Discovery of a detached H I gas shell surrounding α Orionis

T. Le Bertre, 1⋆ L. D. Matthews, 2 E. Gérard 3 and Y. Libert 4

1LERMA, UMR 8112, CNRS & Observatoire de Paris, 61 av. de l’Observatoire, F-75014 Paris, France
2MIT Haystack Observatory, Off Route 40, Westford, MA 01886, USA
3GEPI, UMR 8111, CNRS & Observatoire de Paris, 5 place J. Janssen, F-92195 Meudon Cedex, France
4IRAM, 300 rue de la Piscine, Domaine Universitaire, F-38406 Saint Martin d’Hères, France

Accepted 2012 March 1. Received 2012 February 24; in original form 2011 December 28

ABSTRACT

We report the detection of the H I line at 21 cm in the direction of α Orionis (α Ori) with the Nançay Radiotelescope and with the Very Large Array.

The observations confirm the previous detection of H I emission centred on α Ori, but additionally reveal for the first time a quasi-stationary detached shell of neutral atomic hydrogen ~4 arcmin in diameter (0.24 pc at a distance of 200 pc). The detached shell appears elongated in a direction opposite to the star’s space motion.

A simple model shows that this detached atomic gas shell can result from the collision of the stellar wind from α Ori with the local interstellar medium (ISM). It implies that α Ori has been losing matter at a rate of ~1.2 × 10^-6 M⊙ yr^-1 for the past 8 × 10^8 yr.

In addition, we report the detection of atomic hydrogen associated with the far-infrared arc located 6 arcmin north-east of α Ori, which has been suggested to trace the bow shock resulting from the motion of the star through the ISM. We also report the detection by the Galaxy Evolution Explorer of a far-ultraviolet counterpart to this arc.

Key words: circumstellar matter – stars: individual: α Ori – stars: mass-loss – supergiants – radio lines: stars.

1 INTRODUCTION

Evolved late-type stars [asymptotic giant branch (AGB) stars and red supergiants] are observed to undergo mass-loss at high rates. They are thus surrounded by expanding circumstellar envelopes (CSEs). Observations show a wide variety of different properties of the central stars and of the CSEs, which are not always easily related. The time variability of the mass-loss phenomenon may explain why it is difficult to relate the properties of CSEs to those of the central stars. Also, some stars may share the same observational properties, but be in slightly different evolutionary stages, with different initial masses and different mass-loss histories. It would be extremely useful to get overviews of CSEs that would allow us to smooth the chaotic effects of the mass-loss time variability and also to measure the total mass expelled by the central stars. With this goal in mind, we are exploring the properties of CSEs around evolved stars by using the atomic hydrogen (H I) line at 21 cm.

Indeed, hydrogen is expected to be the dominant species in stellar winds of evolved stars. It is also expected to be in atomic form right from the stellar atmosphere if the effective temperature, T eff, is larger than 2500 K, and to remain atomic in the expanding wind (Glassgold & Huggins 1983). Also, atomic hydrogen should be protected from photoionization by the abundant atomic hydrogen in the interstellar medium (ISM) which absorbs ultraviolet (UV) photons of energy larger than 13.6 eV. The H I line at 21 cm should thus be an important tracer of stellar winds for late-type stars with T eff > 2500 K, including the outer CSEs where molecules are dissociated. H I studies should bring unique information on the kinematics in these media, and in particular in the regions of interaction with the ISM.

However, the detection of red giants in the H I line at 21 cm is hampered by the competing emission from atomic hydrogen in the ISM (which ironically protects the circumstellar atomic hydrogen from destruction) along the same lines of sight. For a long time this difficulty precluded H I observational studies of evolved stars. However, recently, taking advantage of upgraded instruments, we addressed this topic and obtained several detections of AGB stars (Gérard & Le Bertre 2006; Matthews & Reid 2007). In general, a narrow emission line with a quasi-Gaussian profile [full width at half-maximum (FWHM) ~ 3 km s^-1] is observed close to the stellar radial velocity (Vr).

The fate of massive stars is strongly dependent on their mass-loss history, which is still poorly understood, in particular when they are red supergiants (van Loon 2010). Our previous successes encouraged us to extend H I observations to this class of stars. Although suffering from strong galactic H I emission, the supergiant α Orionis (α Ori) was detected by Bowers & Knapp (1987) using the Very Large Array (VLA). At the position of the star, they found emission from the front and backsides of a CSE expanding at a velocity of 14 km s^-1.

⋆E-mail: thibaut.lebertre@obspm.fr

© 2012 The Authors
Monthly Notices of the Royal Astronomical Society © 2012 RAS
In this paper, we report new 21-cm observations of \( \alpha \) Ori that we analyse in combination with the previous data from Bowers & Knapp (1987), in order to revisit in H\(_2\) this otherwise well-documented red supergiant.

2 BASIC DATA

\( \alpha \) Ori (Betelgeuse) is the prototype of red supergiants. It has a spectral type M2\(_{\text{lab}}\). Perrin et al. (2004) have measured its effective temperature by infrared (IR) interferometry: \( T_{\text{eff}} = 3641 \pm 53 \) K. This determination fits well with the revised temperature scale of Galactic Red Supergiants by Levesque et al. (2005; 3650 K for \( \alpha \) Ori). It indicates clearly that atomic hydrogen should be the dominant species in the atmosphere and outflow of \( \alpha \) Ori.

