Differential rotation in very-low-mass stars: a clue to dynamo bistability?

Julien Morin

Institut für Astrophysik Göttingen

J. F. Donati, P. Petit	*IRAP – CNRS / Université de Toulouse*
X. Delfosse, T. Forveille	*IPAG – CNRS / Université de Grenoble*
M. Jardine	*University of St Andrews*
E. Dormy, M. Schrinner	*MAG – ENS Paris / IPGP*
A. Reiners, D. Shulyak, S. Wende	*IfA Göttingen*
U. Christensen, L. Duarte, T. Gastine, J. Wicht	*MPS*

Differential Rotation and Magnetism across the HR Diagram

Nordita, Stockholm

8th April 2013

Institut für Astrophysik Göttingen

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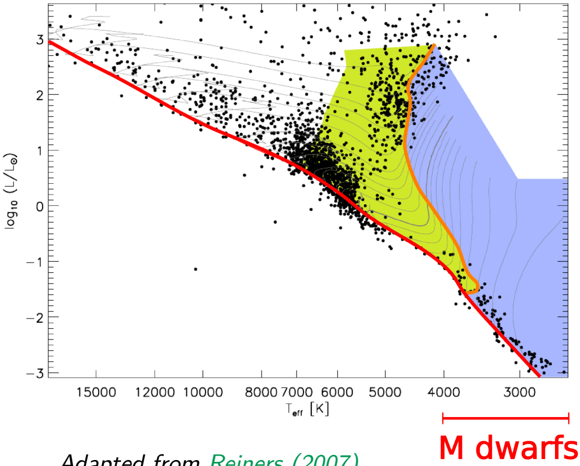
Outline

Outline

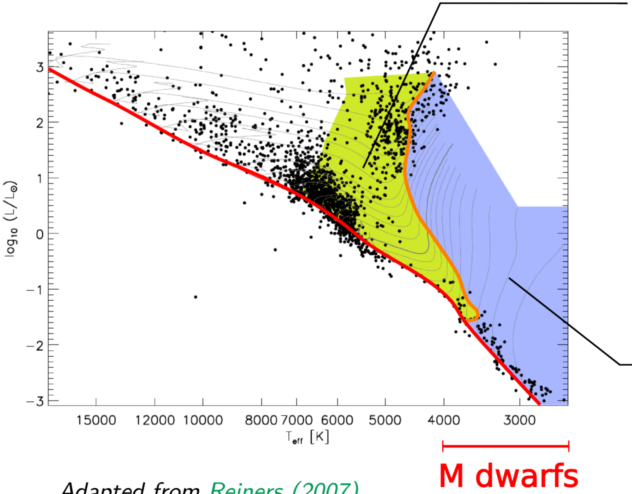
1. Studying magnetic fields of M dwarfs
   - Fully-convective vs solar dynamo
   - Dynamos of stars and planets
   - Magnetic field measurements in unpolarized light
   - Magnetic field measurements with spectropolarimetry
2. Magnetic fields of very-low-mass stars
3. Dynamo bistability

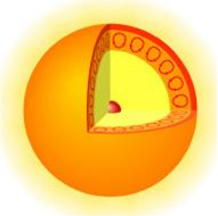
Fully-convective vs solar dynamo

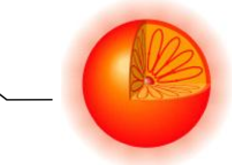


Adapted from Reiners (2007)

Fully-convective vs solar dynamo







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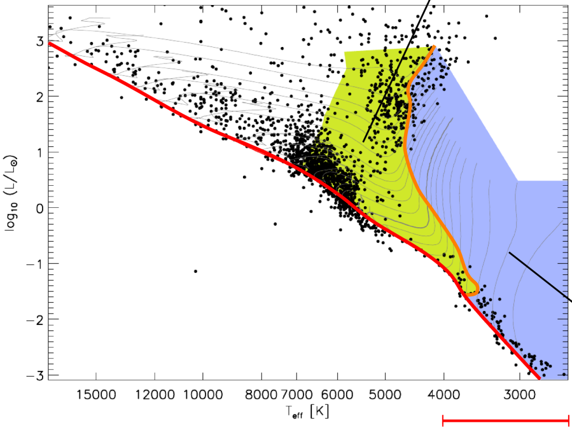
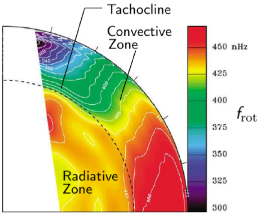


