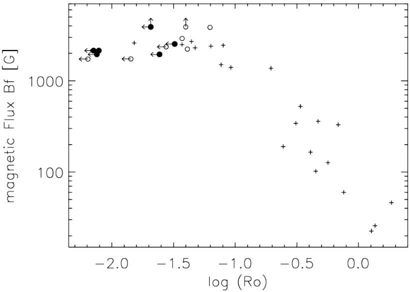

Rotation-total magnetic field relation

Reiners, Basri & Browning et al. (2009)

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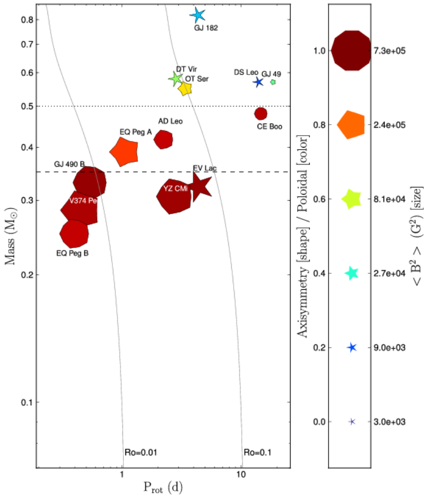

Donati et al. (2006, 2008), Morin et al. (2008a,b), Phan-Bao et al. (2009)

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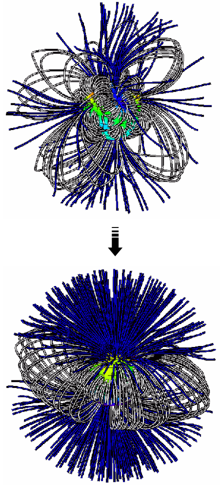

Coronal extrapolations by M. Jardine from surface magnetic fields reconstructed by Donati et al. (2008), Morin et al. (2008)

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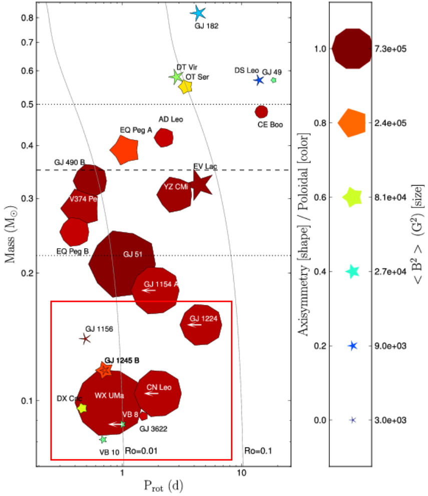
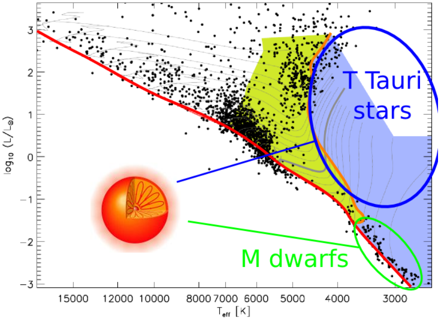


Morin et al. (2010,2011)
Gastine et al. (2013)

Young low-mass stars

- T Tauri stars
  - age 1 – 10 Myr
  - Fossil or dynamo field?
  - Field geometry?
- MaPP LP CFHT
  - Evolution on ~ 1 yr
    Dynamo-generated
  - Variety properties
    Position in HRD
  - Impulse new models



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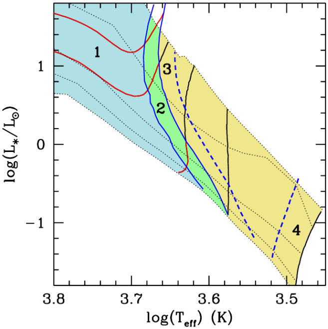

Gregory et al. (2012)

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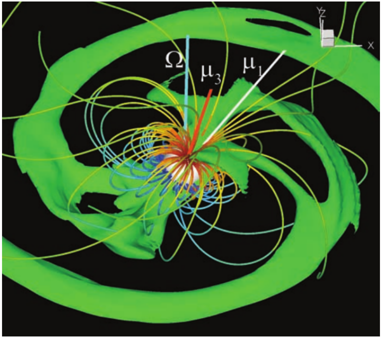
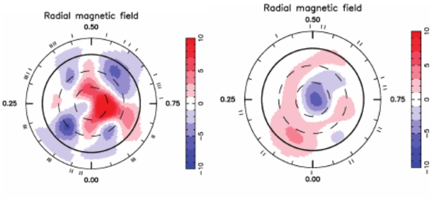


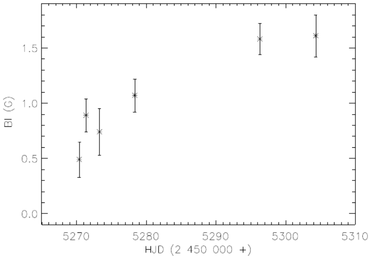
Romanova et al. (2011)

And much more...

- Solar twins
- Planet-host stars
- Intermediate mass stars
- Massive stars
- Evolved stars



Farès et al. (2009)



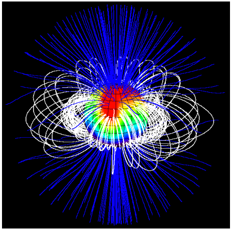
Aurière et al. (2010)

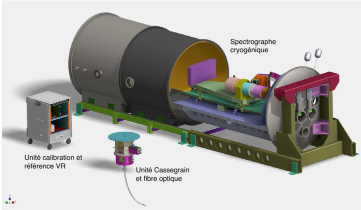
Outline

1. Magnetic fields: a crucial ingredient of stellar physics
2. Detection and characterization of stellar magnetic fields
3. A (likely biased) selection of results
4. **Summary**

Summary

- Magnetic fields
  - Crucial for stellar physics
  - Origin? Properties?
- Spectropolarimetry
  - Very high potential
  - Limitations to overcome
  - Important developments
- Important results
  - Across HRD
  - Detections
  - Physics
- Future
  - nIR spectropolarimetry
  - CFHT/SPIRou
  - CRIRES+





Bibliography

- Stellar magnetism
  - *Stellar Magnetism, Summer School on Stellar Physics XVII*
    Eds. C. Neiner & J.-P. Zahn, 2009, EAS Publication Series, Vol. 39
  - *Magnetic fields of non-degenerate stars*
    J.-F Donati & J. Landstreet, 2009, ARAA, Vol. 47

- Magnetism of cool stars
  - *Observations of Cool-Star Magnetic Fields*
    A. Reiners, 2012, Living Reviews in Solar Physics, Vol. 9
  - *Magnetic Fields from Low-Mass Stars to Brown Dwarfs*
    J. Morin, Eds. C. Reylé, C. Charbonnel & M. Schultheis,
    2012, EAS Publication Series, Vol. 57

- Dynamo theory
  - *The Magnetic Universe*
    G. Rüdiger & R. Hollerbach, 2004, Wiley-VCH
  - *Mathematical aspects of natural dynamos*
    Eds. E. Dormy & A. Soward, 2007, CRC Press/Taylor & Francis