Surface and Circumstellar Magnetism of Cool Evolved Stars
recent results and open questions


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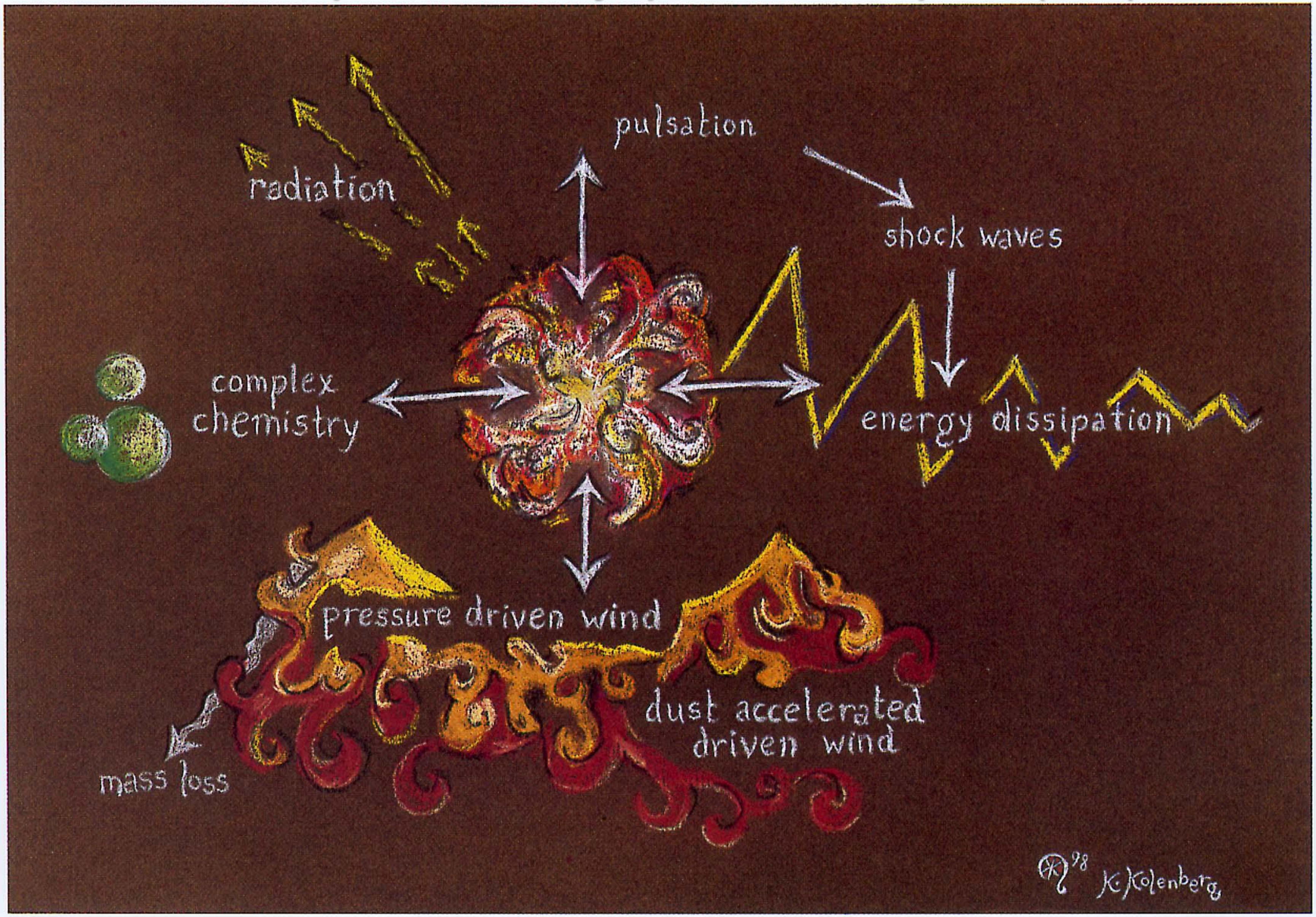
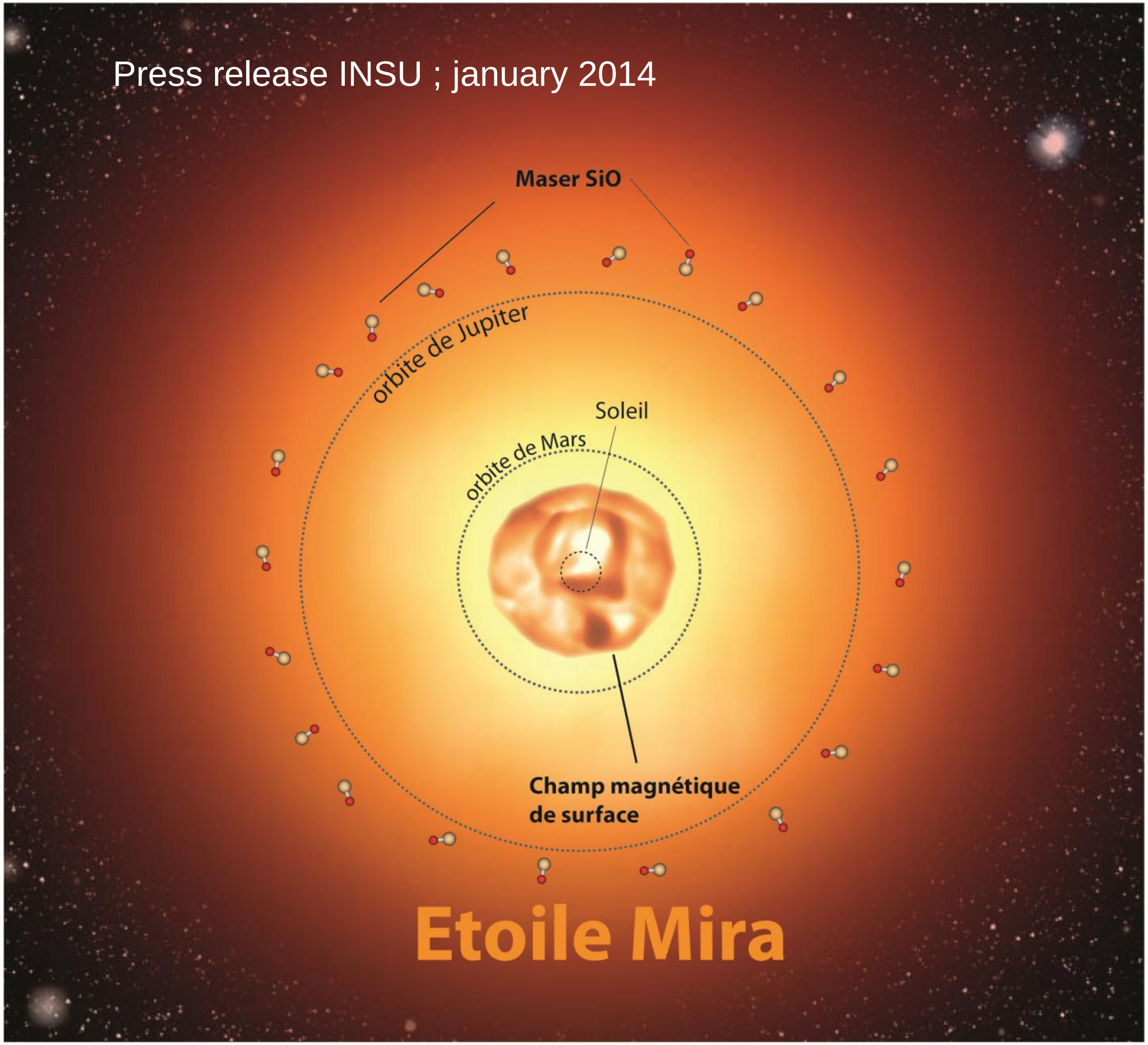
The old AGB picture ! IAU Symposium in Montpellier (1998)




Press release INSU ; january 2014
Maser SiO
orbite de Jupiter
Soleil
orbite de Mars
Champ magnétique
de surface
Etoile Mira

Outline :

-**Cool Evolved stars :** sharing main characteristics and physical processes

- **Magnetism in Circumstellar Envelopes** (Radioastronomy)

- **Surface Magnetic Fields** (Spectropolarimetry)

  - **Tracing Zeeman effect with circular polarisation** (Stokes V)

  -**RGB & early-AGB magnetic fields** — Active giants (global dynamo) / Descendant of Ap stars (magneto-convection)

  -**TP-AGB magnetic fields (Mira stars)**

  -**Post-AGB stars (RV Tauri stars) / PN magnetism** — Amplification by shock waves ? (TP-AGB and Post-AGB)

  -**RSG magnetic fields (special focus : Betelgeuse)** — Turbulent dynamo

- **Perspectives and New Challenges**

Cool Evolved Stars

Main characteristics :

RGB, RSG stars : core He-burning phase

AGB stars : He- and H-shell burning phase

T*eff = 4000-2500 K ; log g = 0 − 2*

Convection :

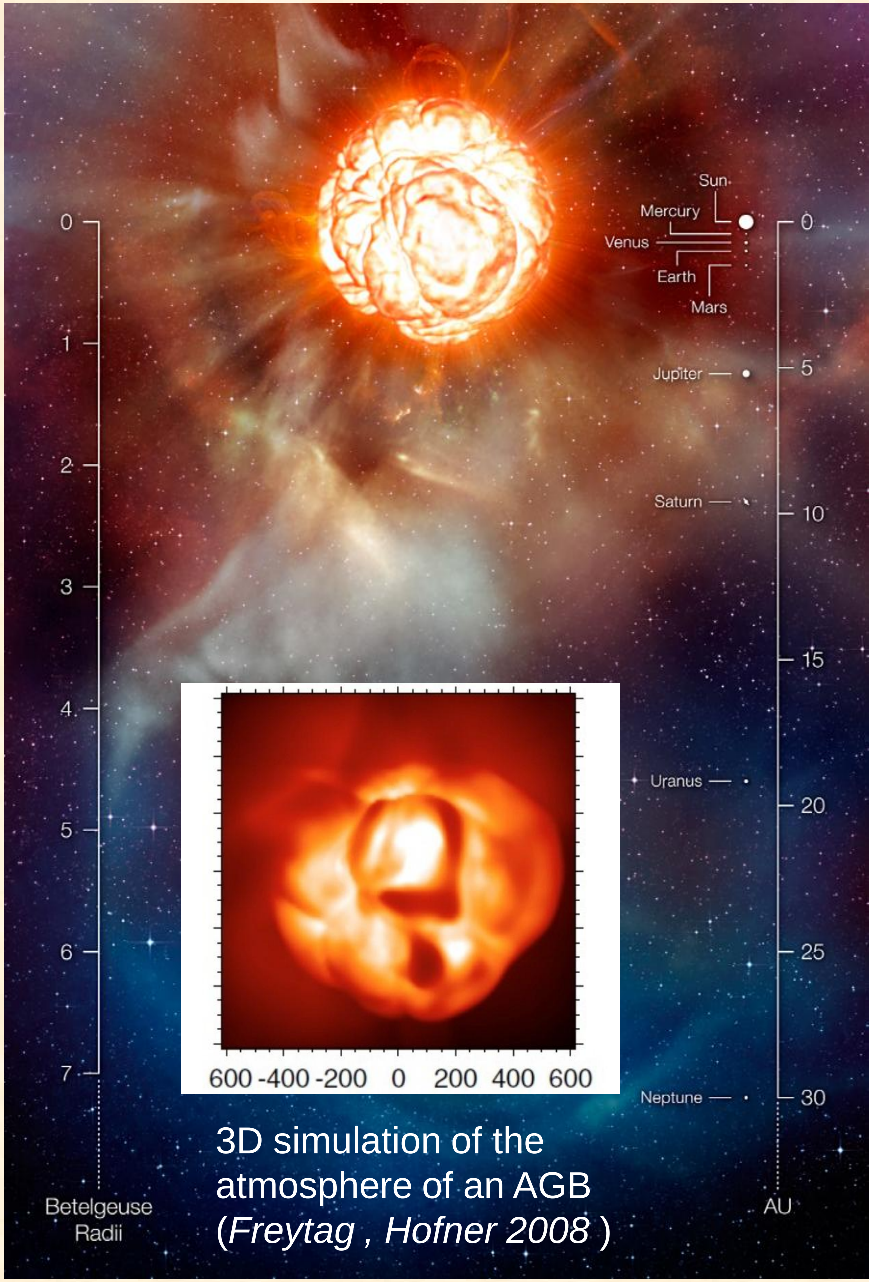
Large-scale convective motions
in an extended atmosphere,
with a few giant cells covering the surface
(Schwarzschild,1975)