Although it is the closest supergiant, its distance is not well known. Hipparcos measured a parallax of 7.63 \( \pm \) 1.64 mas (Perryman et al. 1997). It has been revised to 6.55 \( \pm \) 0.83 mas (van Leeuwen 2007), which translates to a distance of 153 pc (135–175 pc). But Harper, Brown & Guinan (2008), using multiwavelength radio data obtained at the VLA, derived a smaller parallax/larger distance. When combining the original Hipparcos results with VLA data, they get \( d = 197 \pm 45 \) pc. Harper et al. find also proper motions which are reduced with respect to Hipparcos. They suggest that the Hipparcos parallax is in error because of the large angular size of the star and the motions of the stellar photocentre due to convection (Lim et al. 1998; Haubois et al. 2009; Ohnaka et al. 2011). In the following, we follow Harper et al. (2008) and adopt a nominal distance of 200 pc. At this distance, the bolometric luminosity corresponds to \( \log L/L_\odot \approx 5.10 \pm 0.22 \), which, from the Meynet & Maeder (2003) models (see Fig. 1), indicates a progenitor that was an O9V main-sequence star of 20 M\(_\odot\) (Harper et al. 2008). Due to mass-loss from the main sequence to the red supergiant stage, the present stellar mass would be \( \sim 12–16 \) M\(_\odot\). Recently, using predictions of limb darkening by stellar atmosphere models and high spatial resolution observations at 1.64 \( \mu \)m, Neilson, Lester & Haubois (2011) estimate a present mass of \( 11.6_{-0.9}^{+0.9} \) M\(_\odot\), in good agreement with Meynet & Maeder’s 20 M\(_\odot\) models. However, this should not be overemphasized since, as mentioned above, the mass-loss history of red supergiants is rather insecure.

The proper motions, revised by Harper et al. (2008), are 24.95 mas yr\(^{-1}\) in right ascension and 9.56 mas yr\(^{-1}\) in declination. For a distance of 200 pc, and assuming a solar motion, \( U_0 = 11.1 \) km s\(^{-1}\), \( V_0 = 12.24 \) km s\(^{-1}\) and \( W_0 = 7.25 \) km s\(^{-1}\) (Schönrich, Binney & Dehnen 2010), we derive a velocity in the plane of the sky of 30 km s\(^{-1}\) with an apex at position angle PA = 53\(^{\circ}\).

Like most supergiants, \( \alpha \) Ori is surrounded by an extended CSE. The physical processes responsible for red supergiant mass-loss are unclear, but may be related to atmospheric convection (Lim et al. 1998; Ohnaka et al. 2011). The convective cells could levitate cool gas above the photosphere and lead to mass-loss (Josselin & Plez 2007; Chiavassa et al. 2011). Kervella et al. (2011) have obtained spectacular IR images with the Very Large Telescope of the European Southern Observatory that show an inhomogeneous spatial distribution of the material ejected by the central star at scales corresponding to several stellar radii (0.5–3 arcsec). Infrared Astronomical Satellite (IRAS) detected an extended structure at 60 \( \mu \)m, which Young, Phillips & Knapp (1993a) fitted with a detached shell model of inner radius 0.2 arcmin (0.01 pc at 200 pc) and outer radius 10.5 arcmin (0.6 pc). However, through a careful analysis of high-resolution IRAS data, Noriega-Crespo et al. (1997) discovered a ring (‘far-IR arc’) of mean radius 6 arcmin, mostly confined north-east of \( \alpha \) Ori around PA = 60 \( \pm \) 10\(^{\circ}\), in good agreement with the apex of the proper motion (Fig. 2). They interpret this structure as a bow shock resulting from the interaction of the supergiant wind with the ISM. Assuming that the IR emission is due to dust, Noriega-Crespo et al. evaluate the mass in the far-IR arc to be \( \sim 0.034 \) M\(_\odot\) (at 200 pc). This bow-shock structure was confirmed by Akari at far-IR wavelengths (Ueta et al. 2008). A straight filament (‘bar’) is seen at 10 arcmin from the central star ahead of the bow shock. Although perpendicular to the direction

![Figure 1](https://example.com/image1.png)

**Figure 1.** Evolutionary tracks from Meynet & Maeder (2003; \( Z = 0.02 \)) for stars of initial masses 15 and 20 M\(_\odot\) until the end of He burning; full lines: models with rotation (\( V_1 = 300 \) km s\(^{-1}\)) and dashed lines: models without rotation. The star symbol (*) marks the position of \( \alpha \) Ori assuming a distance of 200 pc (\( \log L/L_\odot = 5.1; T_{\text{eff}} = 3650 \) K).

![Figure 2](https://example.com/image2.png)

**Figure 2.** Upper panel: IRAS image at 60 \( \mu \)m centred on \( \alpha \) Ori (star symbol). Note the arc (which is pointed by the three arrows), \( \sim 6 \) arcmin north-east of \( \alpha \) Ori, and the bar, 10 arcmin north-east (Noriega-Crespo et al. 1997). Lower panel: the same field observed by GALEX. Note the faint narrow counterpart to the 60 \( \mu \)m arc detected by IRAS from PA \( \sim 0^\circ \) to 100\(^{\circ}\). The scale is in counts per second and per pixel (1.5 arcsec).
of motion and of maximum intensity close to the apex of the bow shock, it does not seem related to α Ori in a simple manner, but may have contributed to the extended emission reported by Young et al. (1993a), which thus appears to be a blend of two distinct sources.

Very recently, α Ori was observed by Herschel at 70 and 160 μm (Cox et al. 2012). The images have an unprecedented spatial resolution (6 and 12 arcsec, respectively) and bring many new details that could not be seen on IRAS and Akari images. In particular, they reveal substructures in the far-IR arc discovered by IRAS (upper panel of Fig. 2), which breaks up into at least three thin shells. It is also clear that these shells are not circular, and that the radii of curvature, close to apex, are larger than the distance to α Ori, as would be expected from a bow shock. There are also hints of additional arcs at smaller radii.

