Surface Magnetism of Cool and evolved stars 10-year Harvest with the Spectropolarimeters

ESPaDOnS@CFHT

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Outline :

- **Spectropolarimetry** Circular and Linear Polarisation

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

- **Magnetic Fields in cool and evolved stars** (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 ?

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

- **Atmospheric dynamics** (Linear polarisation : Stokes Q and Stokes U)

- **Toward Near-IR spectropolarimeters** SPIRou

Spectropolarimetry : Circular and Linear Polarisation

ESPaDOnS@CFHT
2004+
3.60m Telescope

Narval@TBL
2006+
2mTelescope

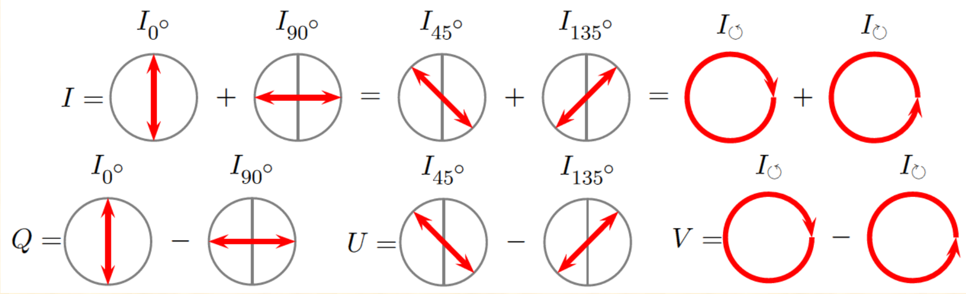
HARPSpol@ESO
2009+
3.60m Telescope

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

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

Simultaneous measurements
in two polarisation states :

⇒ Stokes I (unpolarised) spectrum
+ Stokes V (circularly) or Stokes U
or Stokes Q (linearly) polarised spectrum



⇒ Polarisation **within spectral** (atomic) **lines**

Polarimetric sensitivity ~ 10^{-4} of the unpolarised continuum

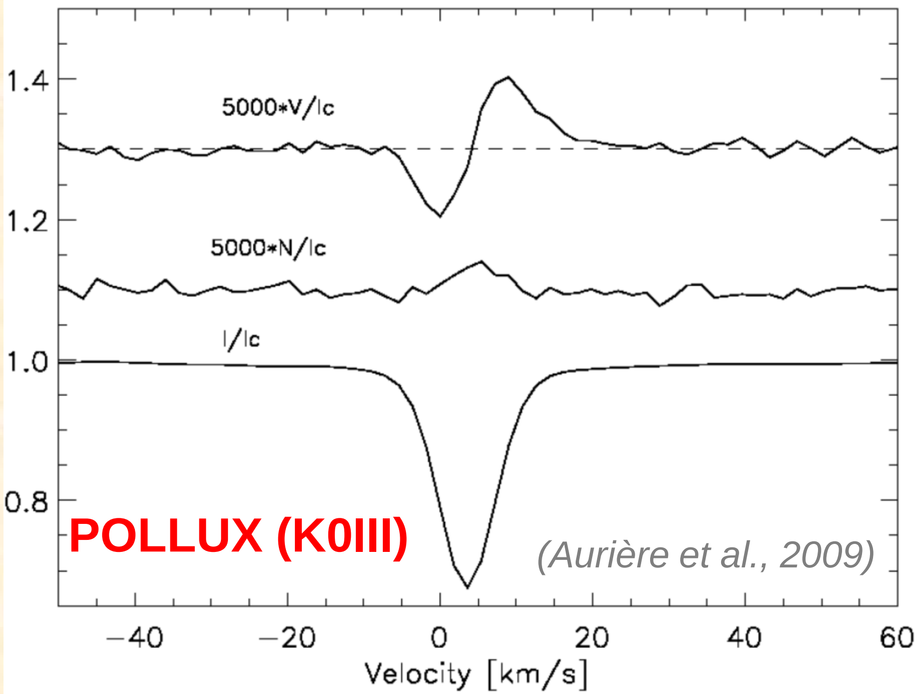
Circular Polarisation :

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)

Zeeman detection : sub-Gauss field



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)

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

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

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

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

Cool & evolved stars

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

Convection

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

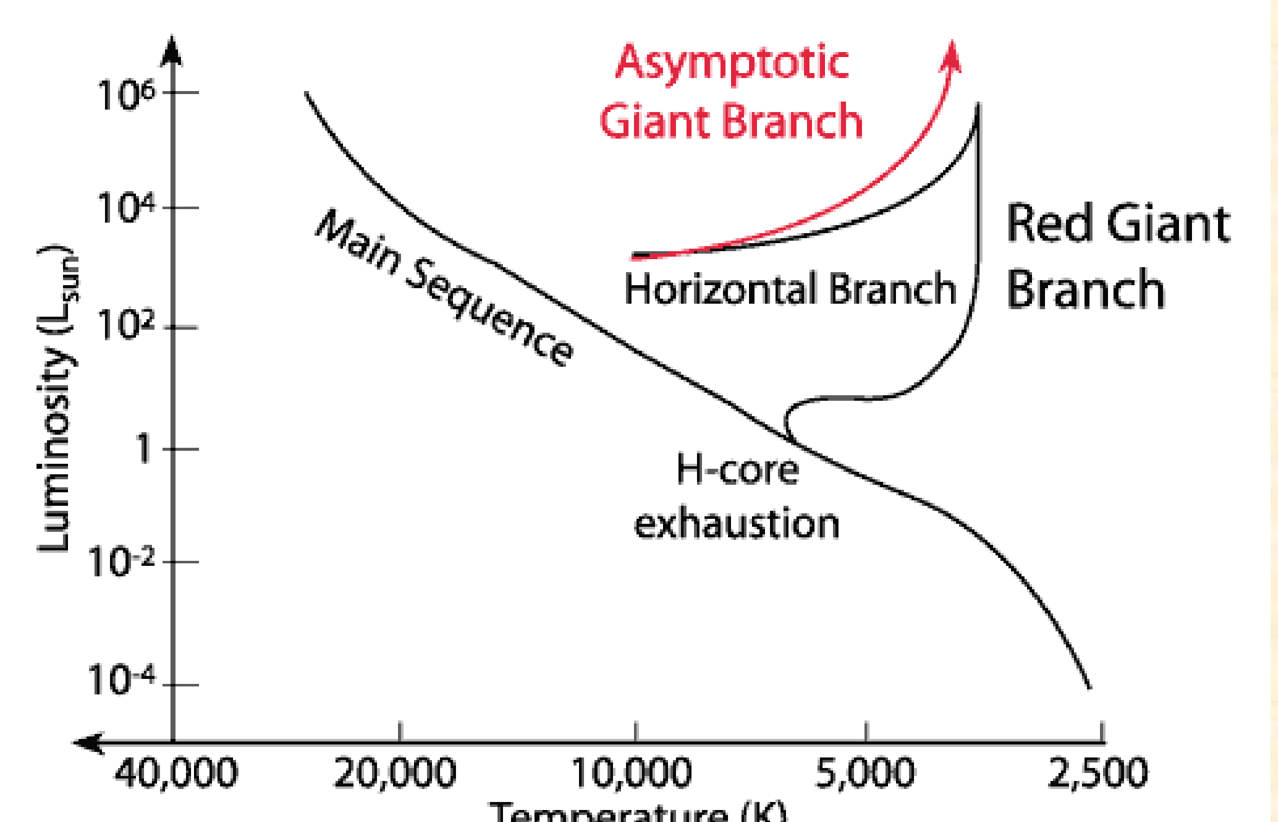
Bug Neb

Pulsation (Mira/RV Tauri)

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

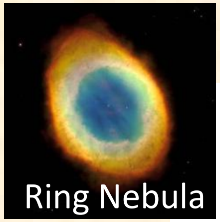
Mass loss

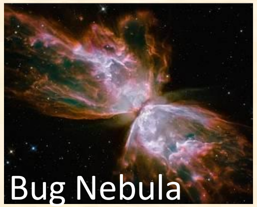
Heavy mass loss : radiation pressure on dust *(Höfner, 2011)* levitation due to shocks

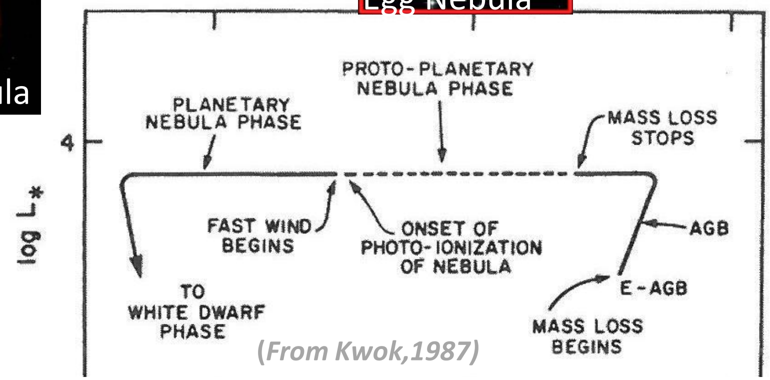


(From , Amiri Ph.D. 2011)

Cool & evolved stars







(From Kwok,1987)

HST images

During the transition from AGB to PN :

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

Binarity ? Magnetic fields ?