Radiative hydrodynamic simulations
(Chiavassa+ 2010)

In RSG : convection is expected to generate supersonic motions and shocks

In AGB (Miras) : pulsation is expected to generate shocks (also in some Post-AGB)

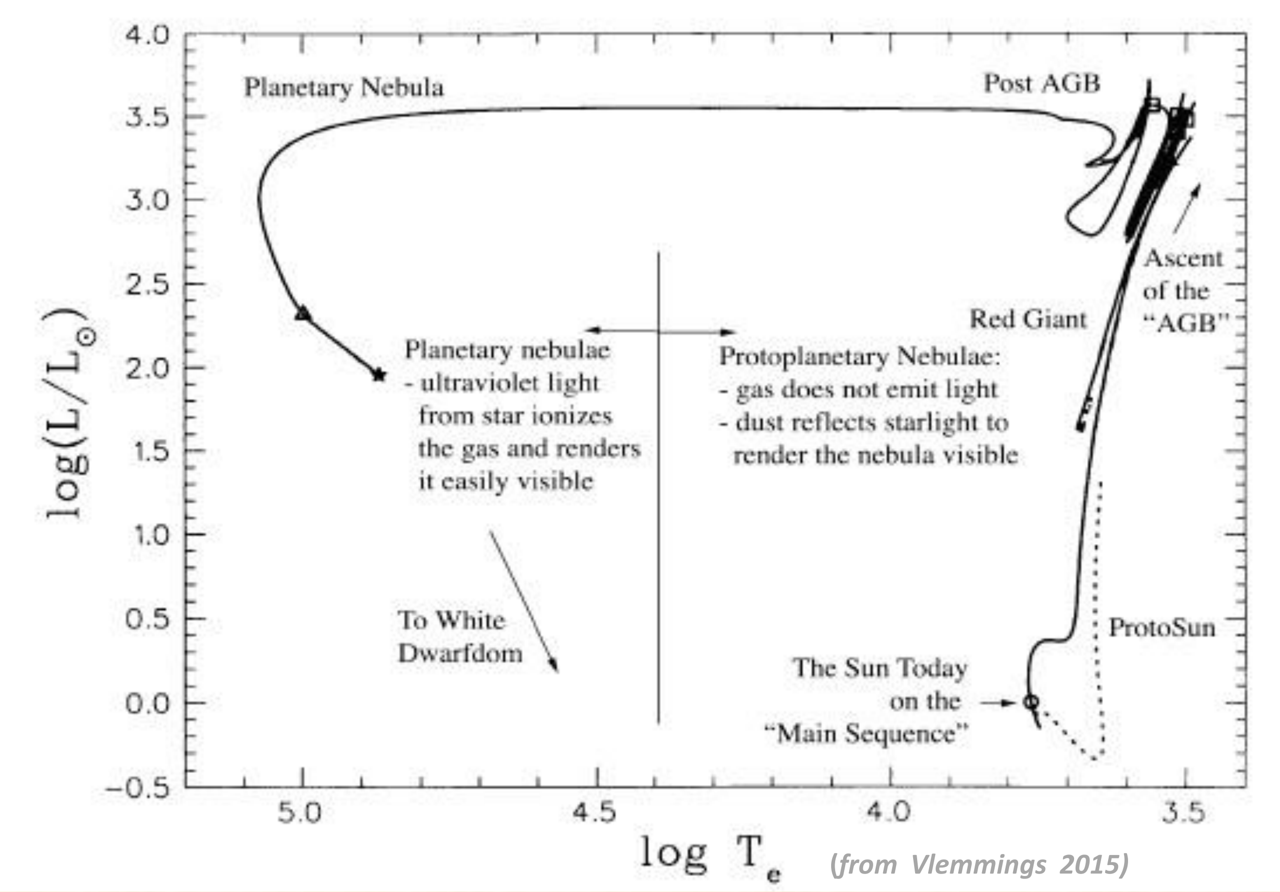
=> **convection-pulsation**



3D simulation of the atmosphere of an AGB (*Freytag , Hofner 2008*)

Cool Evolved Stars

Evolutionary path of an **intermediate mass star** before its transition toward the Planetary Nebulae stage.



(from Vlemmings 2015)

Convection

Large-scale convective motions in an **extended atmosphere**, with **few giant cells** covering the surface *(Freytag & Höfner, 2008)*

Pulsation (Mira/RV Tauri)

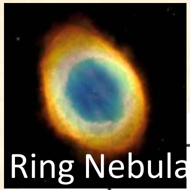
periodically generate **radiative shocks waves** => convection-pulsation

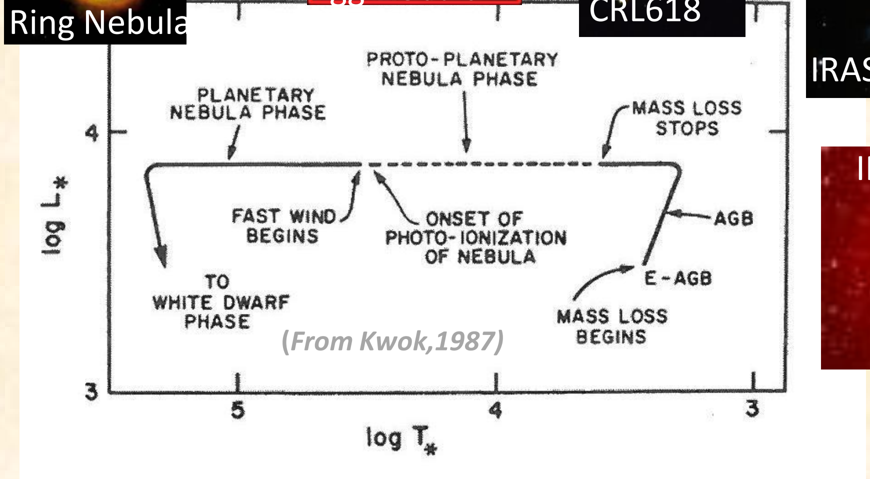
Mass loss

Heavy mass loss : radiation pressure on dust *(Höfner, 2011)* levitation due to shocks

WHAT ELSE … ?

Cool Evolved Stars





(From Kwok,1987)

(HST images)

During the transition from AGB to PN :

- Severe change of the morphology of the circumstellar envelope (departure from spherical symmetry)

- Evidences of magnetically collimated oulflows

Binarity ? Magnetic fields ? Both ?

and

Observational evidences of magnetic fields around AGB, post-AGB, pre-PNe and PNe

Magnetic Fields at the Surface of cool and evolved stars ?

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Circumstellar Magnetic Fields

Magnetic field strength and structure from

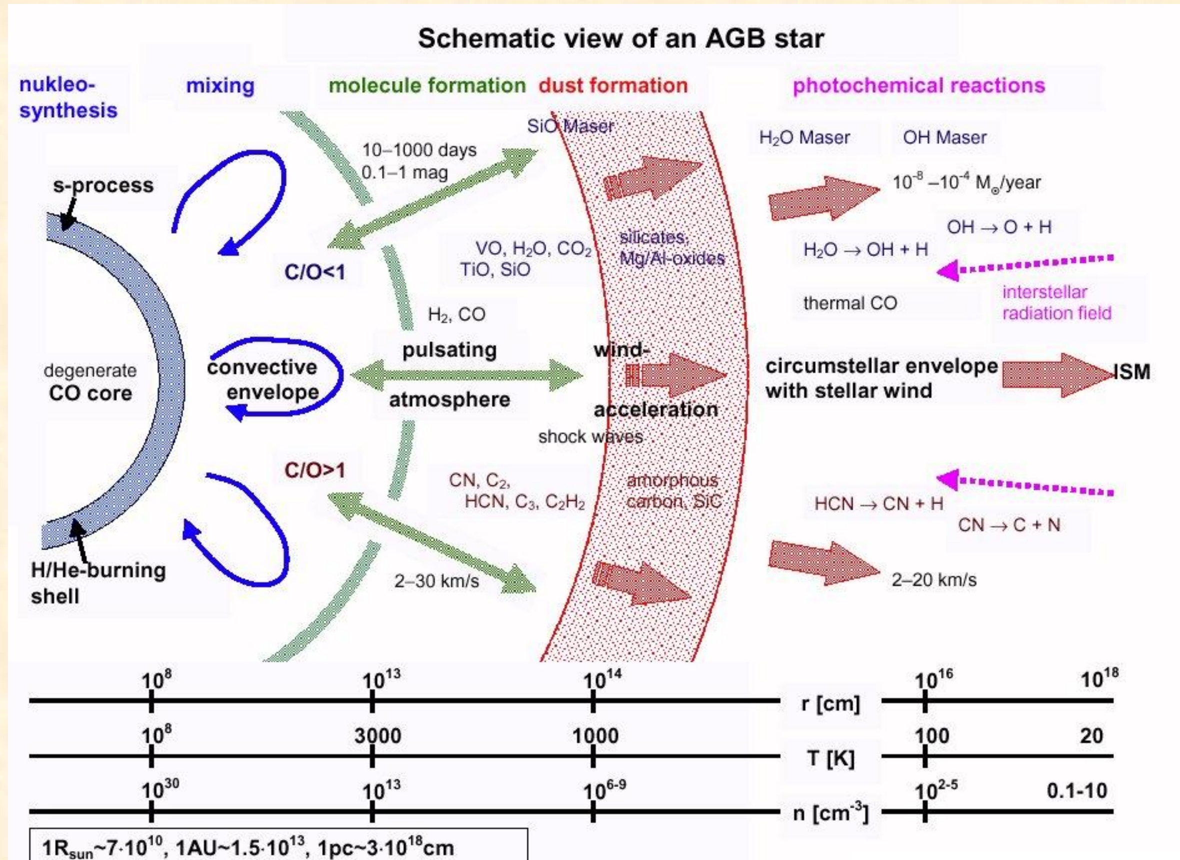
Circular polarization (generated through Zeeman splitting)
=> Line of sight component of Magnetic Field + constraints on its geometry

