AGB stars and their environment

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1. AGB stars and their winds: why, how?

2. New interferometric observations
   ⇒ Physical conditions + Keys to the mass loss mechanism

3. Reconstruction of the envelopes in 3-D
   • 3-D modeling based on velocity fields
   • Test cases
   • Application to the observed X,Y,V cube
     ⇒ IRC +10 216 3-D model

4. The case of multiple stars

5. A rich circumstellar chemistry
1.1 Asymptotic Giant Branch stars

- They are Red Giant stars with a degenerated Carbon-Oxygen core surrounded by burning Helium and Hydrogen shells.
1.2 Asymptotic Giant Branch stars

- **Critical stellar masses:**
  - $M > 0.8 \, M_\odot \rightarrow \text{He core burning}$
  - $M > 8 \, M_\odot \rightarrow \text{C-O core burning}$

- **Chemical types:**
  - $M$-type/oxygen-rich stars ($C/O \approx 0.5$);
  - $S$-type stars ($C/O \approx 0.5-1$);
  - $C$-type/carbon-rich stars ($C/O > 1$).

- **Carbon star masses are in the range** $1.5 \, M_\odot < M < 4 \, M_\odot$.

- **Luminosity Pulsations:** Short period irregular, Long-period (>100 d) regular (Mira-type).

- **Thermal Pulses:** every few $\times 10^4$ years

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1.3 Asymptotic Giant Branch stars

- At the end of the AGB phase (‘Thermally Pulsing’ or TP) the stars experience strong stellar winds:

\[ \dot{M} = \text{few } \times 10^{-8} \text{ to few } \times 10^{-4} \, M_\odot/\text{yr} \]

- They are surrounded by thick expanding envelopes opaque to visible light.

- AGB star envelopes contribute to the regeneration of the ISM providing 80% of newly synthetized elements.

- They are also the main providers of interstellar dust grains.
1.4 Strong AGB stellar winds

• Why do they arise? *Not fully clear as:*
  – Photosphere *temperature is not high enough* for gas particles to reach the escape velocity. Also, AGB stars do *not shine enough UV radiation* to accelerate the gas through UV line absorption.
  – Needs *cooling* of the upper atmospheric layers to *form dust grains* that will be accelerated by radiation pressure and drag the gas.
1.5 Strong AGB stellar winds

1: Stellar pulsation & convection induce strong shock waves in the extended atmosphere which push gas outwards.

2: Dust forms in the wake of the shock and is pushed outwards by radiation pressure, gas is dragged along.

Dust formation ➔ see J. M. Winters’ talk

S. Höfner
Stellar winds across the H-R Diagram

Massive stars: radiation-driven winds

Cool luminous stars: pulsation/dust-driven winds?

Solar-type stars: coronal winds (driven by MHD turbulence?)

TP-AGB stars

K. Gayley

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1.6 Strong AGB stellar winds

– How to lift and cool those layers? Through stellar pulsations? Shocks? Magnetic pressure? Gravitational pull by companion star or planet?

• How may we find out?

– Stars have very small angular sizes and their envelopes are opaque to visible radiation

  IR and mm/sub-mm interferometry

Fortunately, we have new, powerful instruments!
2.1 Powerful interferometers operating in the IR, sub-mm and mm domains

ALMA (JAO)  mm/sub-mm

NOEMA (IRAM)  mm/sub-mm

VLTI (ESO)  Visible/NIR/MIR

SMA (SAO/ASIAA)  sub-mm

See poster of E. Chapillon/IRAM

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2.2 What do we learn from first interferometric observations?

A. Photospheres: **blobs, plumes & hot spots**: magnetic pressure?

B. Envelopes: 3-D morphology may be reconstructed
   1. Detached expanding shells: sporadic mass loss
   2. Filled expanding spheres: continuous mass loss
      a. Spirals (+ detached shells)
      b. Over-dense shells
   3. Bipolar outflows collimated by disks: transition to PPNs

C. Frequent presence of **binary stars**

D. Time dependence of chemistry
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(A.1) We can now resolve stellar photospheres!

