Magnétisme photosphérique/circumstellaire des étoiles froides évoluées et autres apports insoupçonnés de la spectropolarimétrie…

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Magnétisme photosphérique/circumstellaire des étoiles froides évoluées et autres apports insoupçonnés de la spectropolarimétrie...

1- RSG : Focus sur Bételgeuse

2- AGB/Post-AGB : connecter le magnétisme de surface et dans l’ECS

3- Géantes Rouges : Magnétisme de surface le long de la branche des géantes
The (very) weak field regime ....

**Cool Evolved Stars**

among the

**Magnetic HR Diagram**

(from 15 years of spectropolarimetry)
The (very) weak field regime ....

**Cool Evolved Stars**

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**Magnetic HR Diagram**

(from 15 years of spectropolarimetry)

Credit: ESA, B. Tessore; PhD, 2017
**Cool Evolved Stars**

RGB, RSG stars: core He-burning phase
AGB stars: He- and H-shell burning phase

\[ T_{\text{eff}} = 4000-2500 \text{ K} ; \log g = 0 - 2 \]

**Convection:**

Large-scale convective motions in an extended atmosphere with a few giant cells at the surface

(Schwarzschild, 1975; see also papers from Stothers)

Radiative hydrodynamic simulations

(Chiavassa+ 2010; Freytag, 2015)

**Pulsations:**

In AGB (Miras): pulsations are expected to generate shocks (also in some Post-AGB)
In RSG: convection is expected to generate supersonic motions and shocks

**Mass loss:** up to $10^{-4} \, M_\odot/\text{y}$

Radiation pressure on dust (Höfner, 2011)
+ levitation due to shocks
Convection triggered mass loss (Josselin+2007)

⇒ Photospheric and atmospheric dynamics
Spectropolarimetry: Circular and Linear Polarisation

- ESPaDOnS@CFHT
  - 2004+
  - 3.60m Telescope
  - Spectral Range: 375 – 1050 nm
  - Spectral Resolution: 65 000

- Narval@TBL
  - 2006+
  - 2m Telescope
  - Spectral Range: 380 – 690 nm
  - Spectral Resolution: 115 000

- HARPSpol@ESO
  - 2009+
  - 3.60m Telescope
  - Spectral Range: 375 – 1050 nm
  - Spectral Resolution: 65 000

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
Spectropolarimetric data: what do they look like?

The M Dwarf AD LEO
Spectral Type = M4V; Teff = 3400 K; log g = 5.0

- Classical S-type Zeeman profile associated to individual atomic lines
- Estimation of the longitudinal component of the magnetic field:
  \[ B_I = 200 \text{ G} \] (Morin et al., 2008)
The Red Super Giant Betelgeuse  
Spectral Type = M2I ; Teff = 3500 K ; log g = 0.0

⇒ The field is too weak to allow its measurements from individual atomic lines

⇒ Need to use a multi-lines method (LSD software, Donati et al., 1997) exploring the whole spectral domain in the visible : 380 nm – 1100 nm
**Circular Polarisation**: Zeeman detection: sub-Gauss field

Mean Zeeman shift of a transition

\[ \Delta \lambda_B = \frac{\lambda_0^2 eB}{4\pi m_e c^2} = 4.67 \times 10^{-12} \lambda_0^2 g_{eff} B \]

\( g_{eff} \): *Landé factor* (sensitivity of a transition to B)

If weak magnetic field \(< 100 \text{ 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.)

\( (\text{Donati et al., 1997}) \)

Estimation of \( B_l \), the **Longitudinal Component of the Magnetic Field**:

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

First-order moment method \( (\text{Rees & Semel, 1979}) \) adapted to LSD profiles.
Zeeman detection: sub-Gauss field

\[ B_l \sim 1 \text{ Gauss} \]

\[ (\text{Aurière et al., 2010}) \]

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

But the geometry of magnetic field remains unknown!

\[ P_{\text{rot}} = 36 \pm 8 \text{ years} \]

\[ R_o \sim \frac{P_{\text{rot}}}{\tau_{\text{conv}}} \]

\[ \Rightarrow R_o > 100 \text{ !!} \]

not able to sustain a \( \alpha-\omega \) type dynamo

Bételgeuse: M2 Iab
\[ \text{Teff} = 3650 \text{ K} \]
\[ (\text{Levesque et al., 2005}) \]

MHD simulations
\[ (\text{Dorch & Freytag, 2003}) \]
Two new detections of surface field in M-type RSG

Detection of strong linear polarisation
V \ll U & Q \Rightarrow \text{Non Zeeman origin}

\Rightarrow \text{Crosstalk from linear polarisation}

(Tessore et al., 2017 and Tessore B., PhD., 2017)
**Light variations and characteristic timescales in RSG**

AAVSO light curves of RSG variables (10-d bins)

(Kiss et al., 2006)

Power density spectra of AAVSO data (insets: spectral window)

α Ori: $P_1 = 388 \pm 30$ d, $P_2 = 2050 \pm 460$ d (LSP)

μ Cep: $P_1 = 860 \pm 50$ d, $P_2 = 4400 \pm 1060$ d

CE Tau: $P_1 = 1300 \pm 100$ d
**Betelgeuse**

**A spectropolarimetric monitoring along 7 years!**

From March 2010 to April 2017 over 8 seasons (still in progress in QUVI)

Any periodicity?

Magnetic spot(s) model

(Mathias et al., 2018)
2D Fourier analysis (CLEAN analysis)

Stokes-V parameters (30 data)

Fourier periodograms for each velocity-bin and its average (red) and window function (green).

Stokes-I parameters (150 data)

Fourier periodograms for each velocity-bin and its average (red) and window function (green).