Finally, our present analysis has uncovered a faint counterpart to this ring in far-ultraviolet (FUV ~154 nm) imaging obtained by Galaxy Evolution Explorer (GALEX; Martin et al. 2005). The GALEX data presented in Fig. 2 were obtained, from 2008 November 29 to 2009 January 14, as part of the Nearby Galaxies Survey (tile 5786) with an exposure time of 48 915 s. The GR6 pipeline calibrated data were retrieved from the GALEX archive (Morrissey et al. 2007) and smoothed by a Gaussian with kernel width 3 pixels (pixel = 1.5 arcsec). The FUV feature is coincident (in projection) with the outer shell revealed by Herschel. It can be seen most clearly north and north-east of the star, although there are hints that the entire structure subtends an angle of at least ~105° (see arrows in Fig. 2). In the near-UV (~232 nm) the image is unfortunately saturated by a ghost of the central star. A similar, narrow and arc shaped, UV feature has been reported around IRC +10216 by Sahai & Chronopoulos (2010). They ascribed the emission to collisionally excited H2 molecules, although scattering of the interstellar radiation field by small dust particles could also be considered. On the other hand, the α Ori bar does not seem to be detected by GALEX. To our knowledge the FUV emission associated with the far-IR arc of α Ori has not been reported before.

The CSE of α Ori has also been studied in the CO rotational lines. Huggins (1987) observed a CO(2−1) emission line centred at V = 3.7 ± 0.4 km s\(^{-1}\) (local standard of rest, LSR). It implies a 3D space velocity of 31 km s\(^{-1}\), mostly in the plane of the sky. From the profile, Huggins derives an expansion velocity, V\(_{{\text{exp}}}\) = 14.3 km s\(^{-1}\), and a mass-loss rate of ~1 × 10\(^{-6}\) M\(_{⊙}\) yr\(^{-1}\) (scaled to 200 pc).

### 3 NRT SINGLE-DISH OBSERVATIONS

The Nançay Radiotelescope (NRT) is a meridian telescope with a rectangular aperture of effective dimensions 160 m × 30 m. The beamwidth at 21 cm is 4 arcmin in right ascension and 22 arcmin in declination. The point source efficiency is 1.4 K Jy\(^{-1}\), and the system noise temperature 35 K. The observations of α Ori have been obtained in the course of a large survey programme (Gérard, Le Bertre & Libert 2011) over the period from 2006 October to 2011 September.

In Fig. 3, we present a spectrum obtained in the frequency-switched mode of observation. It illustrates that in the direction of α Ori the H\(_{\text{II}}\) emission is dominated by galactic emission due to interstellar atomic hydrogen along the same line of sight. The emission peaks at ~7.5 km s\(^{-1}\). Our spectrum is in good agreement with the spectrum extracted from the Leiden/Argentina/Bonn (LAB) survey (Kalberla et al. 2005; ϕ ~ 36 arcmin). No distinctive feature can be seen in the velocity range expected from the CO observations of α Ori (Huggins 1987).

Data were also obtained in the position-switched mode of observation with the central star placed at the ‘on-position’ and the ‘off-positions’ taken at ±2, ±4 and ±6 arcmin in the east–west direction (Fig. 4). These spectra are strongly affected by interstellar confusion. Nevertheless, an emission feature is detected at the radial velocity expected for α Ori (3 km s\(^{-1}\)). This is seen in the spectrum with the smallest throw (2 arcmin = 1/2 beam in right ascension, left-hand panel) with a peak intensity of ~0.5 Jy. The intensity is about 1 Jy at ±4 arcmin (1 beam, middle panel) and about 1.2 Jy at ±6 arcmin (1.5 beam, right-hand panel). However, the confusion

![Figure 3](https://example.com/figure3.png)

**Figure 3.** NRT frequency-switched spectrum obtained on the position of α Ori (continuous line) compared to the LAB spectrum (dashed line; Kalberla et al. 2005). We adopted a main beam efficiency of 0.60 for the NRT at 21 cm. The vertical line marks the CO centroid velocity of α Ori and the horizontal bar the velocity extent of its CO emission (Huggins 1987).

![Figure 4](https://example.com/figure4.png)

**Figure 4.** α Ori spectra obtained with the NRT in the position-switched mode. Left: off-positions taken at ±2 arcmin. Centre: off-positions taken at ±4 arcmin. Right: off-positions taken at ±6 arcmin. The thin lines correspond to the modelled spectra discussed in Section 5.

© 2012 The Authors, MNRAS 422, 3433–3443
Monthly Notices of the Royal Astronomical Society © 2012 RAS
Table 1. VLA calibration sources.

<table>
<thead>
<tr>
<th>Source</th>
<th>$\alpha$(J2000.0)</th>
<th>$\delta$(J2000.0)</th>
<th>Flux density (Jy)</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>3C48$^a$</td>
<td>01 37 41.29</td>
<td>+33 09 35.13</td>
<td>16.038*</td>
<td>1985 September 22</td>
</tr>
<tr>
<td>–</td>
<td>–</td>
<td>–</td>
<td>15.8778*</td>
<td>2010 January 2–4</td>
</tr>
<tr>
<td>0521+166$^b$</td>
<td>05 21 09.88</td>
<td>16 38 22.05</td>
<td>8.66 ± 0.08†</td>
<td>2010 January 2–3</td>
</tr>
<tr>
<td>–</td>
<td>–</td>
<td>–</td>
<td>8.40 ± 0.12†</td>
<td>2010 January 3–4</td>
</tr>
<tr>
<td>0532+075$^c$</td>
<td>05 32 38.99</td>
<td>07 32 43.34</td>
<td>2.11 ± 0.01</td>
<td>1985 September 22</td>
</tr>
<tr>
<td>0632+103$^c$</td>
<td>06 32 15.32</td>
<td>10 22 01.67</td>
<td>2.39 ± 0.05†</td>
<td>2010 January 2–3</td>
</tr>
<tr>
<td>–</td>
<td>–</td>
<td>–</td>
<td>2.25 ± 0.04†</td>
<td>2010 January 3–4</td>
</tr>
</tbody>
</table>

Units of right ascension are hours, minutes and seconds, and units of declination are degrees, arcminutes and arcseconds.