Best tracers
(compactness and strength) :
maser circular polarization
(sub)-mm regime

typical molecules
probing different zones in CSE

SiO, **H_2O**, **OH** for O-rich stars

CN lines for C-rich stars
(Herpin, 2009 + PhD. A. Duthu)
1rst attempt to detect
Zeeman splitting
of non-maser molecular lines



(From J. Hron)

Magnetic Field strength in AGB envelopes

O-rich Miras :
SiO at 2 R*
B ~ 3.5 (up to 10s) G
Assuming Zeeman

H_20 at ~ 5-80 AU
B ~ 0.1 – 2 G

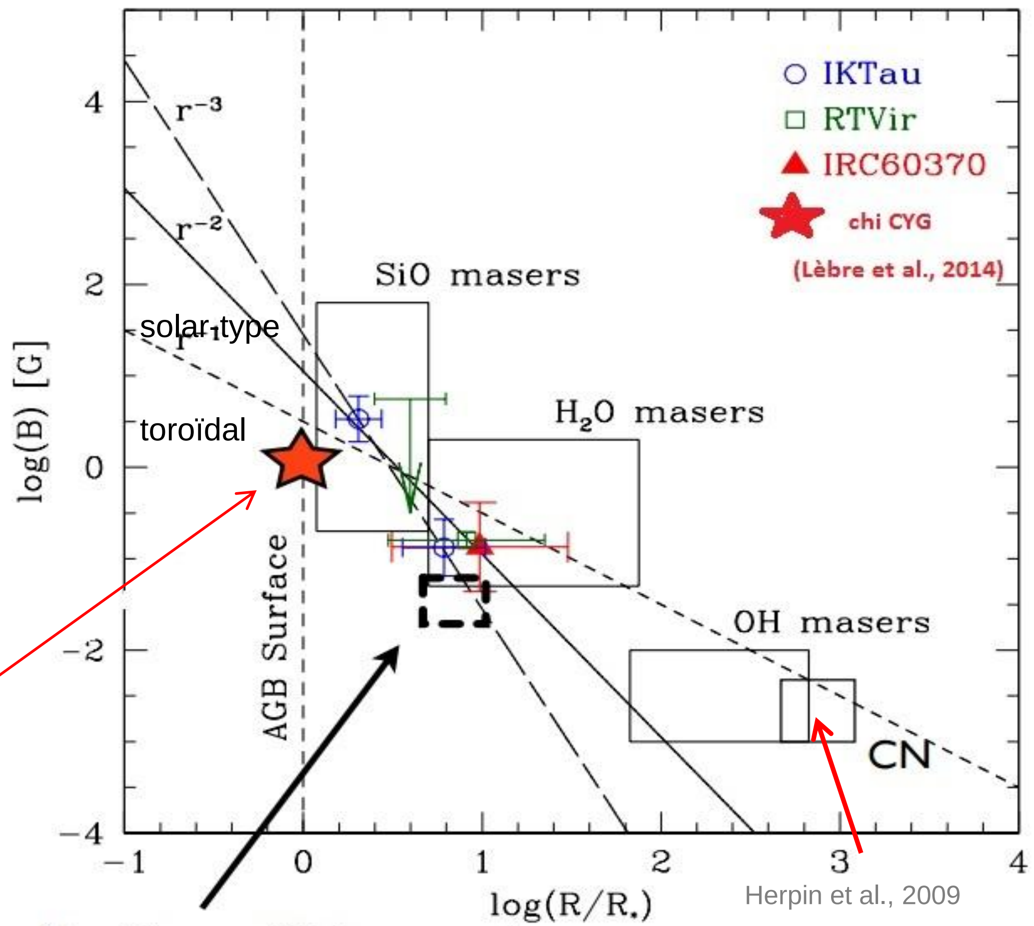
OH at 100-10 000 AU
B ~ 1-10 mG

C-rich Miras :
CN at ~ 2 500 AU
B ~ 7-10mG

Geometry of the field :
Toroidal field B ~ 1/r

→ **Extrapolation ?**
the magnetic field strength
at the stellar surface of Miras
could be of the order of a few G.

Magnetic field strength vs. radius



Herpin et al., 2009
Non-Zeeman SiO interpretation
Houde 2014
Leal-Ferreira et al. 2013
after Vlemmings et al. 2002,2005

Circumstellar Magnetic Fields

Magnetic field strength and structure from

Linear polarization (generated through anisotropy with/without magnetic field)
=> Structure of the plane of sky component of Magnetic Field

Observed both
-in the dust (through aligned grains) => strength of MF

- in the molecular lines (through radiation anisotropy and small Zeeman splitting)
  = Goldreich-Kylafis effect *(Kylafis, 1983)*

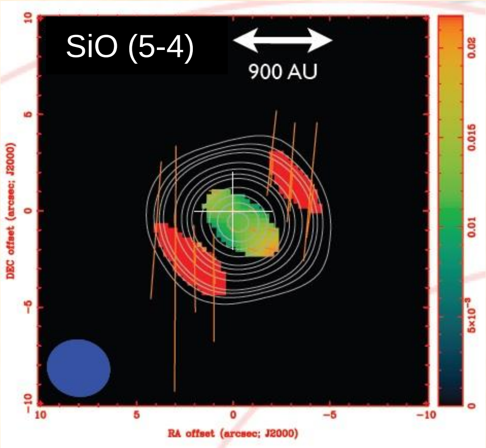
CO & SiO, H_2O, OH masers => 3D field morphology (in few specific cases)

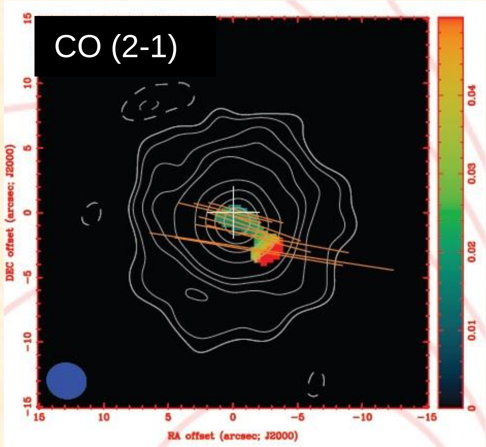
e.g., 1rst map (SMA) of GK effect in CO lines on the Mira IK Tau *(Vlemmings+2012)*
IK Tau shows consistent large scale field from thermal SiO out to CO(2-1)

Now with ALMA !

On the Mira X Cyg
(Tafoya, Vlemmings in prep.)

Toward a full description of the circumstellar magnetic field structure !





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Surface Magnetic Fields (spectropolarimetry)

ESPaDOnS@CFHT
2004+
3.60m Telescope

Narval@TBL
2006+
2mTelescope

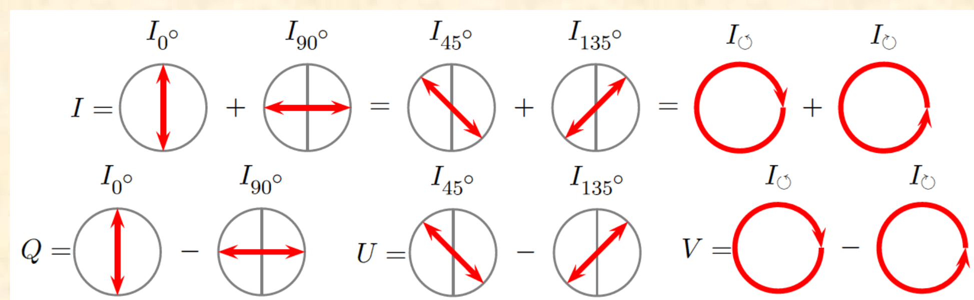
HARPSpol@ESO
2009+
3.60m Telescope

Spectral Range : 375 – 1050 nm Spectral Resolution : 65 000

Spectral Range : 380 – 690 nm Spectral Resolution : 115 000

Simultaneous measurements in two polarisation states :

$\Rightarrow$ Stokes I (unpolarised) spectrum
\+ Stokes V (circular)
or Stokes U (linear) } polarised spectrum
or Stokes Q (linear)

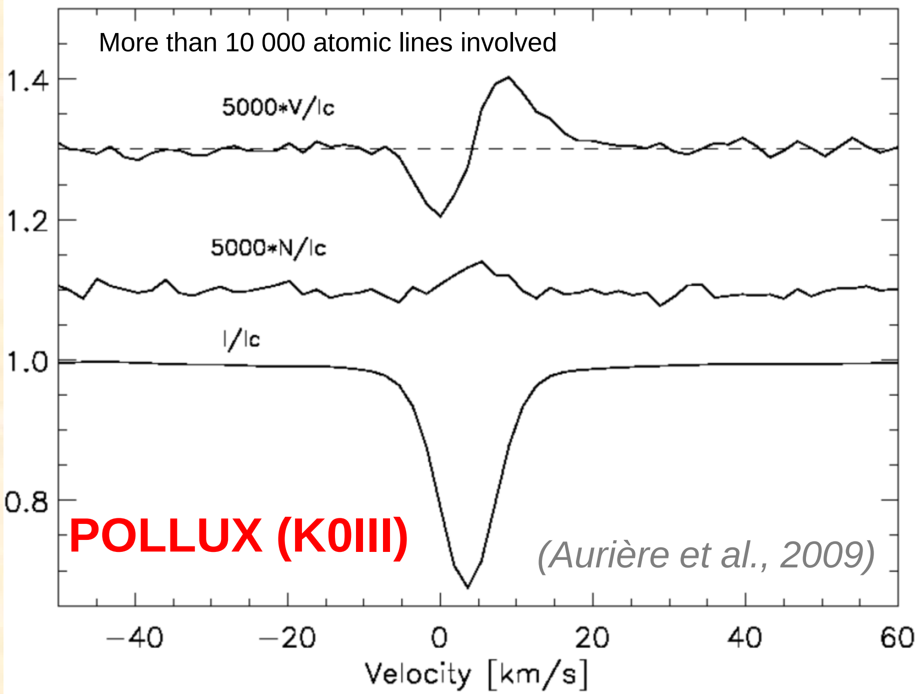


$\Rightarrow$ Polarisation (circular or linear) **within spectral** (atomic) **lines**

Polarimetric sensitivity $\sim 10^{-4}$ of the unpolarised continuum

Tracing Zeeman Effect with Circular Polarisation

Zeeman detection : sub-Gauss field



Mean Zeeman shift of a transition

$$\Delta\lambda_B = \frac{\lambda_0^2 e B}{4\pi m_e c^2} = 4.67 \times 10^{-12}\, \lambda_0^2 g_{eff} B$$

g_{eff} : Landè factor (sensitivity of a transition to B)

If **weak magnetic field** (< 100 G) :

Polarised signatures undetectable at the level of individual lines

=> A multiplex approach
over the observed spectral range
(thousands of atomic lines involved through a LSD Mask)

