Imaging large-scale magnetic fields with spectropolarimetry: methods & results for M dwarfs

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Outline

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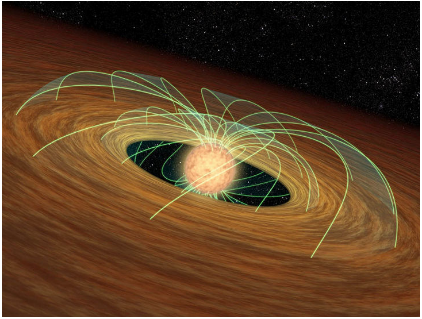
1. Why studying large-scale magnetic fields of M dwarfs ?
   - Magnetic fields play a key role
   - Fully-convective vs solar dynamo
2. Direct methods for magnetic field measurements
3. The first spectropolarimetric survey of M dwarfs
4. From M dwarfs to T Tauri stars

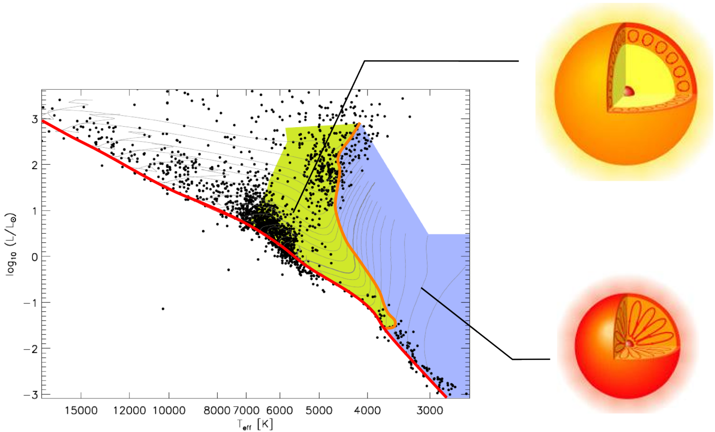
Magnetic fields play a key role

- Star–disc interaction
  - Magnetospheric accretion
  - Braking torque
  - Winds/outflows
- ➥ Large-scale field is relevant



Credit: NASA / JPL-Caltech / R. Hurt

Fully-convective vs solar dynamo



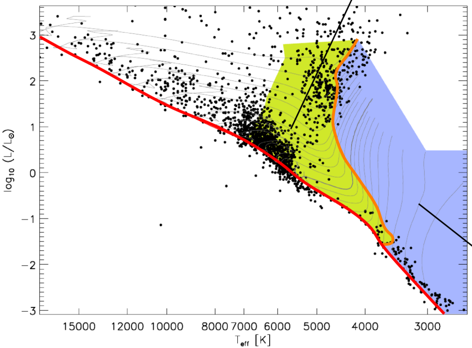
Solar-type dynamo

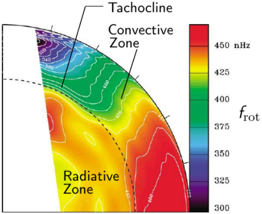
- $\alpha\Omega$: cyclonic concvection + $d\Omega$
- Crucial role of the tachocline ?

Fully-convective dynamo

- Differential rotation ? α^2 ?
- Importance of aspect ratio ?

Fully-convective vs solar dynamo





Schou et al. (1998) ; from SOHO–MDI data

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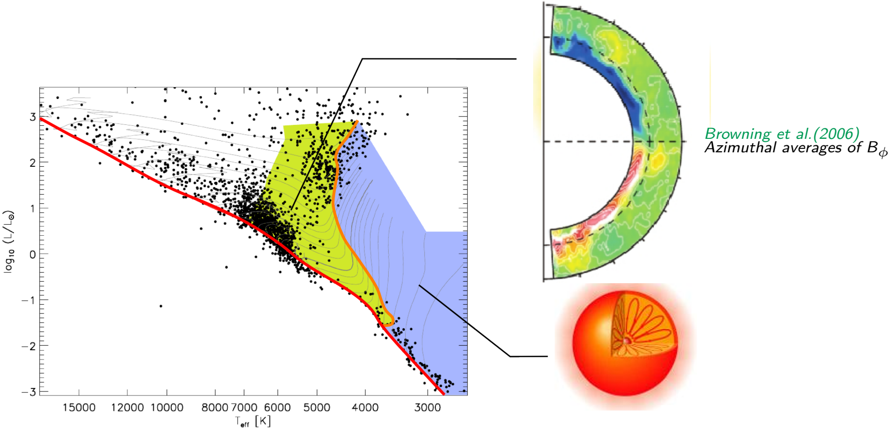