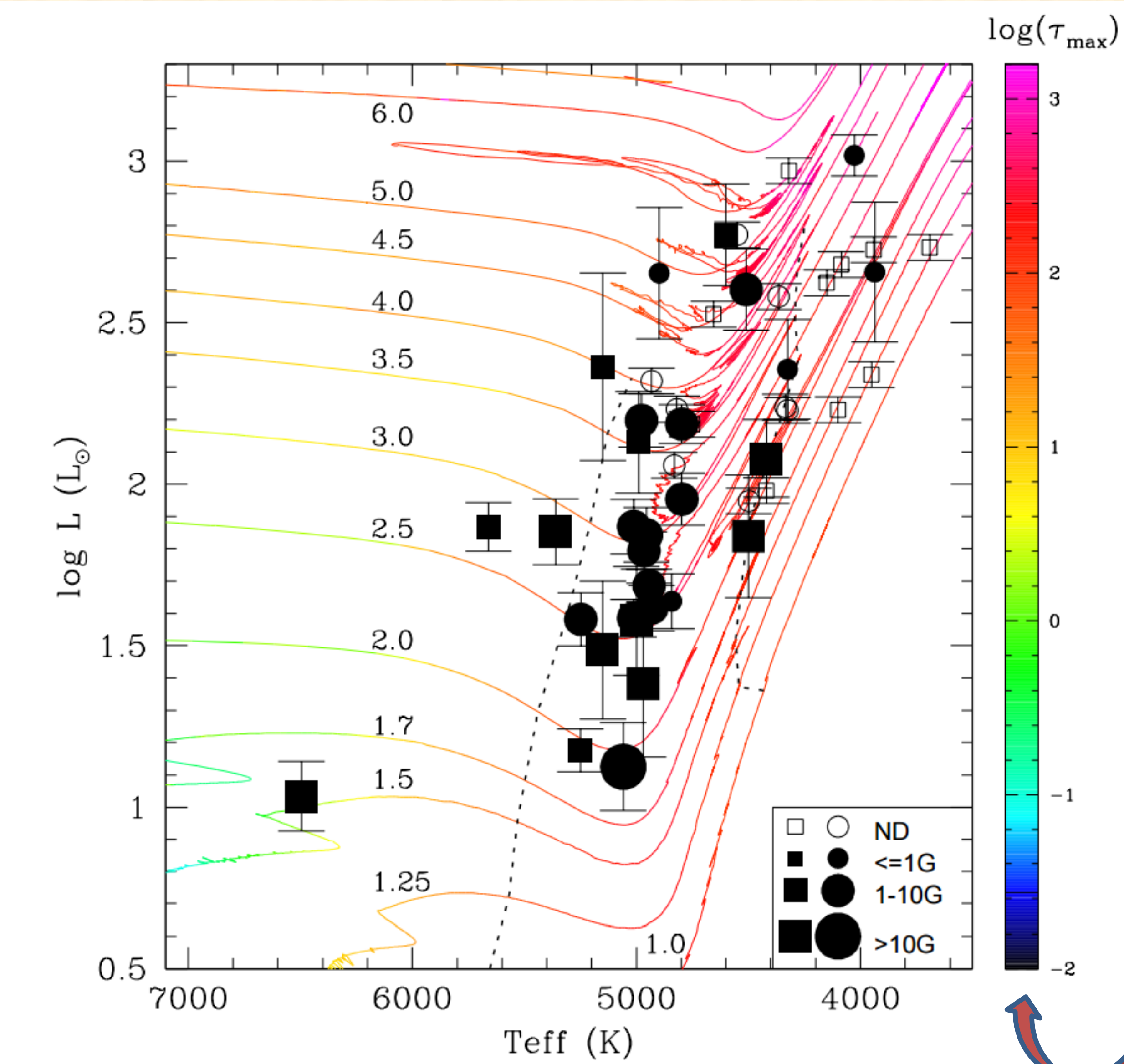
and

Observational evidences of magnetic fields around PNe and AGB /post-AGB

(talks : W. Vlemmings ; L. Sabin ; A. Duthu)

Magnetic Fields at the Surface of cool and evolved stars ?

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 » ?

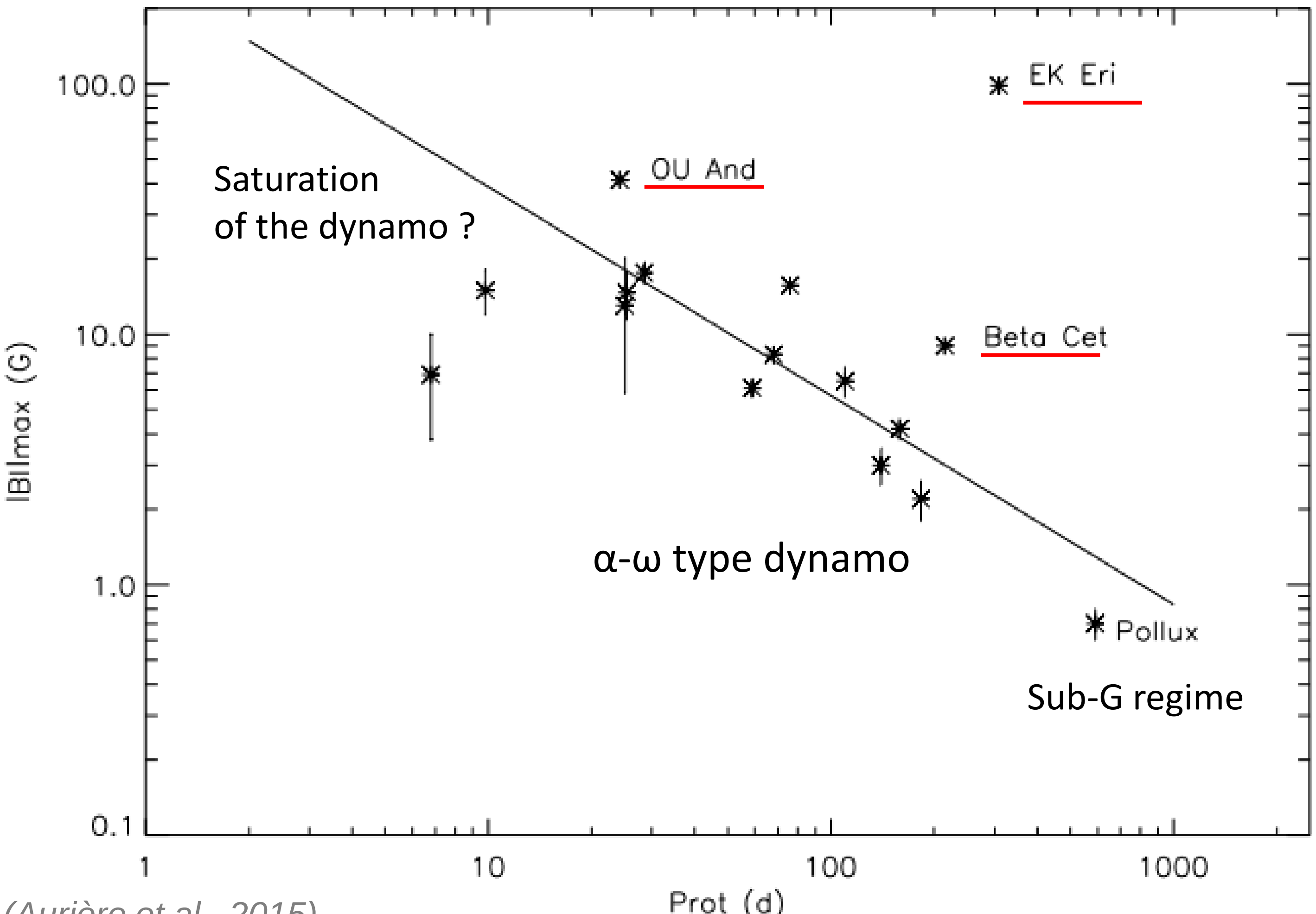
1rst Dredge-up and
Core Helium burning phases.

Evolutionnary models :
Solar metallicity with rotation
(Charbonnel et al., in prep.)

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)

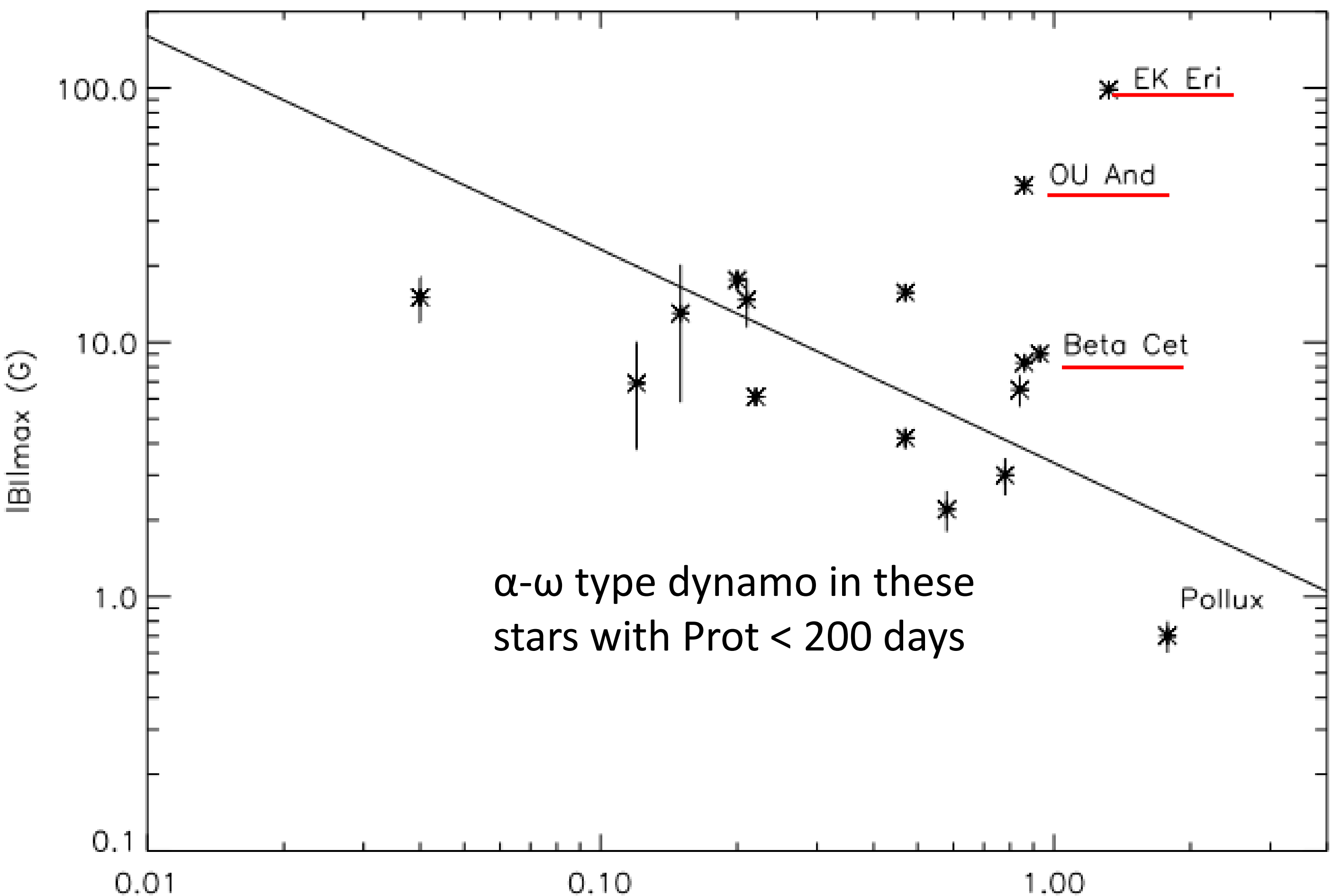
Ap star descendant candidates :

fossil field interacting with convection

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

Preliminary trends with rotation from 16 G-K Giants

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



Ro = Prot / τ_{max}

Ap star descendant candidates :