C-star R Sculptoris (VLTI/PIONIER)

S-star $\pi^1$ Gruis (VLTI/PIONIER)

Wittkowski et al. 2017

Paladini et al. 2018

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(A.2): Photosphere of the Red supergiant *Betelgeuse* in the 338 GHz continuum (*ALMA*)

Radius \( \sim 10^3 R_\odot \)

Hot spots/blobs

40 mas

*O’Gorman et al. 2017; Kervella et al. 2018*
(A.3) Betelgeuse

Molecular plume condensed into dust

Radius $\sim 10^3 \, R_\odot$
Rotation period $\sim 36$ years

*Kervella et al. 2018*
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(B.1) Sporadic mass loss: detached envelope

U Antliae
ALMA CO(1–0)

Simple geometry → reconstruct the 3-D morphology from velocity-channel maps

Credit: F. Kerschbaum
ALMA (ESO/NAOJ/NRAO)

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ALMA velocity-channel maps
U Antliae in CO(1–0)

Kerschbaum et al. 2017
Velocity-channel maps for a uniformly expanding circumstellar shell

Velocity-channels close to the systemic velocity $V_\star (X,Y,V_\star)$ trace the gas in the meridional plane parallel to the plane of the sky.

Velocity-channel maps $(X,Y,V)$ trace the emissivity distribution from conical shells.

$$V = V_\star$$

$$2R \sqrt{1 - (V_2 - V_\star)^2 / V_{exp}^2}$$

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Velocity-channel maps $(X,Y,V)$ trace the emissivity distribution from conical shells.

$V = V_{\star}$

$|V_2| < |V_{\star}|$

$2R \sqrt{1 - \frac{(V_2 - V_{\star})^2}{V_{\exp}^2}}$

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Velocity-channel maps for a uniformly expanding circumstellar shell

Imply a **thin** (200 yr-thick), **almost spherical, detached** shell of gas ejected 2700 yr ago, plus a recent one!  

*Kerschbaum et al. 2017*

\[ V = V_\star \]

\[ 2R \sqrt{1 - (V_2 - V_\star)^2/V_{\text{exp}}^2} \]
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(B.2) Continuous mass-loss: spiral pattern

**ALMA velocity-channel maps**

**AFGL 3068 (LL Pegasi)**

Central channel in polar coordinates

Archimedean spirals (orbital plane in the plane of the sky) + bifurcation (eccentric orbit)

Kim et al. 2017
(B.3) Continuous mass-loss after sporadic flare: inner spiral + outer detached shell

Maercker et al. 2012

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(B.4) Continuous mass-loss with periodic enhancements: FILLED ENVELOPE

IRC+10 216 (CW Leonis)
Archetype of (and among the closest) TP-AGB stars

\[ D \approx 130 \text{ pc} \]

Fig. 3. FORS1 deconvolved V-band image of IRC+10216. North is up and East is left.
Properties of IRC+10 216 (CW Leo)

- **Massive envelope** of large apparent size (several arcmin)
- **Simple** symmetric shape
- **Uniform** expansion velocity (14.5 km/s)
  \[ 1 \text{ arcsec} \approx 130 \text{ a.u.} \approx 50 \text{ yr} \]
- **Rich molecular content** (>80 molecular species, including all known **interstellar anions**)

**Fig. 3.** FORS1 deconvolved V-band image of IRC+10216. North is up and East is left.
IRC+10 216: V-band, C$_6$H, and CO emission in the plane of the sky at the same scale

Fig. 3. FORS1 deconvolved V-band image of IRC+10216. North is up, and East is left.

16” radius empty shell

C$_6$H/PdBI

Guelin et al. 1999

Leão et al. 2006

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CO(2–1) $X,Y,V$ cube: whole envelope (6 arcmin) at 3″ resolution
ALMA

+ 30-m

CO(2–1) X,Y,V cube: central 1.5 arcmin at 0.3” resolution

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Same image (CO(2–1)) in polar coordinates

Horizontal sinusoids → slightly off-centred **circular rings**

**Guélin et al. 2018**

No spirals in IRC+10 216!

