Modelling the H I 21-cm line profile from circumstellar shells around red giants

D. T. Hoai, P. T. Nhung, E. Gérard, L. D. Matthews, and T. Le Bertre

1LERMA, UMR 8112, CNRS & Observatoire de Paris/PSL, 61 av. de l’Observatoire, F-75014 Paris, France
2VNSC/VAST, 18 Hoang Quoc Viet, Cau Giay, 10000 Hanoi, Vietnam
3GEPI, UMR 8111, CNRS & Observatoire de Paris/PSL, 5 place J. Janssen, F-92195 Meudon Cedex, France
4MIT Haystack Observatory, Off Route 40, Westford, MA 01886, USA
5Departamento de Física Teórica, Universidad Autónoma de Madrid, Cantoblanco 28049 Madrid, Spain

Accepted 2015 March 3. Received 2015 March 3; in original form 2015 February 2

ABSTRACT
We present H I line profiles for various models of circumstellar shells around red giants. In the calculations we take into account the effect of the background at 21 cm, and show that in some circumstances it may have an important effect on the shape and intensity of the observed line profiles. We show that self-absorption should also be considered depending on the mass-loss rate and the temperature reached by circumstellar gas. H I emission from circumstellar shells has been mostly reported from stars with mass-loss rates around $10^{-7}$ M⊙ yr⁻¹. We discuss the possible reasons for the non-detection of many sources with larger mass-loss rates that are hallmarks of the end of the asymptotic giant branch (AGB) phase. Although radiative transfer effects may weaken the line emission, they cannot alone account for this effect. Therefore, it seems likely that molecular hydrogen, rather than atomic hydrogen, dominates the composition of matter expelled by stars at the end of their evolution on the AGB. However sensitive H I observations can still yield important information on the kinematics and physical properties of the circumstellar material at large distances from central stars with heavy mass-loss, despite the low abundance of atomic hydrogen.

Key words: stars: AGB and post-AGB – circumstellar matter – stars: individual: Y CVn – stars: mass-loss – radio lines: stars.

1 INTRODUCTION

Asymptotic giant branch (AGB) stars are undergoing mass-loss via slow stellar winds (Olofsson 1999). They get surrounded by expanding circumstellar shells that are well characterized by CO emission lines in the millimetre range (Knapp & Morris 1985; Loup et al. 1993). From the modelling of the CO line profiles, expansion velocities are derived to be in the range from a few to 40 km s⁻¹, and mass-loss rates, from $10^{-7}$ to a few $10^{-4}$ M⊙ yr⁻¹.

Most of the matter in circumstellar shells should be in hydrogen (≈70 per cent in mass). Early searches for 21-cm line emission from atomic hydrogen were mostly unsuccessful (Zuckerman, Terzian & Silverlagle 1980; Knapp & Bowers 1983) leading to the conclusion that hydrogen in stellar envelopes is molecular rather than atomic. However, more recently, the H I line at 21 cm has been detected from several AGB stars (Gérard & Le Bertre 2006). A number of the detected stars have also been imaged in H I with the Very Large Array (VLA; Matthews & Reid 2007; Matthews et al. 2008, Matthews et al. 2011, 2013). In general, the detected sources have mass-loss rates $\sim 10^{-7}$ M⊙ yr⁻¹, and they show a narrow H I line profile (3–5 km s⁻¹). On the other hand, many sources with large mass-loss rate ($\geq 10^{-6}$ M⊙ yr⁻¹) remain undetected.

Again, a possible explanation could be that hydrogen in sources with large mass-loss rates is mostly in molecular form. However, this is not entirely satisfactory for at least two reasons. First, molecular hydrogen is expected to be photodissociated by UV photons from the interstellar radiation field (ISRF) in the external parts of circumstellar shells (Morris & Jura 1983). Secondly, the mass-loss rate from AGB stars is supposed to be highly variable (e.g. Vassiliadis & Wood 1993), so that a given star should be surrounded by interacting shells, originating from different episodes of mass-loss at different rates, from $10^{-8}$ M⊙ yr⁻¹ upwards, and different velocities (Villaver, García-Segura & Manchado 2002), with probably a mix of atomic and molecular hydrogen.

Another possibility is that radiative transfer effects are weakening the 21-cm line emission, thus rendering difficult the detection of H I. The narrowness of the line profiles could increase the optical depth.

* E-mail: thibaut.lebertre@obspm.fr
at particular frequencies, thus exacerating self-absorption. The presence of an intense background at 21 cm may also play a role (Levinson & Brown 1980). In this paper, we examine the formation of the H\textsc{i} line in circumstellar shells around AGB stars, taking into account these effects.

2 CONTEXT

Hydrodynamical models of dust-forming long-period variable stars reproduce outflows with mass-loss rate ranging from \(\sim 10^{-8}\) to \(10^{-4}\) M\(_\odot\) yr\(^{-1}\), and expansion velocity ranging from a few to 40 km s\(^{-1}\) (Winters et al. 2000). Close to the central star, the density is much larger than in the interstellar medium (ISM), and the wind expands freely (freely expanding wind). We hereafter refer to the case where the wind expands freely as scenario 1. However, at some point, the stellar wind is slowed down by the ambient medium, and a structure develops in which both circumstellar and interstellar matter accumulates. Such structures were discovered with IRAS owing to the presence of spatially resolved 60-\mu m continuum emission (Young, Phillips & Knapp 1993) and are referred to as ‘detached shells’.\(^1\)

Subsequently, the H\textsc{i} line at 21 cm was detected in the direction of several resolved IRAS sources (Le Bertre & Gérard 2004; Gérard & Le Bertre 2006). The H\textsc{i} emission is more extended than the CO emission and generally corresponds with the far-infrared size. Also the main components of the H\textsc{i} line are narrower than the CO line profiles, thus demonstrating that stellar outflows are slowed down by an external medium, and that the H\textsc{i} line profiles can be used to probe the kinematics in the external regions of circumstellar shells. Imaging obtained with the VLA has revealed detached H\textsc{i} shells with narrow-line profiles, sometimes associated with extended tails (Matthews et al. 2013).

