Exploring the magnetic Hertzsprung-Russell diagram with spectropolarimetry: Cool stars

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LUPM LABORATOIRE MONTPELLIER UNIVERS & PARTICULES

UNIVERSITÉ MONTPELLIER 2 SCIENCES ET TECHNIQUES

Outline

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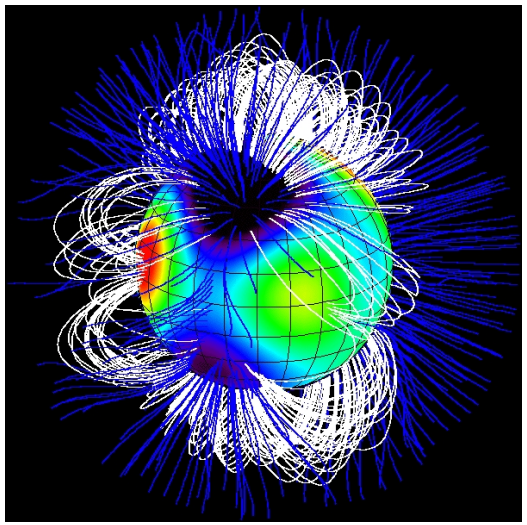
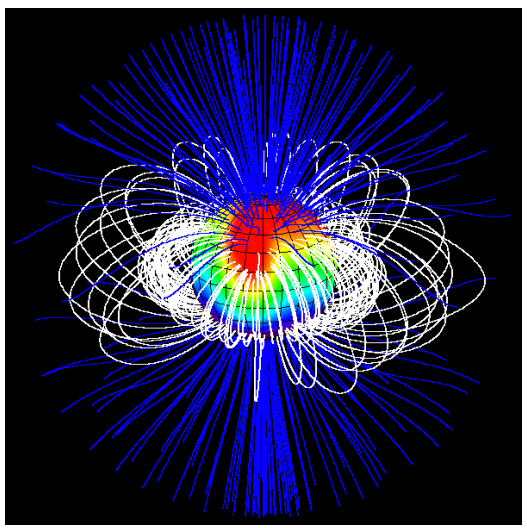
Stellar magnetic fields are ubiquitous

- 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)*



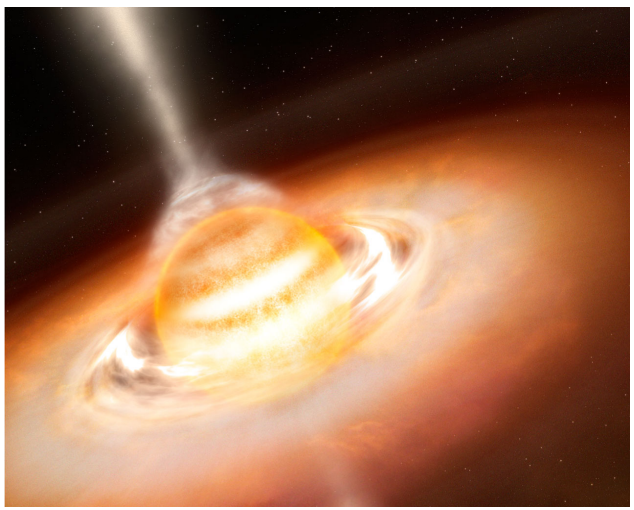
V374 Peg, 0.3 $\mathrm{M}_{\odot}$ *Donati et al.(2006b)*

Magnetic fields play a key role (1/2)

- Activity
  - Observable across electromagnetic spectrum
  - Impact of **B** on all atmospheric layers

Credit: F. Espenak

- Formation
  - Phase where **B** has strongest impact
    - Jets launching
    - Magnetospheric accretion



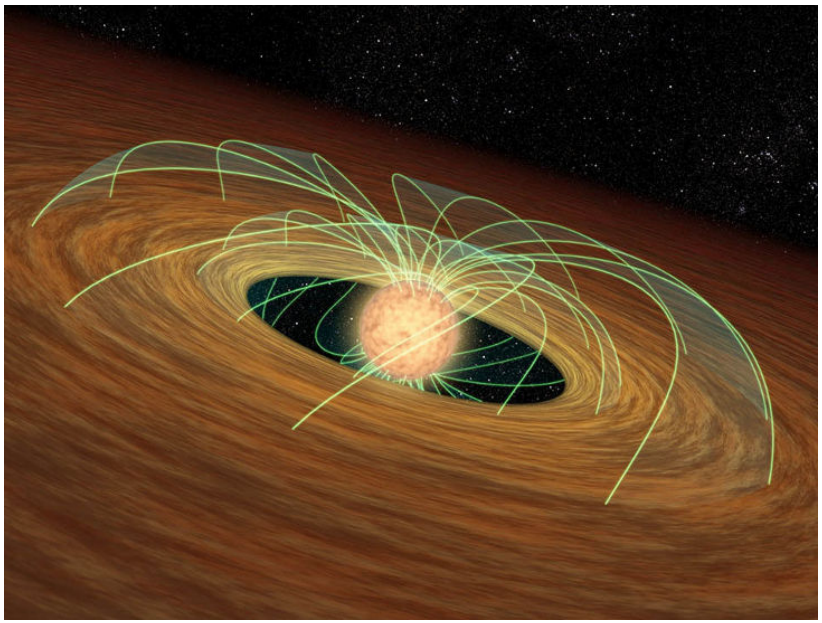
Credit: ESO

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

➔ Planetary magnetosphere

➔ Planetary atmosphere



Credit: NASA / JPL-Caltech / R. Hurt

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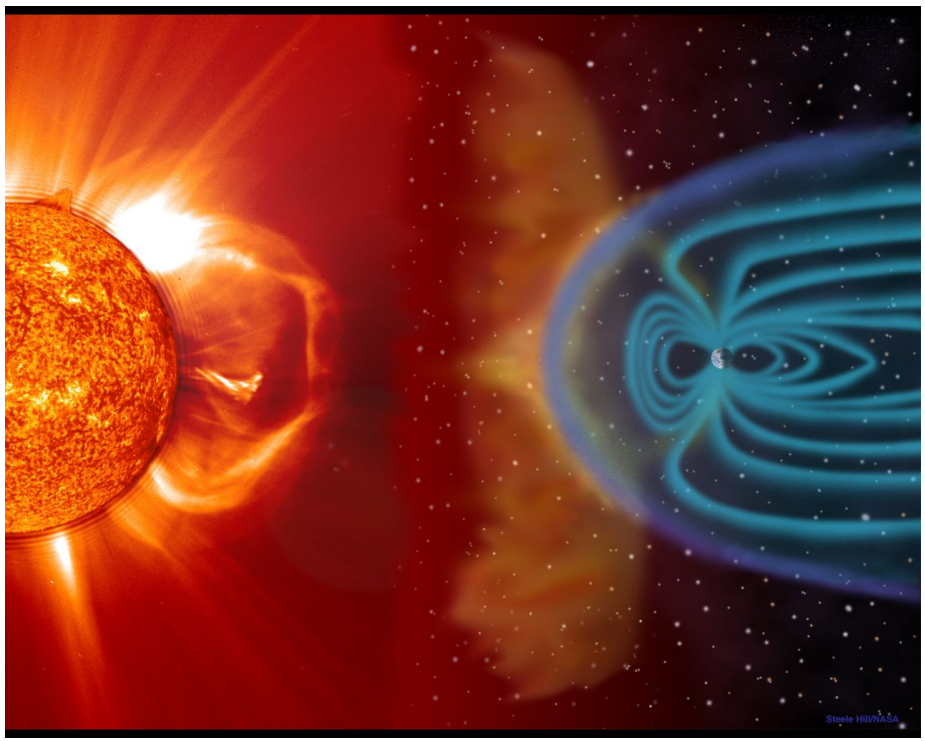
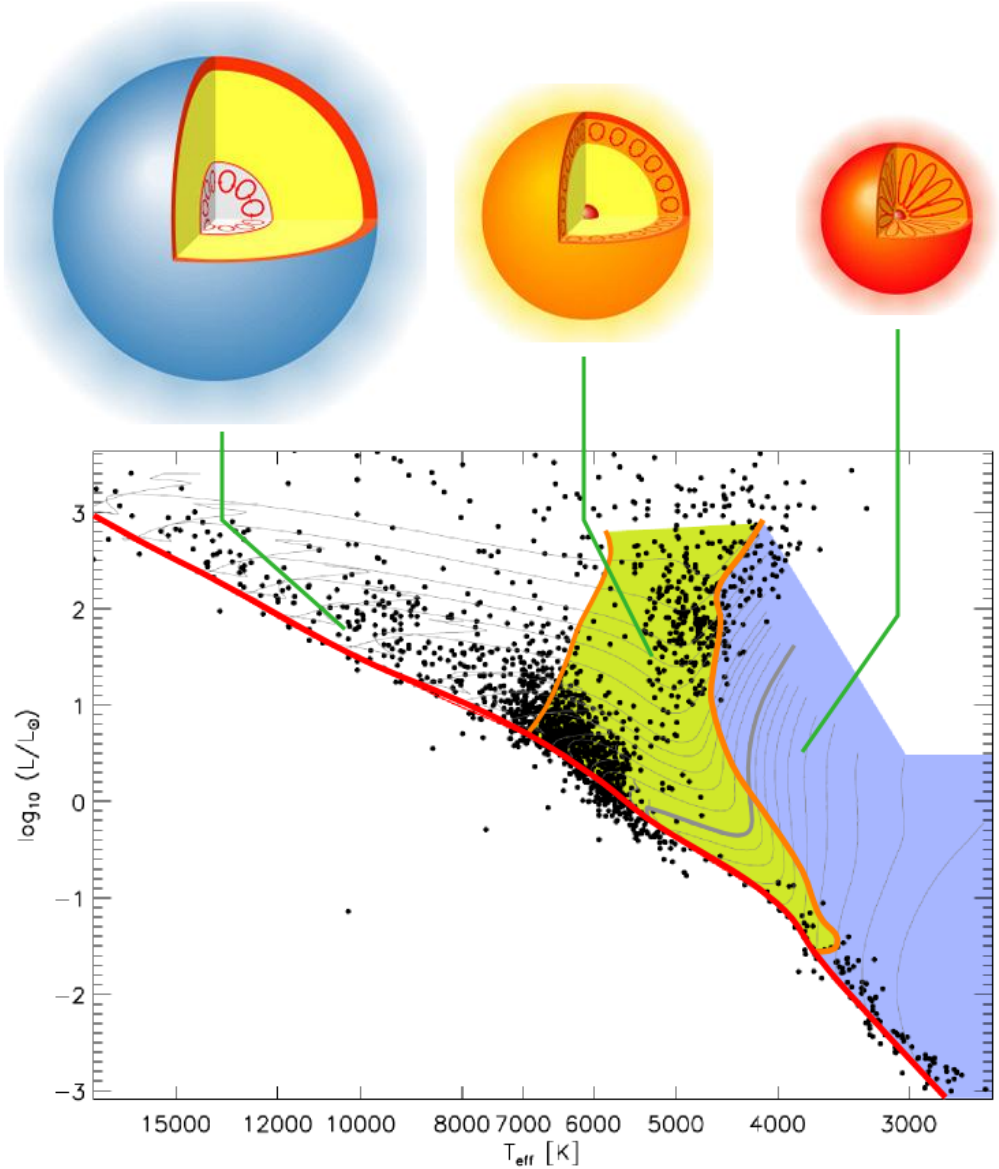