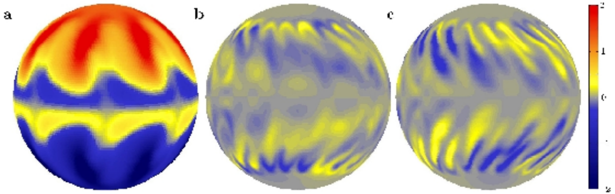


Schou et al. (1998)

M dwarfs

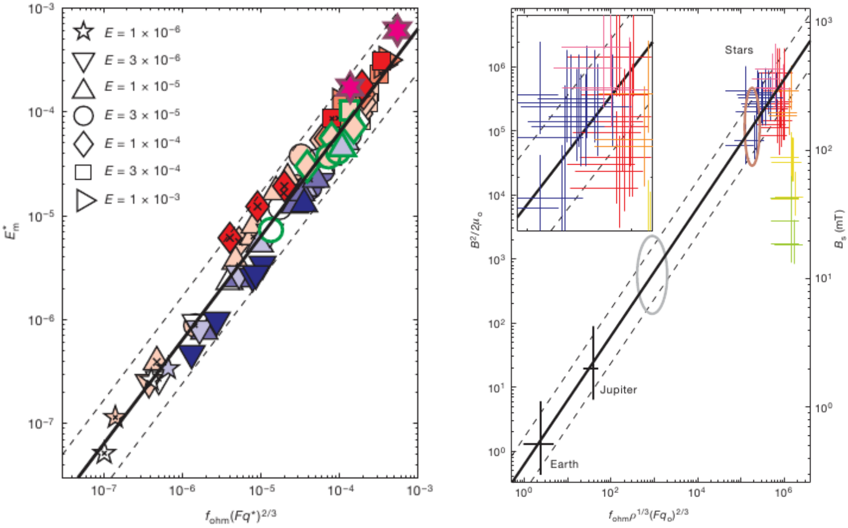
Adapted from Reiners (2007)

Dynamos of stars and planets



Goudard & Dormy (2008)

Dynamos of stars and planets

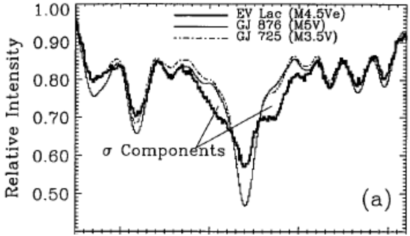


Christensen, Holzwarth & Reiners (2009)

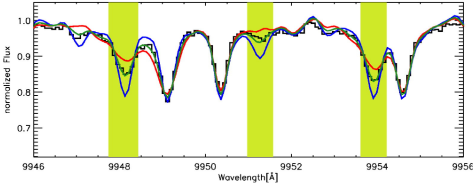
Magnetic fields measurements in unpolarized light

- Zeeman effect
- Measure "magnetic flux"
  - Atomic lines
    - *Saar (1988)*
      Johns-Krull & Valenti (1996)
  - Molecular lines
    - *Reiners & Basri (2007+)*
      Shulyak et al. (2010)

➔ Single Ro-Bf relation for partly- and fully-convective stars (SpT<M6)



Johns-Krull & Valenti (1996)



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

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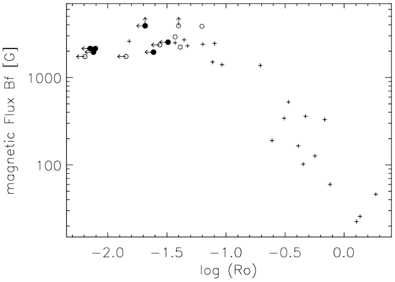
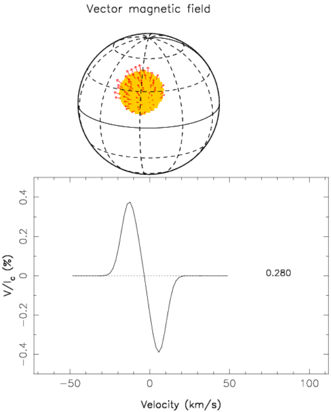


Reiners, Basri & Browning (2009)

B measurements with spectropolarimetry



- Zeeman effect
- Field orientation + polarity
- Large-scale field only
  - ➥ Zeeman-Doppler Imaging *Semel (1989)*
- Efficient instruments
- Multi-line techniques
  - ➥ M dwarfs within reach!