*Adopted flux density at 1420.76 MHz.
†Mean computed flux density from observations at 1419.57 and 1422.0 MHz; see Section 4.
$^a$Primary flux calibrator.
$^b$Bandpass calibrator.
$^c$Phase calibrator.

4 VLA OBSERVATIONS

4.1 C-configuration observations

Bowers & Knapp (1987) previously observed $\alpha$ Ori in the $H_\alpha$ 21-cm line with the VLA of the National Radio Astronomy Observatory (NRAO) in its C configuration (0.08–3.2 km baselines). These data comprise 32 frequency channels in a single (right circular) polarization with a channel spacing of 6.10 kHz (1.29 km s$^{-1}$) after online Hanning smoothing, resulting in a total bandwidth of 0.189 MHz ($\sim$41 km s$^{-1}$). The band was centred at an LSR velocity of 3.7 km s$^{-1}$. The integrated intensity is $\approx$5 Jy km s$^{-1}$, which translates to $\approx$0.05 M$\odot$ in atomic hydrogen at 200 pc. This relatively strong emission in $H_\alpha$ at a velocity for which Bowers & Knapp (1987) did not report any signal was puzzling and motivated a reassessment of the case at the VLA.

increases rapidly with throw (see for instance the emission feature at $-2$ km s$^{-1}$, and the absorption troughs at $+10$ and $+20$ km s$^{-1}$, that may affect the $\alpha$ Ori line profiles). We have also obtained spectra with larger throws, but the confusion becomes so large that the emission feature at 3 km s$^{-1}$ gets drowned.

Finally, position-switched spectra were obtained with the on-positions at $+11$ arcmin (1/2 beam north) and at $-11$ arcmin (1/2 beam south) of the central star. We find that the $H_\alpha$ source is centred on the stellar position in declination and that there is no evidence of an extension in the north–south direction (FWHM $\lesssim$ 11 arcmin).

Despite the high level of confusion, we can infer that the $H_\alpha$ source, coincident with $\alpha$ Ori, is detected at $V_{\text{LSR}} = 3$ km s$^{-1}$. This source does not appear extended in right ascension as compared to the NRT beam (diameter $\sim$4 arcmin). The line profile is narrow with a FWHM $\sim$ 3 km s$^{-1}$. The integrated intensity is $\approx$5 Jy km s$^{-1}$, which translates to $\approx$0.05 M$\odot$ in atomic hydrogen at 200 pc. This relatively strong emission in $H_\alpha$ at a velocity for which Bowers & Knapp (1987) did not report any signal was puzzling and motivated a reassessment of the case at the VLA.

4.2 D-configuration observations

To obtain improved sensitivity to large-scale $H_\alpha$ emission towards $\alpha$ Ori, we obtained additional VLA observations of the star using the VLA D configuration (0.035–1.0 km baselines) over the course of two observing sessions on 2010 January 2 and 3 (4 h) and 2010 January 3 and 4 (6 h). In total, $\sim$6.7 h were spent on-source.

The VLA correlator was used in 1A mode with a 1.56 MHz bandpass, yielding 512 spectral channels with 3.05 kHz, ($\sim$0.64 km s$^{-1}$) spacing in a single (right circular) polarization. The band was centred at an LSR velocity of 3.7 km s$^{-1}$. Observations of $\alpha$ Ori were interspersed with observations of a phase calibrator, 0632+103, approximately every 20 min. 3C48 (0137+331) was used as a flux calibrator, and an additional strong point source (0521+166) was observed as a bandpass calibrator (Table 1). To ensure that the absolute flux scale and bandpass calibration were not corrupted by Galactic emission in the band, the flux and bandpass calibrators were each observed twice, with frequency shifts of $+1.27$ and $-1.19$ MHz, respectively, relative to the band centre used for the observations of $\alpha$ Ori. 0632+103 was also observed once at each of these offset frequencies to permit more accurate bootstrapping of the absolute flux scale to the $\alpha$ Ori data. We estimate that the resulting absolute flux scale has an uncertainty of $\sim$10 per cent.

Data processing was performed using AIPS. At the time of our observations, the VLA contained 21 operational antennas with L-band receivers, 19 of which had been retrofitted as part of the Expanded Very Large Array (EVLA) upgrade. Data obtained during this EVLA transition period require special care during calibration.2 After applying the latest available corrections to the antenna positions and performing an initial excision of corrupted data, we computed and applied a bandpass calibration to our spectral line data to remove closure errors on VLA-EVLA baselines. The bandpass was normalized using channels 164–447, thus excluding the portion of the band affected by aliasing. We next computed a frequency-averaged (channel 0) data set for use in calibrating the frequency-independent complex gains, again using channels 164–447.

1 The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

2 See http://www.vla.nrao.edu/astro/guides/evlareturn/
Following gain calibration, we applied time-dependent frequency shifts to the data to compensate for changes caused by the Earth’s motion during the course of the observations. At this stage, we also applied Hanning smoothing in velocity and discarded every other channel, yielding a 256-channel data set with a velocity resolution of \(1.3\) km s\(^{-1}\). There were no continuum sources brighter than \(-0.02\) Jy within our primary beam and none detected within a single spectral channel within \(\sim 10\) arcmin of the stellar position; hence, no continuum subtraction was performed.