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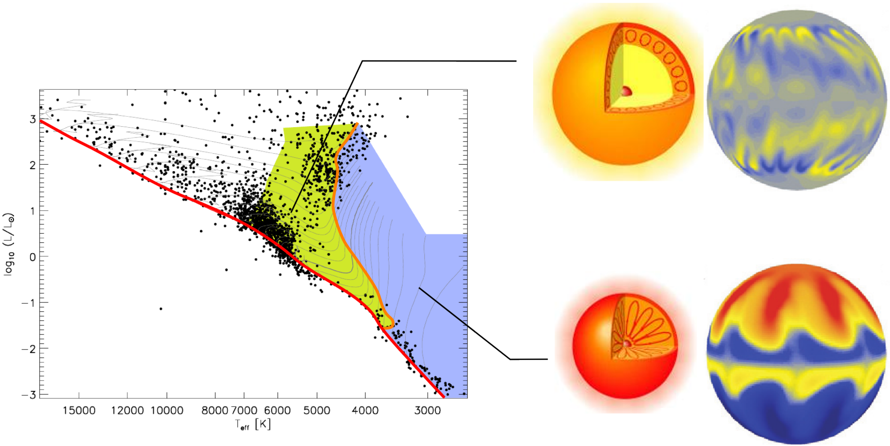

Goudard & Dormy (2008)

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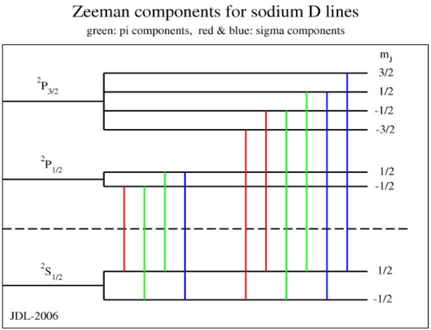
Zeeman Effect

- Component separation σ_b, π, σ_r
- Zeeman splitting
  - $\Delta\lambda_B = 4.67 \times 10^{-12}\, \lambda_0^2 g_{eff} B$
- Polarization
  - **B** modulus
  - Vector properties

    Direction : linear/circular

    Polarity : sign



Credit: J. Landstreet

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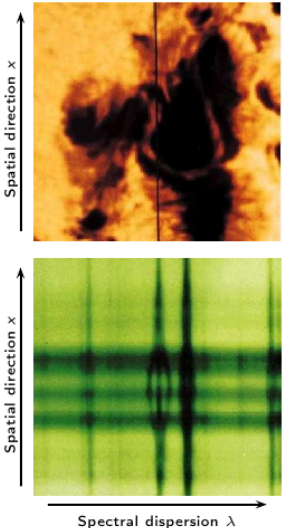

Credit: NOAO

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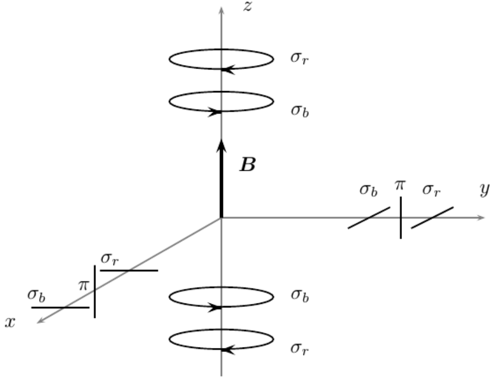

Zeeman polarization in spectral lines

Adapted from Landi & Landolfi (2004)