➔ Sharp transition large-scale B
- strong axial dipolar component
- weak differential rotation

➔ $\langle B_V \rangle / \langle B_I \rangle$ increases
- *Reiners & Basri (2009)* *Morin et al. (2010)*

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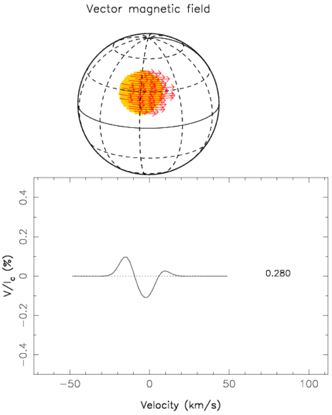

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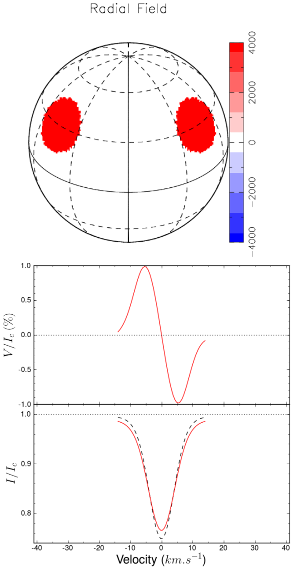

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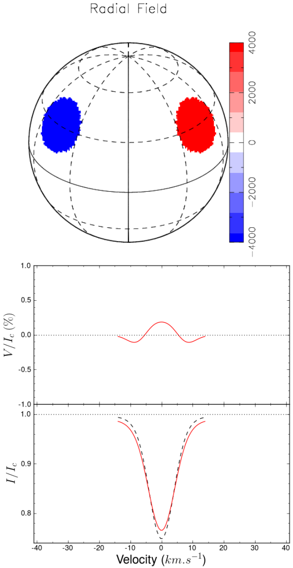

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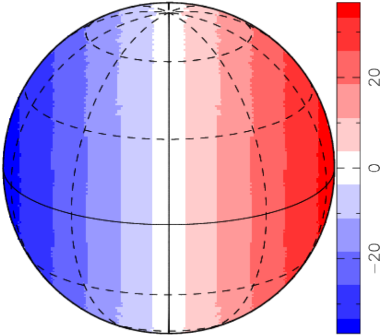

Equal RV stripes

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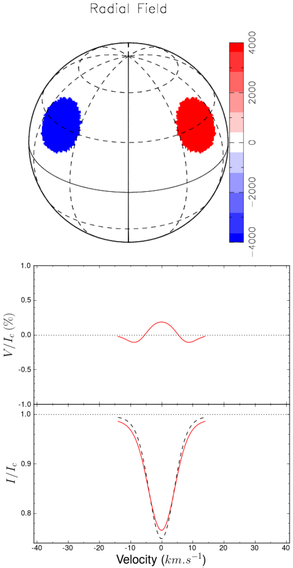

$v \sin i = 1\ km\,s^{-1}$

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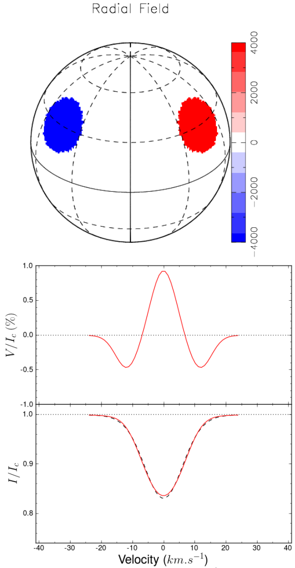

$v \sin i = 10 \ km \, s^{-1}$

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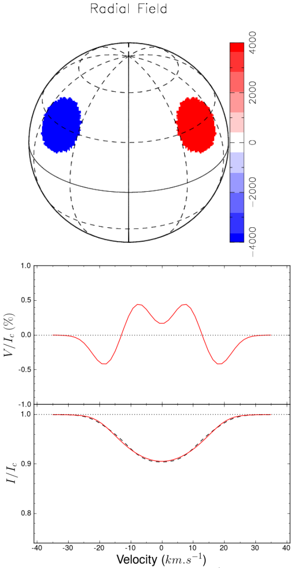