1850 d  500 d  250 d  200 d

Characteristic timescales (Mathias et al., 2018)

A common information (@ 1850 d) in both Stokes V and Stokes I parameters!

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A 1850 d period?

A connexion to the Long Secondary Period (LSP)?

LSP: origin from convective motions (Stothers, 2010)

Surface magnetism might be connected to a long term process e.g. the turnover timescale of giant convective cells.

Open & full symbols: ESPaDOnS & Narval, resp.

(Mathias et al., 2018)
Strong linear polarisation signal within atomic lines (and a marginal detection on V, from a single sequence)

LSD with maks composed of ~16 000 metallic lines!

Linear polarisation in the lines (individual / global)

(Aurière et al., 2016)

Also detected in other RSGs (Tessore+2017), and in pulsating AGB (Mira stars) and P-AGB (RV Tauri stars) - (Lèbre+2015)
Strong linear polarisation signal within atomic lines
(and a marginal detection on V, from a single sequence)

But why there is a net signal after integrating over the disk?

LSD with maks composed of ~16 000 metallic lines!

Linear polarisation in the lines
(individual / global)

Cf. solar case

Line depolarisation of the continuum polarised by Rayleigh scattering.

Potential diagnostic of photospheric asymmetries ...

Also detected in other RSGs (Tessore+2017), and in pulsating AGB (Mira stars) and P-AGB (RV Tauri stars) - (Lèbre+2015)

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Time variable linear polarisation in Betelgeuse!

=> Monitoring over more than 3 years (in UQ)

Courtesy A. Lopez-Ariste – IRAP
A geometrical interpretation of the position/brightness of spots vs observational parameters.

\[ \tan 2\theta = \frac{U}{Q} \]

\[ Q^2 + U^2 = B \sin^2 \mu \]

\[ \Delta \lambda = \frac{\nu}{c} \cos \mu \]

=> surface location and relative brightness of the spots inducing anisotropies in the radiation field.

Courtesy A. Lopez-Ariste – IRAP
Betelgeuse : confrontation to VLTI/PIONIER data

single spot model
(Montargès+ 2016)

spectropola. maps

Courtesy
A. Lopez-Arête
(IRAP)
CE Tau: Spectropolarimetry vs VLTI/PIONIER image reconstruction

Tessore+2018, en préparation

SQUEEZE image reconstruction (Baron+2010)

Montargès+2018

Courtesy
A. Lopez-Ariste – IRAP
M. Montargès - Louvain

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2- Connecting Surface to Circumstellar Magnetic Fields (AGB ; P-AGB)

Magnetic field strength and structure in Circumstellar Envelope (CSE) from:

Circular polarization
=> 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, H₂O, OH for O-rich stars
- CN lines for C-rich stars (Herpin+2009)

1rst attempt to detect Zeeman splitting of non-maser molecular lines Confirmed by Duthu+2017

(From J. Hron)

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*(From J. Hron)*
Extrapolating the 1/r law (toroidal field) toward the photosphere → the magnetic field strength at the stellar surface of Mira stars could be of the order of a few G.

Magnetic field strength vs. radius relation as indicated by current maser polarization observation of Miras, carbon stars, ...

(Duthu et al., 2017, from Vlemmings et al., 2011)

Detected with Narval on χ Cyg (Lèbre+ 2014)
**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 \(\approx 92\) days
- \(B_l = 10.2 \pm 1.7\) G

**R Sct** (Narval July 2014)
- Pulsation period \(\approx 142\) days
- \(B_l = 0.6 \pm 0.6\) G

Impact of atmospheric shock waves?

Prediction of maser strengths in the envelope of U Mon?

Favoring again toroidal field \((Sabin et al., 2015)\)
Theoretical trends with Rossby number for G-K giants

Evolution (from the ZAMS to the tip of RGB/AGB) of the Rossby number (Ratio of inertial to Coriolis force)

\[ \text{Ro} = \frac{\text{Prot}}{\tau} \]

Magnetic Strip:
1rst D-up and core He burning phase

\[ \text{Ro} \sim 1 \Rightarrow \text{Magnetic Strip}! \]

(Charbonnel et al., 2017) (Observations: Aurière et al., 2015)
Schematic view of an AGB star

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Schematic view of an AGB star

- Nucleosynthesis
- Mixing
- Molecule formation
- Dust formation
- Photochemical reactions

- Xpol@30m-IRAM
- ALMA

- H/He-burning shell
- Degenerate CO core

- 1R_{\odot} \approx 7 \times 10^{10}, 1\text{AU} \approx 1.5 \times 10^{13}, 1\text{pc} \approx 3 \times 10^{18} \text{cm}
Exploitation des raies moléculaires :

**besoin de listes de raies et de facteurs de Landé**

(oxydes TiO, VO, ZrO et molécules carbonées CN, CH, CO, C2)
Many thanks!

To the people involved in PNPS group project MAGEVOL/FIESTA:

Michel Aurière (IRAP) - Alizée Duthu (LAB) - Denis Gillet (OHP) - Fabrice Herpin (LAB) - Eric Josselin (LUPM-IRAP) – Arturo Lopez-Ariste (IRAP) - Philippe Mathias (IRAP) – Miguel Montargés (Louvain) - Julien Morin (LUPM)- Ana Palacios (LUPM) – Pascal Petit (IRAP) - Yohann Scribano (LUPM) – Benjamin Tessore (LUPM)

and to our regular collaborators:
Renada Konstantinova-Antova (Sofia, Bulgarie) and her team
Laurence Sabin (Ensenada, Mexico)
Gregg Wade (Kingston, Canada)
Helmut Wiesemeyer (Bonn, Germany)

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