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

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Betelgeuse - 5-8 September 2016 - CIES Meudon
The old AGB picture! IAU Symposium in Montpellier (1998)

- Radiation
- Pulsation
- Shock waves
- Energy dissipation
- Complex chemistry
- Pressure driven wind
- Dust accelerated driven wind
- Mass loss
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**

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

- **Post-AGB stars (RV Tauri stars) / PN magnetism**

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

- **Perspectives and New Challenges**

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

  - Amplification by shock waves?

  - Turbulent dynamo
**Cool Evolved Stars**

**Main characteristics:**
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 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
Cool Evolved Stars

Evolutionary path 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)

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 ... ?
During the transition from AGB to PN:

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

- Evidences of magnetically collimated outflows

Binarity? Magnetic fields? Both?

and

Observational evidences of magnetic fields around AGB, post-AGB, pre-PNe and PNe.
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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$_2$O, 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

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**Magnetic Field strength in AGB envelopes**

**O-rich Miras:**
- SiO at 2 $R^*$
  - $B \sim 3.5$ (up to 10s) G
- Assuming Zeeman
- $H_2O$ at $\sim 5\text{-}80$ AU
  - $B \sim 0.1 \text{-} 2$ G
- $OH$ at $100\text{-}10\ 000$ AU
  - $B \sim 1\text{-}10$ mG

**C-rich Miras:**
- CN at $\sim 2\ 500$ AU
  - $B \sim 7\text{-}10$ mG

Geometry of the field:
- Toroidal field $B \sim 1/r$

→ **Extrapolation ?**
the magnetic field strength at the stellar surface of Miras could be of the order of a few G.
**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$_2$O, 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+
2m Telescope

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 (circular)
or Stokes U (linear) polarised spectrum
or Stokes Q (linear)

⇒ Polarisation (circular or linear) **within spectral** (atomic) **lines**

Polarimetric sensitivity ~ $10^{-4}$ of the unpolarised continuum
Estimation of $B_l$, the **Longitudinal Component of the Magnetic Field**:

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

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.)

(Rees & Semel, 1979)

**POLLUX (K0III)**

(Aurière et al., 2009)
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
\[ T_{\text{max}} = \frac{\alpha H_p}{V_{\text{conv}}} \]
Preliminary trends with rotation from 16 G-K Giants
with known rotational period (Prot from few 10s of days to few 100s of days)

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

Unlikely for Pollux: Sub-Gauss regime!

(Aurière et al., 2015)
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with known rotational period (Prot from few 10s of days to few 100s of days)

Ap star descendant candidates:
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Ro:
Rossby number
Ratio of inertial to Coriolis force

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

(Aurière et al., 2015)

\[ Ro = \frac{\text{Prot}}{\tau_{\text{max}}} \]
**Exploration of unbiased sample (magV < 4)**

40 Red Giants 
(with Narval/ESPaDOnS)

Magnetic RGB/AGB with $B_l < 1$ 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 : \( B \sim 1/r \) ...
*(Herpin et al. 2006, 2009; Sabin et al., 2013)*

=> Extrapolation toward the photosphere...

**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)*

*ο 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

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.

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

Surface field estimation: 2-3 G

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

Bl = 10.2 ± 1.7 G

Impact of atmospheric shock waves?

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

Bl = 0.6 ± 0.6 G

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)

\[ P_{\text{rot}} = 17 \text{ years} \]

\[ R_0 \sim \frac{P_{\text{rot}}}{\tau_{\text{conv}}} \]

\[ \Rightarrow R_0 \sim 90 \]

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 a Large program Narval
(Mathias et al., in preparation)
Field Variations at the Surface of Betelgeuse
New DetectionS of Surface Field in other M-type RSG

**α¹ Her, 11Jul15 (M5I)**

\[ B_l = -4.3 \pm 0.4 \text{ G} \]

**µ Cep, 01Sep15 (M2I)**

\[ B_l = 2.1 \pm 0.6 \text{ G} \]

**CE Tau, 06Mar15 (M2I)** (Tessore et al., in preparation)

\[ B_l = 0.2 \pm 0.5 \text{ G} \]

**ρ Cas, 08Sep15 (G2I)**

No Detection

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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!