$v \sin i = 20\ km\, s^{-1}$

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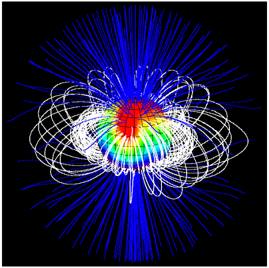
B measurements with spectropolarimetry

Credit: J.-C. Cuillandre, CFHT



Donati et al. (2006)

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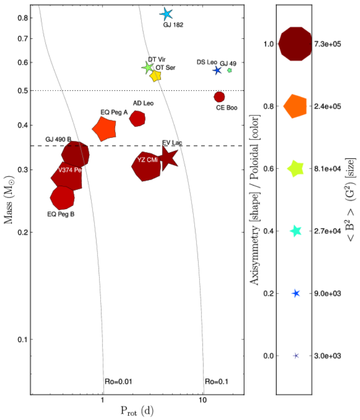

Morin, Donati et al. (2008+)
Phan-Bao et al. (2009)

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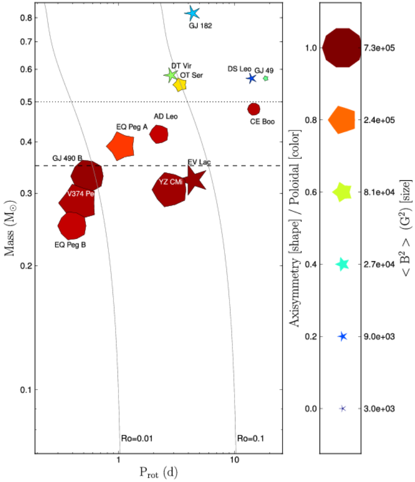
Outline

B of VLMS from spectropolarimetry



- 11 fully-convective stars
  - M5-M8 – $M_\star < 0.22\ \mathrm{M}_\odot$
  - $P_{\mathrm{rot}} < 4.3\ \mathrm{d}$ – Ro$\sim 10^{-2}$
  - Similar stellar parameters
  - Two distinct magnetisms
  - ➥ Strong aligned dipole, long-lived
  - ➥ Weaker multipolar field, evolving

Morin et al. (2010)

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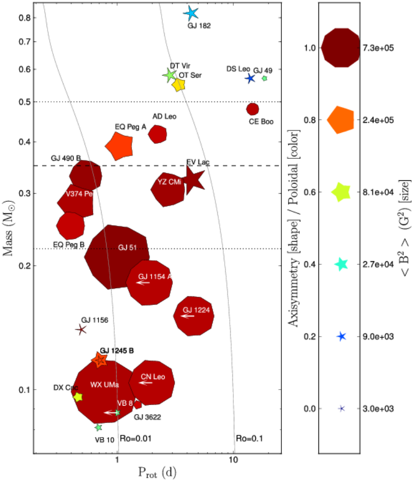

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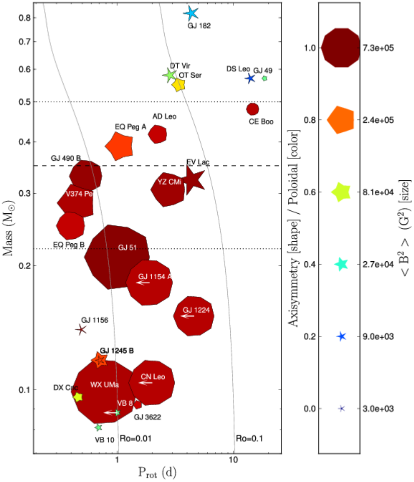

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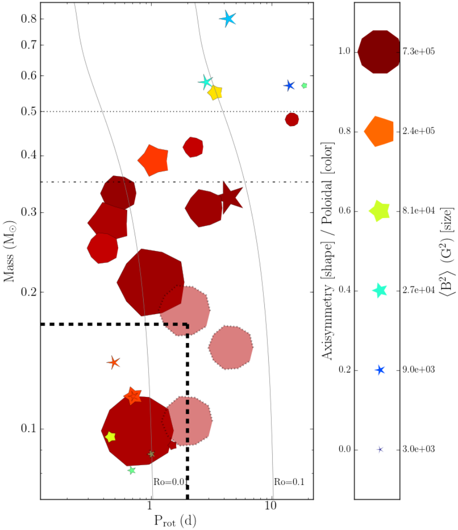
Only large-scale field affected?