**Spirals in AFGL 3068**

**Kim et al. 2017**
CO(2–1) in the meridional plane

a set of nearly concentric rings over an extended pedestal

CO(2–1) V=V_★
**ZOOM on the CO(2-1) emission in the meridional plane (V=V★)**

- **Mass-loss rate**
  - derived from $^{12}$CO and $^{13}$CO (2–1) and (1–0) lines
  - roughly constant over the last 7000 yr with a 3× periodic modulation

**Temperature**

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\( \text{C}_4\text{H}(24-23) \ X,Y,V \text{ cube: central 1 arcmin at 0.3'' resolution} \)

\( \text{CN, C}_2\text{H, C}_4\text{H, C}_6\text{H: an empty spherical shell} \)

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CO (yellow) and CN (cyan) emission contours on VLT optical image

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CONCLUSIONS from meridional plane images of IRC+10 216

• **Quasi-regular** pattern of CO-bright shells
  ▪ Typical shell spacing in the outer envelope is \( \sim 16" \) or 700 yr
  ▪ Pattern is **tighter** inside 40"

• Very good spatial correlation between CO, C\(_4\)H, CN and dust (optical) ⇒ **density pattern**

• Shell/intershell density contrast of \( \sim 3 \)

• Pattern may be explained with mass loss modulation by a **low-mass companion** with an orbit in the plane of the sky.

**BUT, IS THE MASS LOSS ISOTROPIC?**
From the XYV cube to 3-D XYZ envelope

Two Algorithms were developed for the envelope reconstruction:

Non-iterative: (A)
Starts from the central (V★) velocity bin and moves alternatingly to neighboring velocity bins. Tries to match velocity images.

Iterative: (B)
• Converts initial model to spherical coordinates.
• Smooths the spherical grid in polar (θ) direction.
• Converts back into Cartesian and normalises to match velocity images.

Test model: spherical shells
Results: the reconstructed envelope in 3-D

Method A and B yield very similar results!

So far, with the X,Y,V=V★ velocity-channel maps, we have considered the trace of the dense CO-bright shells in one single Meridional Plane.

Now, using the reconstructed 3-D XYZ cube, we can follow the shells throughout the whole envelope, e.g. following a set of inclined meridional planes.
Animation of the IRC +10 216 morphology in 3-D through a set of meridional planes. The two extreme velocity channels with high opacity have been masked. The shells have spherical shapes and can be followed over large angular ranges (>3 steradian).
Conclusion: the mass loss is (nearly) isotropic!
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(B.5) A more evolved case: bipolar winds collimated by a dense molecular disk

M2-9 (Minkowski’s Butterfly Nebula)

PdBI (now as NOEMA) & ALMA CO emission maps

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M2-9 in CO observed with NOEMA & ALMA

Castro-Carrizo et al. 2017

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Binary effects on different AGB stars

CIT 6
- VLA
  - HC$_3$N(4–3)

AFGL 3068
- ALMA
  - $^{12}$CO, $^{13}$CO, HC$_3$N

Mira
- ALMA
  - $^{12}$CO(3–2)

W Aquilae
- ALMA
  - $^{12}$CO(3–2)

Kim et al. 2013
Kim et al. 2017
Ramstedt et al. 2014; 2017
Binary effects on different AGB stars

Mastrodemos & Morris 1999

Kim & Taam 2012a, b, c

Mohamed & Podsiadlowski 2012

Homan et al. 2015
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Growth of carbon chain species \( \text{C}_2\text{H}, \text{C}_4\text{H}, \text{C}_6\text{H}, \text{CN}, \text{HC}_3\text{N}, \text{HC}_5\text{N}, \) and \( \text{C}_3\text{N} \)

→ see M. Agúndez’ talk

Agúndez et al. 2017
## MOLECULES DETECTED IN AGB STARS

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<th>CN</th>
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Conclusion and future prospects

• New/upgraded interferometers, operating in the near-/mid-IR, (sub-)millimetre, and radio domains, yield clues to the mass-loss process in AGB stars and the morphology and chemical content of their envelopes.

• Observations of a dozen of dusty envelopes show a variety of morphologies that can be related to:
  ▪ the mechanisms expelling gas from the upper stellar atmosphere
  ▪ the mass-loss history (sporadic or continuous)
  ▪ its modulation by a companion star

• High angular-/spectral-resolution observations of more stars are needed to assess the effectiveness of those mechanisms.

• Positions of various molecules in the envelope allow us to test time-dependent chemistry.

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Thank you!