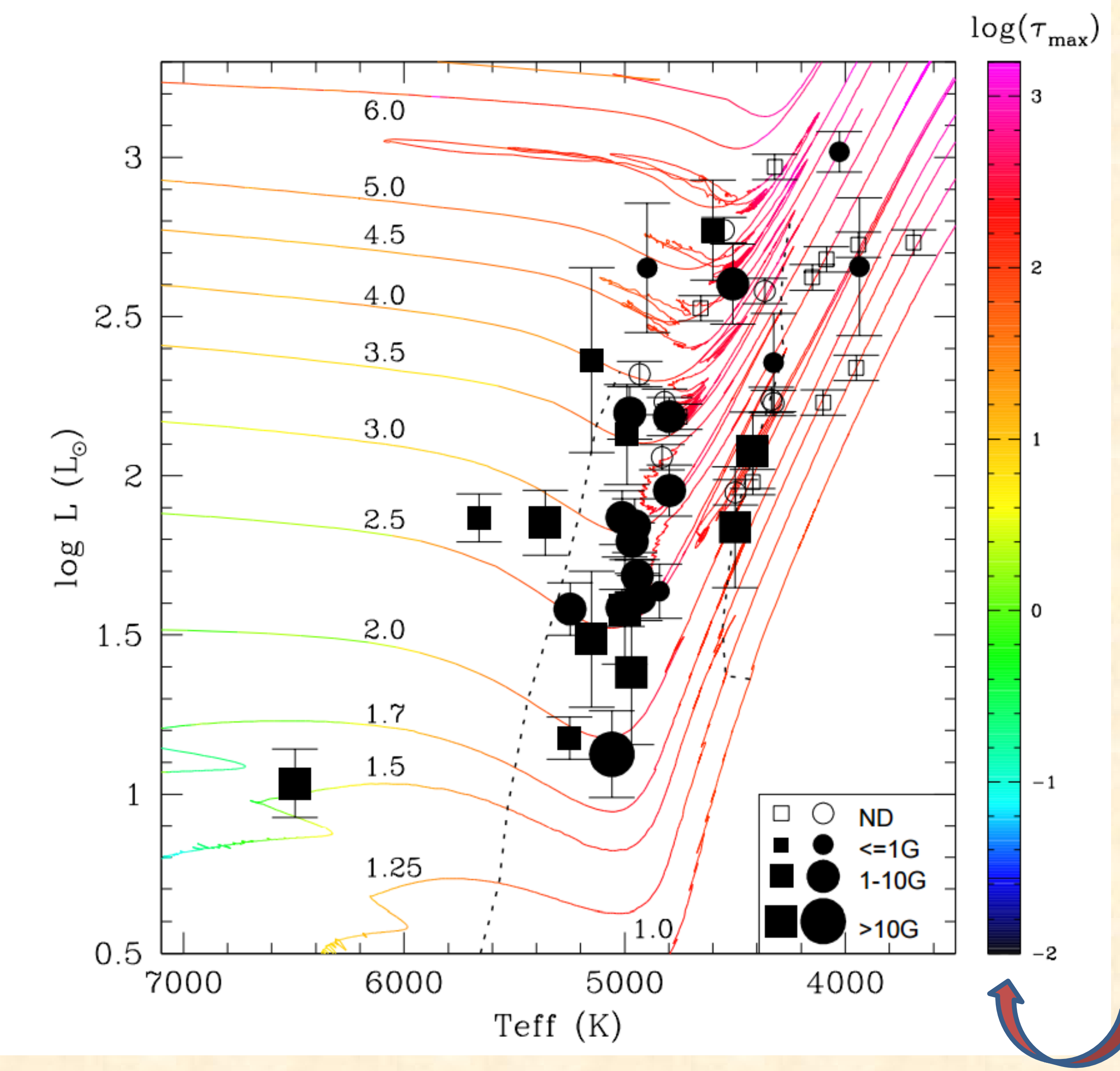
The Least Square Deconvolution (L.S.D.)
(Donati et al., 1997)

Estimation of Bl, the **Longitudinal Component of the Magnetic Field** :

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

First-order moment method
(Rees & Semel, 1979)
adapted to LSD profiles.

RGB & AGB surface magnetic fields (Aurière et al, 2015, A&A 574, A90)



Sample of 48 single G-K giants
(24 with activity signatures)

29 Zeeman detections
(with Narval/ESPaDOnS

The most active magnetic giants are concentrated in a

« Magnetic Strip » ?

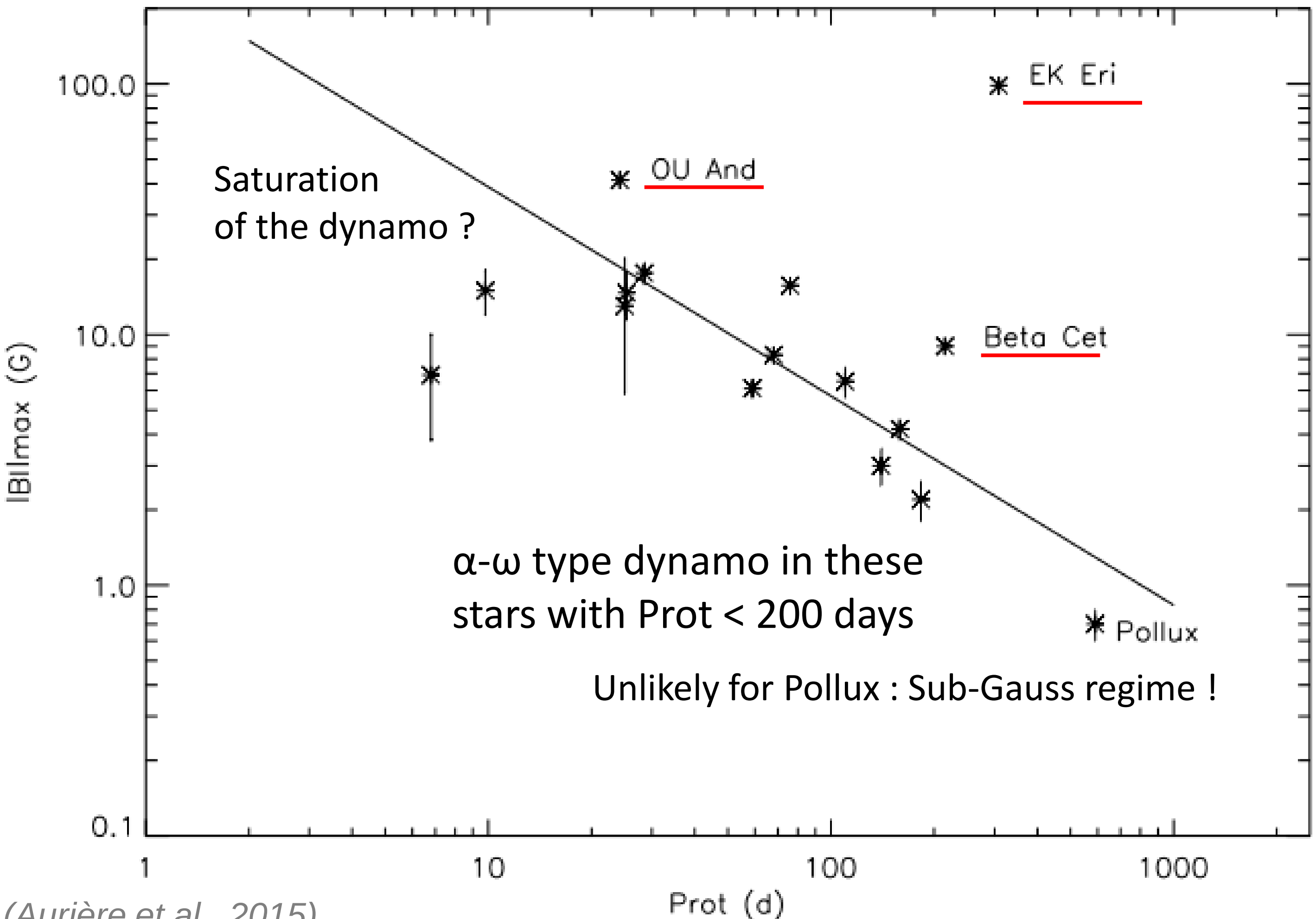
1rst Dredge-up and
Core Helium burning phases.

Evolutionnary models
Solar metallicity with rotation
(from C. Charbonnel et al.)

Convective turnover timescale
$\tau_{max} = (\alpha H_p) / V_{conv}$

Preliminary trends with rotation from 16 G-K Giants

with **known rotational period (Prot** from few 10s of days to few 100s of days)



(Aurière et al., 2015)

Ap star descendant candidates :

fossil field interacting with convection

(Aurière et al., 2011; Tsetkova et al., 2013)

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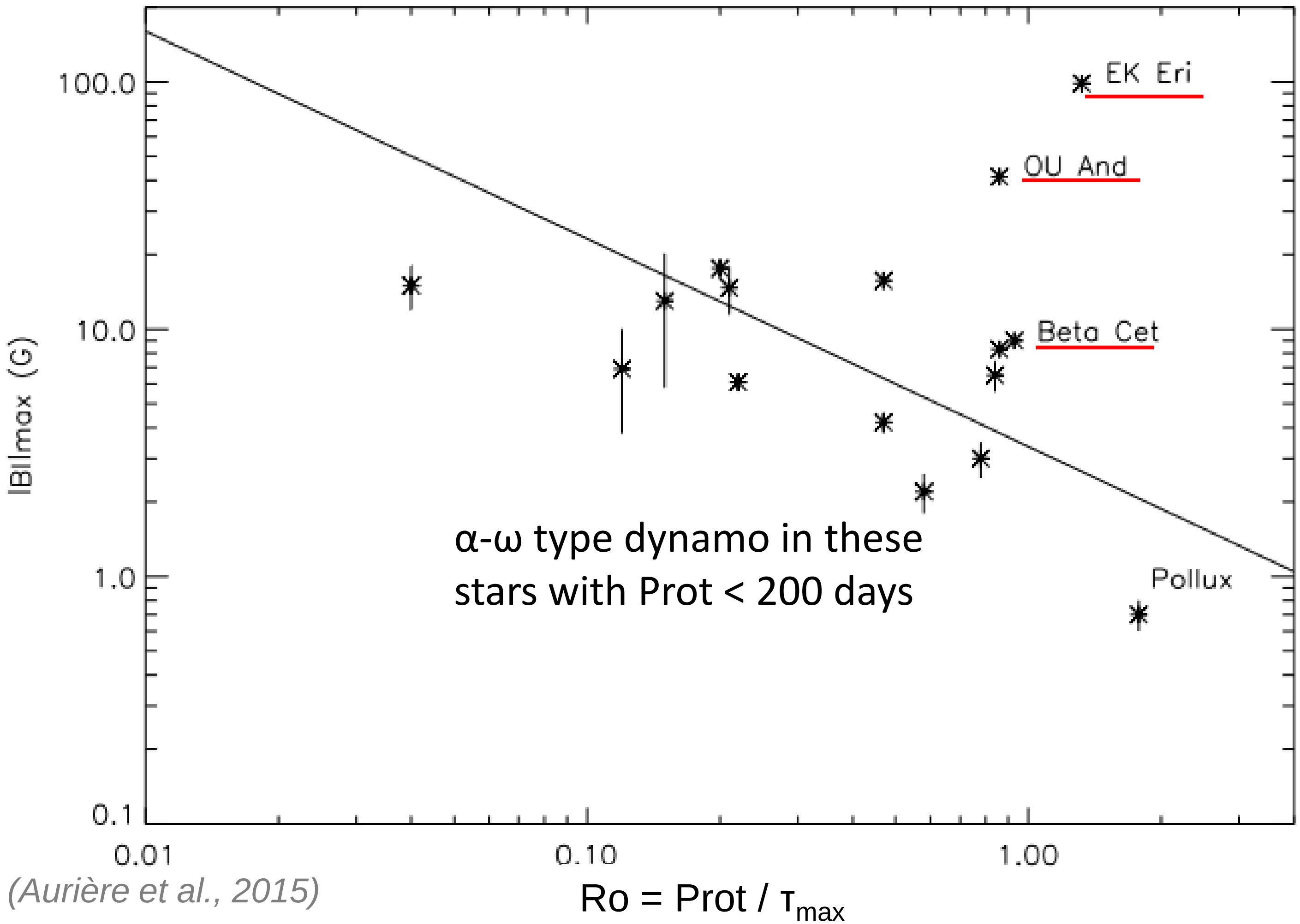