Scenarios for the magnetism of VLMS



- Cyclic change SD ↔ WM?
  - up to 3 yr time-series
  - ∃ variability
  - No such change observed
- An effect of age?
  - WM younger
  - SD older
  - Phenomenology?
- Another "hidden" parameter?
- Dynamo bistability
  - Two distinct solutions for one set of parameters
  - Depend on initial conditions

Outline

Weak and strong field dynamos

Large-scale dynamo bistability

- Similar Bf on both branches

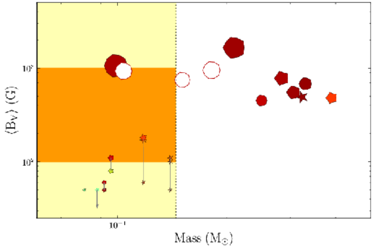
Field strength

- Strong field branch
  - Coriolis–Lorentz force balance
  - $\Lambda = \dfrac{B^2}{\rho\mu\eta\Omega} = \mathcal{O}(1)$
- $B_{sf} \sim 2 - 50\ \mathrm{kG}$

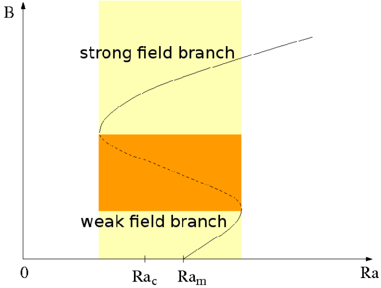
Gap between branches

- Lorentz-inertia
  ➔ Lorentz-Coriolis balance
  - $\dfrac{B_{sf}}{B_{wf}} = Ro^{-1/2} \sim 10$

- Not yet observed in DNS
- *V. Morin & Dormy (2009)*



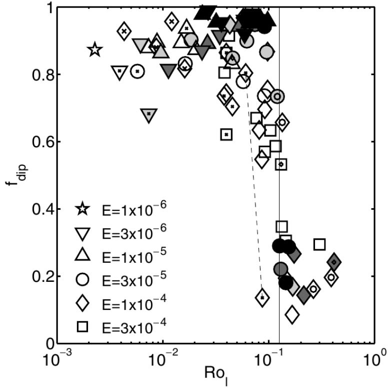
Morin, Dormy, Schrinner & Donati (2011)



Adapted from Roberts (1978)

Low Ro_ℓ transition in DNS

- *Christensen & Aubert (2006)*
  - Boussinesq simulations
  - Inertia-Coriolis balance: $Ro_\ell = Ro\frac{\bar{\ell}_u}{\pi}$
  - Low *Ro* ➔ dipolar
- *Schrinner et al. (2012)*
  - Stress-free boundary conditions
    Simitev & Busse (2009)
  - Bistability at low *Ro*
    dip vs multipolar depending on IC
- *Gastine et al. (2012)*
  - Similar results in anelastic
  - For moderate stratification
- *Duarte et al. (2013)*
  - Extend to higher stratification



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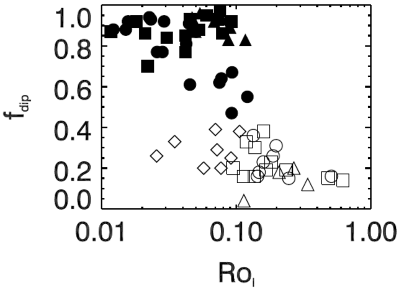

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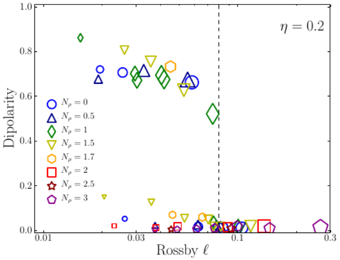

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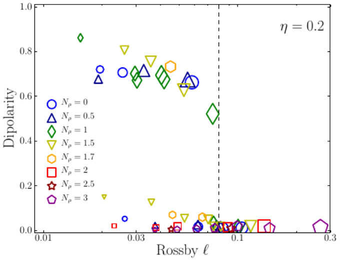
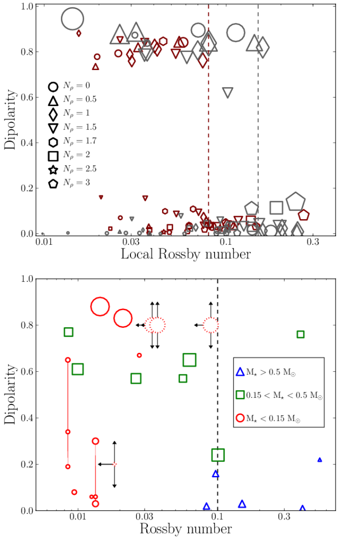