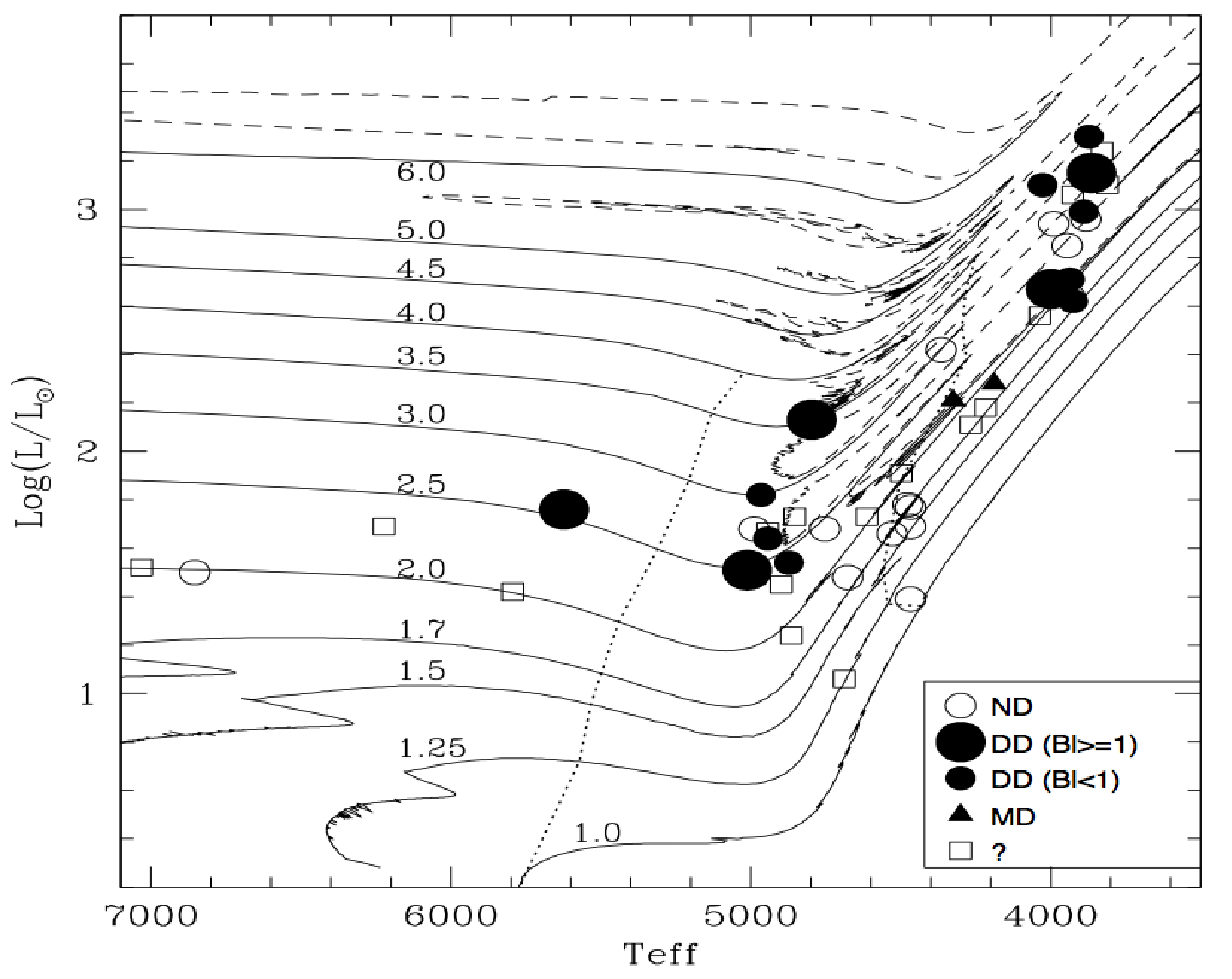
fossil field interacting with convection

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

Ro :
Rossby number
Ratio of inertial to Coriolis force

(Aurière et al., 2015)

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

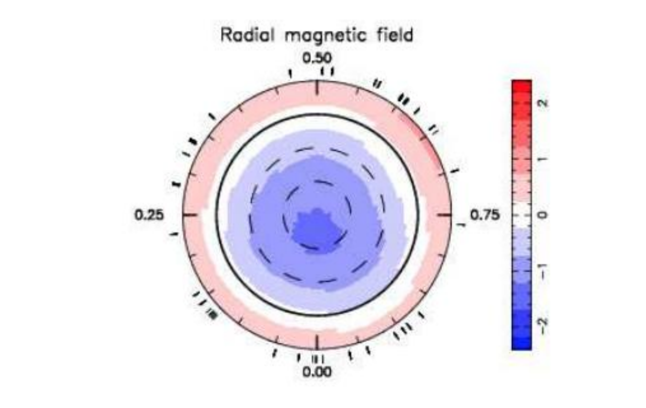
RGB & AGB surface magnetic fields - perspectives

Kepler Giants with seismic constraints *(Mosser et al. 2012)*
Angular momentum transfer from the core to the convective envelope
=> 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)

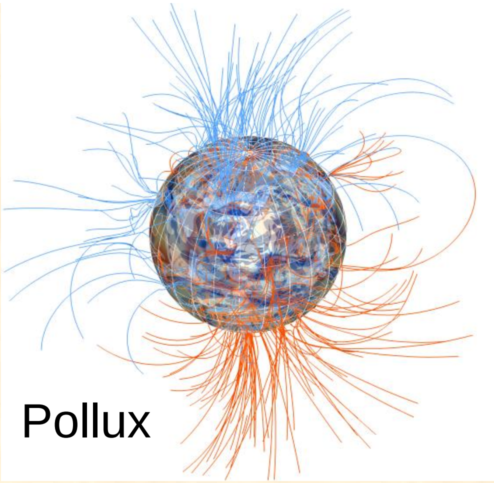
and on Pollux



(Aurière et al., 2014, IAU 302 Proc.)

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

Dipolar configuration

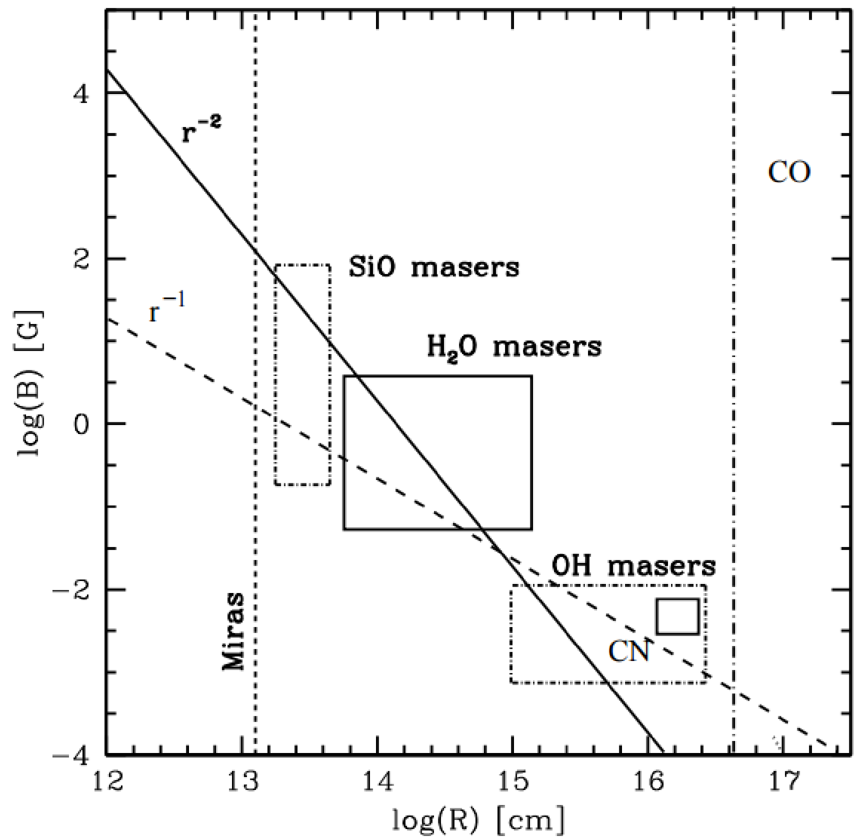


(Palacios & Brun, 2014, IAU 302 Proc.)

Thermal Pulsing-AGB (2-4 M_sun)

Circumstellar magnetic field through CSE
from Masers SiO & CN lines

⇒ Geometry of the field : *B ~ 1/r ...*
(Herpin et al. 2006, 2009; Vlemmings et al. 2011)



Mira Stars

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

- Balmer lines in emission
=> shock wave (atmospheric dynamics)
+ linear polarization @ max. of light *(Fabas et al., 2011, A&A, 535, 12)*

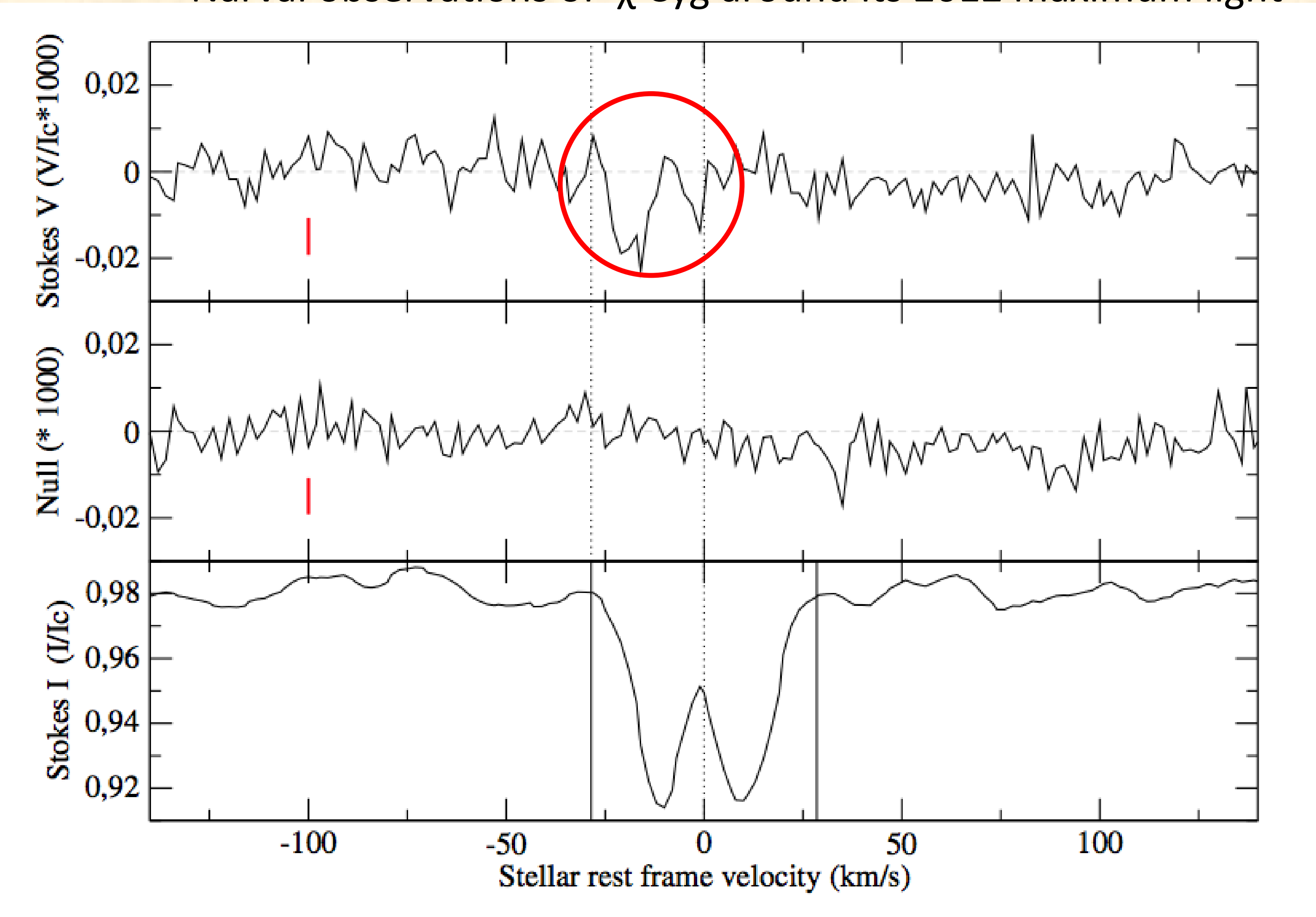
- photospheric field ~ a few G (expected from theoretical works *: Thirumalai & Heyl, 2013)*
but not detected (so far ?) with Narval