(Aurière et al., 2015)

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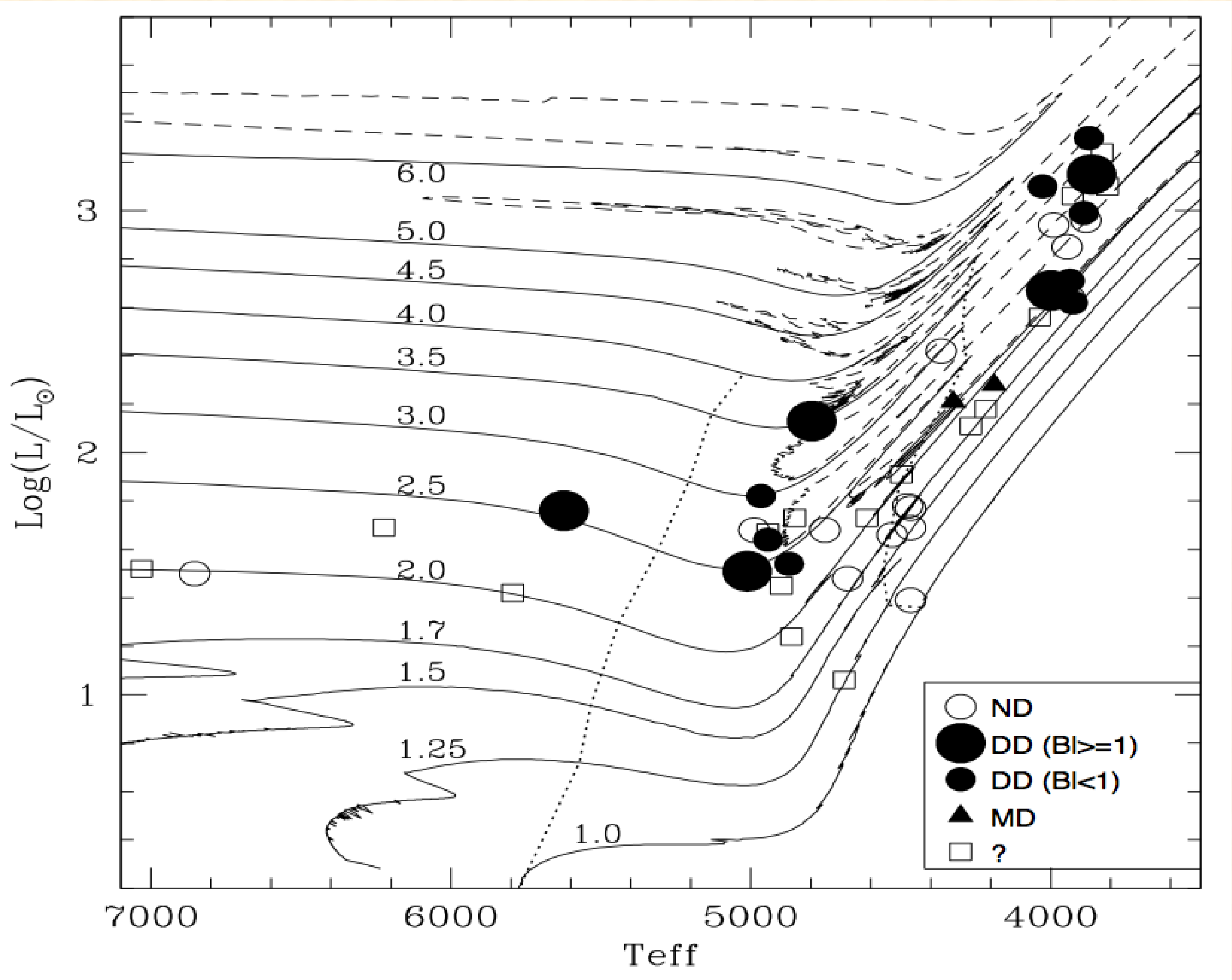
Ro :

Rossby number
Ratio of inertial to Coriolis force

RGB & AGB surface magnetic fields *(Konstantinova-Antova et al. 2014, UAI 302)*



Exploration of unbiased sample (magV < 4)

40 Red Giants (with Narval/ESPaDOnS)

Magnetic RGB/AGB with Bl < 1 Gauss (e.g. Pollux)

« 2nd magnetic strip » :

Tip RGB / AGB

- low surface rotation
- convection

⇒Local dynamo ?

Transitory fields ?

~ 50 % of RGB/AGB with a magnetic field at the Gauss level
Magnetic field and activity is more common than expected !

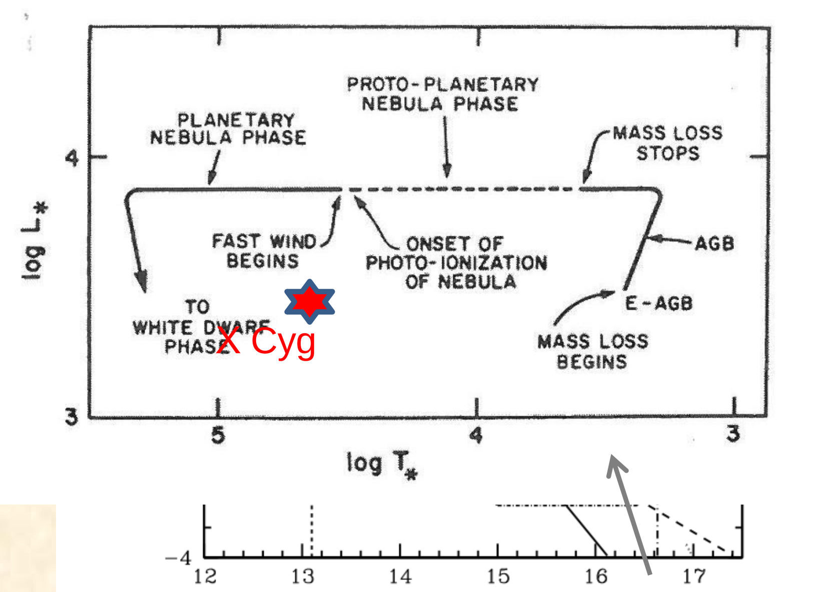
Tip of AGB - Post-AGB stars -PNe

Detection of magnetic fields from Masers SiO & CN lines in their environment *(Vlemmings+ 2011)*

=> Geometry of the field : *B ~ 1/r ...*

(Herpin et al. 2006, 2009; Sabin et al., 2013)

=> Extrapolation toward the photosphere...



Herpin et al., 2009

Mira Stars

Common picture :

Hydrogen emission lines (Balmer) => shock wave propagation (atmospheric dynamics)

Time variable linear polarization associated to Balmer lines *(Fabas et al., 2011)*

***o Ceti* and *R Leo* (M-type Miras)**

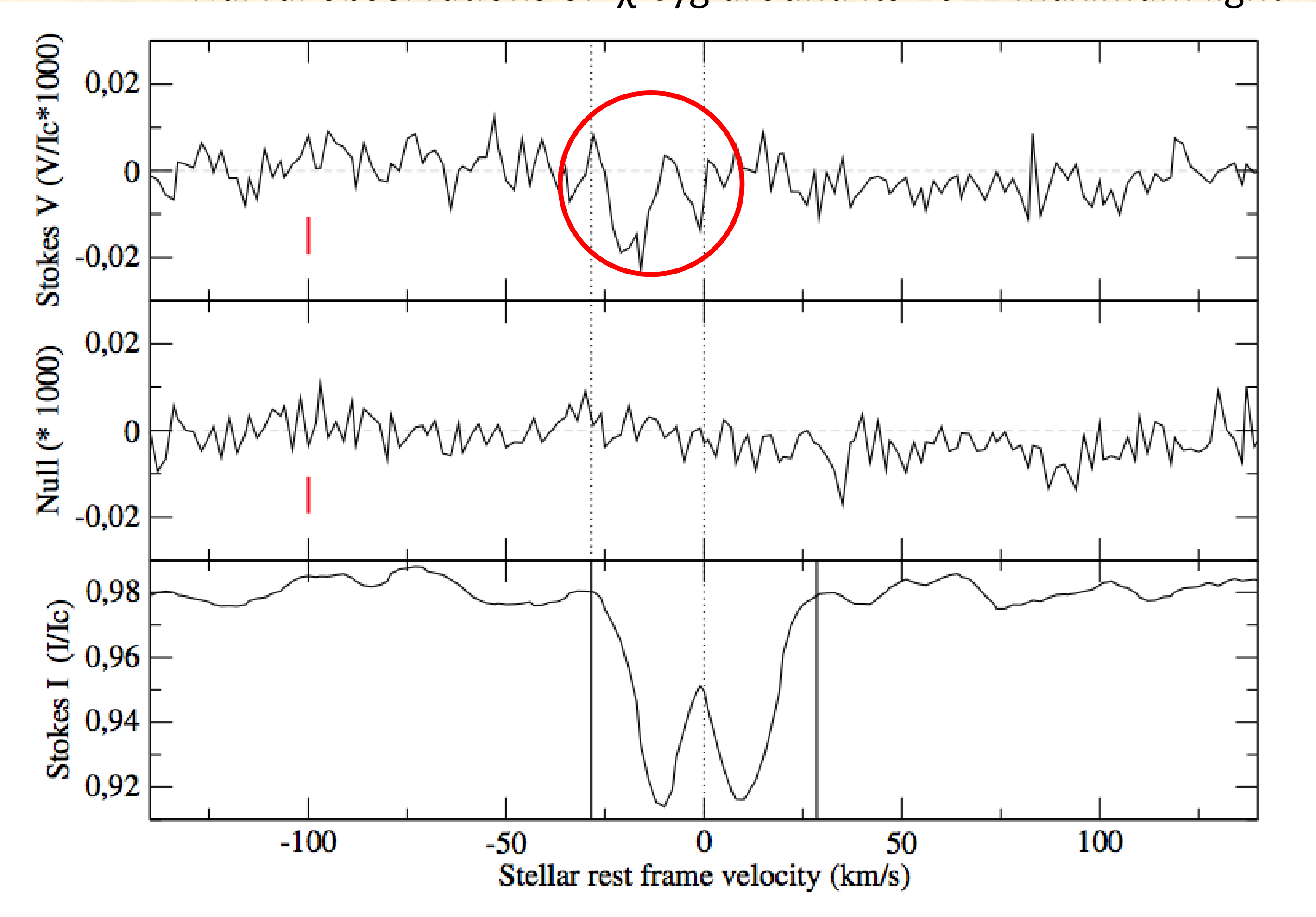
Photospheric magnetic field (~ a few G) expected from theoretical works *(Thirumalai & Heyl, 2013)* but not detected (so far ?) with Narval

***χ Cyg* (S-type Mira)**

Detection of a weak photospheric magnetic field *(Lèbre et al., 2014)*
=> Connexion surface magnetic field - atmospheric shock wave

First detection of a surface magnetic field on a Mira star

Narval observations of χ Cyg around its 2012 maximum light



Definite Detection

$\chi 2=1.81$,

fap=5.2 10^{-10}

a (magnetic) Zeeman effect origin

Surface field estimation : 2-3 G

Stokes V signal : associated to the blue component of the I profile

Stokes I profile : **typical line doubling of metallic lines** due to **a shock wave** in the atmosphere.