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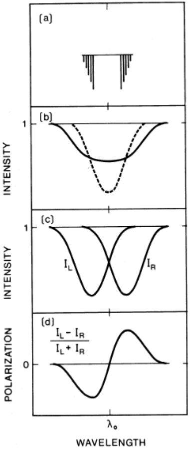
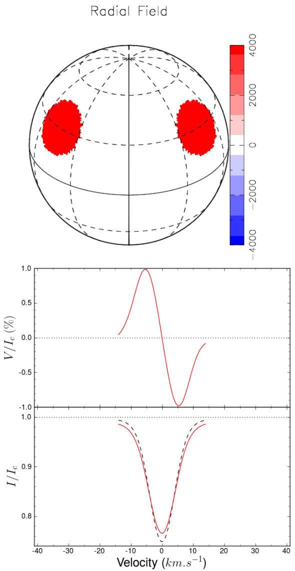


Stokes V

Credit: J. Landstreet

Disk-integrated stellar measurements

- **Unpolarised spectrum**
  - Total magnetic flux*
  - But almost no information on field geometry
  - ➥ Dynamo energetics
- **Polarized spectrum**
  - Large-scale component
  - Contains info on **B**
  - ➥ Tomography ⇒ topology



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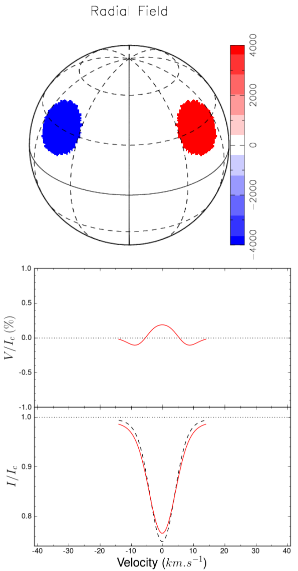

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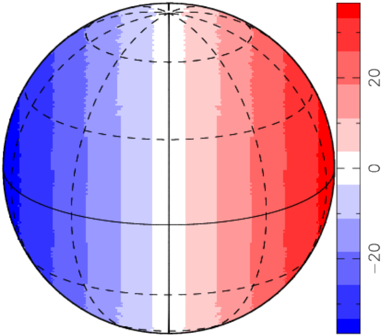

Equal RV stripes

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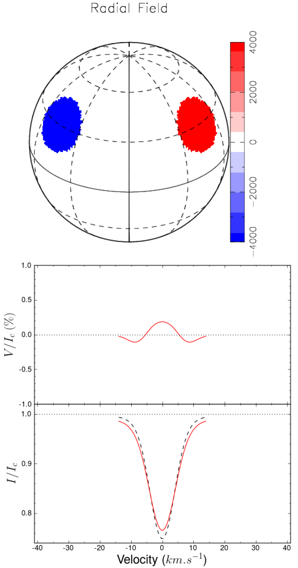

$v \sin i = 1 \ km\,s^{-1}$

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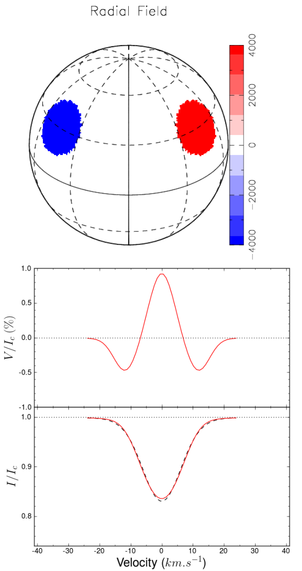

$v \sin i = 10\ km\,s^{-1}$

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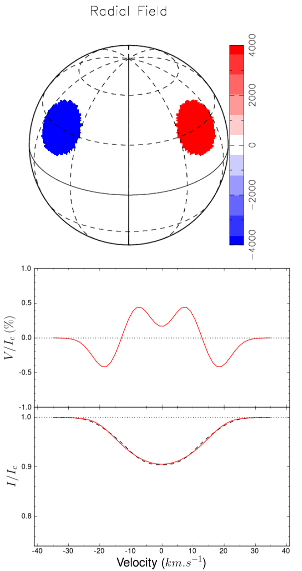