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

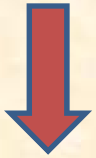
Narval observations of χ Cyg around its 2012 maximum light



Definite Detection

χ2=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

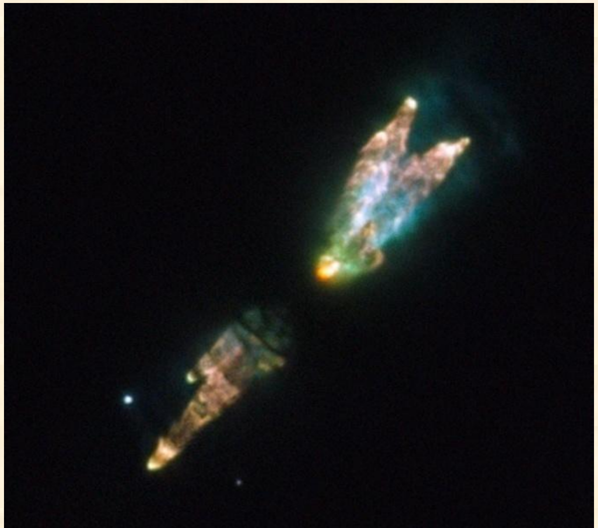
Stokes I profile : **typical line doubling of metallic lines** due to **a shock wave** in the atmosphere.

(Lèbre et al. 2014, A&A 561, 85)

Post-AGB stars/ PPNe magnetism

Detection of large scale magnetic fields in the circumstellar environment mainly from radioastronomy
(Sabin et al., 2013 ; Vlemmings et al., 2011)

CRL 618, OH 231.8+4.2 : studied with sub-mm polarimetry
OH 231.8+4.2: well defined and organized polar magnetic field (continuum cm linear polarization : alignment of non-spherical spinning dust grains)
No detection in molecular lines (Goldreich-Kylafis effect)
Role in dragging and collimating of the (high velocity) bipolar outflow still unclear ...


CRL618 HST (*Trammel, 2000)*

RV Tauri stars *(Sabin, Wade, Lèbre, 2015, MNRAS, 446, 1988)*

The first positive detections of a photospheric magnetic (ESPaDOnS)
=> more in L. Sabin's talk, tomorrow !

Planetary Nebulae : small-scale structures due to magnetic fields

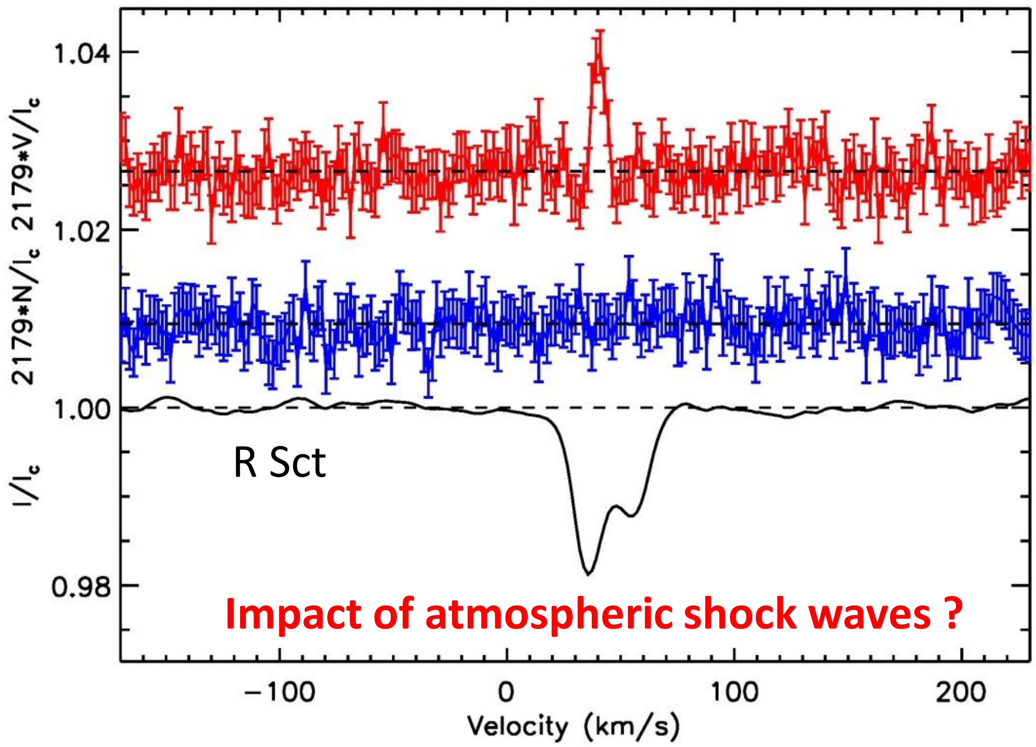
Detection of large scale magnetic fields in the nebulae
Central star : **null or inconclusive detections** : no K.Gauss field !
(Jordan et al., 2012 ; Leone et al., 2014, Steffen et al., 2014)


Spirograph nebula
(Huggins et al. 2011)

Detection of surface magnetic field in RV Tauri stars

(Sabin, Wade, Lèbre, 2015, MNRAS 446, 1988)

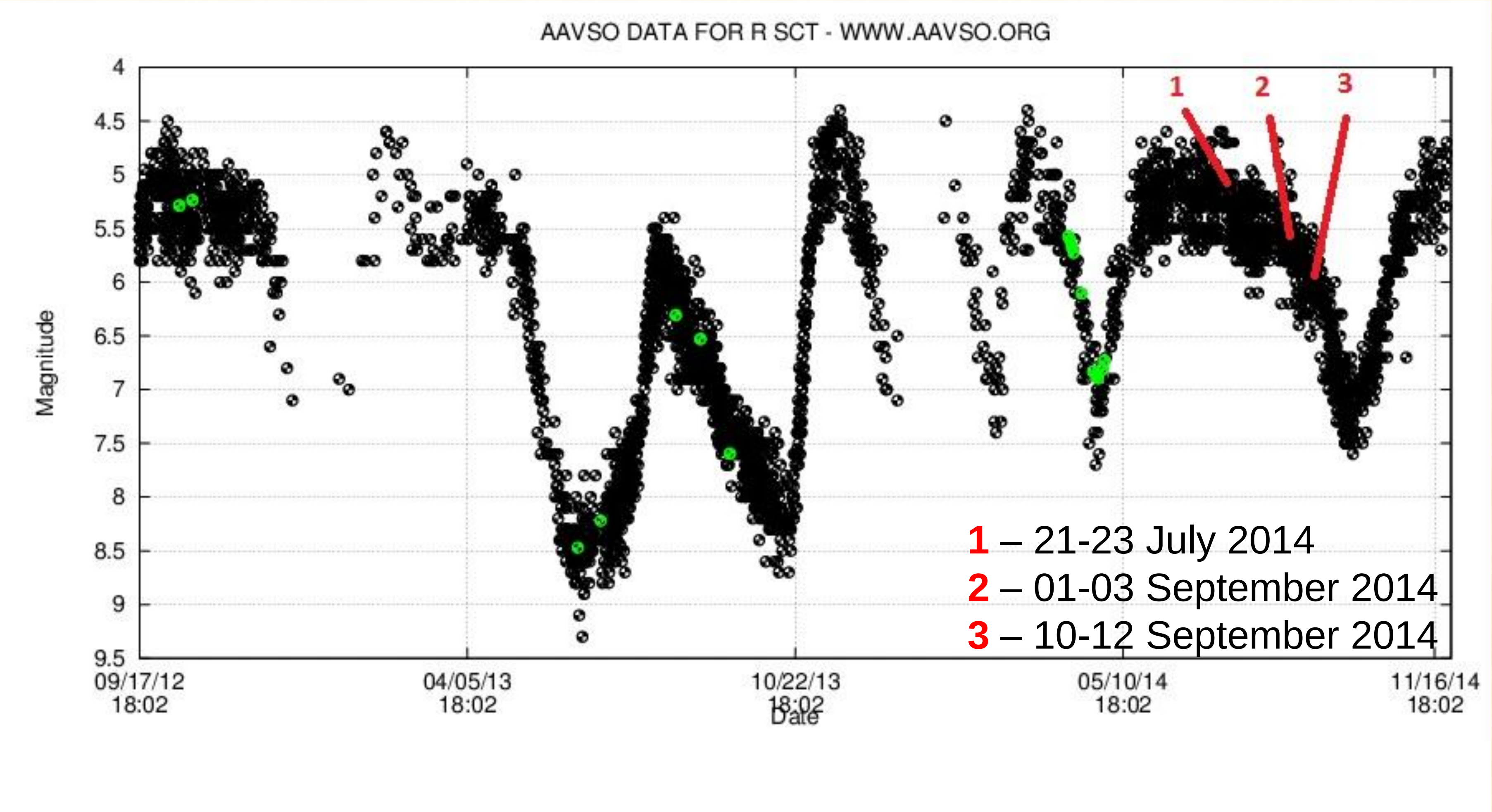
Narval observations July 2014



R Scuti (pulsation period ~ 142 days)

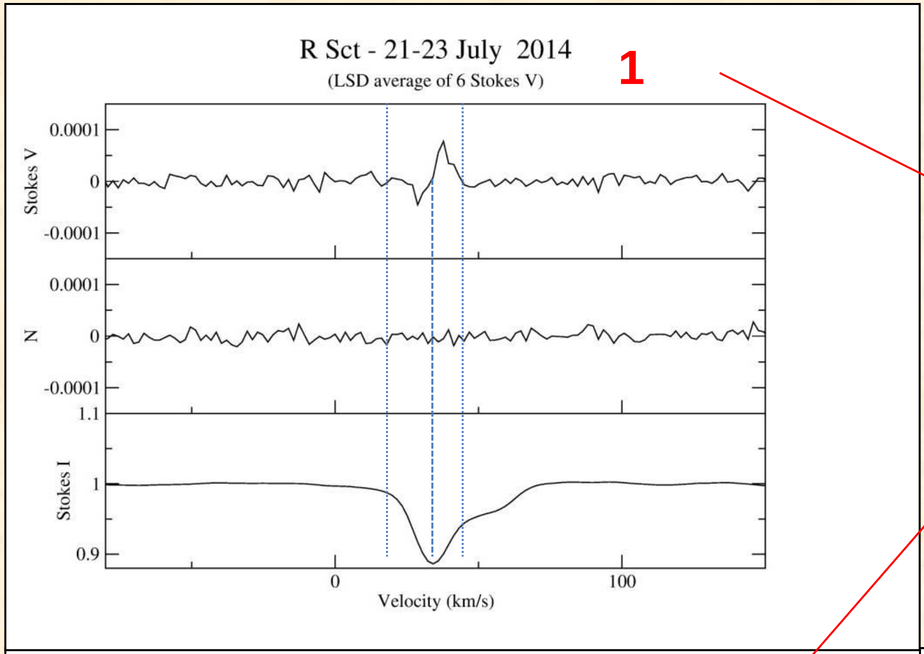
Bl = 0.6 ± 0.6 G

Spectropolarimetric monitoring of pulsating variables : R Sct



Impact of atmospheric shock waves ?