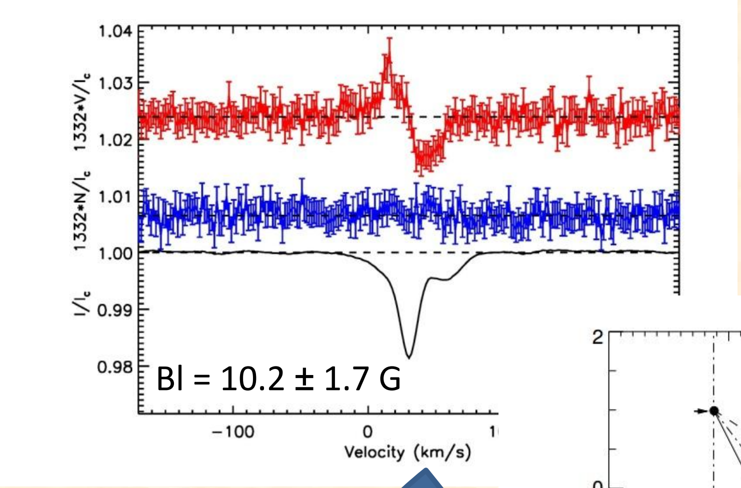
(Lèbre et al. 2014, A&A 561, 85)

Post-AGB stars (incl. Pulsating RV Tauri stars)

RV Tauri stars

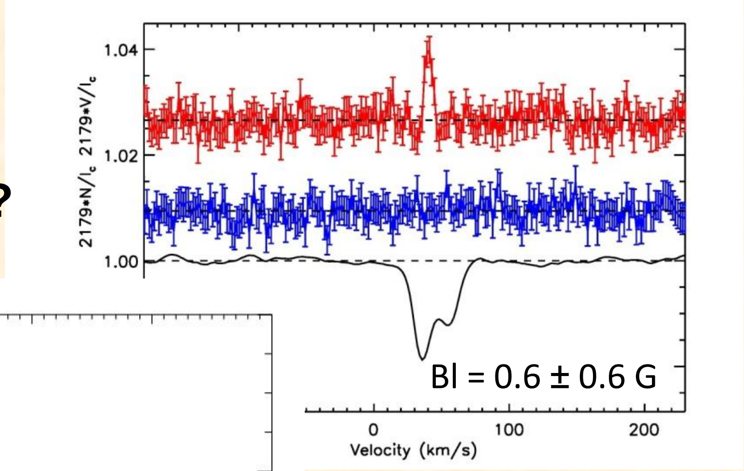
The first positive detections of a photospheric magnetic field *(Sabin et al., 2015)*

U Mon (ESPaDOnS april 2014)
pulsation period ~ 92 days

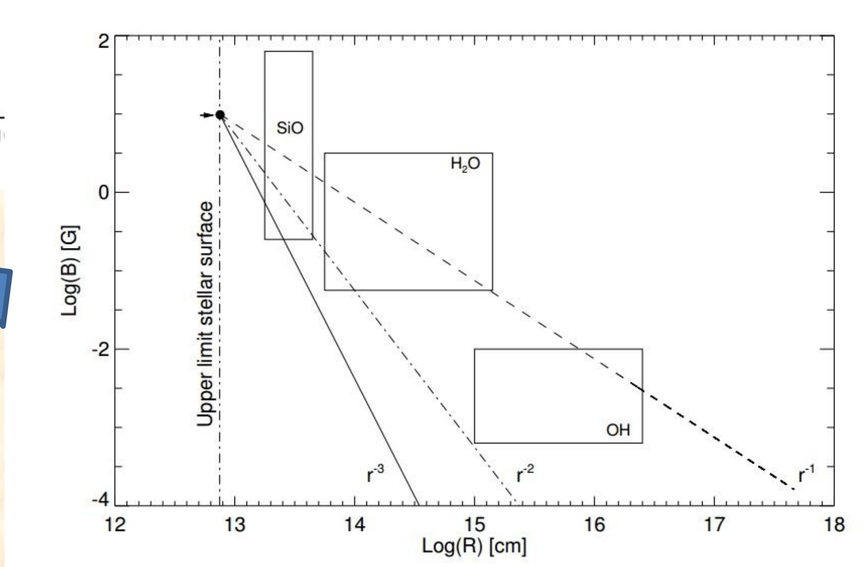


Impact of atmospheric shock waves?

R Sct (Narval july 2014)
pulsation period ~ 142 days



Prediction of maser strengths in the envelope of U Mon ?



Favoring again toroidal field *(Sabin et al., 2015)*

Planetary Nebulae

small-scale structures due to magnetic fields
e.g. Spirograph nebula *(Huggins et al. 2011)*

Central Star of Planetary Nebulae

From FORS2@VLT (low resolution spectropolarimetry) :

Early controversial detections *(Jordan+2012 ; Leone+2014)*

No strong global magnetic field (KG !) from a sample of 12 bright CSPN but marginal and weak fields (below 100 G) in 3 targets *(Steffen+2014)*

Magnetic PN Shaping still not proven !

Time to move to the massive counterparts … RSG !

Magnetic fields in Red Super Giants (RSG)

Red Supergiants :

Are they all magnetic stars ?

Common occurrence

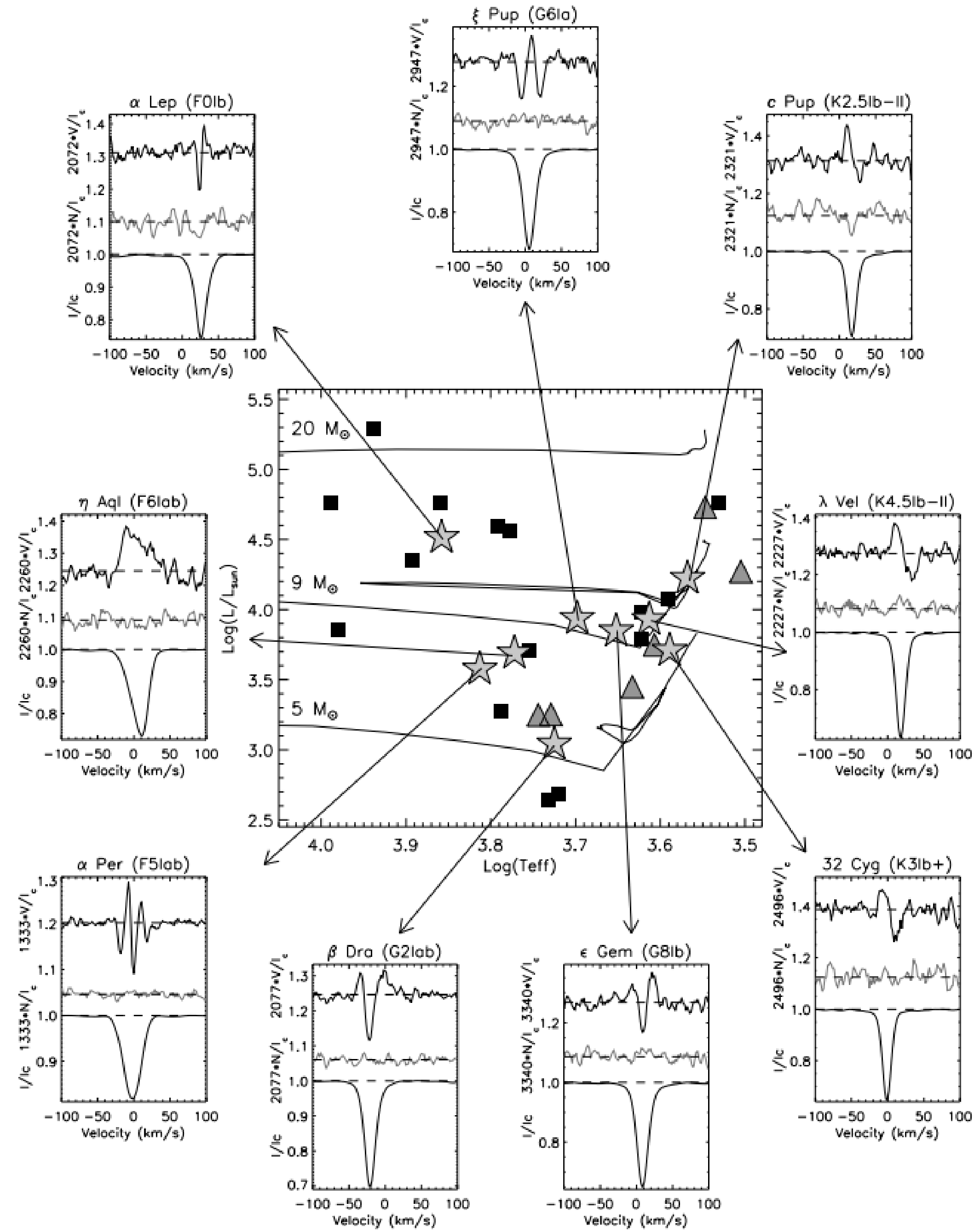
of magnetic fields at the

(sub-)Gauss level

in F- to K- type RSG.

(Grunhut et al. 2010)

In M-type RSG?