4.3 A combined VLA data set

To obtain a data set with the maximum possible \(u - v\) coverage, we have concatenated the VLA C- and D-configuration data over the velocity range where the two data sets overlap (\(-14.3 \geq V_{\text{LSR}} \geq 24.3\) km s\(^{-1}\)). This velocity range is sufficient to encompass the range of CO velocities previously observed towards \(\alpha\) Ori (see Fig. 3). The \(u, v\) and \(w\) values of the C-configuration data were precessed to J2000.0 values prior to concatenation.

We imaged the combined data using the AIPS IMAGR program with ‘robust +1’ weighting of the visibilities. The large-scale Galactic emission along the line of sight (Fig. 3) is poorly spatially sampled by the VLA, even in the combined (C+D)-configuration data set, resulting in patterns of strong positive and negative motling across a number of the channel images. Because such emission cannot be readily deconvolved by standard CLEAN deconvolution algorithms, we performed only a shallow clean (20 iterations) on each spectral channel to reduce sidelobes from strong compact emission features. The rms noise per channel is variable and in most channels is dominated by the complex, large-scale emission.

Despite these complications, we find clear evidence of \(H_\text{I}\) emission associated with \(\alpha\) Ori. The channel maps from \(-11.8\) to \(+23.0\) km s\(^{-1}\) are presented in Fig. 5. They are strongly affected by extended interstellar emission for velocities above \(-5\) km s\(^{-1}\). Nevertheless an isolated feature coincident with \(\alpha\) Ori is clearly seen from \(-10.5\) to \(-5.3\) km s\(^{-1}\). In order to facilitate the identification of small sources, we present in Fig. 6 the channel maps obtained when selecting only the largest \(u - v\) spacings (\(\geq 0.4\) k\(\lambda\)). The spatial resolution is \(\sim 34\) arcsec. A source coincident with the central star is detected in the channel maps from \(-9.2\) to \(-6.6\) km s\(^{-1}\), and from \(+17.9\) to \(+19.2\) km s\(^{-1}\). These detections are obtained in channels which correspond approximately to the extreme velocities expected from the wind of \(\alpha\) Ori (\(V_s - V_{\text{exp}} = -10.6\) km s\(^{-1}\), \(V_s + V_{\text{exp}} = 18.0\) km s\(^{-1}\)).

We also find emission associated with \(\alpha\) Ori at \(+2.4\) and \(+3.7\) km s\(^{-1}\). Enlarged versions of the two channel maps are shown in Fig. 7 (all baselines) and in Fig. 8 (limited to baselines larger than \(0.2\) k\(\lambda\)). At \(+2.4\) km s\(^{-1}\) (upper panels), the emission peaks on the central star. On the other hand, in the \(+3.7\) km s\(^{-1}\) channel map, one notes rather a ring of emission peaks surrounding the position of the star (bottom panels in Figs 7 and 8). Outside this ring of \(\sim 4\) arcmin in size the emission decreases steeply, except south-west where a plateau of emission seems to extend away from the star. The \(H_\text{I}\) emission associated with \(\alpha\) Ori in these two channels fits well with that observed at the NRT (Section 3).

In addition, the channel maps from \(+6.3\) to \(+10.1\) km s\(^{-1}\) (Fig. 6) show \(H_\text{I}\) emission seemingly associated with the arc of far-IR emission discovered by \textit{IRAS} 6 arcmin north-east of \(\alpha\) Ori (Noriega-Crespo et al. 1997). Several clumps are also noticeable along the far-IR arc at lower velocities, from \(-1.5\) to \(+5\) km s\(^{-1}\), and
Figure 6. Same as Fig. 5, but selecting baselines larger than 0.4 kλ.

5 INTERPRETATION

A star which is undergoing mass-loss gets progressively surrounded by an expanding circumstellar shell. However, the collision of the supersonic stellar wind with the surrounding medium (ISM or an older envelope) produces a shell of denser material that is slowly expanding (Lamers & Cassinelli 1999). ‘Detached shells’ have been reported to be detected by IRAS around many evolved stars (Young et al. 1993a). The emission of the detached shells observed at 60 and 100 µm is commonly assumed to be continuum emission radiated thermally by dust (Kerschbaum et al. 2010). Young, Phillips & Knapp (1993b) developed a model of a dust shell expanding into the ISM that simulates the formation of a detached shell and accounts for the IRAS results.

The Young et al. (1993b) scenario was revived by Libert, Gérard & Le Bertre (2007) who developed a spherical model adapted to the gas and to the modelling of its H I line emission. In this model a detached shell is produced by a stellar outflow that is abruptly slowed down at a termination shock. This first shock defines the inner limit of the detached shell ($r_i$). The outer limit ($r_o$) is defined by the leading shock (bow shock) where external matter is compressed by the expanding shell (Fig. 10). Between these two limits, the detached shell is composed of compressed circumstellar matter and interstellar matter separated by a contact discontinuity at $r_f$. The circumstellar matter is decelerated and heated when crossing the shock in $r_i$. As it cools down from $T_i$ to $T_f$ (in $r_f$), the expansion velocity decreases further, from $v_i$ to $v_f$, and the density increases from $n_i$ to $n_f$. Adopting an arbitrary temperature at $+10$ km s$^{-1}$. In Fig. 9, the H I emission integrated over the range $-1.5$ to $+8.9$ km s$^{-1}$ is overlaid on the IRAS image. The integrated intensity of the H I emission associated with the far-IR arc is $\sim4.9$ Jy × km s$^{-1}$. This is rather uncertain since the structures blend with background emission at low levels and because the maps in Fig. 6 are probably missing some flux. It translates to a mass of $\sim0.047$ M⊙ in atomic hydrogen. Assuming 10 per cent in helium, the total mass can be estimated to be $\sim0.068$ M⊙, which is within a factor 2 of the Noriega-Crespo et al. (1997) estimate for the mass in the far-IR arc. There is perhaps also H I emission at $+7.6$ km s$^{-1}$ associated with the bar ahead of the arc, but the spatial coincidence is less convincing.

