The kinematics in the large-scale environment of Betelgeuse from radio HI-line observations

T. Le Bertre, E. Gérard
Observatoire de Paris
& L.D. Matthews
MIT Haystack Observatory

HI at 21 cm

- hyperfine-structure line of hydrogen in the ground state
  \[ \lambda = 21 \text{ cm}, \upsilon = 1400 \text{ MHz}, \quad A_{10} \sim 3 \times 10^{-15} \text{ s}^{-1} \]
- generally optically thin
- \( \upsilon = 1.4 \text{ GHz} \Rightarrow \frac{h\upsilon}{kT} \ll 1 \)

**measured flux \( \propto N_H \)**

*the emission in HI line is a good tracer of morphology*

- If the distance is known, we can estimate the mass in atomic hydrogen
- \(~70\% \text{ of mass in hydrogen: } \text{HI} \rightarrow \text{mass} \)
- circumstellar HI should be protected by the surrounding ISM
Hydrogen in HI or H$_2$?


• if $T_{\text{eff}} > 2500$ K, all hydrogen in the atmosphere should be atomic;

• if $T_{\text{eff}} < 2500$ K, all hydrogen should be molecular,

  but H$_2$ should be photodissociated at $r \sim$ few $10^{17}$ cm

Betelgeuse: $T_{\text{eff}} \sim 3641 \pm 53$ K (Perrin et al., 2004, A&A, 418, 675)
main difficulty: HI is ubiquitous

Kalberla et al., 2005, A&A, 440, 775; total galactic HI

-400 km s$^{-1}$ < v < +400 km s$^{-1}$
• In 2000, we started a programme of observations of evolved stars with the Nançay Radiotelescope (160m by 30m → 4'x22' at λ=21 cm)

• The spectra are obtained in the position-switched mode of observation (+/- 2' in RA, +/- 4' in RA, +/- 6', etc.).

• several detections that showed emission lines with line profiles narrower than in CO
Y CVn: $b^H = 72^\circ$ (Le Bertre & Gérard 2004, A&A 419, 549)

**Slowing down of the circumstellar outflow**


(ISOPHOT 90 µm : 12 x 8 arcmin$^2$; $\Phi \sim 8''$, or 0.5 pc)

[dust emission]
A new view on the “detached shells” (Young et al. 1993): the matter in the shell is the sum of slowed down circumstellar material and accelerated external (ISM ?) material.

Libert’s PhD thesis (2009)

Lamers & Cassinelli (2004)
“Introduction to Stellar Winds”
\( \sim 0.8 \times 10^{-7} \, M_{\text{sol}} \, \text{yr}^{-1} \) (H) during \( 4.5 \times 10^5 \) years

\( T_{\text{detached shell}} \sim 100-2000 \, \text{K} \)

unresolved shell (all)

spatially resolved shell
HI observations of Betelgeuse

  - emission peaks at ~ -9 and +16 km s\(^{-1}\)
  - Φ ~ 2 arcmin
  - \(\frac{dM}{dt} = 2.2 \times 10^{-6} \text{ Msol yr}^{-1}\) (200 pc)

- VLA data in the D-configuration (0.035 – 1.0 km; 2010)

  + NRT data obtained in the position-switched mode of observation.

Betelgeuse

- Galactic latitude: $b^\Pi = -9^\circ$
- $V_* = 3.7 \pm 0.4$ km s$^{-1}$
- $V_{\text{exp}} = 14.3$ km s$^{-1}$ (radio CO observations)

ISM on the line of sight

NRT position-switched spectra + model

- $V_{\text{lsr}} (\text{HI}) = 3 \text{ km s}^{-1}$
- $\Phi \sim 4 \text{ arcmin}$
- FWHM $\sim 3 \text{ km s}^{-1}$
- integrated intensity $\sim 5 \text{ Jy km s}^{-1}$
  $\Rightarrow 0.05 \text{ Msol in HI (@200 pc)}$
α Ori, VLA C+D, all baselines
channel maps from –11.8 to + 23 km s\(^{-1}\)

channel spacing = 1.29 km s\(^{-1}\)
2.4 km s$^{-1}$

3.7 km s$^{-1}$

all baselines

baselines $> 0.2$ k$\lambda$ (0.042 km)
Φ = 34 arcsec
α Ori, VLA C+D

diameter = 34 arcsec

inner radius = 80 arcsec
external radius = 160 arcsec
Implication: detection of an HI compact source

- diameter \( \sim 4 \) arcmin (\( \sim 0.24 \) pc)
- coincident with Betelgeuse
- with same radial velocity
- emission in a narrow spectral line (FWHM\( \sim 3 \) km s\(^{-1}\))

**HI detached shell model**

- \( d = 200 \) pc
- \( \frac{dM}{dt} = 1.2 \times 10^{-6} \) \( M_{\text{sol}} \) yr\(^{-1}\)
- duration = \( 8 \times 10^{4} \) yr
- \( V_{\text{exp}} = 14 \) km s\(^{-1}\)
- \( r_{\text{in}} = 0.12 \) pc (2.0 arcmin)
- \( r_{\text{out}} = 0.18 \) pc (3.0 arcmin)
- \( T \sim 6000 - 200 \) K
α Ori, VLA C+D, baselines > 0.4 kλ (0.084 km)

background: IRAS image at 60 μm
Herschel (70 µm)  IRAS (60 µm)  GALEX (FUV)
HI spectrum of the arc
implication: HI arc

- emission seems associated with the far-IR/UV arc

- \( V_{\text{lsr}} \approx +6.3 \pm 10.1 \text{ km s}^{-1} \) different from star velocity (and from HI compact source velocity), but corresponding to the ISM peak of emission (7.5 km s\(^{-1}\))

- integrated intensity \( \sim 4.9 \text{ Jy km s}^{-1} \)
  \( \Rightarrow 0.05 \text{ Msol in atomic hydrogen (at 200 pc)} \)
Summary

We have detected atomic hydrogen from the environnement of Betelgeuse, and found three components:

- two peaks at $\sim V_\ast \pm V_{exp}$ (-9 and +16 km s$^{-1}$) coincident with the central star and arising from the free-flowing wind;
- a quasi-stationary detached shell of $\sim 0.24$ pc diameter at 3 km s$^{-1}$ ($\sim V_\ast$) that can be accounted for by a mass loss rate of $\sim 1.2 \times 10^{-6}$ $M_{\odot}$ yr$^{-1}$ for a duration of $\sim 8 \times 10^4$ yr;
- an emission coincident with the far-IR ring at $\sim 6 – 10$ km s$^{-1}$. 