Credit: NASA / ESA

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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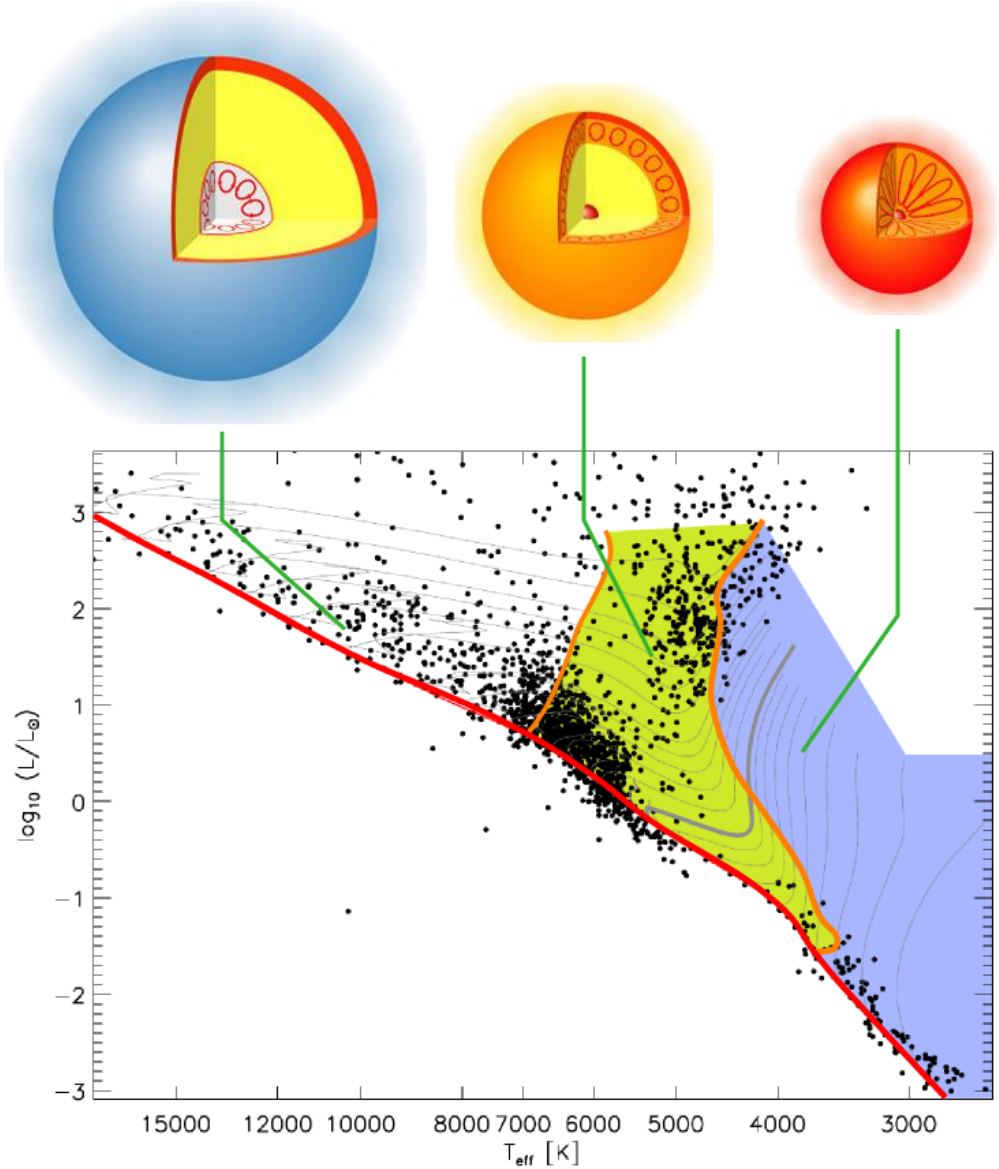

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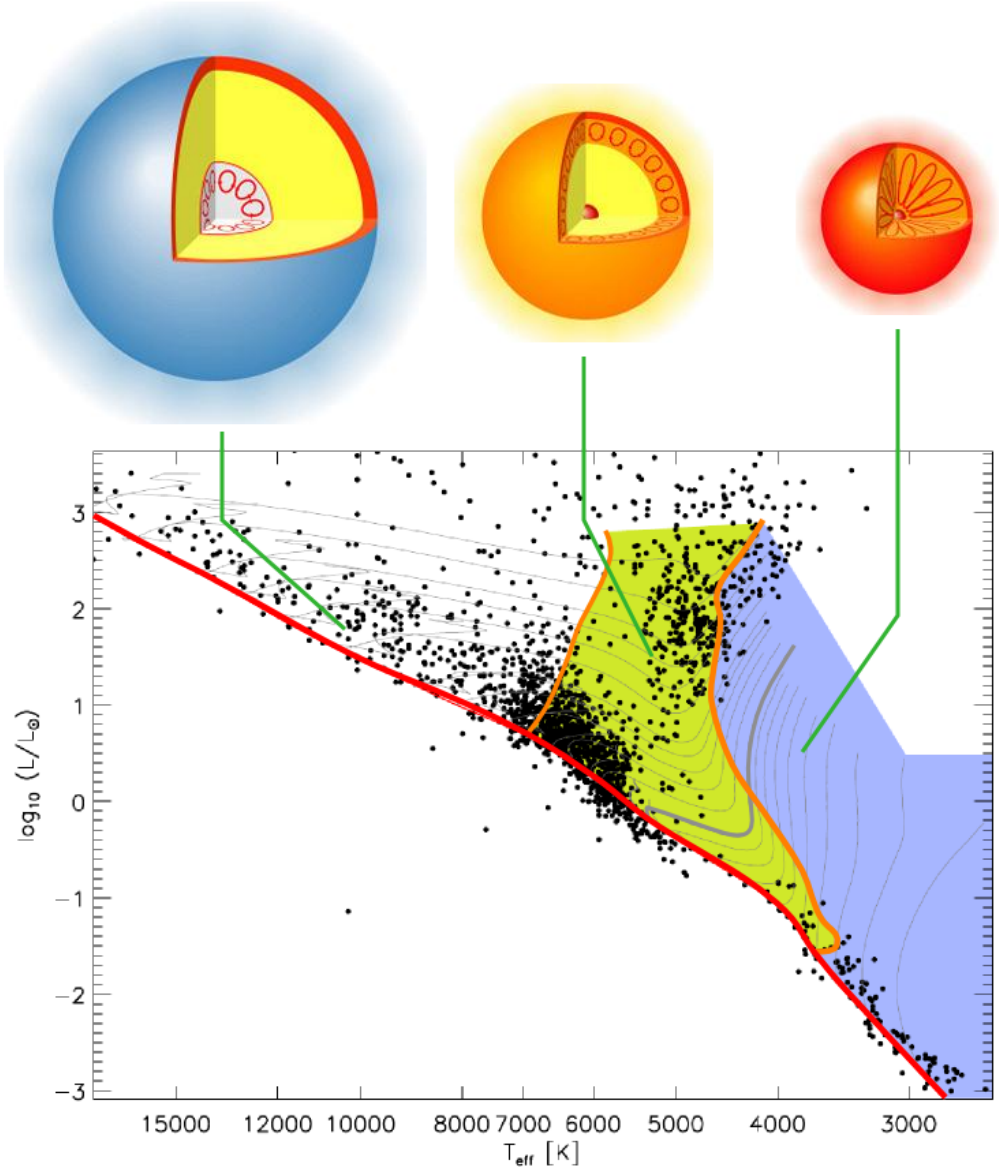

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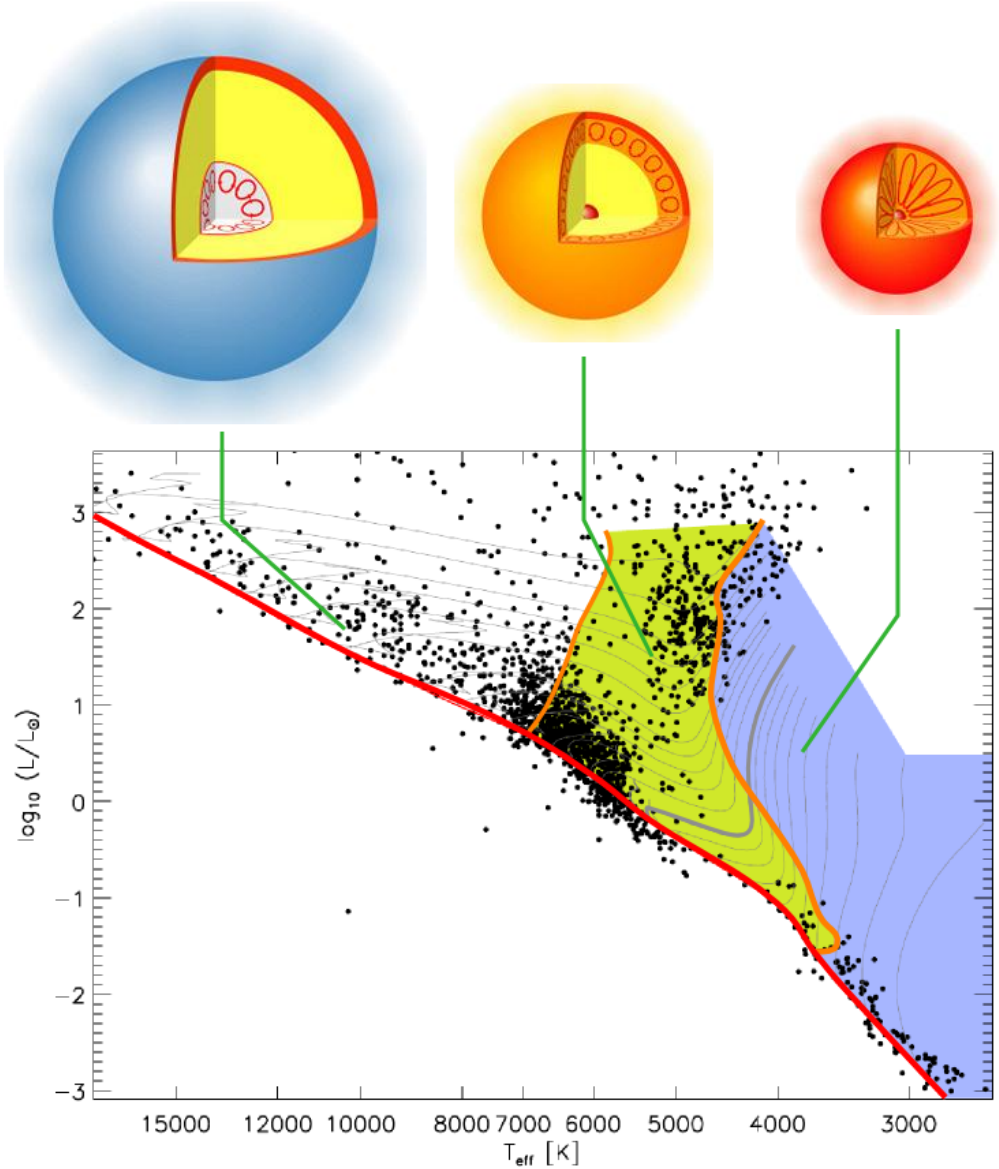

