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

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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
  - TP-AGB magnetic fields (Mira stars)
  - Post-AGB stars (RV Tauri stars) / PN magnetism
  - RSG magnetic fields (special focus: Betelgeuse)

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

- **Toward Near-IR spectropolarimeters**

Active giants (global dynamo)
Descendant of Ap stars (magneto-convection)

Amplification by shock waves?

Turbulent dynamo
**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

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 $\sim 10^{-4}$ of the unpolarised continuum
**Circular Polarisation:**

Mean Zeeman shift of a transition

\[ \Delta \lambda_B = \frac{\lambda^2 \mu_0 B}{4 \pi m_e c^2} = 4.67 \times 10^{-12} \lambda^2 g_{\text{eff}} B \]

\( g_{\text{eff}} \) : Land\`{e} 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)

The Least Square Deconvolution (L.S.D.)

**(Donati et al., 1997)**

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

First-order moment method

**(Rees & Semel, 1979)** adapted to LSD profiles.
**Cool & evolved stars**

**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

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

*Bug Nebula* (From, Amiri Ph.D. 2011)

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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)
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

$$\tau_{\text{max}} = \left( \alpha H_p \right) / V_{\text{conv}}$$
Preliminary trends with rotation from 16 G-K Giants
with known rotational period (Prot from few 10s of days to few 100s of days)

α-ω type dynamo
Sub-G regime

Saturation of the dynamo?

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)

Ap star descendant candidates:
fossil field interacting with convection

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

α-ω type dynamo in these stars with Prot < 200 days

Ro : Rossby number
Ratio of inertial to Coriolis force

(Ro = Prot / τ_{max})
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!
Kepler Giants with seismic constraints \cite{Mosser2012}
Angular momentum transfer from the core to the convective envelope
=> Constraints on/from the dynamo?

Zeeman Doppler Imaging on few targets so far
\cite{Donati1999, Petit2004}
- RS CVn stars (active binaries)
- FK Com stars (very fast rotators and active giants)
and on Pollux
\cite{Auriere2014}

3D MHD simulation of the convective envelope
(with ASH code)
Dipolar configuration
\cite{Palacios2014}
**Thermal Pulsing-AGB (2-4 M_\text{sun})**

Circumstellar magnetic field through CSE from Masers SiO & CN lines

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

**Mira Stars**

\(\alpha\) 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 \(\sim\) a few G (expected from theoretical works: Thirumalai & Heyl, 2013)  
  but not detected (so far ?) with Narval

\(\chi\) 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 $\chi$ Cyg around its 2012 maximum light

Definite Detection
$\chi^2 = 1.81$, $fap = 5.2 \times 10^{-10}$

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.

**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 ...

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)
Detection of surface magnetic field in RV Tauri stars


Narval observations July 2014

Impact of atmospheric shock waves?

R Scuti (pulsation period ~ 142 days)

Bl = 0.6 ± 0.6 G
Spectropolarimetric monitoring of pulsating variables: \( R \) Sct

Impact of atmospheric shock waves?
Circular polarization (Stokes U & Q)

1: DD  $B_l = 0.6 \pm 0.72$ G

2: MD  $B_l = -0.23 \pm 0.72$ G

3: ND  $B_l = -1.62 \pm 0.83$ G

(Sabin et al., 2015)
**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

![Graph showing linear polarization](image)
X Cyg : Linear polarization

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)

Stokes Q :
Definite Detection
($\chi^2=3.01$)

Stokes U :
Definite Detection
($\chi^2=4.57$)

Stokes V :
No Detection (1 sequence)
($\chi^2=1.16$)
Noise level ~ $0.5 \times 10^{-4}$

LSD profiles : thousand lines involved !

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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)

\[ P_{\text{rot}} = 17 \text{ years} \]
\[ (Kervella et al., 2009) \]

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

\[ \Rightarrow R_o \sim 90 \]
not able to sustain a \( \alpha-\omega \) type dynamo

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 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)

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)
**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:

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

**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).
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!