R SCT
Circular polarization (Stokes U & Q)

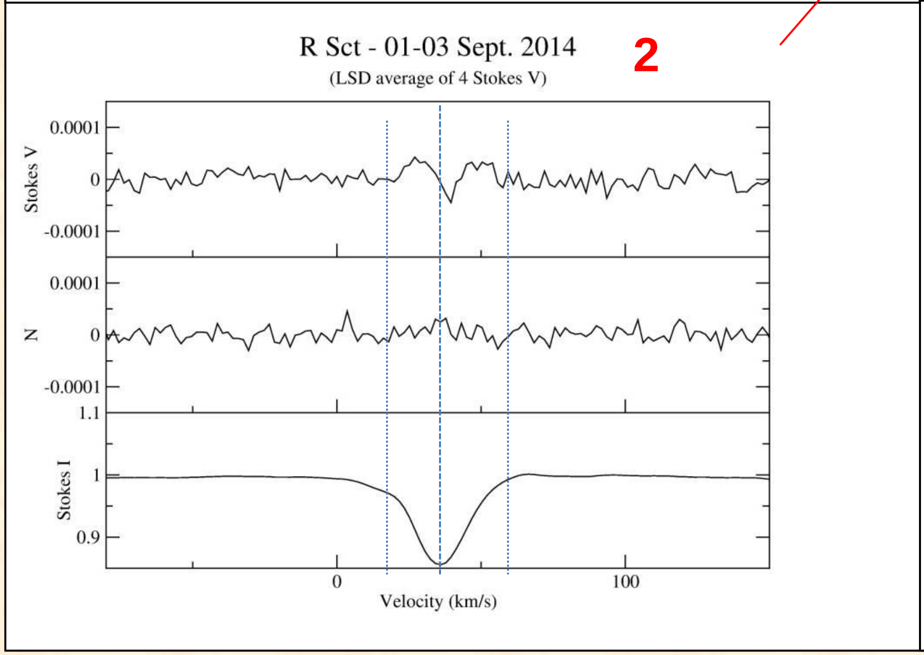


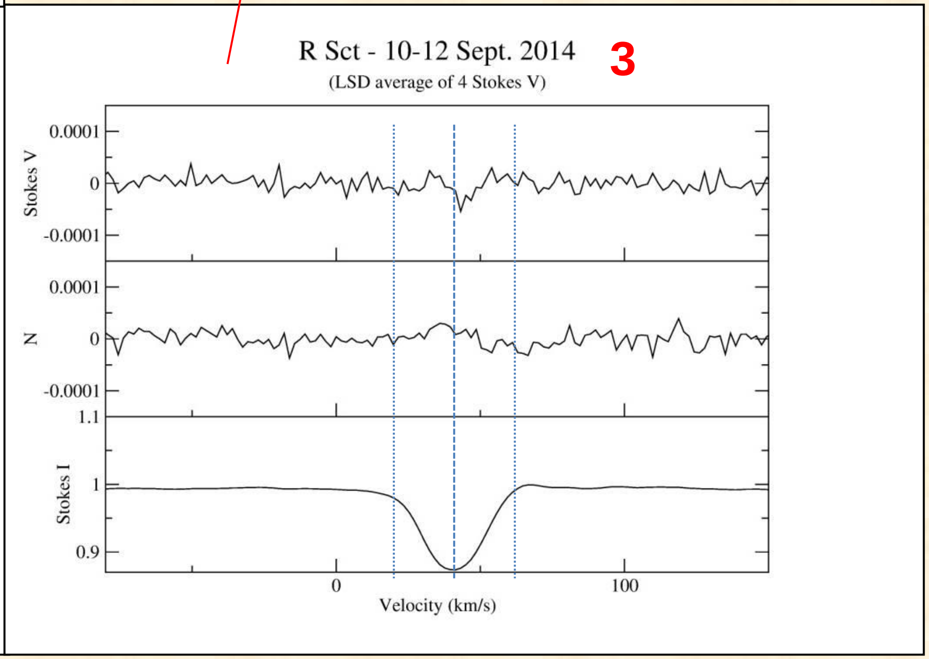
1: DD Bl = 0.6 +/- 0.72 G

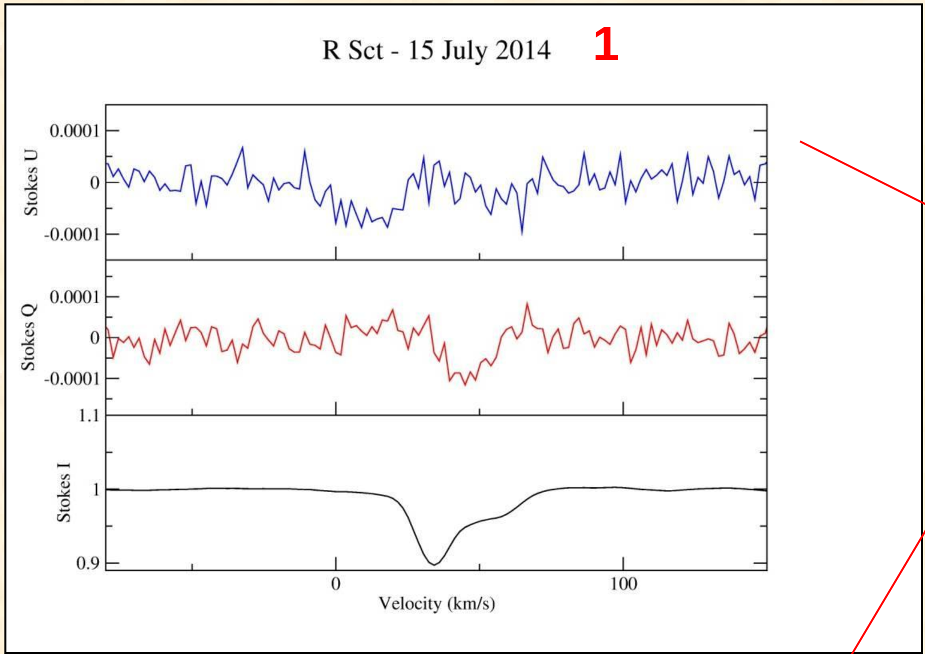
(Sabin et al., 2015)

2: MD Bl = -0.23 +/- 0.72 G

3: ND Bl = -1.62 +/- 0.83 G







R SCT
Linear polarization (Stokes U & Q)

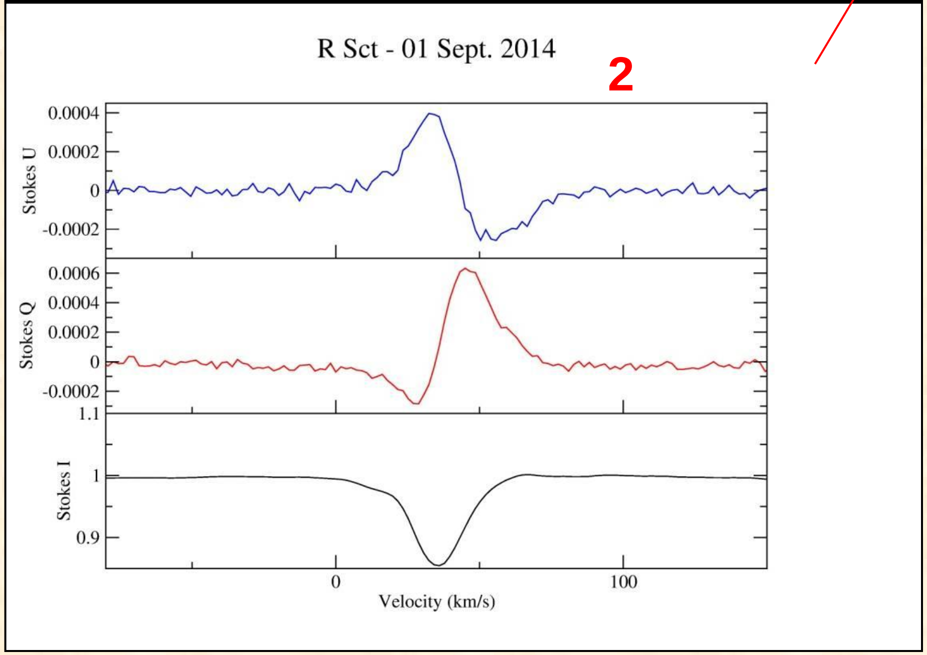
1: U: ND ; Q : DD

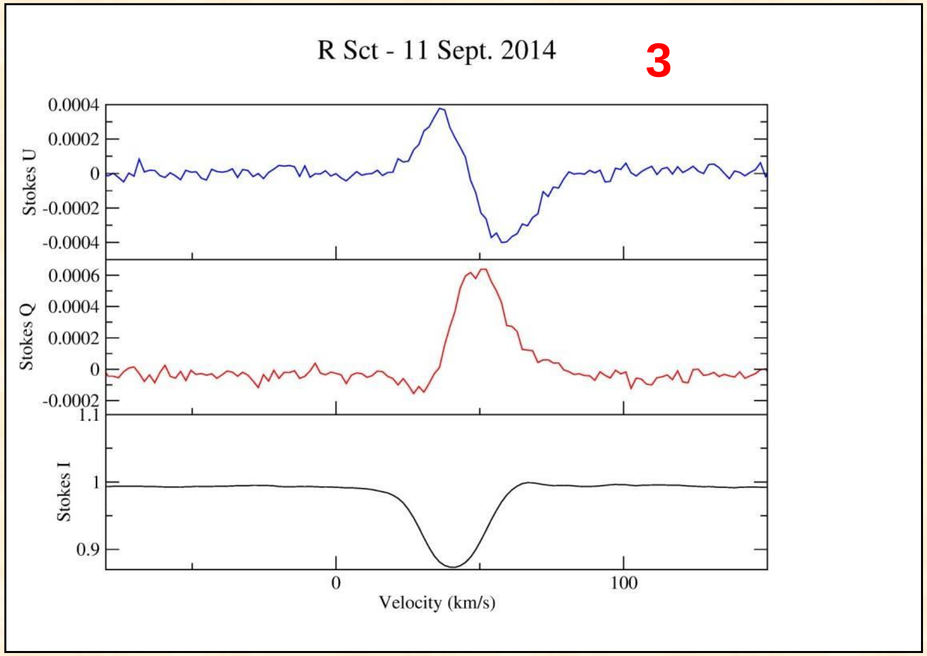
2: U : DD ; Q : DD

3: U : DD ; Q : DD

LSD profiles : Thousand lines involved !