Based on their C-configuration data, Bowers & Knapp (1987) reported emission associated with α Ori at $\sim-9$ km s$^{-1}$ and at $\sim+17$ km s$^{-1}$, but not at $\sim+3$ km s$^{-1}$. The reason is that they presented results based only on the largest $u-v$ spacings ($\geq0.4$ kλ). By doing so, they filtered out emission on large scales. As they noted, it is an efficient approach to get rid of most of the confusing interstellar emission. However, excluding the short spacings from the C-configuration data also removes all signatures of the shell. In particular for α Ori at $\sim+3$ km s$^{-1}$, it removed the source of $\sim4$ arcmin in size associated with α Ori which was detected by the NRT. If the same filtering is applied to the merged C + D data, only the ring of emission peaks is left, as can be seen in the 3.7 km s$^{-1}$ channel map of Fig. 6.

Conversely, when we isolate the data obtained in configuration D, we only detect unambiguously a point source around $-8$ km s$^{-1}$. The channel maps at LSR velocities larger than $-5$ km s$^{-1}$ suffer heavily from interstellar emission. In spite of this confusion, a source is detected at $+3$ km s$^{-1}$, but it does not show the complex structure visible in Fig. 7 because of the lower spatial resolution. Also a peak of emission is visible around $+17$ km s$^{-1}$, but it is immersed in a larger structure. The combination of data obtained in configurations C and D is thus essential to reveal the full range of features that have been described above.
The detached shell of $\alpha$ Ori

profile, Libert et al. (2007) solve numerically the equation of motion between $r_1$ and $r_f$. The temperature profile in the detached shell is constrained by the observed H I line profiles. For the external part of the detached shell (between $r_f$ and $r_2$), Libert et al. (2007) assume a density profile that falls off as $1/r^2$ with the condition that the total mass ($M_{DT,CS}$) is given by the equivalent ISM mass enclosed in a sphere of radius $r_2$. Inside $r_1$, Libert et al. assume a spherical wind in uniform expansion.

Originally Libert et al. (2007) developed this model for Y CVn, a carbon star surrounded by a dust detached shell discovered by IRAS (Young et al. 1993a) and imaged by Infrared Space Observatory (Izumiura et al. 1996). H I line profiles obtained at different positions on and around the central star were well fitted by such a model with a gas temperature decreasing from 1800 K, in $r_1$, to 170 K, in $r_f$. Libert et al. applied the same model to other sources, like RX Lep, an oxygen-rich star (Libert et al. 2008), and V1942 Sgr, another carbon star (Libert et al. 2010a). In general, the gas detached shell model of Libert et al. (2007) accounts well for the H I emission of evolved stars, which are characterized by a narrow-line profile ($\sim 2$–$4$ km s$^{-1}$) approximately centred on the stellar radial velocity.

(Gérard & Le Bertre 2006). Indeed the emission from the detached shell where matter has been accumulating generally dominates the emission from the freely expanding wind region inside $r_1$. The H I emission from an unresolved spherical wind would be characterized by a rectangular line profile of width twice the expansion velocity (Gardan, Gérard & Le Bertre 2006).

However, at high spatial resolution, the inner region ($<r_1$) may be resolved. In such a case a spectrum obtained on the stellar position should show two horns separated by twice the expansion velocity. In addition, a central line, corresponding to the detached shell, should be observed in the middle, at the stellar radial velocity. Thus, for mass losing evolved stars, the Libert et al. (2007) model predicts a characteristic three-peaked profile at the central position and a single-line profile away from it ($>r_1$) with a maximum intensity close to the inner shell boundary.

The merged VLA data show two peaks of emission centred on $\alpha$ Ori at $V_c \pm V_{exp}$. Close to $V_c$, one also notes a peak on the star (Fig. 7, upper panel) and a ring of emission around the star (Fig. 7, lower panel). Fig. 11 shows spectra that have been extracted from the VLA merged data set at the position of the star and in a ring of internal radius 80 arcsec and external radius 160 arcsec. We expect that such a ring encloses most of the H I emission from the detached shell. In the upper panel of Fig. 11, the predicted
Figure 9. H I emission from Fig. 6, summed from \(-1.5\) to \(8.9\) km s\(^{-1}\). The contour levels are \((-8, -5.6, -4, -2.8, 2.8, 4, 5.6, 8) \times 1.8\) mJy beam\(^{-1}\). The background image is from IRAS (see Fig. 2). Note the association between H I emission and the far-IR arc.

Figure 10. Schematic view of the \(\alpha\) Ori detached shell. The termination shock is located in \(r_1\), the contact discontinuity in \(r_2\) and the bow shock in \(r_2\). CS stands for circumstellar material and EX for external material.

A three-peaked profile is seen, with the peaks close to the expected velocities. On the other hand, a single peak at \(V_*\) is visible in the spectrum shown in the lower panel. It thus seems that the VLA data contain information which, at least qualitatively, agrees with the Libert et al. (2007) model. However, the emission intrinsic to \(\alpha\) Ori is partly hidden by the confusion due to the ISM emission, as evidenced by the negative peaks at \(9\) km s\(^{-1}\). Similarly, the NRT data show an emission feature centred close to \(V_*\). Due to its large beam, the NRT cannot detect the emission from the free-flowing wind of \(\alpha\) Ori.