$v \sin i = 20\ km\,s^{-1}$

Spectropolarimetry and Zeeman-Doppler Imaging

- Zeeman effect
  - Polarized signatures
  - ➥ Geometry/Large-scale component
- ZDI: principle (*Semel 1989*)
  - Doppler effect
  - Rotational modulation
    - Magnetogram vector **B**
- Description of **B** (*Donati 2006*)
  - SH + Poloidal/Toroidal
    - Physical **B**
    - Global topologies

→ Comparison w/ theory

→ Cycles

→ Magnetospheric models

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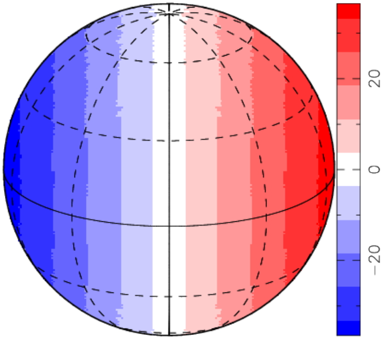

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The survey

- Multi-line + New generation instruments ESPaDOnS and NARVAL

➥ Systematic study of H-R diagram

- Explore dynamo response to
  - Mass
    - Depth of convective zone
  - Rotation period

- Measurements
  - Stokes V time-series
  - **B**: pol., tor., axi.
  - Differential rotation
  - Long-term evolution

- M dwarfs
  - 23 stars
  - $0.08 < M_\star < 0.75\ \mathrm{M}_\odot$
  - $0.33 < P_{\mathrm{rot}} < 18.6\ \mathrm{d}$
  - Active

Examples of ZDI reconstructions

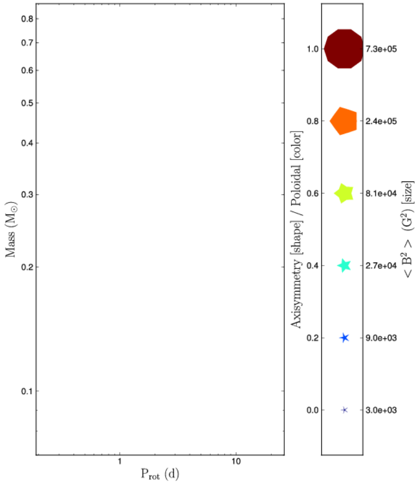
DT Vir (0.59 $M_\odot$)

- Partly convective
- Complex B_r
- Azimuthal ring
- $\langle B \rangle = 150$ G
- $B_{\mathrm{max}} = 500$ G
- $d\Omega \gtrsim d\Omega_\odot$

EQ Peg B (0.25 $M_\odot$)

- Fully convective
- Strong B_r polar spot
- Axisymmetric
  - $\langle B \rangle = 450$ G
  - $B_{\mathrm{max}} = 1200$ G
- no hint of DR

Mass–period diagram



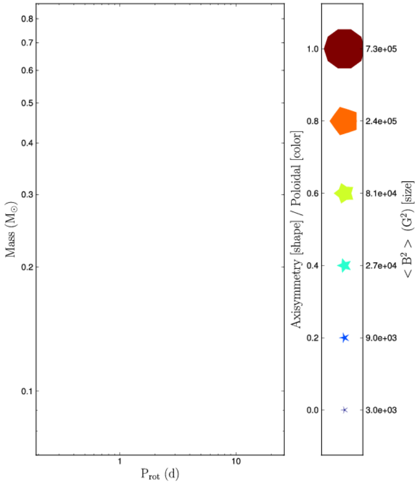
Stellar parameters

- Mass
- Rotation period

Magnetic topologies

- Magnetic energy
- Poloidal/toroidal
- Axisymmetry

Mass–period diagram



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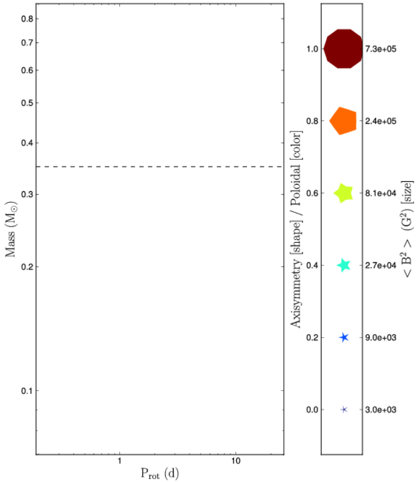