(Lèbre et al., 2015, IAU 305, in press)

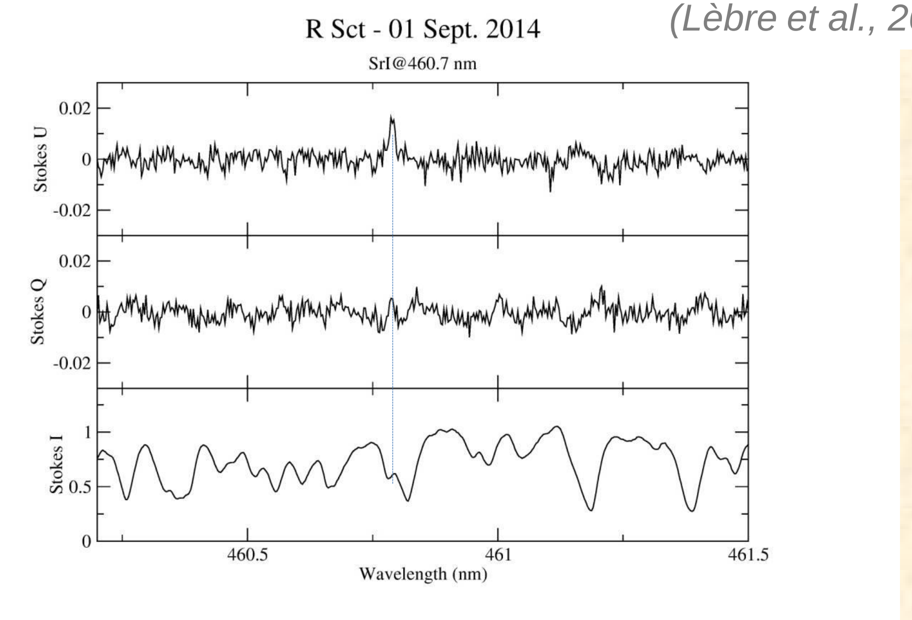


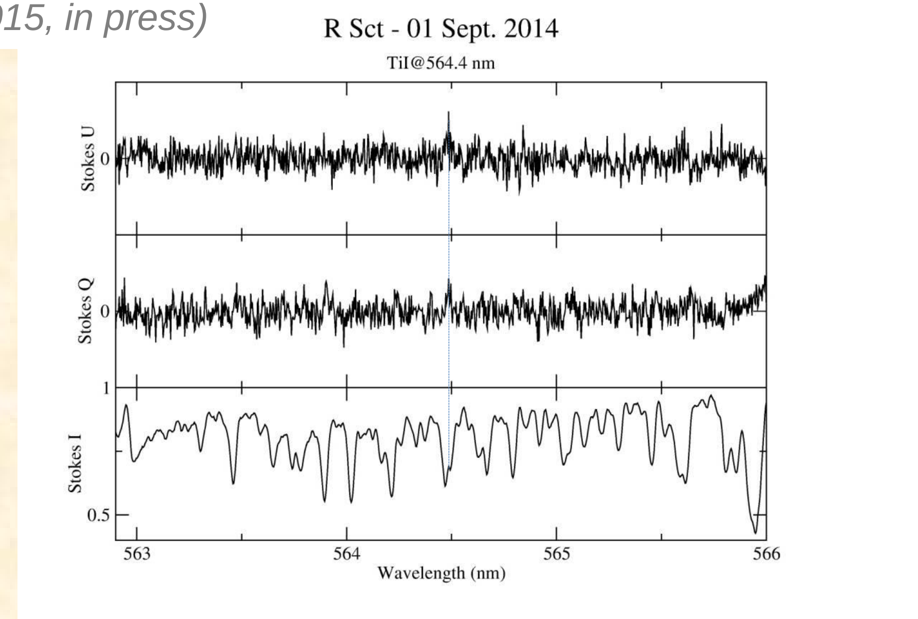


R Sct : Linear polarization detected in individual lines !

SrI@460.7 nm and TiI@564.4 nm

(Lèbre et al., 2015, in press)

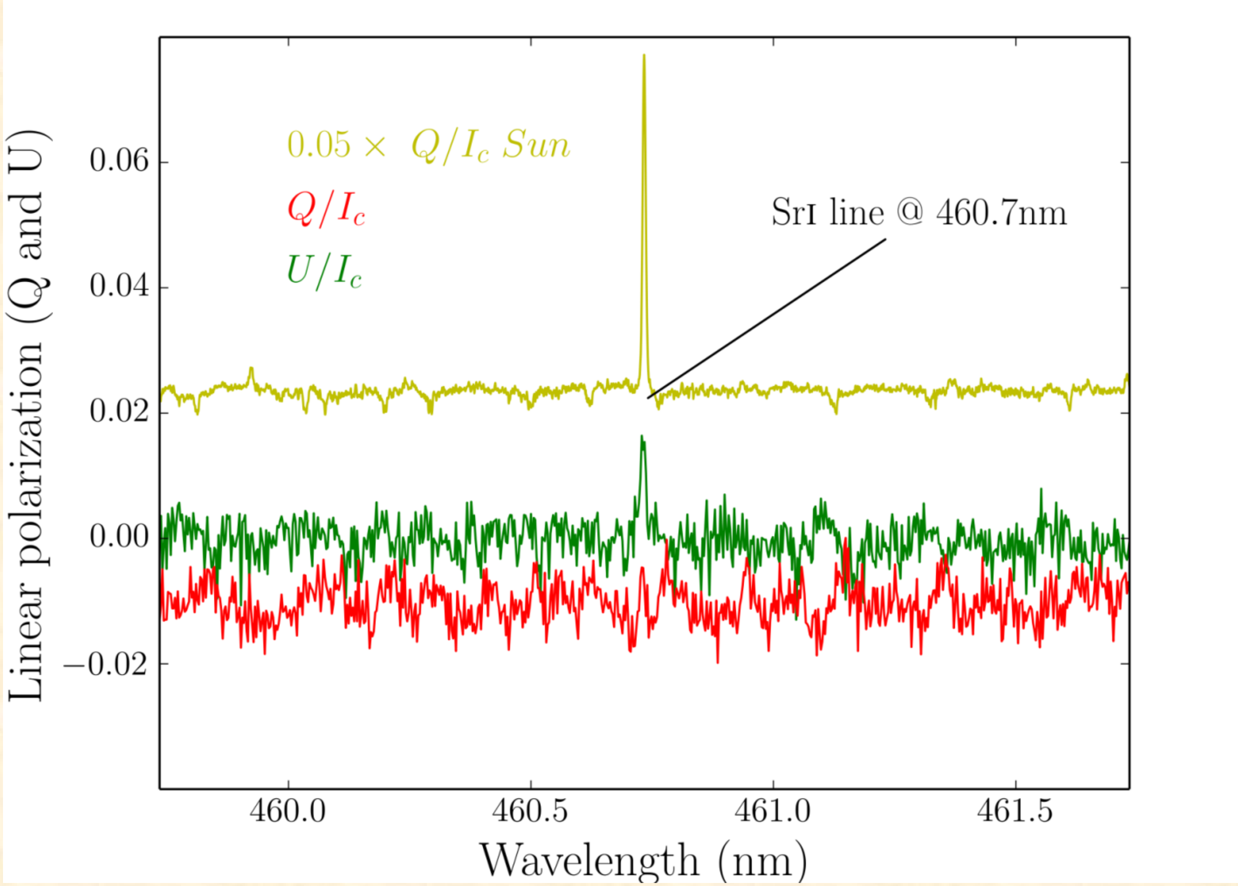




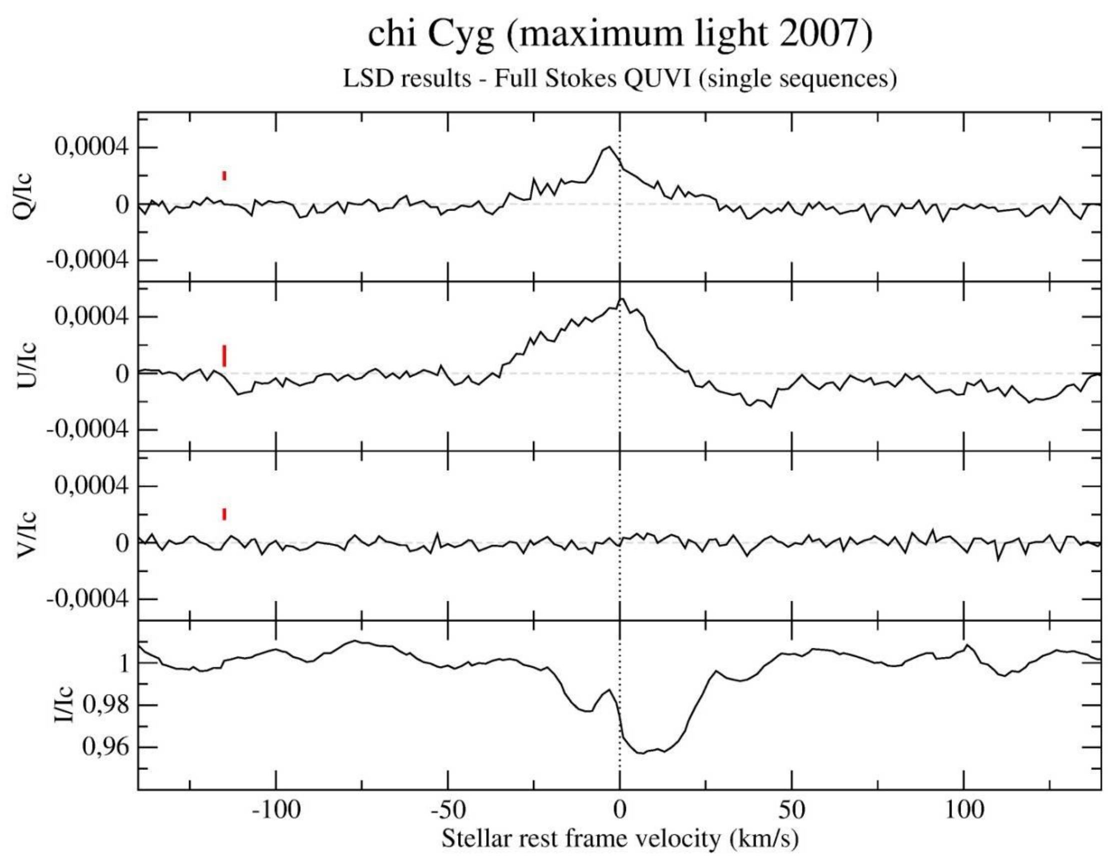
R Sct : Linear polarization detected in individual lines !

See Benjamin Tessore's poster (N°34) !

Magnetic Field of variable cool and evolved stars: Interaction with complex atmospheric dynamics



χ Cyg : Linear polarization



LSD profiles :
thousand lines involved !