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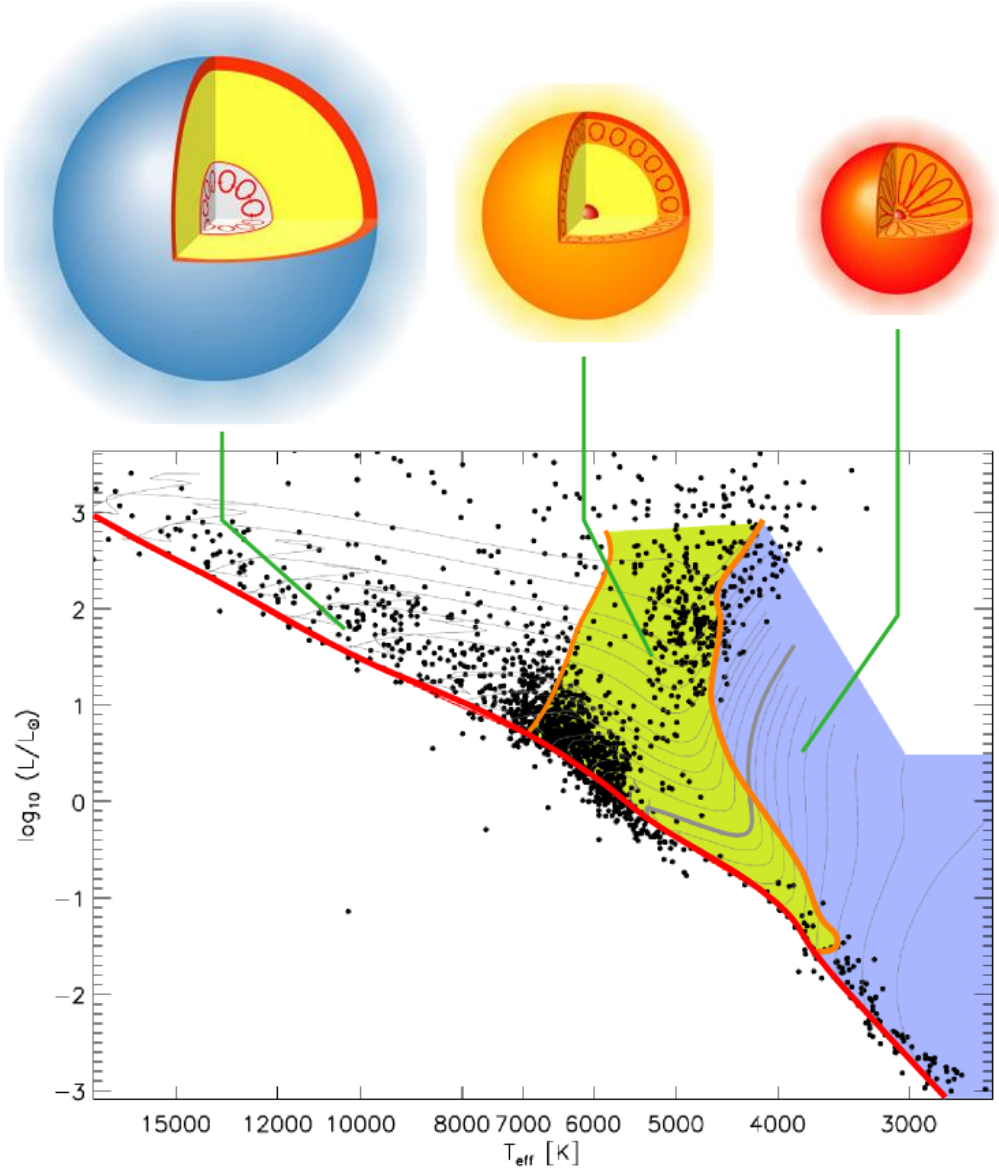

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Relation
$\star$ parameters
$\leftrightarrow$ **B** properties?

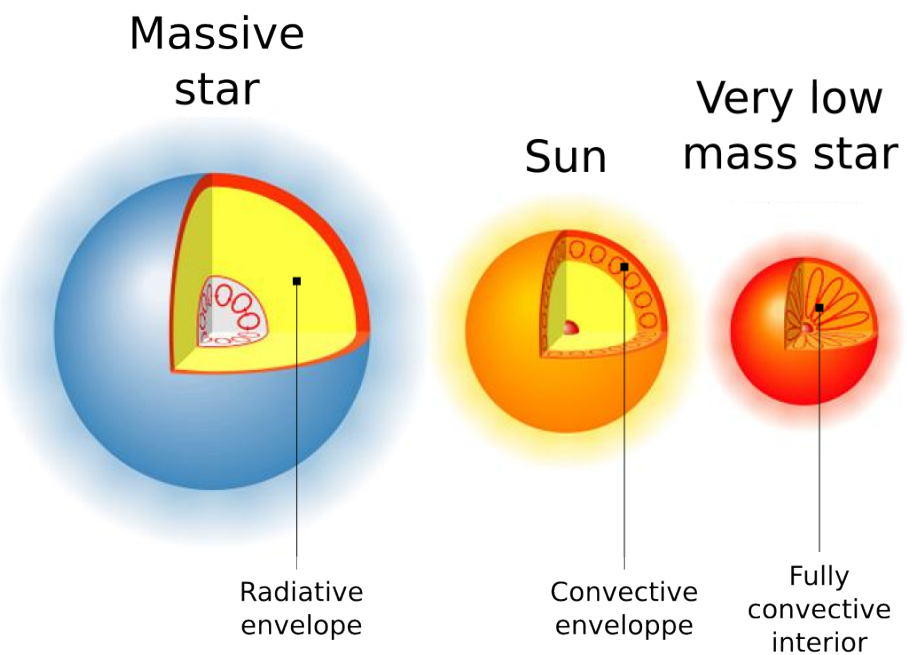
The origin of stellar magnetic fields (2/2)

Dynamo action

- Amplifies and sustains **B**
  - Conversion $E_{\rm kin}$ ➔ $E_{\rm mag}$
  - 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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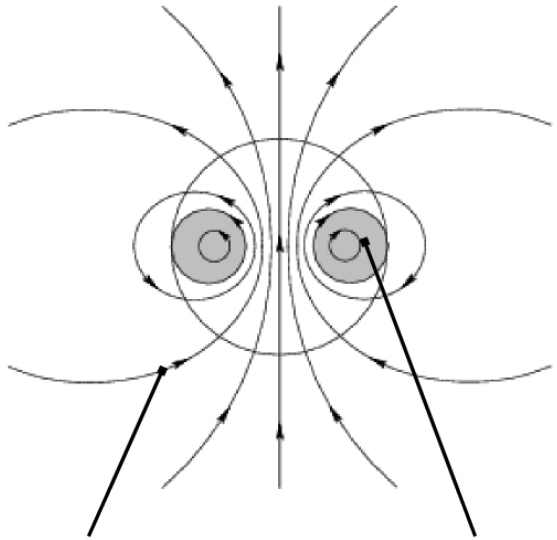
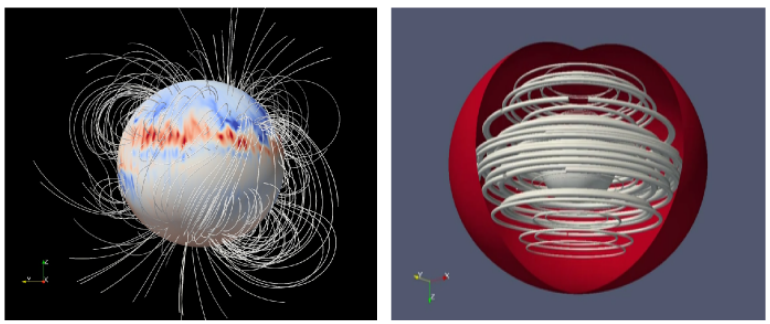


Poloidal + Toroidal



Adapted from figures by J. Braithwaite and T. Gastine

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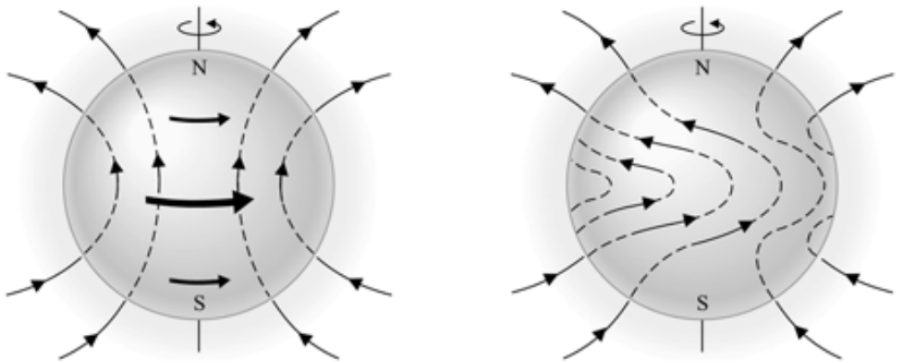

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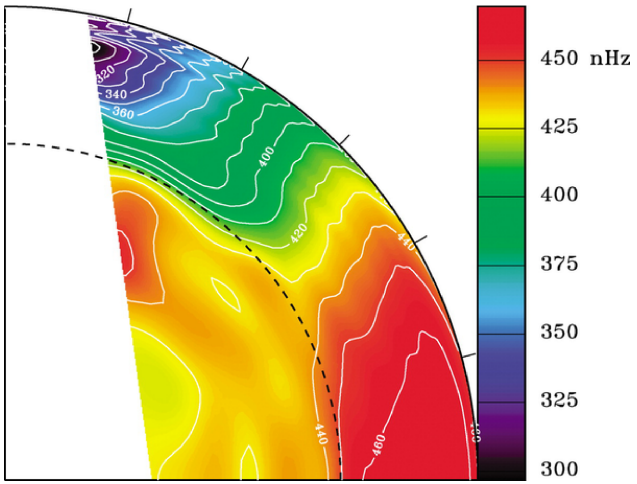
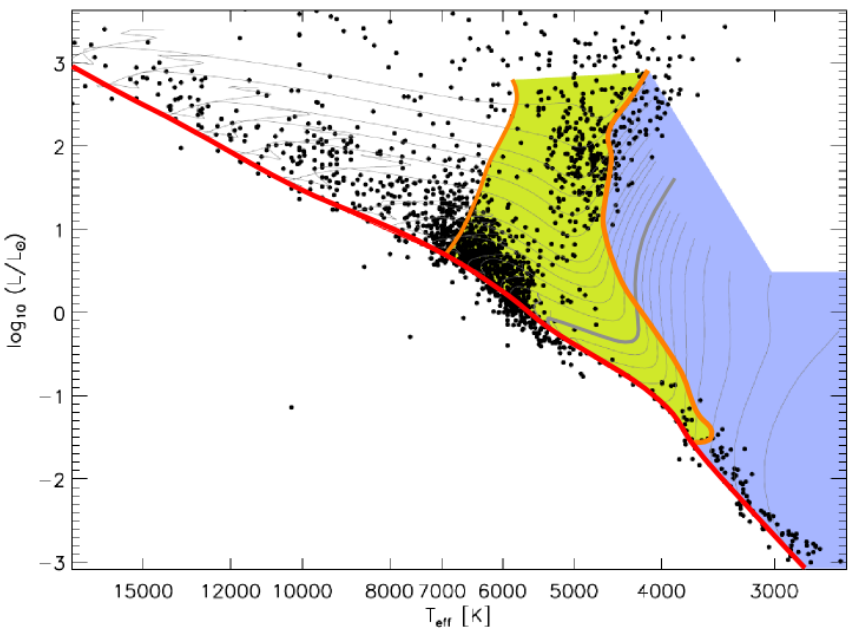