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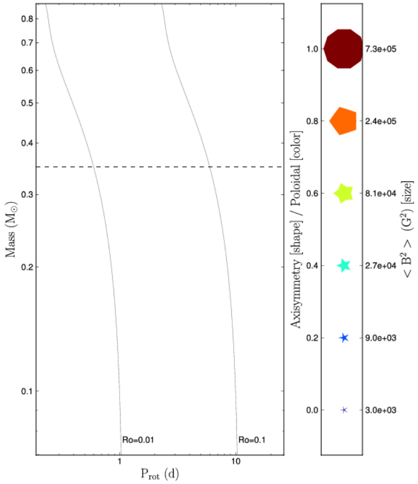

Stellar parameters

- Mass
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Magnetic topologies

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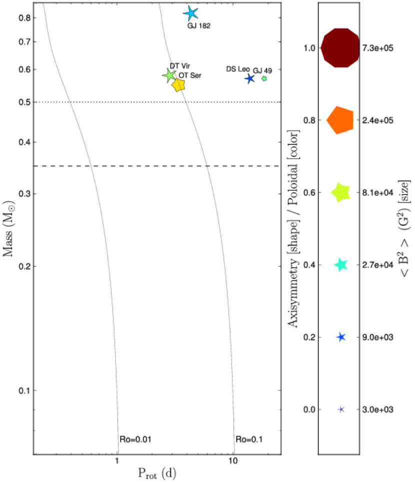
- Axisymmetry

Mass-period diagram: $M_\star > 0.5\ \mathrm{M}_\odot$



Magnetic field

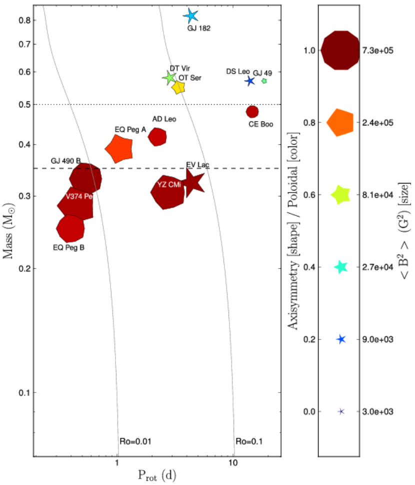
- Toroidal component
  - Significant or even predominant
- Poloidal component
  - Non-axisymmetric

Differential rotation

- $d\Omega \gtrsim d\Omega_\odot$
- Short-lived magnetic features

Donati et al.(2008)

Mass-period diagram: $0.2 < M_\star < 0.5\ \mathrm{M}_\odot$



Magnetic field

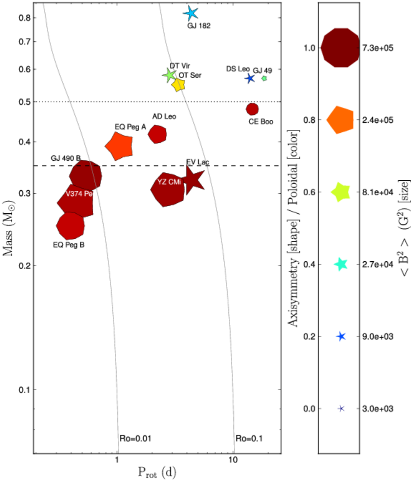
- Poloidal
- Axisymmetric
- Stronger
- ➥ $\sim$ Dipole