Stokes Q :
Definite Detection
(χ2=3.01)

Q/U ~1

Stokes U :
Definite Detection
(χ2=4.57)

Stokes V :
No Detection (1 sequence)
(χ2=1.16)
Noise level ~ 0.5 10^{-4}

→ **The shock favours a direction, inducing a net linear polarization.**
In agreement with *Fabas et al., 2011*

→ **Departure from spherical symmetry at the photospheric level.**
also seen from interferometric data *(Ragland et al., 2006)*

Magnetic fields in Red Super Giants (RSG)

Red Supergiants :

Are they all magnetic stars ?

Common occurrence

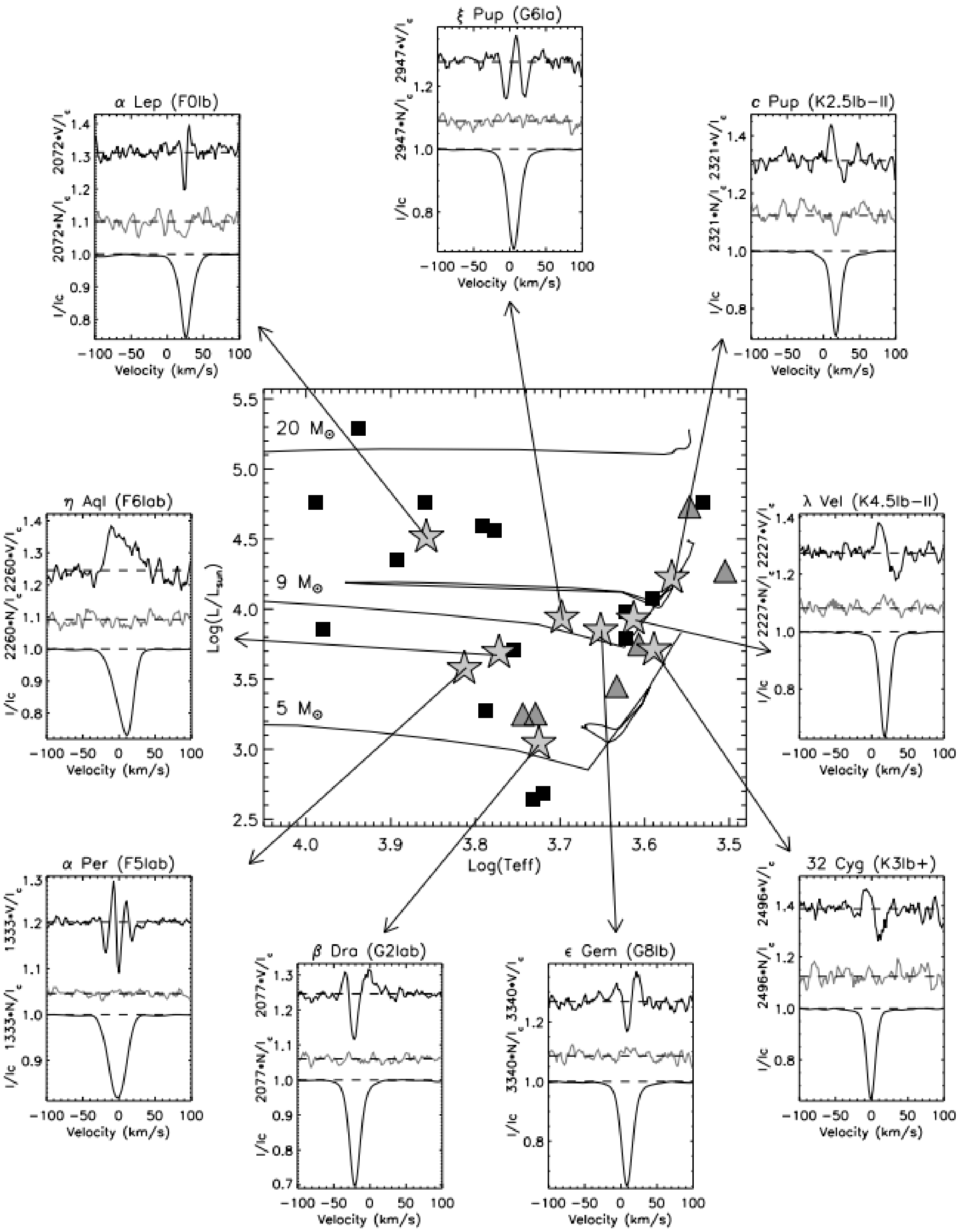
of magnetic fields at the

(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)

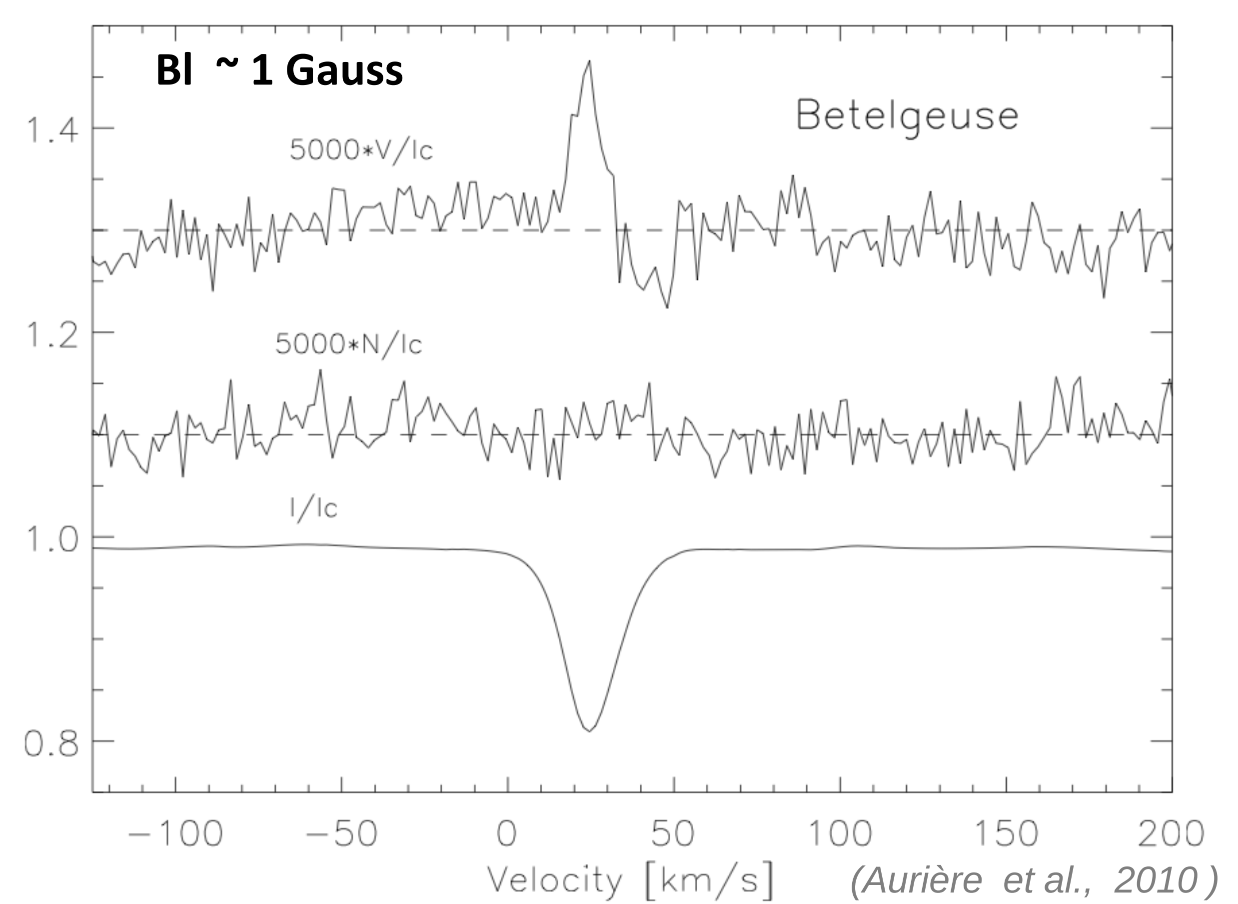
P_{rot} = 17 years
(Kervella et al., 2009)

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

=> $R_o \sim 90$

not able to sustain a α-ω type dynamo

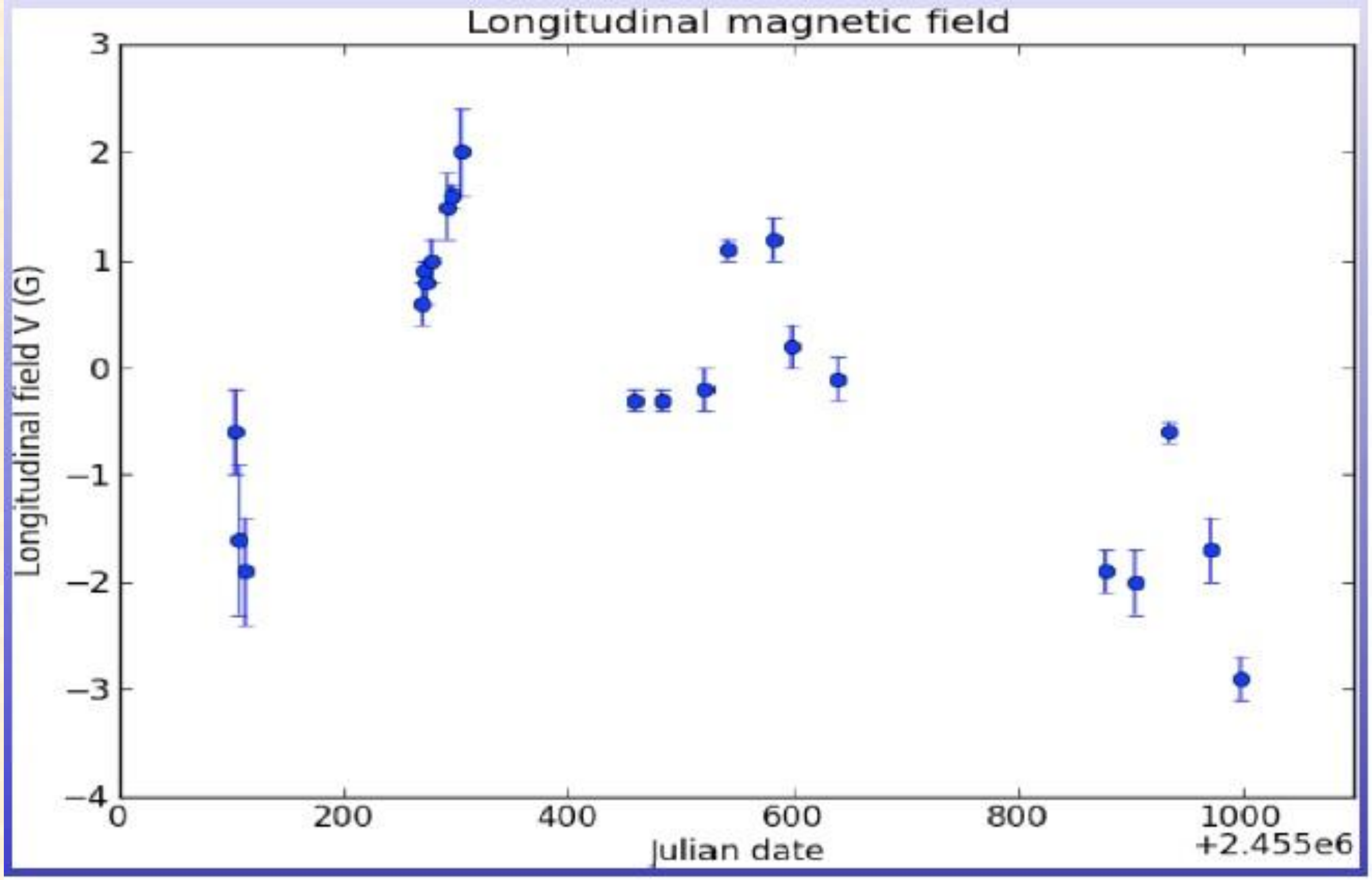
The large-scale convective motions can generate **small-scale dynamo action,** and thus transitory fields.