Gastine et al. (2012)

Anelastic simulations *vs* observations (1/2)

- Compare simulations w/ spectropolarimetric measurements
  - large-scale component of **B**
  - “scale separation” assumption
  - ➥ similar transition to bistable regime
- Caveats and questions
  - $Ro_\ell \leftrightarrow$ empirical Ro ?
  - Can we find multipolar fields
    - $M_\star > 0.15\ \mathrm{M}_\odot$?
    - $Ro > 0.02$?
  - Outlier



Gastine, Morin et al. (2013)

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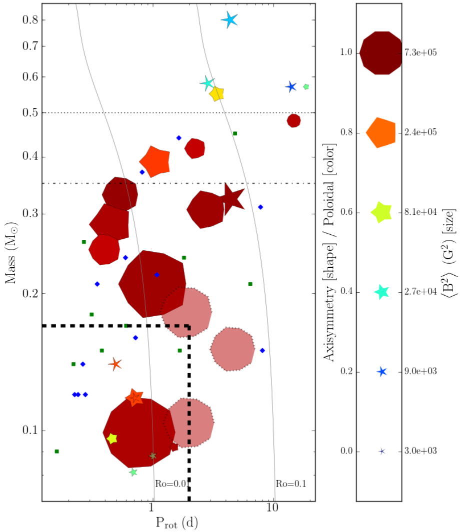
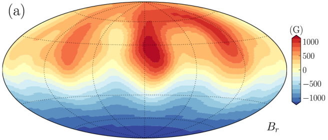
➥ Larger survey of active M dwarfs

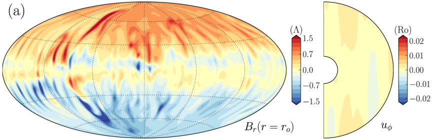


Anelastic simulations *vs* observations (2/2)

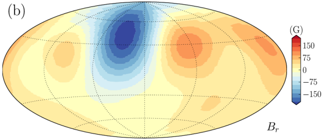


$\frac{\Delta\Omega}{\Omega} \simeq 0.04\,\%$

V374 Peg

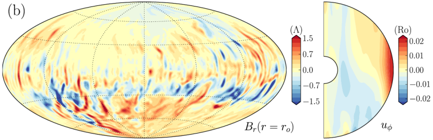


Dipolar branch



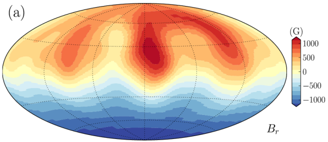
$\frac{\Delta\Omega}{\Omega}$?

GJ 1245 B



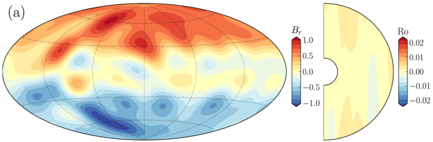
Multipolar branch

Anelastic simulations *vs* observations (2/2)

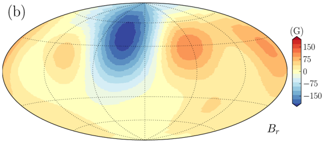


$\frac{\Delta\Omega}{\Omega} \simeq 0.04\,\%$

V374 Peg

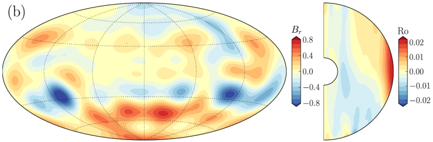


Dipolar branch



$\frac{\Delta\Omega}{\Omega}$?