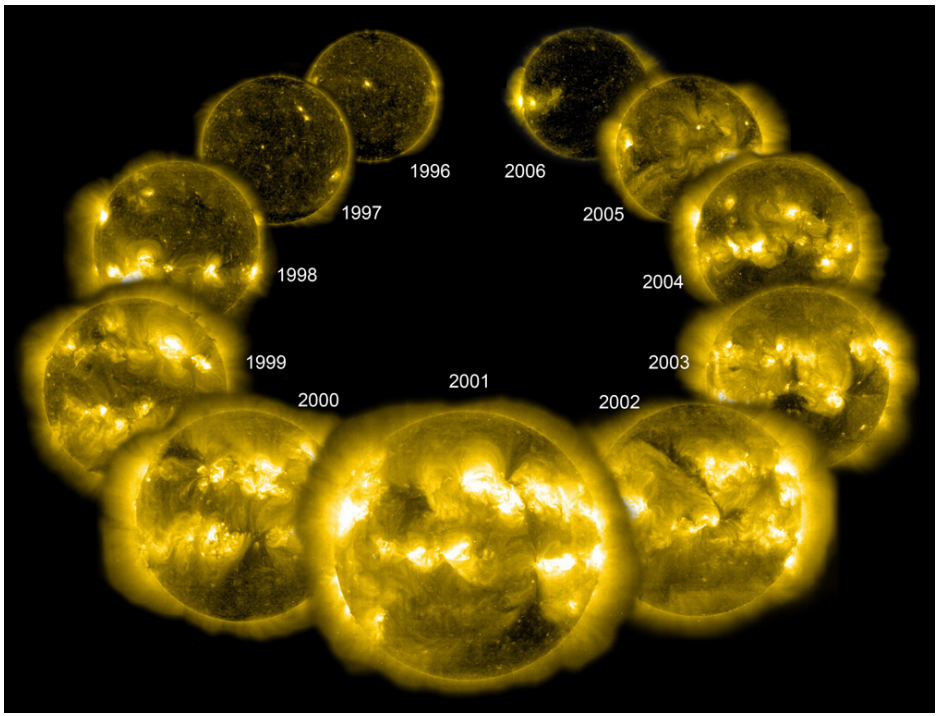
Internal angular velocity
Shu et al., 2006; from SOHO–MDI data



Outline

Indirect measurements: stellar activity

- Interaction **B** $\leftrightarrow$ atmosphere
  - Spots, plages
    - Vis. photometry/spectroscopy
  - Chromosphere, TR, corona
    - Radio ➔ X-rays
- Usual proxies for stellar **B**
  - CaII H&K emission
  - Coronal X-ray emission
- $\exists$ cyclic variations
- Rotation–activity relation
  - Growth + saturation
  - Rossby number : $Ro = \dfrac{P_{\rm rot}}{\tau_c}$



SOHO, EUV

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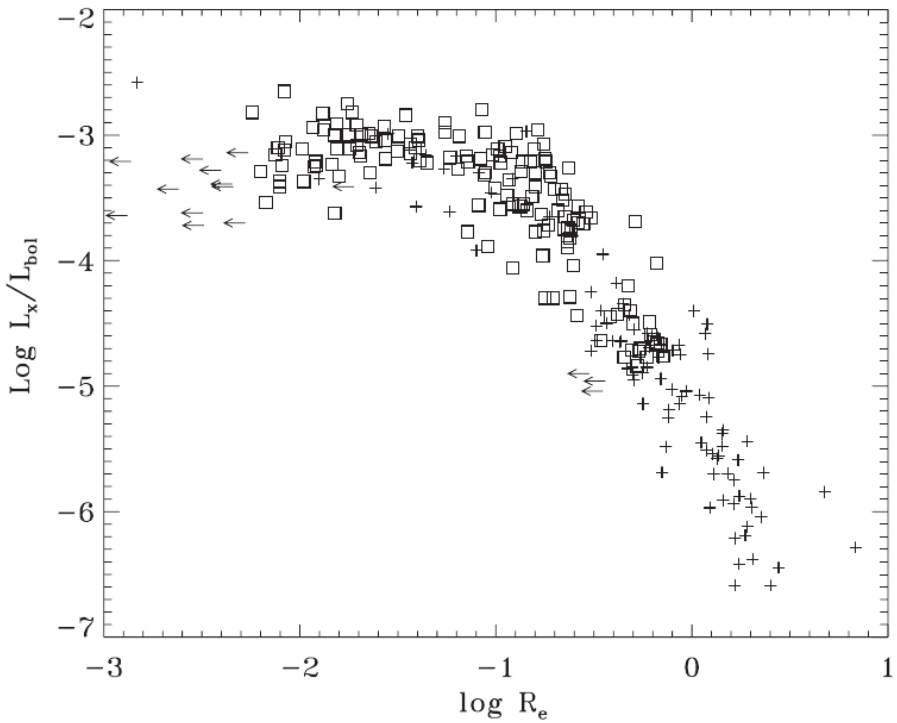


Pizzolato et al. (2003)

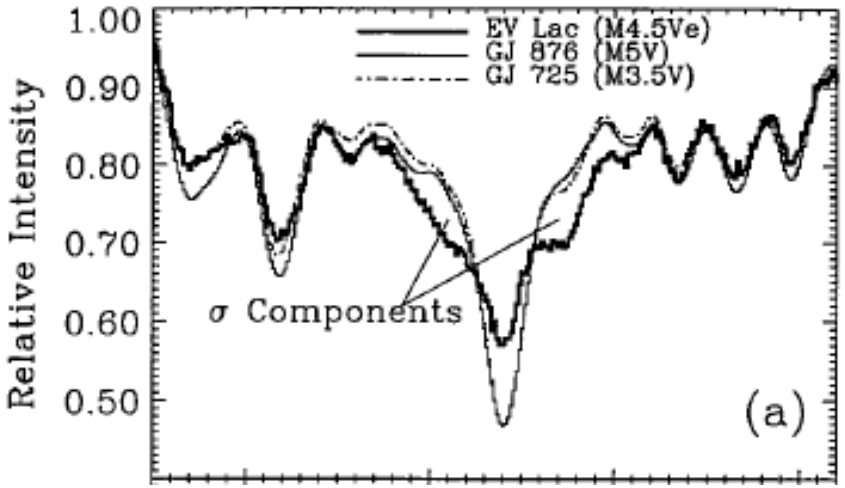
Direct measurements of **B**: unpolarised light

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

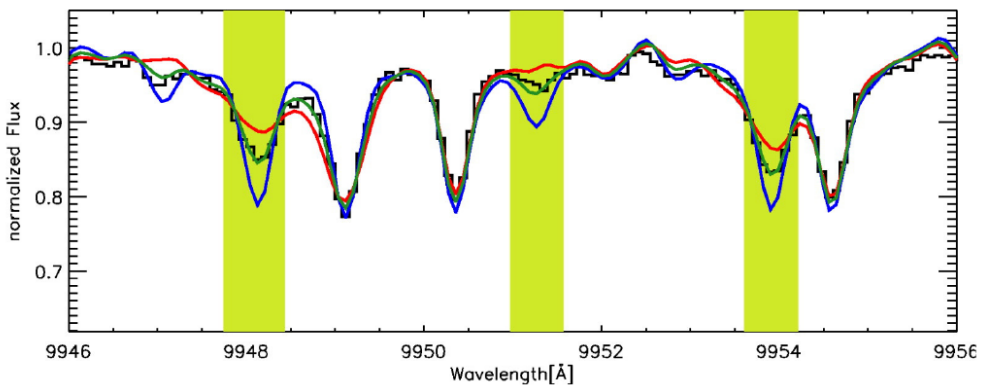
- Measure "magnetic flux": $\langle \|\mathbf{B}\| \rangle$
  - Atomic lines
  - Molecular lines

- 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)

Direct measurements of **B**: spectropolarimetry

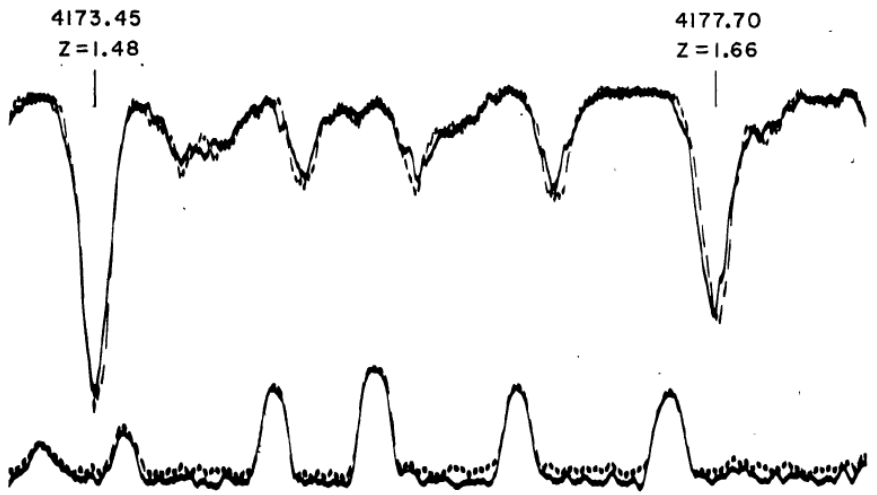
- Zeeman-induced polarisation
  - circ. pol.: longitudinal field
  - lin. pol. : transverse field

➥ 1^{st} detection on another star than the Sun: *Babcock (1947)*

➥ Information on vector **B**

- Differential measurement / weakly affected by modelling error
- Requires high S/N ($\sim 10^4$)