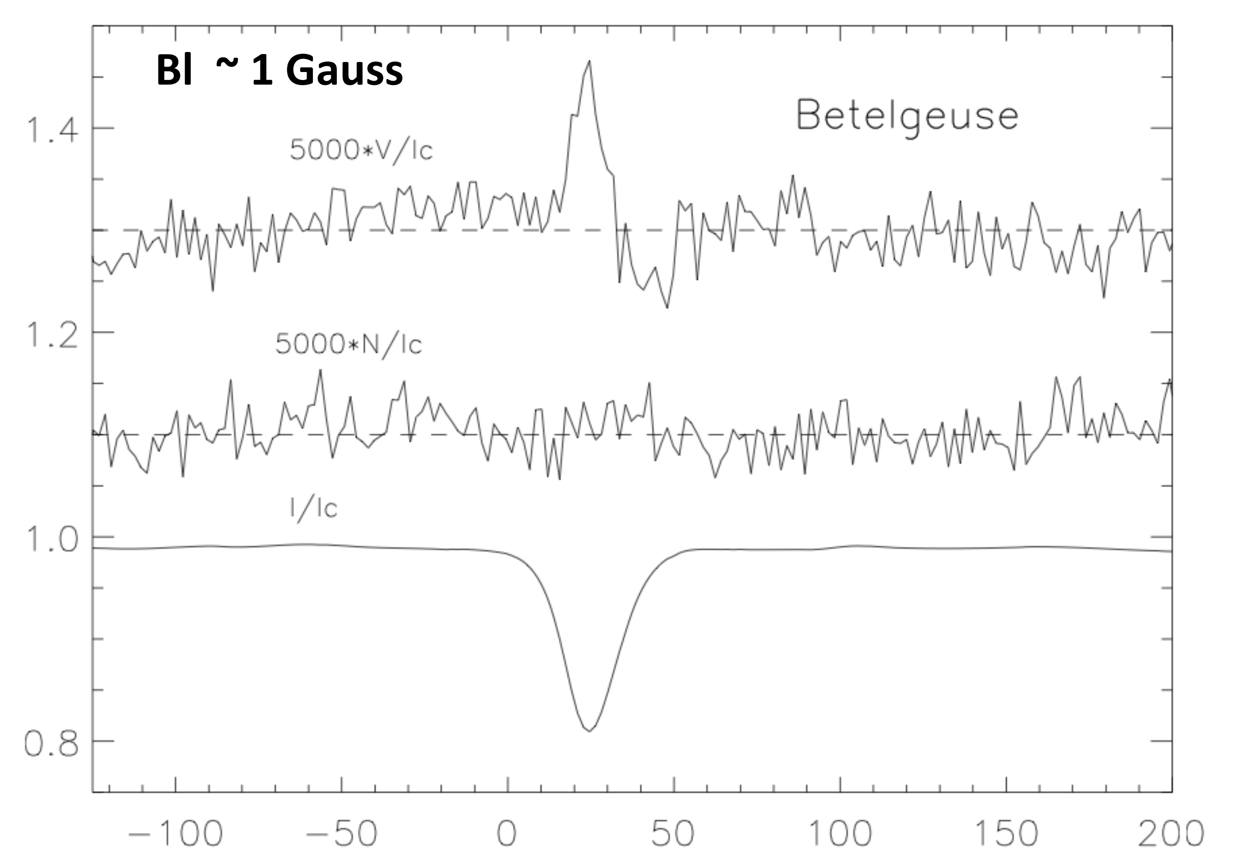
Detection of Surface Field in Betelgeuse (M-type RSG)

P_{rot} = 17 years
(Kervella et al., 2009)

$Ro \sim P_{rot} / \tau_{conv}$

=> $R_o \sim 90$

not able to sustain a α-ω type dynamo

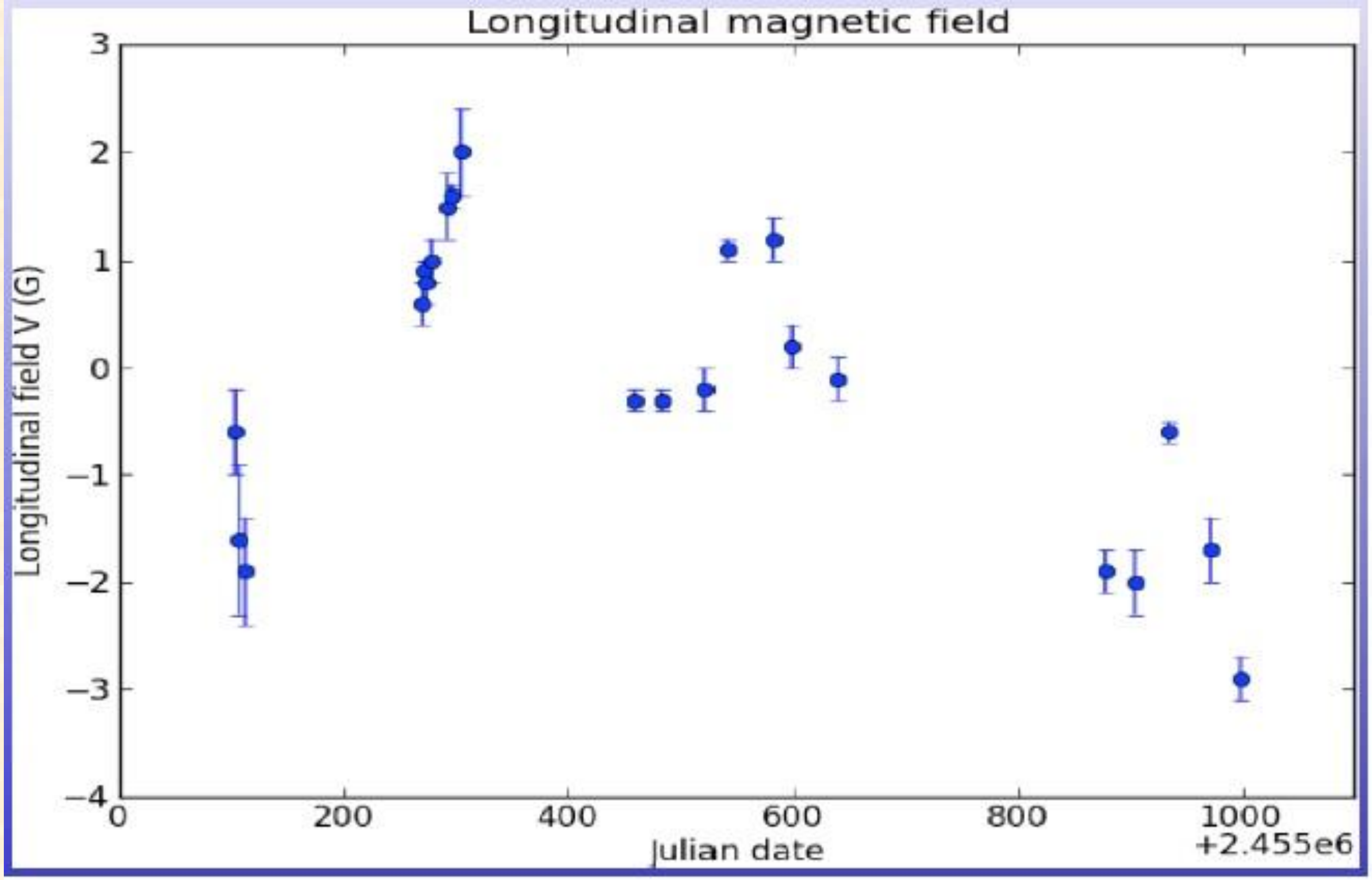


(Aurière et al., 2010)

The large-scale convective motions can generate **small-scale dynamo action,** and thus transitory fields.

Geometry of magnetic field remains unknown !

Variations of the Magnetic Field of Betelgeuse (2009-2012)



Field variability
< 1 month !

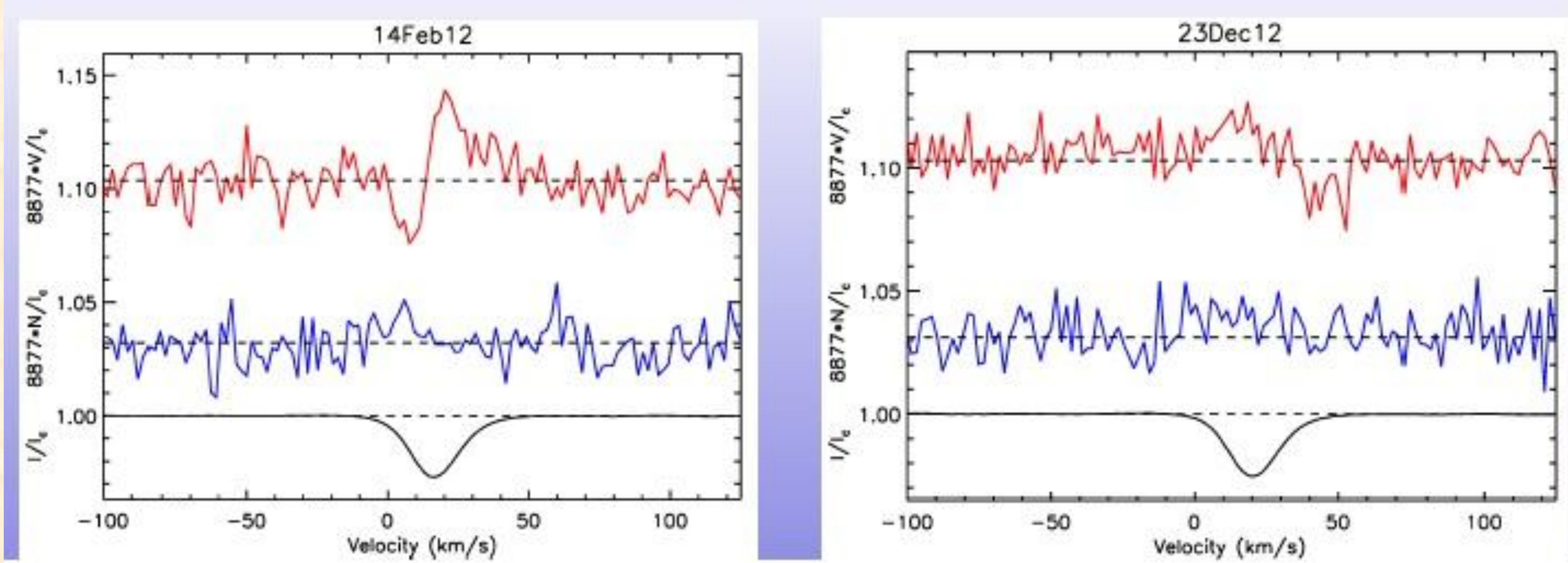
(stellar rotation
17 years !)

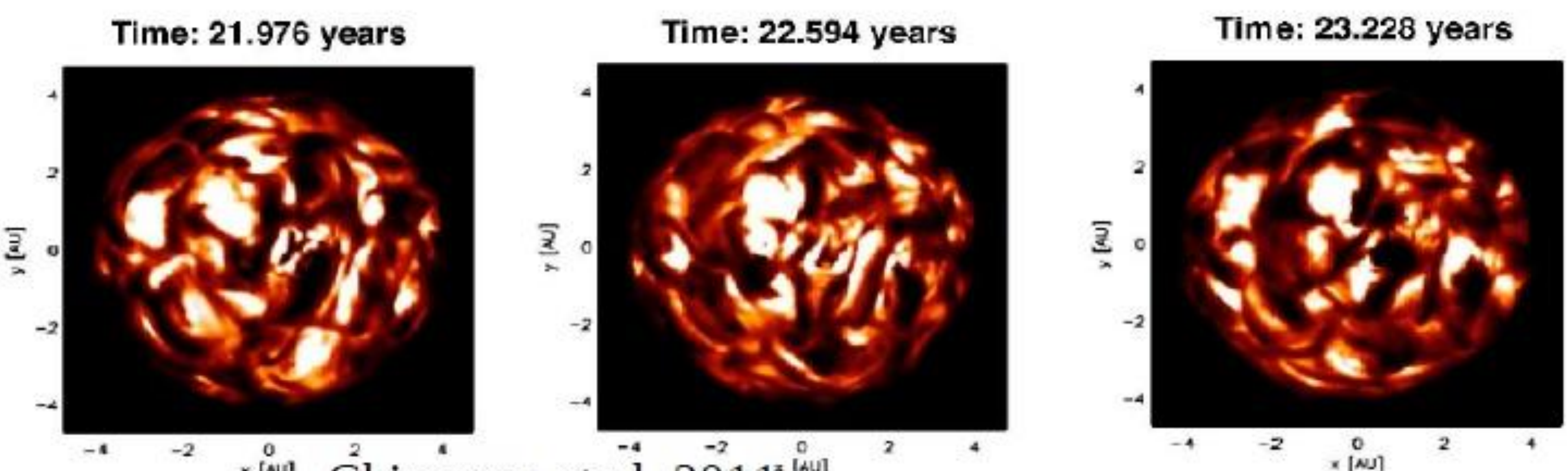
Consistent with convective timescales *(Dorch & Freytag, 2004)*