GJ 1245 B



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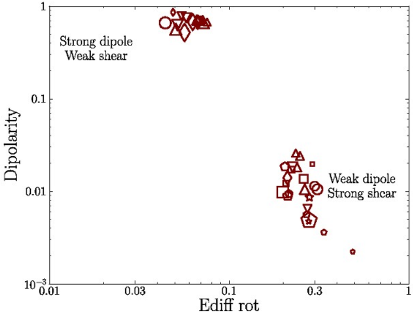
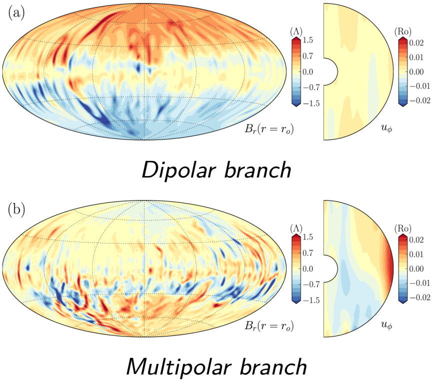


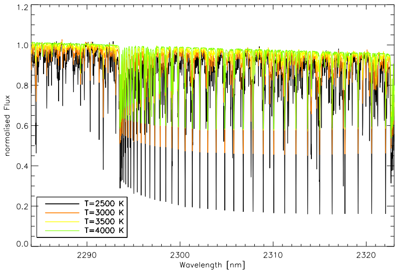


- DR plays a key role in dynamo on the multipolar branch
  Schrinner, Petitdemange & Dormy (2012)

➡ Clue to assess parallel observations/numerical models?

Observations of DR in VLMS

- CO band at 2.3 μm
  - Landé factors ~ 0
  - Several 10s deep lines
  - Low spot-to-photosphere contrast
- CRIRES observations
  - R=10^5
  - $\sim$ Full CO band
  - Deconvolve rotation profile
  - Use ratio zeros FT



PHOENIX models, S. Wende

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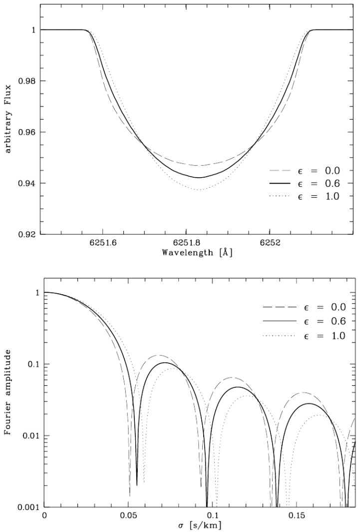
    - *Reiners & Schmitt (2002+)*
    - $\sim$ 10 dMe w/ moderate $v \sin i$

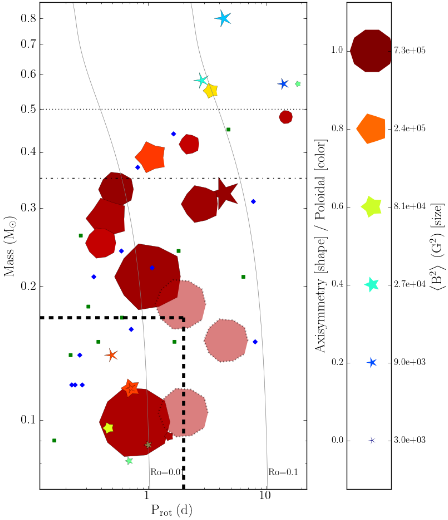


Reiners & Schmitt (2002)

Summary and conclusions

- M dwarfs: prime interest for dynamos
  - non-solar dynamo
  - fast-rotation
- Observations
  - Unpolarized spectroscopy
  - Spectropolarimetry
    - Bistable domain VLMS/fast rotation
- Theory/Simulations
  - Ro_ℓ ➔ drives **B** geometry
  - Bistable domain
  - Interplay DR ↔ **B**

➔ More to come !



CFHT 2013 observations

Summary and conclusions

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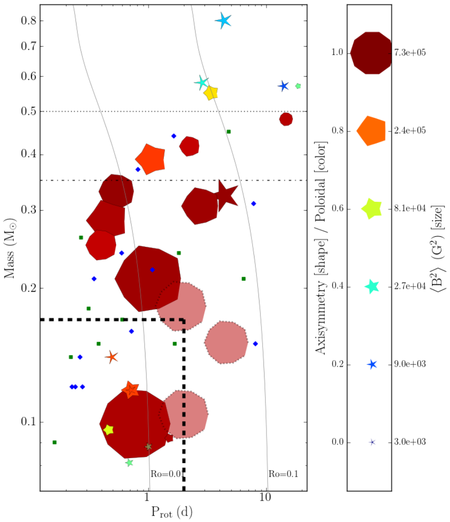

CFHT 2013 observations