➥ Multi-line techniques (LSD) *Donati et al. (1997)*



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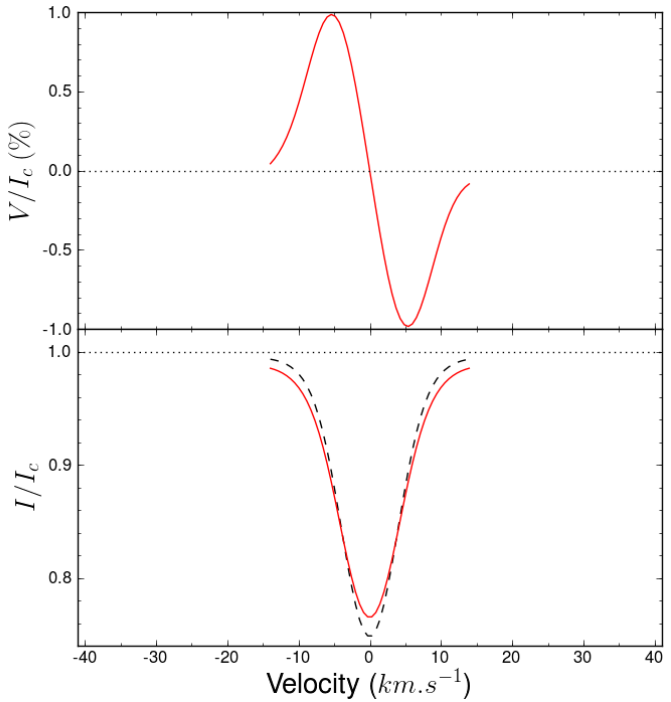


Direct measurements of **B**: spectropolarimetry

- Sensitive to vector properties
- Partial cancellation
  - Blind to small-scale field

- Interpretation/modelling
  - Longitudinal/transverse field monitoring

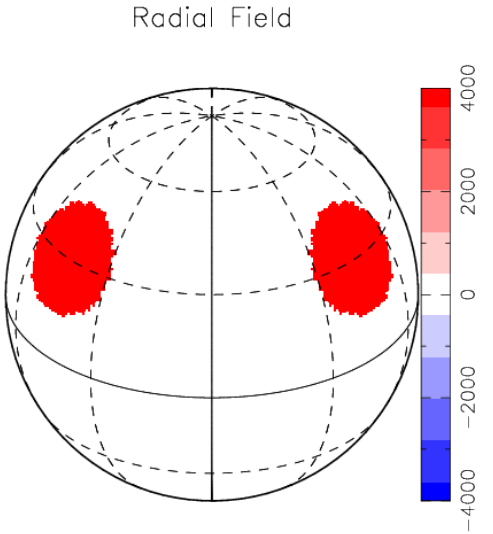
➥ Dipolar model

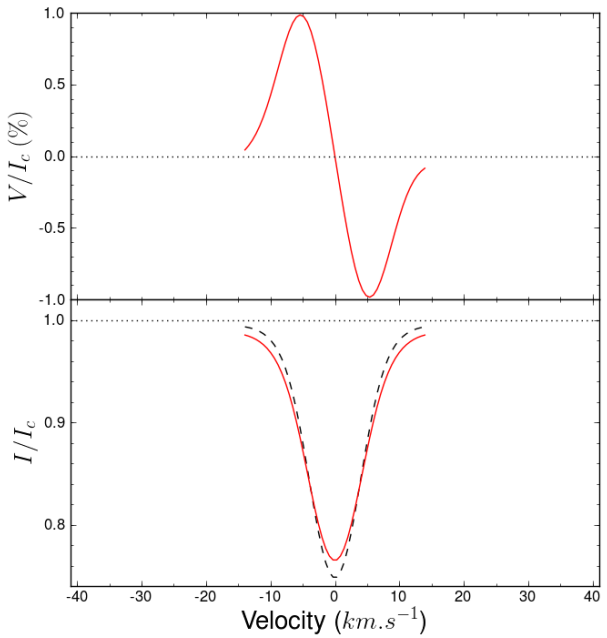
  - Zeeman-Doppler Imaging

Semel (1997)

Donati & Brown (1997)

➥ Use full information





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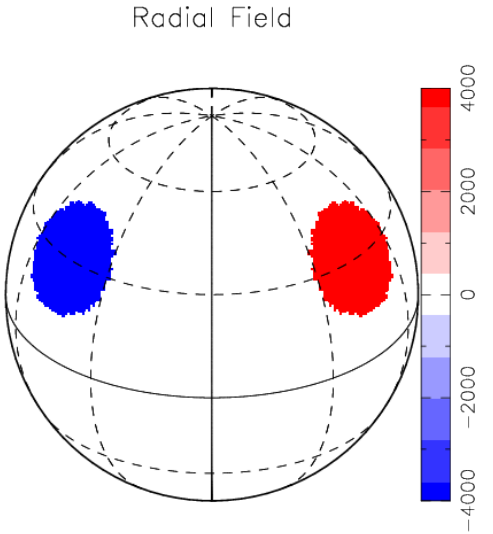

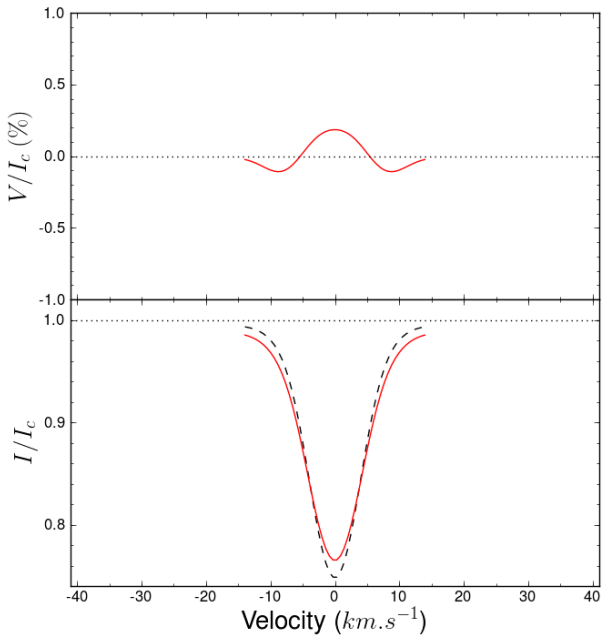

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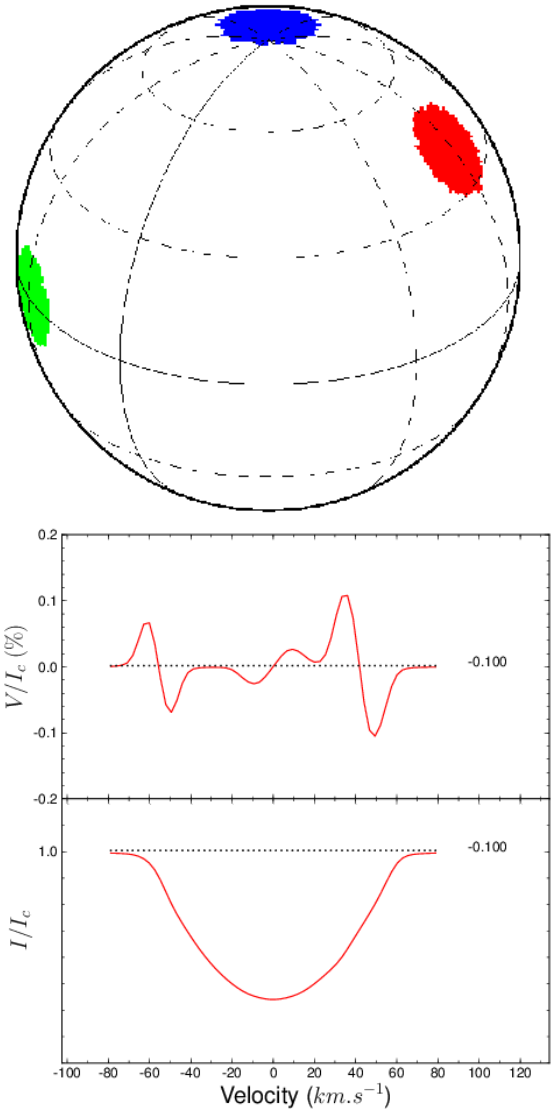

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Outline

A new window opened on stellar magnetic fields

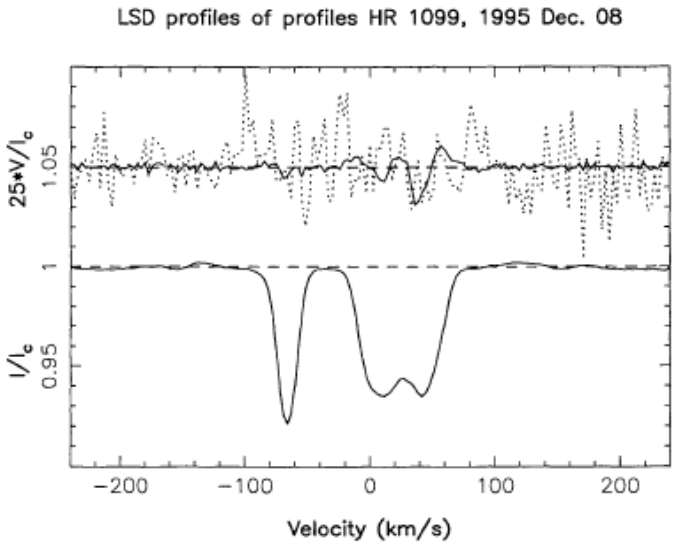
- First stellar studies
  - Bright and very magnetic stars
  - Ap/Bp
  - G-K: RS CVn/FK Com/PMS
- New instrument generation
  - 2005: CFHT/ESPaDOnS
  - 2006: TBL/NARVAL

  ➥ High resolution, high efficiency, full optical range

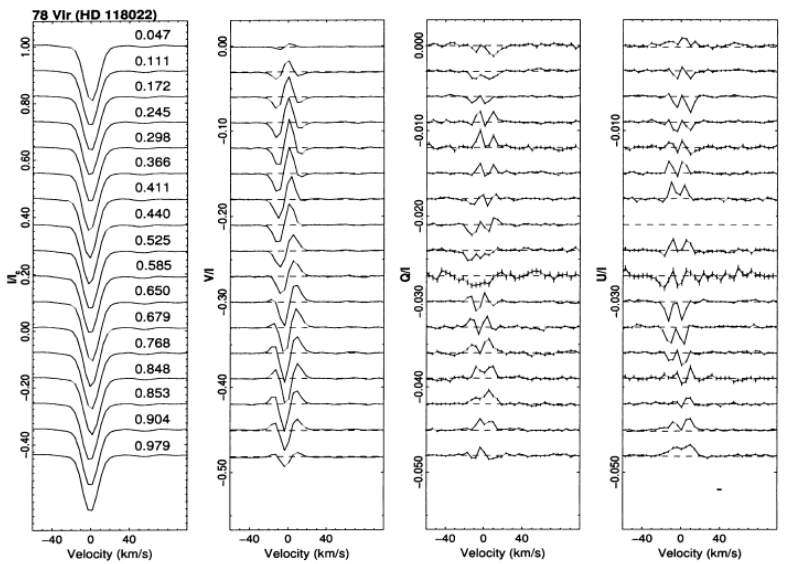
➔ Systematic exploration of HRD

- Since 2010:

  La Silla 3.6m/HARPSpol



HR 1099 *Donati et al. (1997)*



78 Vir *Wade et al. (2000)*

Fully-convective stars

Dynamo action in FC stars

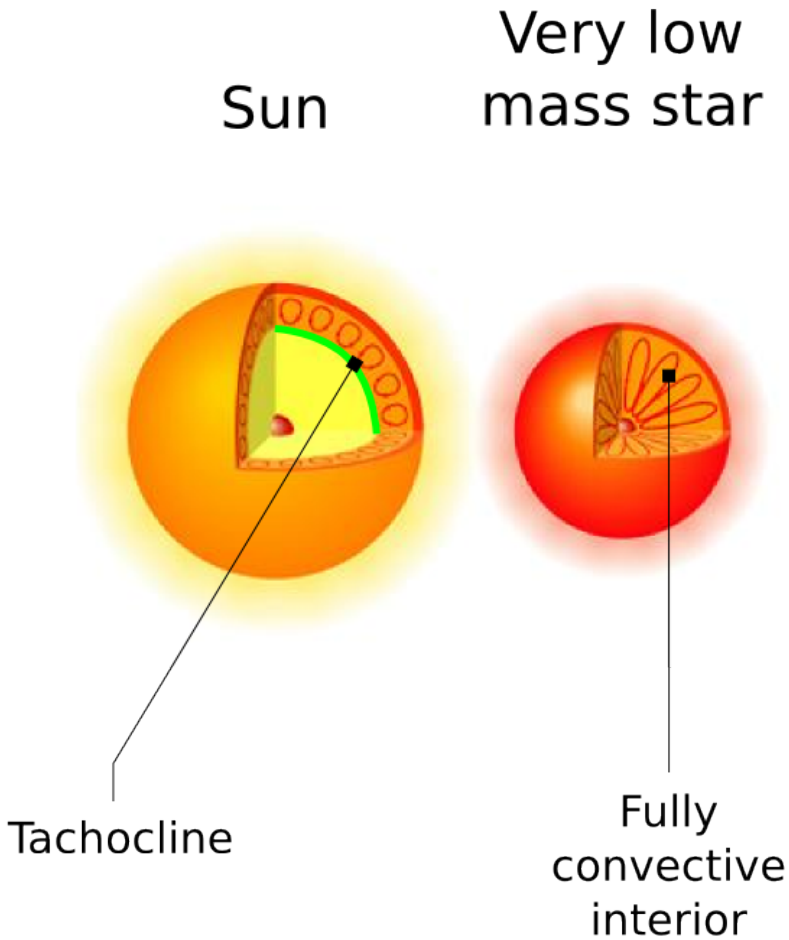
- Solar dynamo
  - Tachocline: crucial role?
- Fully convective stars
  - Tachocline → solar-dynamo

➥ observable effects?

- Activity
- **B** from Zeeman broadening

➥ No change at the fully-convective boundary

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



Internal structure of cool main sequence stars

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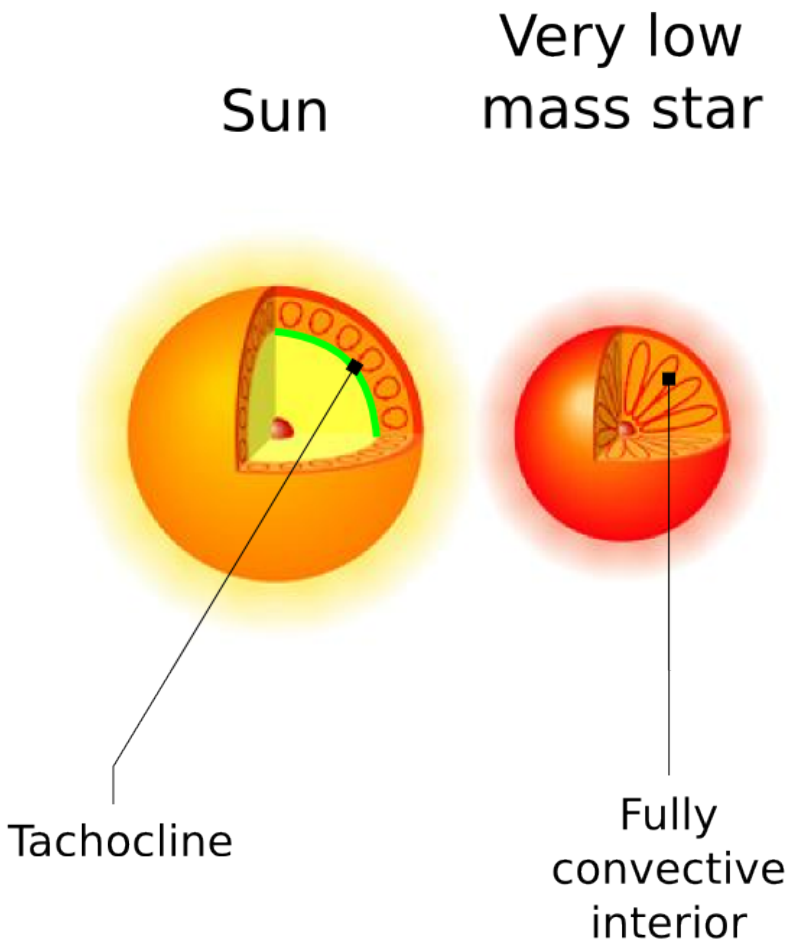

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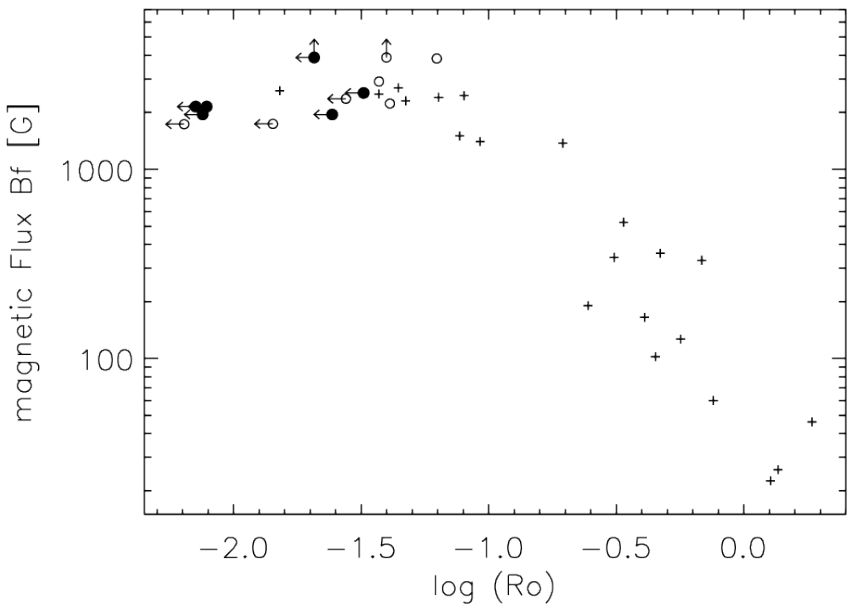

Rotation-total magnetic field relation

Reiners, Basri & Browning et al. (2009)

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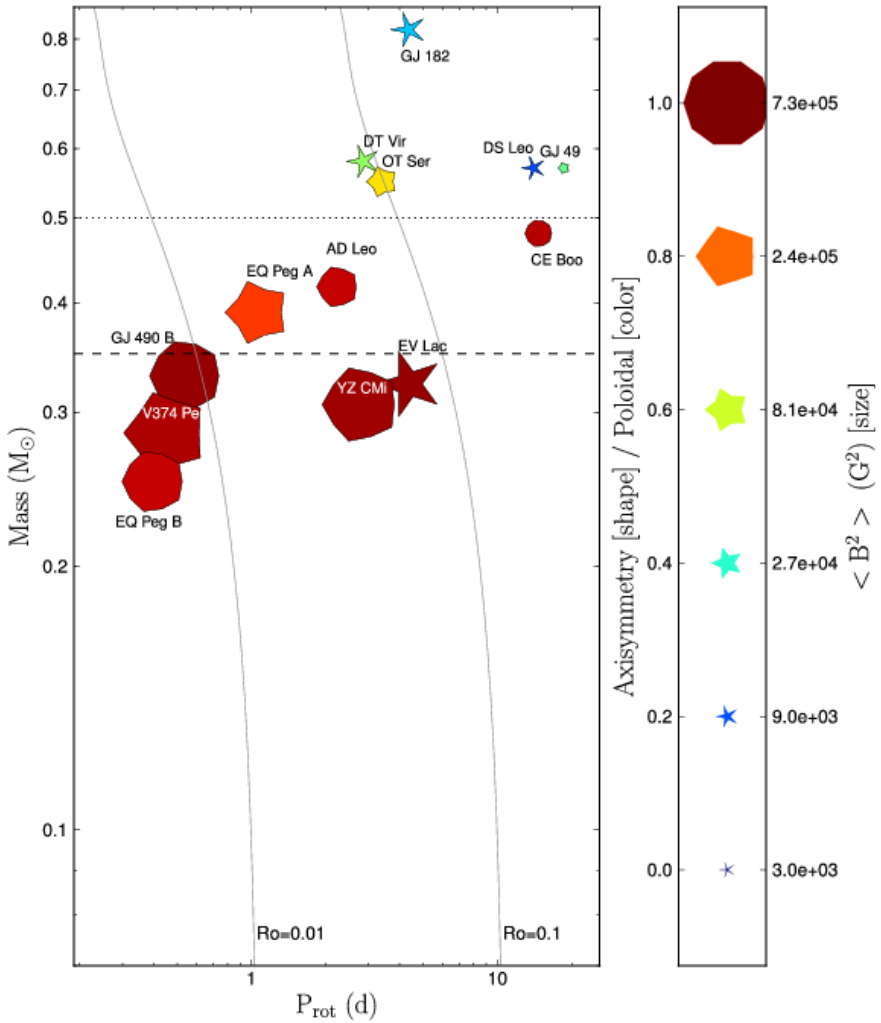

Donati et al. (2006, 2008), Morin et al. (2008a,b), Phan-Bao et al. (2009), E. Hébrard et al. in prep.