(Bedecarrax et al., 2013) + long term monitoring in progress with a Large program Narval

(Mathias et al., in preparation)

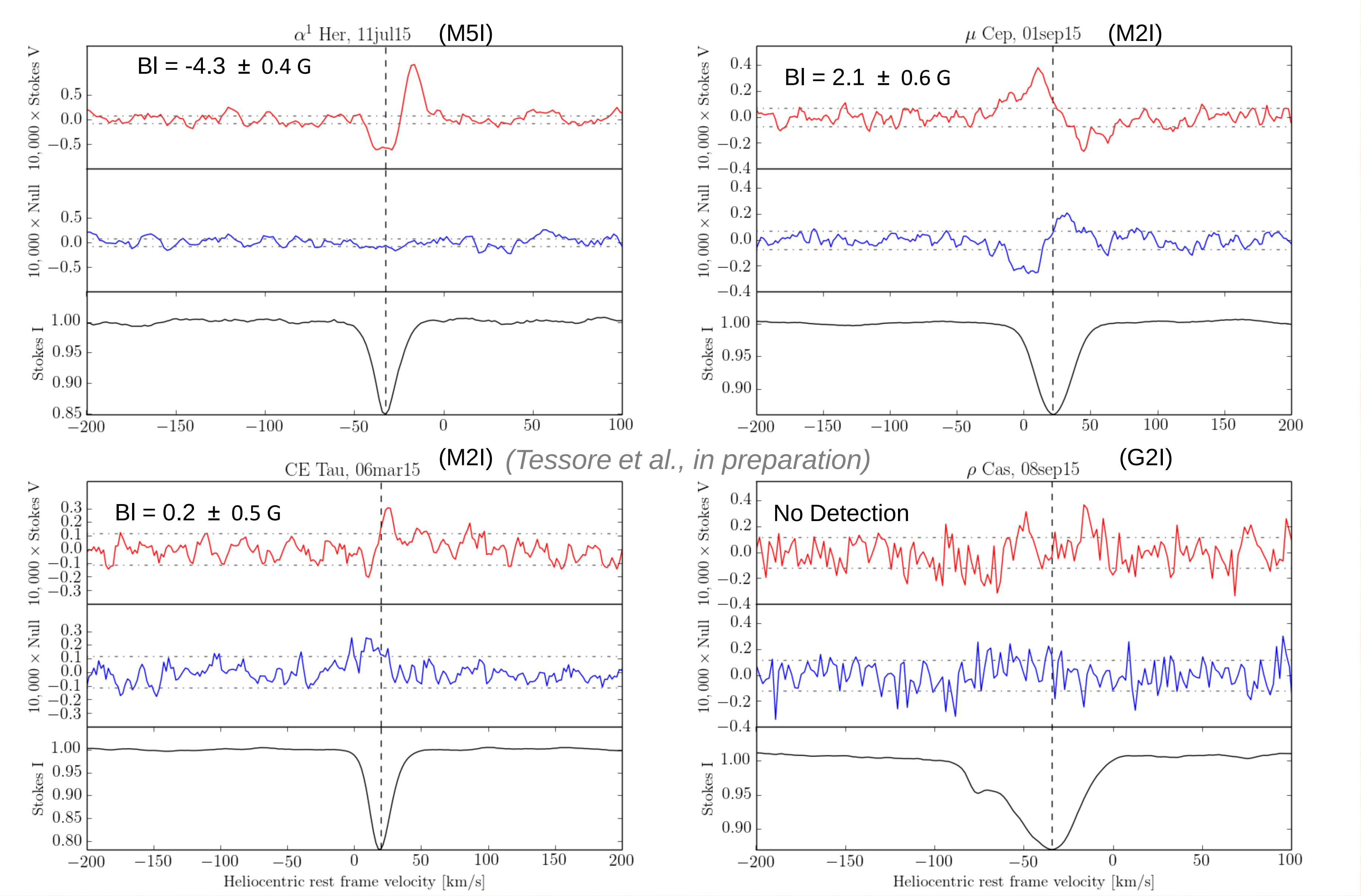
Field Variations at the Surface of Betelgeuse





Chiavassa et al. 2011

New DetectionS of Surface Field in other M-type RSG



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Theoretical predictions for magnetic fields at the surface of cool and evolved stars :

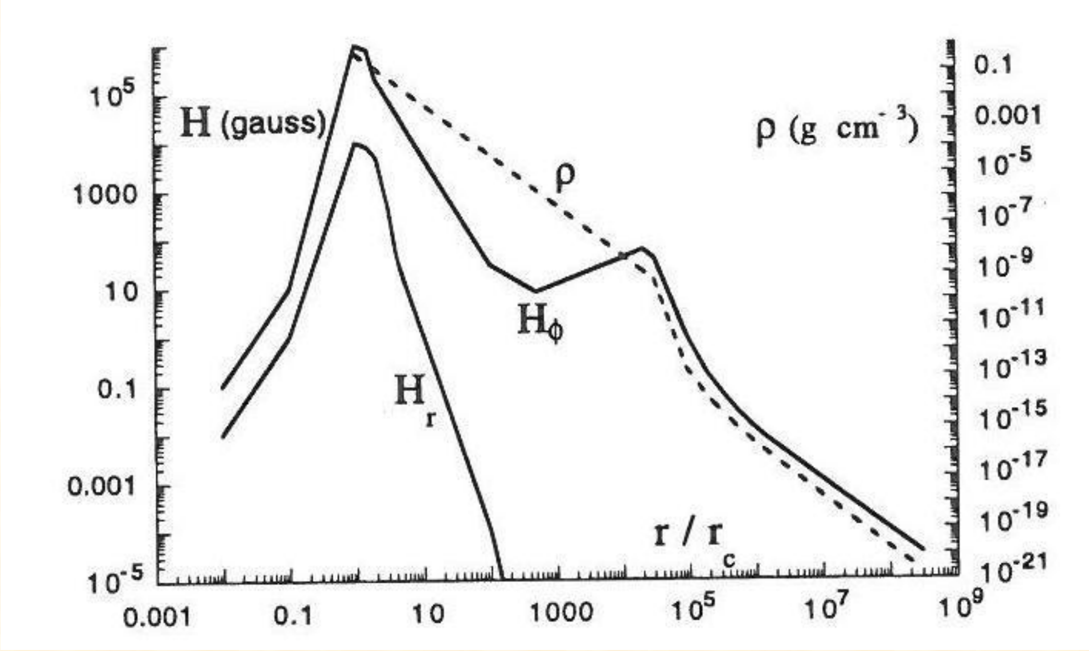
- *Pascoli & Lahoche (2008)*:

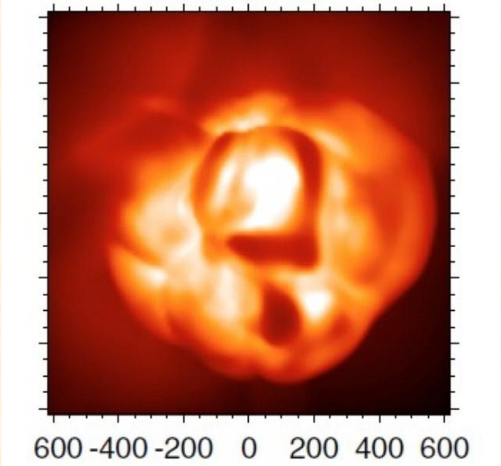
Magnetic activity in an AGB's core

→ **toroidal field (10 G @ surface)**

→ decrease through envelope

→ ejection of massive winds





- *Dorch (2004)*, for Red Supergiants (Betelgeuse) :

Generation of a magnetic field from a local dynamo powered by convection

Freytag & Hoefner (2008)
3D simulation of the atmosphere of an AGB

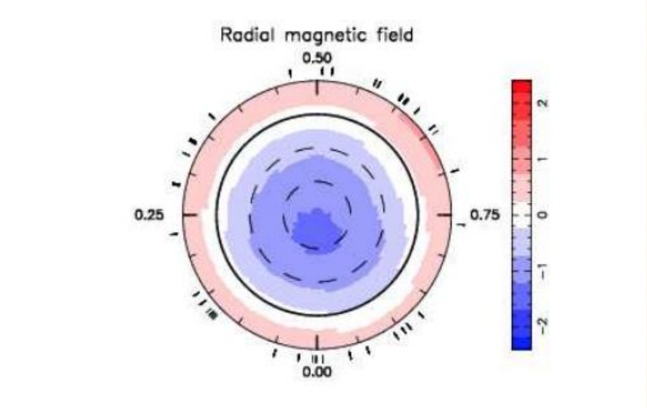
RGB & AGB magnetic fields – new challenges

Kepler Giants with seismic constraints (mixed modes in red giants) :
Asterosismic signatures of internal magnetic field *(Fuller et al. 2015 ; Cantiello et al. 2016)*
Angular momentum transfer from the core to convective envelope *(Mosser et al. 2012, 2014)*
=> Constraints on/from the dynamo ?

Zeeman Doppler Imaging on few targets so far
(Donati et al., 1999 ; Petit et al., 2004)
- RS CVn stars (active binaries)
- FK Com stars (very fast rotators and active giants)

and on Pollux (K0III)

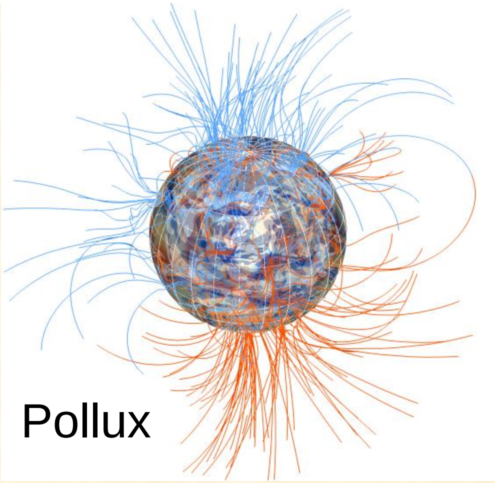
(Aurière et al., 2014, IAU 302 Proc.)



3D MHD simulation of the convective envelope
(with ASH code)

Dipolar configuration

(Palacios & Brun, 2014, IAU 302 Proc.)



Magnetic Fields in Cool Evolved Stars (AGB-RSG) – new challenges

Need for **long term monitoring** + coordination of instruments ?

e.g., RGB/AGB observed for +4yr *(Aurière et al. 2015)*
=> derive rotational period
=> intermittent fields (variations)

Betelgeuse followed over +6yr *(Aurière et al. 2010, Petit et al. 2013)*
=> Magnetic Field timescales variations

New **molecular tracers** (for CSE and surface field)

Linear polarization : complementary diagnostics (for CSE and surface field)

Toward IR spectropolarimetry
(SPIRou@CFHT, SPIP@TBL, CRIRES+@VLT)

Toward UV spectropolarimetry (ARAGO/M5-ESA)

Exciting Time Ahead !