In view of these results, we have run the Libert et al. (2007) model with parameters (distance, expansion velocity, etc.) that apply to \(\alpha\) Ori (see Section 2). As the stellar effective temperature is larger than \(2500\) K, we assume that all hydrogen is in atomic form (Glassgold & Huggins 1983). We also assume that 90 per cent of the mass is in hydrogen and 10 per cent in helium, so that the mean molecular weight, \(\mu\), is equal to 1.3. An expansion velocity of the free wind, \(v_0 = 14\) km s\(^{-1}\), implies a post-shock temperature in \(r_1\) of almost \(5800\) K (see Table 2). For the internal radius we select a value of \(2\) arcmin (\(\equiv 0.12\) pc) in order to get a maximum H I intensity at a position corresponding to the emission peaks identified in Fig. 7. The external radius was set arbitrarily to \(r_2 = 3\) arcmin, and the ISM density to \(n_H = 1\) cm\(^{-3}\). The calculated H I emission is convolved with the telescope beam profile. For the NRT, we adopt the response of a rectangular aperture of \(160\) m \(\times\) \(30\) m (Gardan et al. 2006), and for the VLA a Gaussian response of FWHM \(= 34\) arcsec.

We have tried several combinations of mass-loss rate and duration of the mass-loss episode. The mass-loss rate is constrained by the intensity of the peaks observed at \(V_* \pm V_{exp}\) (i.e. \(-10\) and \(+18\) km s\(^{-1}\)) on the star. The mass in atomic hydrogen in the detached shell (which can be estimated by the emission feature observed at \(V_*\)) constrains the product of the mass-loss rate and the duration. We found satisfactory fits for values of \(\dot{M}\) in the range \(1.0\)–\(1.5 \times 10^{-6}\) M\(_\odot\) yr\(^{-1}\) and values of the duration in the range \(0.7\)–\(1.0 \times 10^5\) yr.

In Figs 4 and 11 we present the results of our best compromise that was obtained with \(\dot{M} = 1.2 \times 10^{-6}\) M\(_\odot\) yr\(^{-1}\) and a total duration of \(0.8 \times 10^5\) yr. The parameters corresponding to this preferred model are summarized in Table 2. A rapid cooling of the gas (with a temperature assumed to vary as a power law from \(5800\) K in \(r_1\) to \(220\) K in \(r_2\)) is needed in order to reproduce the observed narrow-line width (\(\sim 3\) km s\(^{-1}\)) of the emission coming from the detached shell.
In this spherical modelling we have adopted a systemic radial velocity of \(3 \text{ km s}^{-1}\), which gives the best agreement with NRT data. The H\(\alpha\) emission from AGB stars is known to be sometimes shifted by \(\sim 1\)–3 km s\(^{-1}\) with respect to the CO emission which is believed to provide the most precise estimate of the stellar radial velocity (Gérard & Le Bertre 2006). In general this shift is towards 0 km s\(^{-1}\) (LSR), probably an effect of the dragging of the circumstellar shell by the ambient ISM. In Fig. 11 (upper panel) it is clear that the central peak is not centred at the average of the two horn velocities. Consistently the model predicts horns that are blueshifted by \(\sim 1\) km s\(^{-1}\).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(M)</td>
<td>(1.2 \times 10^{-6} , M_\odot , \text{yr}^{-1})</td>
</tr>
<tr>
<td>(\mu)</td>
<td>1.3</td>
</tr>
<tr>
<td>(t_1)</td>
<td>8140 yr</td>
</tr>
<tr>
<td>(t_\text{LSR})</td>
<td>71860 yr</td>
</tr>
<tr>
<td>(r_1)</td>
<td>0.12 pc (2.0 arcmin)</td>
</tr>
<tr>
<td>(r_1)</td>
<td>0.14 pc (2.35 arcmin)</td>
</tr>
<tr>
<td>(r_2)</td>
<td>0.18 pc (3.0 arcmin)</td>
</tr>
<tr>
<td>(T_0(= T_\text{s}), T^+)</td>
<td>20,5796 K</td>
</tr>
<tr>
<td>(T_1 (= T_2))</td>
<td>223 K</td>
</tr>
<tr>
<td>(v_0(= v_\text{s}), v^+_1)</td>
<td>14.3, 35.1 km s(^{-1})</td>
</tr>
<tr>
<td>(v_\text{LSR})</td>
<td>0.06 km s(^{-1})</td>
</tr>
<tr>
<td>(v_2)</td>
<td>0.9 km s(^{-1})</td>
</tr>
<tr>
<td>(n_1, n^+_1)</td>
<td>14.0, 55.8 H cm(^{-3})</td>
</tr>
<tr>
<td>(n_2)</td>
<td>1.8 \times 10^3, 2.5 H cm(^{-3})</td>
</tr>
<tr>
<td>(M_{r&lt;1})</td>
<td>9.8 \times 10^{-3} , M_\odot</td>
</tr>
<tr>
<td>(M_{\text{DT,CS}})</td>
<td>0.086 , M_\odot</td>
</tr>
<tr>
<td>(M_{\text{DT,EX}})</td>
<td>0.8 \times 10^{-3} , M_\odot</td>
</tr>
</tbody>
</table>

### 6 DISCUSSION

With the NRT and the VLA, we have detected an H\(\alpha\) source coincident with \(\alpha\) Ori and relatively compact (\(\sim 4\) arcmin in right ascension). The emission is centred at \(V_{\text{LSR}} \sim 3\) km s\(^{-1}\), and has a narrow-line profile (FWHM \(\sim 3\) km s\(^{-1}\)). In addition, the VLA channel map at 3.7 km s\(^{-1}\) shows a ring of emission encircling the position of the star and a tail extending south-west. Furthermore, the VLA data show emission lines at \(\sim 9\) and at \(\pm 18\) km s\(^{-1}\), right at the position of the central star. Although our data are affected by confusion, these features can be clearly ascribed to the circumstellar shell expelled by the supergiant.