Differential rotation

- $d\Omega \simeq \frac{d\Omega_\odot}{10}$
- Stable magnetic features

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

Mass-period diagram: $0.2 < M_\star < 0.5\ \mathrm{M}_\odot$



Magnetic field

- Poloidal
- Axisymmetric
- Stronger

➥ ∼ Dipole

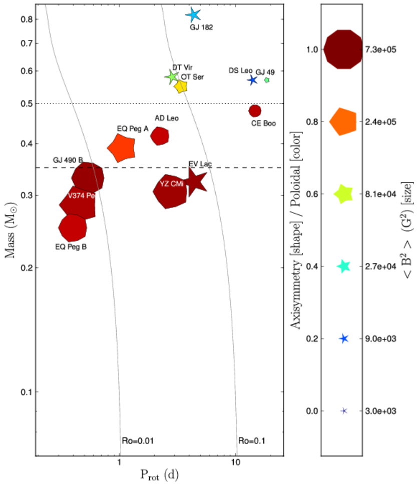
Differential rotation

- $d\Omega \simeq \frac{d\Omega_\odot}{10}$
- Stable magnetic features

➔ Sharp transition
➔ Full-convection boundary
➔ Partial agreement w/ DNS
Browning (2008)

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

Mass-period diagram: $M_\star < 0.2\ \mathrm{M}_\odot$



Two distinct groups of stars
Similar stellar parameters

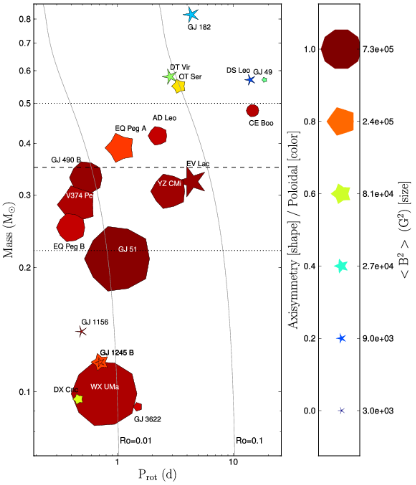
- Field similar to stars

  $0.2 < M_\star < 0.5\ \mathrm{M}_\odot$

- $\sim$ strong dipole

- Weak field
- Non-axisymmetric

Mass-period diagram: $M_\star < 0.2\ \mathrm{M}_\odot$



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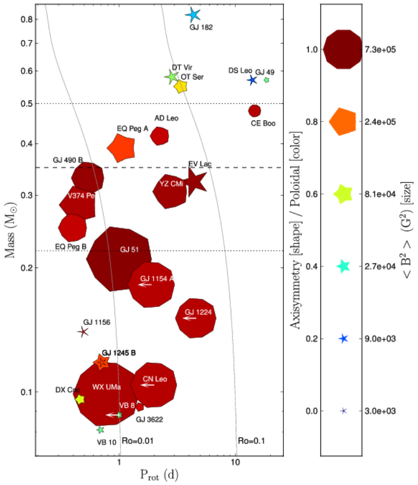

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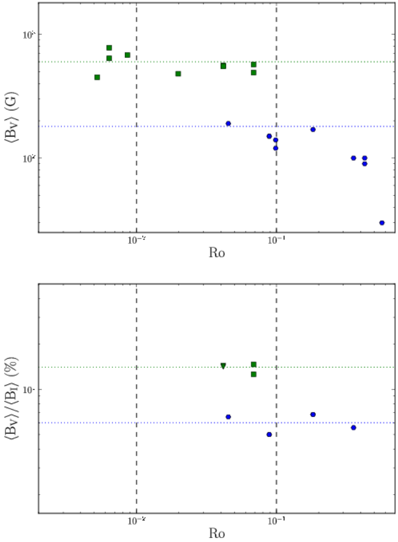
→ Two possible dynamo modes ?
→ Switch between two states ?
→ Influence of age ?