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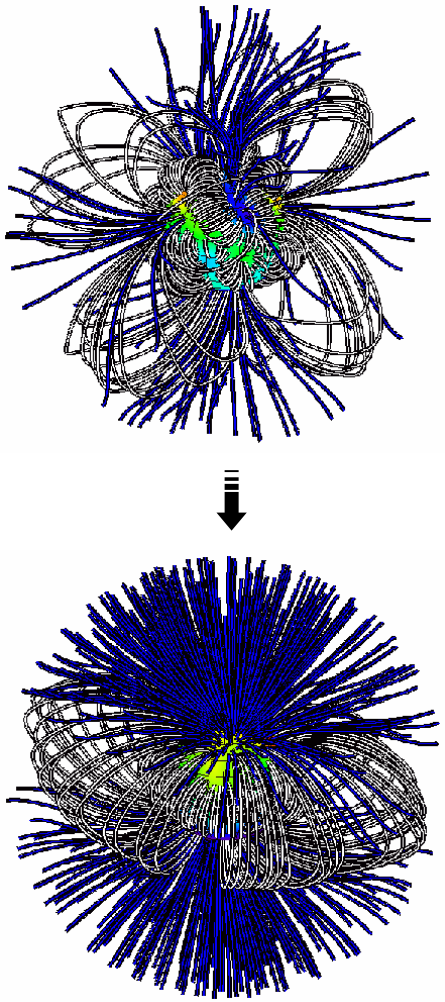
- **B** from Zeeman broadening

➥ No change at the fully-convective boundary

- 1st spectropolarimetric survey
  - Sharp transition $\sim 0.5\ \mathrm{M}_{\odot}$
  - Multipolar ➔ Dipolar **B**
  - Significant $d\Omega$ ➔ $\sim$ solid-body



Coronal extrapolations by M. Jardine from surface magnetic fields reconstructed by

Donati et al. (2008), Morin et al. (2008)

Fully-convective stars

Dynamo action in FC stars

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

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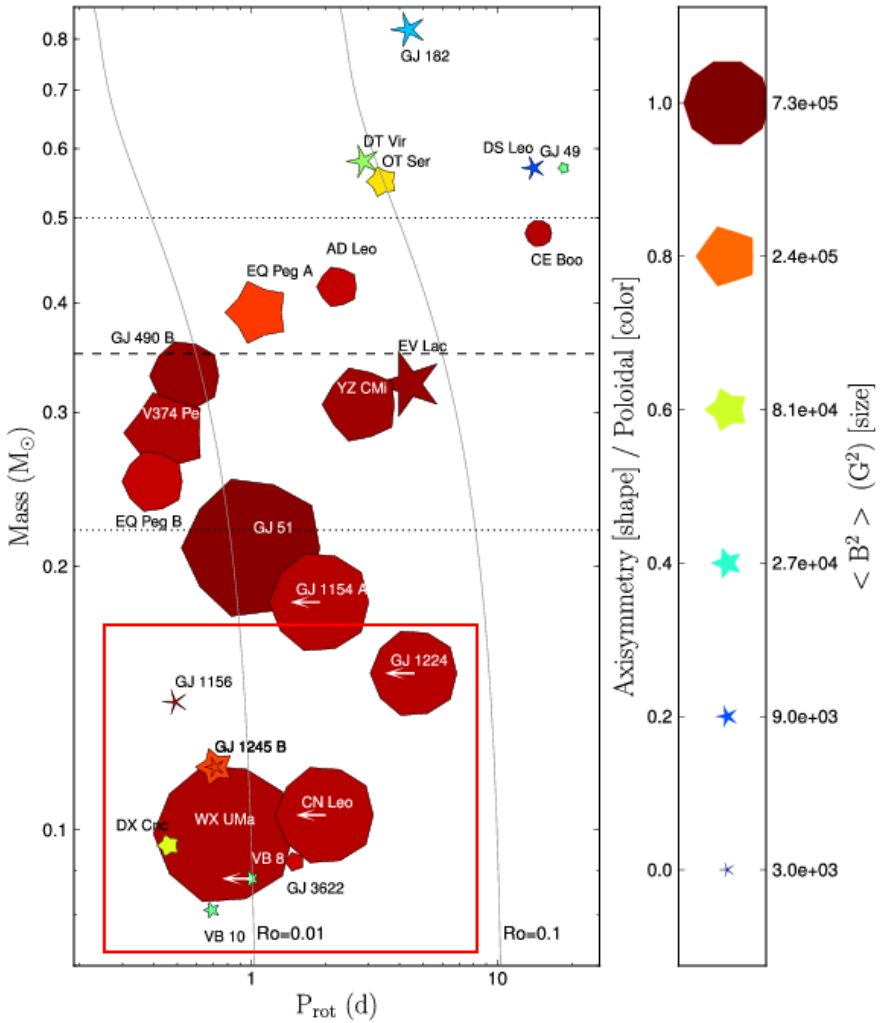
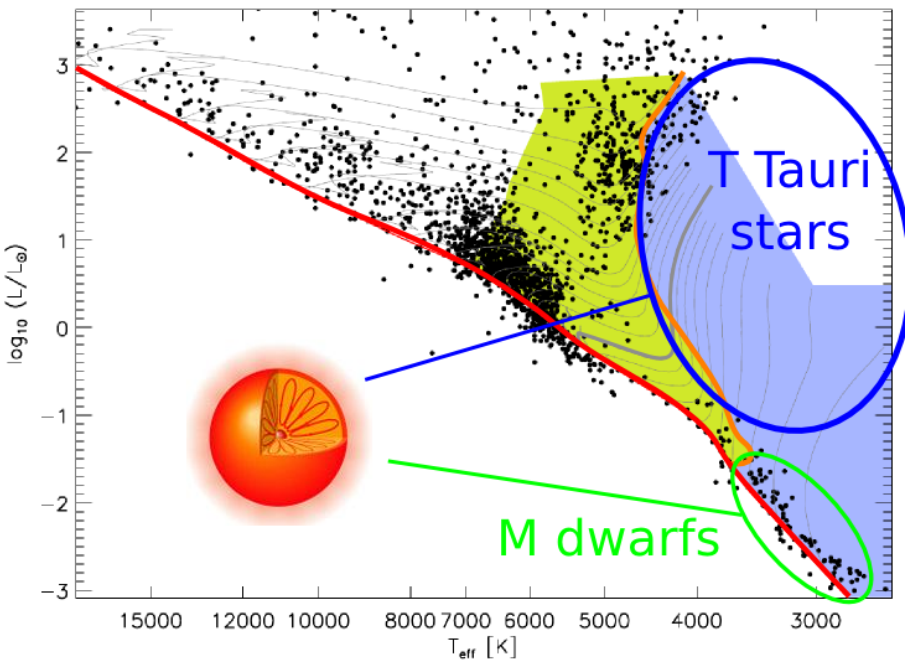


Morin et al. (2010,2011)
Gastine et al. (2013)

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
  - Similar behaviour as M stars
  - Impulse new models

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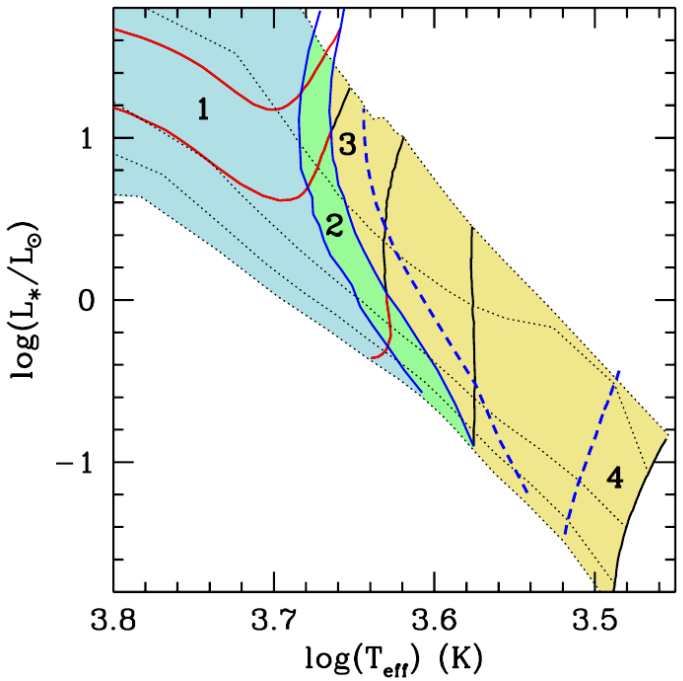

Gregory et al. (2012)

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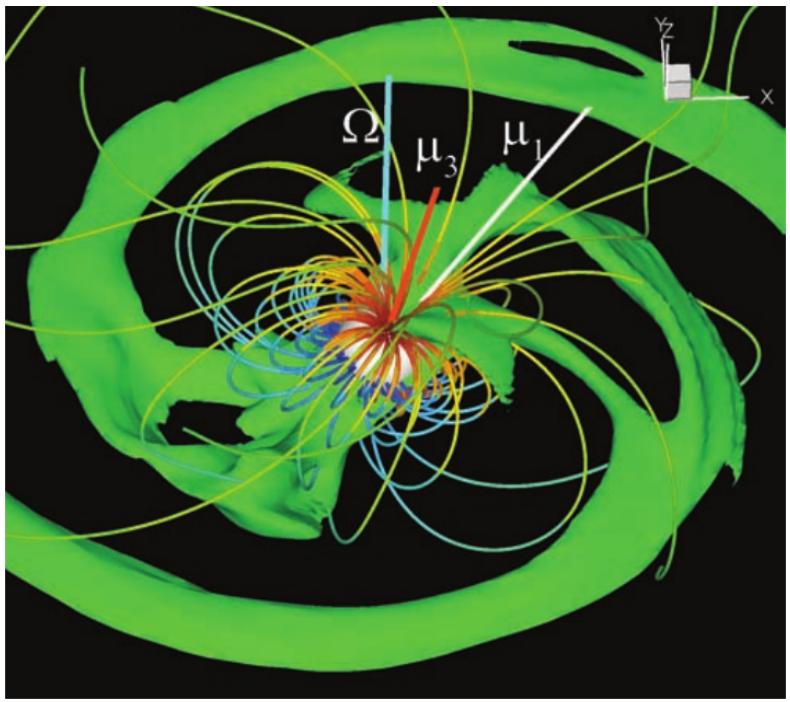
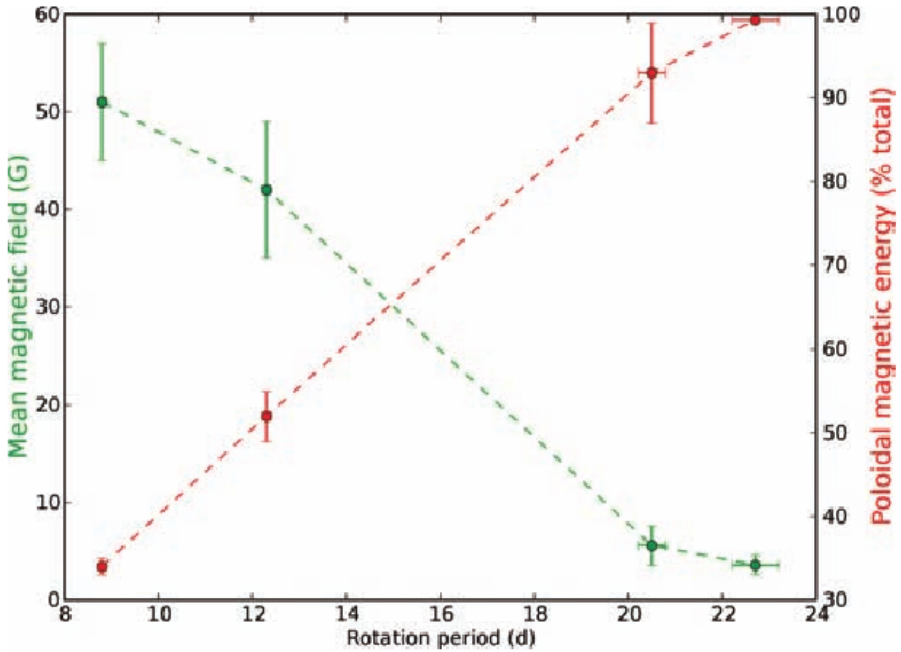