These features can be explained qualitatively by the Libert et al. (2007) detached shell model. In particular, the spectrally narrow emission observed close to \(V_\ast\), which the VLA shows to peak along a ring encircling the position of \(\alpha\) Ori at 3.7 km s\(^{-1}\), is characteristic of the emission expected from a detached shell. Using parameters which are representative of \(\alpha\) Ori, the model gives a fair agreement with the observations. The main result is that the detached gas shell of \(\alpha\) Ori can be accounted for by a mass-loss episode of \(\sim 10^5\) yr duration at a rate in the range \(1\)–\(2 \times 10^{-6} \, M_\odot \, \text{yr}^{-1}\).

In Section 4.3, we noted that Bowers & Knapp (1987) detected only the horns at \(V_\ast \pm V_{\text{LSR}}\) corresponding to the free flowing wind of \(\alpha\) Ori, because they had selected large \(\lambda - v\) spacings. They modelled these horns with a wind of \(2.2 \times 10^{-6} \, M_\odot \, \text{yr}^{-1}\).
Ori and C II line (3 km s$^{-1}$) emission at various distances from the central star. The plateau emission that we observe in Ori is moving is also uncertain.

1.3 km s$^{-1}$ beyond 6 arcmin from the central star. The cooling line should be within the reach of the ISM gas that crosses the bow shock at a temperature $\sim$25 000 K, and hydrogen may be ionized. Except to the south-west, we have found no unambiguous evidence of atomic hydrogen associated with $\alpha$ Ori beyond 3 arcmin from the star. This suggests that hydrogen in the region between the interface and the bow shock remains ionized during the lapse of $\sim$10$^5$ yr that we infer for the formation of the detached shell, or that it remains sufficiently warm that its emission is widened over a large range of velocities, preventing its detection. In these conditions, our H I modelling cannot bring real constraints on the region of the detached shell which is filled by matter from the ISM. In particular, the value that we have adopted for the parameter $r_1$ has no real significance.

Conversely, the parameters that we find for the circumstellar part of the detached shell could be used as constraints for the 3D hydrodynamic simulations of the Betelgeuse’s bow shock that start to be developed (e.g. Mohamed, Mackey & Langer 2011). In this specific case, we note that the interface is at $\gtrsim$0.3 pc from the central star, which seems too large compared to our H I observations, which suggest a smaller value. Possibly the rate of mass-loss adopted by Mohamed et al. (3 $\times$ 10$^{-8}$ M$_{\odot}$ yr$^{-1}$) is too large. The density of the ISM material through which $\alpha$ Ori is moving is also uncertain.

Another possibility is that the far-IR arc seen at 6 arcmin from $\alpha$ Ori is not the true bow shock related to the detached gas shell that is detected at 21 cm. The examination of the images published by Cox et al. (2012) suggests that there are other structures inside the far-IR arc, in particular another arc at 3 arcmin north-east of $\alpha$ Ori. It is tempting to hypothesize that this 3 arcmin radius arc is the true bow shock related to the detached shell that we have modelled. In that case the 6 arcmin radius arc which is also seen in H I and FUV would be related to a more ancient episode of mass-loss. Clearly spectral information on the far-IR emission of this arc and imaging in H I at a higher spatial resolution is needed in order to elaborate on its true nature. The characteristics of the internal medium, between the detached shell and the far-IR arc, are also an issue.

Figure 12. Simulation of the C II line emission at various distances from $\alpha$ Ori. For clarity, the spectra are successively shifted by 2 K.
7 CONCLUSIONS

Observations in the H I line at 21 cm of α Ori have been performed with the NRT and the VLA. A source (φ ~ 4 arcmin) has been detected at the position of the star. The emission is dominated by a narrow line (FWHM ~ 3 km s⁻¹) centred close to $V_t$. The VLA data show that this source has the structure of a detached shell elongated towards the south-west. This shape agrees with the numerical simulations of a CSE moving through the ISM. Emission peaks at $V_t = \pm V_{exp}$ are also observed by the VLA at the position of the central star. Presently the data bring no clear evidence of atomic hydrogen outside this source.

We have developed a working model adapted to α Ori and its detached neutral gas shell that accounts for the spectral features that are observed and for the size of the source. In this model, the detached gas shell of α Ori results from the collision of a $1.2 \times 10^{-6} \ M_\odot \ yr^{-1}$ stellar wind, expanding at 14 km s⁻¹, with the surrounding ISM for a lapse of $10^7$ yr. The gas is cooling from a post-termination-shock temperature of 5800 to $\sim 220 \ K$ at the interface with the ISM.

The high level of confusion in the direction of α Ori forces us to be cautious. Nevertheless, by selecting different ranges of baselines, it is possible to obtain images revealing the detached shell of α Ori as well as H I emission coincident with the 6 arcmin far-IR/FUV arc. Presently, we cannot conclude on the exact nature of the structure in arc discovered by IRAS. We suggest that the H I emission might come from a precursor of the α Ori bow shock, or that the whole structure could be related to an ancient episode of mass-loss.

ACKNOWLEDGMENTS

The Nançay Radio Observatory is the Unité scientifique de Nançay of the Observatoire de Paris, associated as Unité de Service et de Recherche (USR) No. B704 to the French Centre National de la Recherche Scientifique (CNRS). The Nançay Observatory also gratefully acknowledges the financial support of the Conseil Régional de la Région in France. The VLA observations presented here are part of the NRAO programme AM1001. LDM acknowledges support from grant AST-1009644 from the National Science Foundation. This research has made use of the SIMBAD and ADS data bases. We thank Dr. Graham Harper for his careful reading of the manuscript and useful comments.

REFERENCES

Gardan E., Gérard E., Le Bertre T., 2006, MNras, 365, 245
Ueta T. et al., 2008, PASJ, 60, S407

This paper has been typeset from a \TeX/\LaTeX\ file prepared by the author.