Morin et al.(2010)

Rotation–magnetic field relation



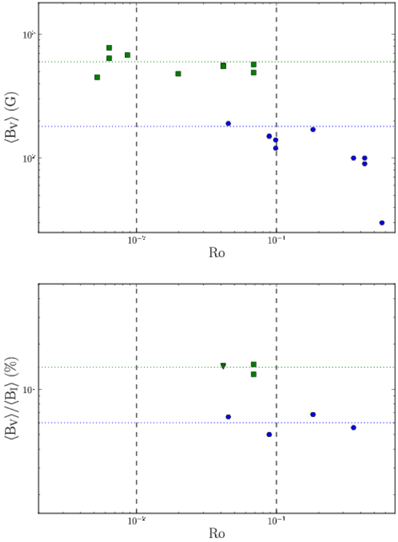
Large-scale magnetic flux

- Boundary at $0.4\ \mathrm{M}_\odot$
  - $M_\star > 0.4\ \mathrm{M}_\odot$: $B_{\rm sat} \simeq 180$ G
  - $M_\star < 0.4\ \mathrm{M}_\odot$: $B_{\rm sat} \simeq 600$ G

Ratio of total and large-scale magnetic fluxes

- Unpolarized / molecular lines FeH
- $M_\star > 0.4\ \mathrm{M}_\odot$: $\simeq 6\%$
- $0.2 < M_\star < 0.4\ \mathrm{M}_\odot$: $\simeq 14\%$

Rotation–magnetic field relation



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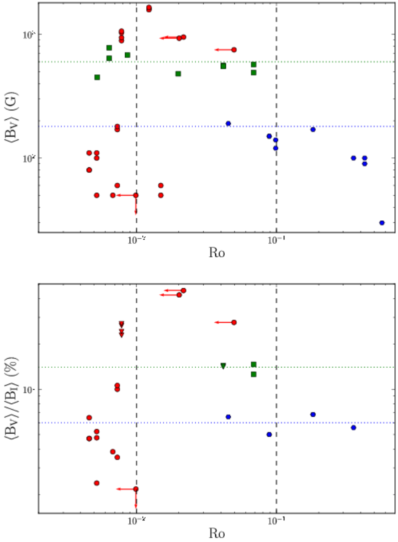
More efficient at generating large-scale magnetic field

Rotation–magnetic field relation



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Rapidly rotating VLMS:
WF/SF bistability ?

Morin, Dormy, Schrinner & Donati (2011)

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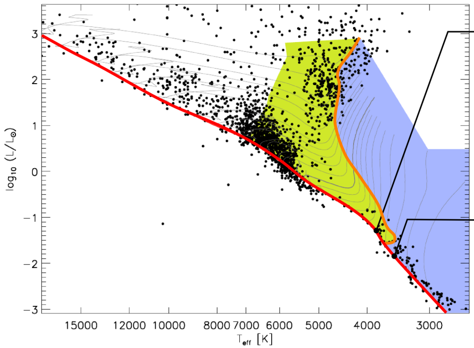
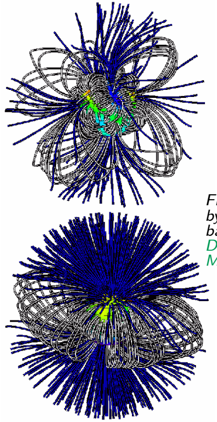
From M dwarfs to T Tauri stars





Field extrapolations by M.Jardine based on ZDI maps from Donati et al. (2008) Morin et al. (2008)

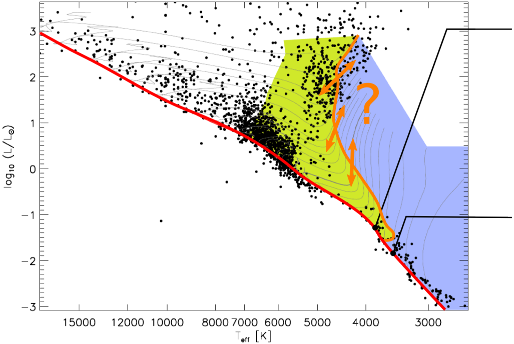
M dwarfs

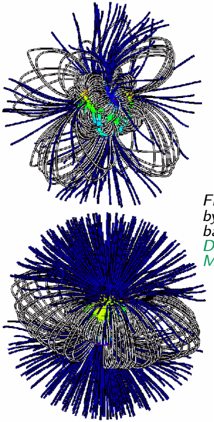
- Sharp transition close to FC limit
- What happens at very low masses ?

T Tauri stars

- Similar transition at FC limit ?
- Impact on stellar evolution ?

From M dwarfs to T Tauri stars





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