(Aurière et al., 2010)

Geometry of magnetic field remains unknown !

Variations of the magnetic field of Betelgeuse (2009-2012)



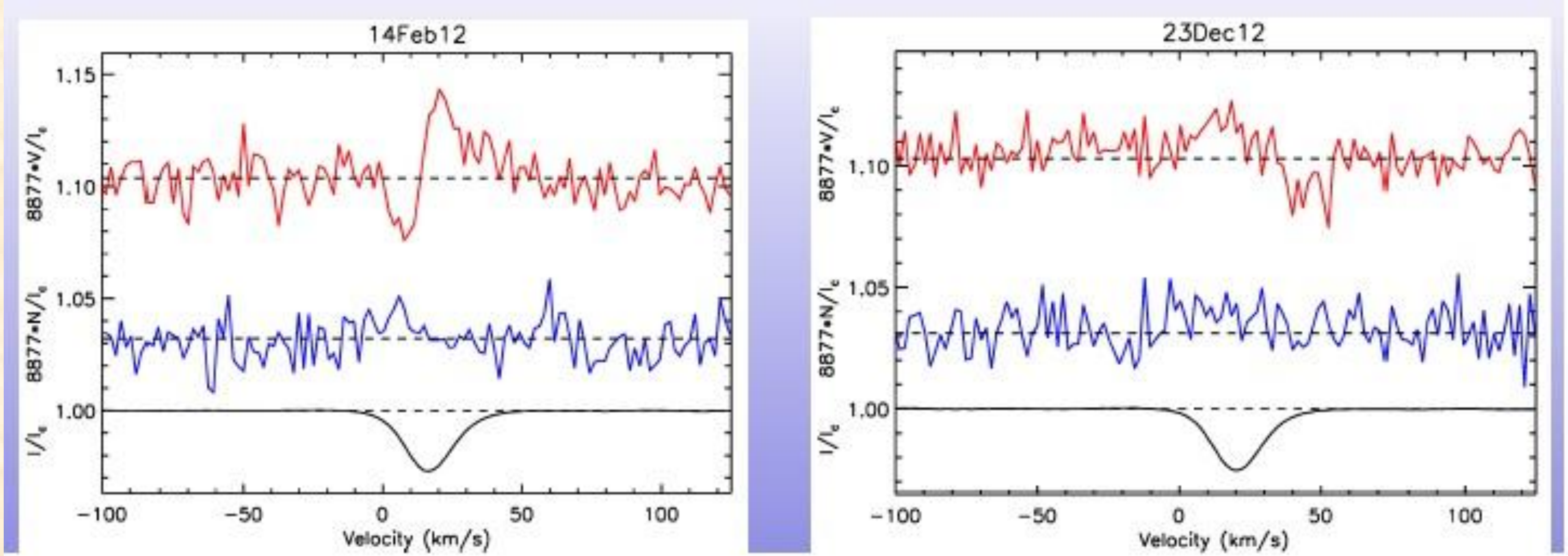
Field variability
< 1 month !

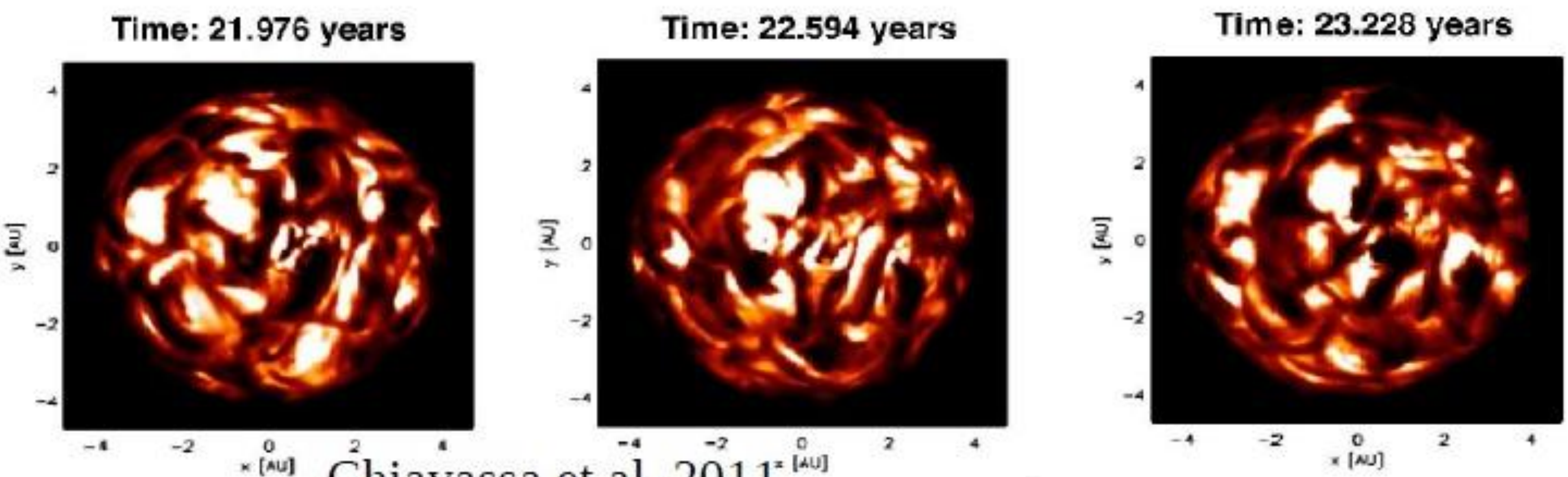
(stellar rotation
17 years !)

Consistent with convective timescales
(Dorch & Freytag, 2004)

(Bedecarrax et al., 2013) long term monitoring in progress with Narval

Variations at the surface of Betelgeuse

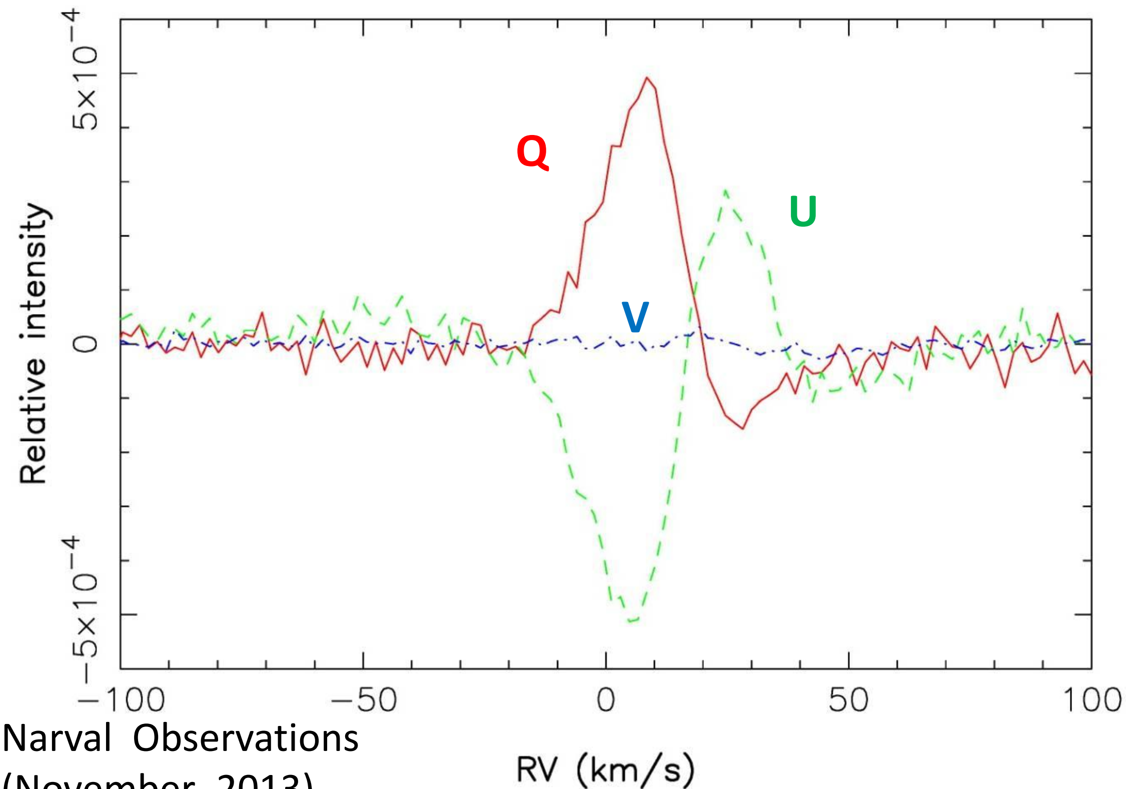




Chiavassa et al. 2011

And also on **Betelgeuse !** Full Stokes QUVI → Same behavior than on Miras !

Strong linear polarisation signal within atomic lines
(and a **marginal detection on V**, from a single sequence)



Narval Observations
(November 2013)

LSD with maks composed of ~16 000 metallic lines !

Linear polarisation in the lines (individual / global) :

Line depolarisation of the continuum polarised by Rayleigh scattering.

(Josselin et al., 2015, in press)

a potential diagnostic of photospheric asymmetries ...

(Aurière et al., 2015, in preparation)

Exciting Time Ahead !

SPiRou

SPIRou@CFHT - SPIP@TBL

(2017+ - 2019+)

Main scientific specifications :

Spectral Domain : 0.98-2.35 µm (simultaneous)

Spectral Resolution : 75 000

Accuracy_VR : 1 m/s

Achromatic circular and linear polarimetry

S/N~100 per pixel (2.3 km/s) @ H=11.0 - 9.5

Zeeman effect easy to detect in nIR :

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

Main scientific drivers :

- Exo-earths around M dwarfs
- Stellar and Planetary Formation

+ *Other Science*

=> ***Cool and Evolved Stars***

Necessity to improve the knowledge on parameters (g_{eff}) for molecular lines (TiO).

Crédit:ESO/L. Calçada

Thank you !

Take Away Messages

Weak magnetic field commonly detected among cool and evolved stars

Necessity for a multiplex approach to reveal Sub-G level surface fields
+ a dedicated observational strategy

Linear polarisation can help to reveal photospheric structure
+ magnetic field diagnostic ?

Plenty of data already available (POLARBASE tool) in the Visible
+ the nIR window is coming soon !