Romanova et al. (2011)

Solar-type stars from ZAMS to mature MS

- Large observing campaigns
  - Bcool project
  - TOUPIES project
- Evolution topology w/ rotation
  - faster ➔ toroidal
  - solar twins
  - extended to solar-type stars
- Large-scale field evol. w/ age
- Magnetic cycles of τ Boo



Petit et al. (2008, 2014)

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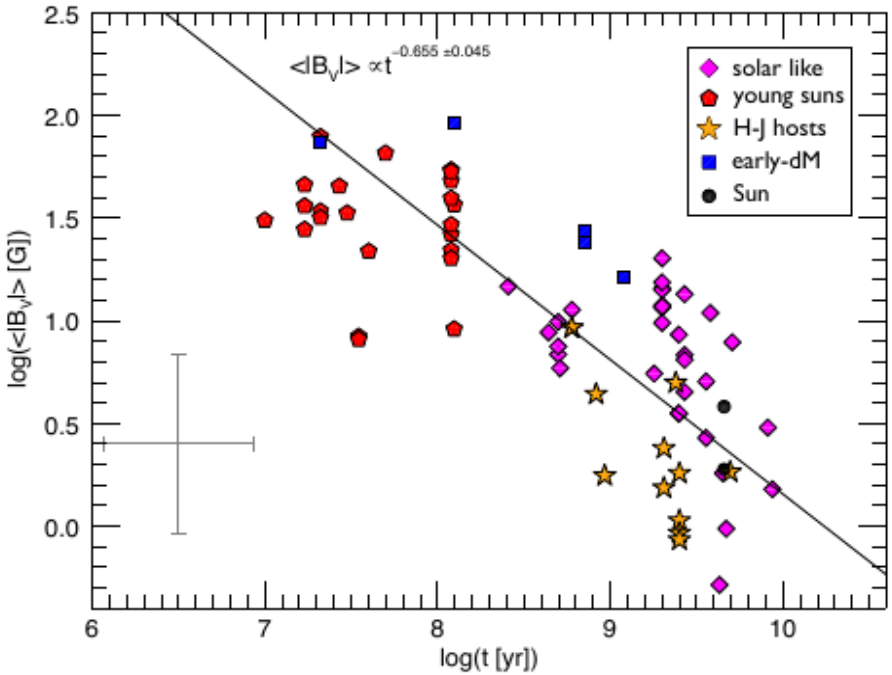

Vidotto et al. (2014)

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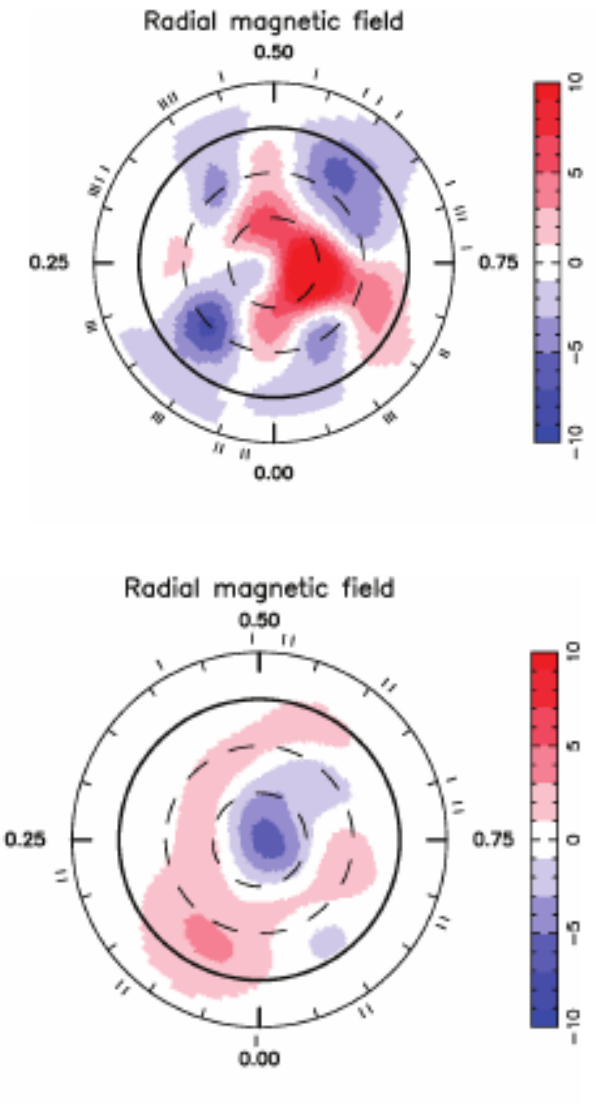
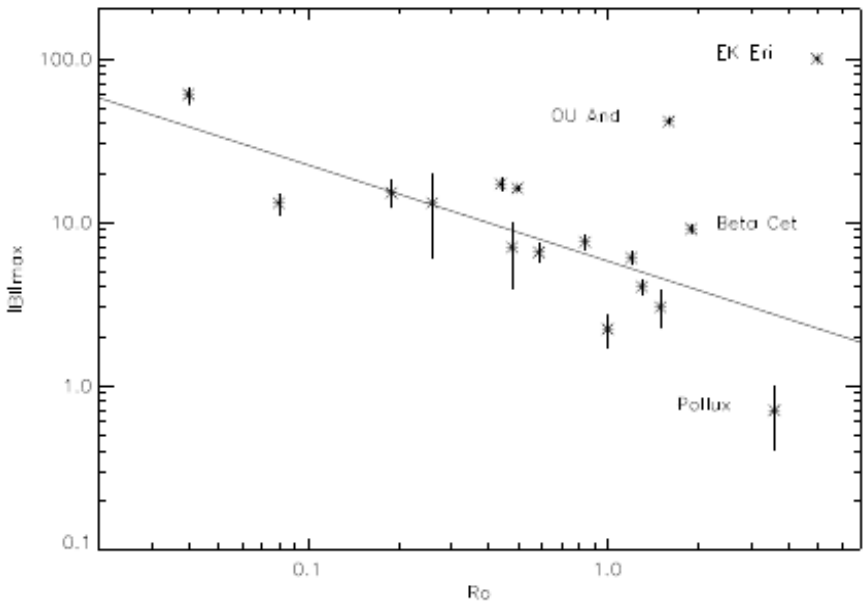


Farès et al. (2009)

Cool evolved stars: down to the sub-gauss level

- First survey of RGB stars
  - Rotation–activity relation
  - Outliers : EK Eri
    - Ap star-descendent?
- 1st detections on supergiants
  - Betelgeuse
    - Local dynamo and giant convective cells?
  - Wider survey *Grunhut (2013)*
- 1st detection on a Mira star
  - Related to shock-wave?

➔ Role of **B** in mass-loss?



Aurière et al. (2013)

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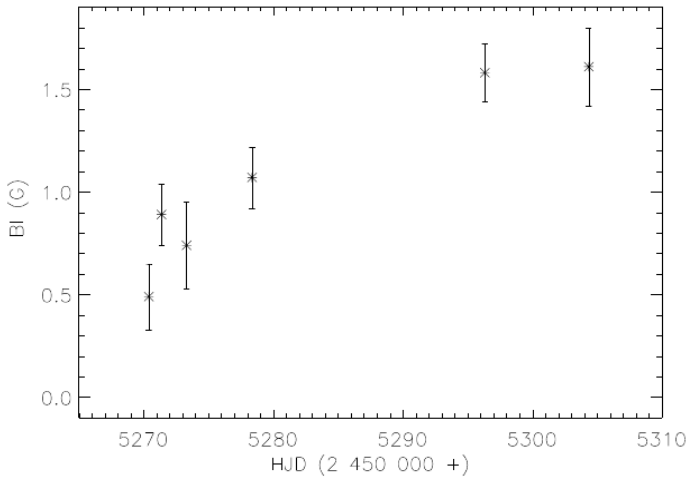
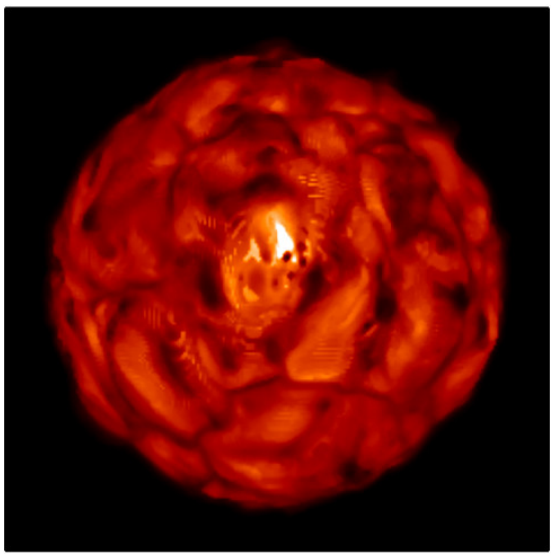


Aurière et al. (2010)



Chiavassa et al. (2010)

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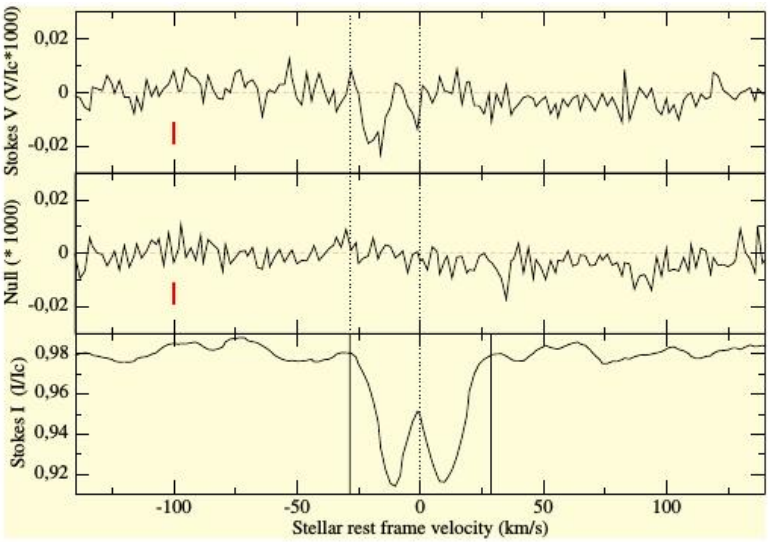

Lèbre et al. (2014)

Outline

Summary

- Magnetic fields
  - Crucial for stellar physics
  - Origin? Properties?
- Spectropolarimetry
  - Very high potential
  - Important developments/results
- Ongoing projects
  - Binamics
    - **B** of close binary systems
  - Matysse
    - **B** of young stars & survival of close-in exoplanets
- Future
  - CFHT/SPIRou
  - CRIRES+
  - UVMag