Libert, Gérard & Le Bertre (2007) developed a model of a detached shell (hereafter scenario 2) adapted to the H\textsc{i} emission from the prototypical case of Y CVn. In this model, a double-shock structure develops, with a termination shock, facing the central star, where the supersonic stellar wind is abruptly slowed down, and a leading shock (i.e. outward facing shock) where interstellar matter is compressed and integrated in the detached shell. These two limits define the detached shell which is thus composed of circumstellar and interstellar matter separated by a contact discontinuity. The circumstellar matter is decelerated, by a factor \(~1\), when it crosses the termination shock, and heated. It then cools down, while the expansion velocity further decreases and the density increases until the contact discontinuity. The model assumes spherical symmetry and stationarity. Adopting an arbitrary temperature profile, the equation of motion is solved numerically between the two limits of the detached shell. The H\textsc{i} line profile is then calculated assuming that the emission is optically thin.

Libert et al. (2007) could reproduce the H\textsc{i} line profile observed in Y CVn and generalize the model to other cases of sources with mass-loss rates of about \(10^{-7}\) M\(_\odot\) yr\(^{-1}\) (e.g. Libert et al. 2010). However, as discussed in Matthews et al. (2013), although this model is effective in reproducing spatially integrated line profiles, it faces some difficulties in reproducing the spatial distribution of the H\textsc{i} emission. Namely, at small radii, it seems to predict too much flux in both the shell component and the freely expanding wind component of the spectral profile. The mass-loss variations with time and the interaction between consecutive shells may need to be taken into account (see Villaver et al. 2002). The more elaborate numerical modelling performed by Villaver et al. follows the mass-loss and velocity variations of the stellar winds of thermally pulsing AGB (TP-AGB) stars, and describes self-consistently the formation and development of circumstellar shells embedded in the ISM (hereafter scenario 3). They show that large regions (up to 2.5 pc) of neutral gas may be formed around AGB stars.

In this work, we will simulate the H\textsc{i} line profiles that would be expected for these three kinds of scenarios and examine how they compare with observations presently available.

3 GENERAL COMMENTS ON THE FORMATION OF THE H\textsc{i} LINE PROFILE

The H\textsc{i} line at 21 cm is produced by a transition between two levels of the ground state of hydrogen. The rest frequency, \(v_0\), corresponds to 1420.4 MHz, and the transition probability, \(A_{21}\), to 2.87 \(10^{-15}\) s\(^{-1}\). As the transition probability between the two levels is very low, the natural width of the line is extremely small, and the frequency dependence of the absorption and emission coefficients are entirely defined by the atomic hydrogen velocity. This is determined by the bulk motion of the gas (including, if present, turbulence), and the hydrogen kinetic temperature \((T)\). We assume local thermal equilibrium. Also, in general, as the frequencies are small, one may replace \(\exp(hv/kT)\) with \(1\), by \(hv/k \sim 0.07\) K.

The intensity emitted, at a frequency \(v\), along an element \(ds\), \(dI_v\), is given by
\[
\frac{dI_v}{ds} = \frac{h v}{4\pi} n_2(v) A_{21},
\]
where \(n_2(v)\) is the number density of hydrogen atoms in the upper level with a velocity along the line of sight corresponding to \(v\).

Similarly the absorption part is given by
\[
\frac{dI_v}{ds} = -\kappa(v) I_v,
\]
with the absorption coefficient, \(\kappa(v)\), given by
\[
\kappa(v) = \frac{c^2 n_1(v) g_2}{8\pi v_0^2 g_1} A_{21} \frac{h v}{kT}.
\]
(cf. equation 3.14 in Lequeux 2005). \(g_2\) and \(g_1\) are the statistical weights of the upper and lower levels, respectively, and \(n_1(v)\) is the number density of hydrogen atoms in the lower level with a velocity along the line of sight corresponding to \(v\). It is interesting to note that, in general, the absorption coefficient varies as \(1/T\).

For the H\textsc{i} line at 21 cm: \(g_1 = 1, g_2 = 3\), and for a population in statistical equilibrium, \(n_1 = 1/4 n_H\) and \(n_2 = 3/4 n_H\), where \(n_H\) is the total number density of hydrogen atoms in the ground state \((n_1 = n_1 + n_2)\), and assuming \(\exp(hv/kT)\) \(= 1\) for the Boltzmann factor.

In practice, spectra are represented as a function of the velocity, \(V\). We may thus replace \(n_1(v)\) by \(1/4 n_H\) and \(n_2(v)\) by \(3/4 n_H\). With this convention, the absorption coefficient can be rewritten as
\[
\kappa(V) = \frac{3 c^2 n_H(V)}{32\pi v_0^2} A_{21} \frac{h}{kT}.
\]

Finally, the radiative transfer equation is written as
\[
\frac{dI(V)}{ds} = \frac{3 h v_0}{16\pi} n_H(V) A_{21} - \frac{3 c^2 n_H(V)}{32\pi v_0^2} A_{21} \frac{h}{kT} I(V).
\]

---

\(^1\) This designation has also been used for shells resulting from an outburst of mass-loss and observed in CO molecular lines (Olofsson et al. 2000). In this paper, we adopt to the definition of Young et al.
At radio frequencies, it is usual to express the intensity in terms of the equivalent temperature of a blackbody that would give the same intensity in the same spectral domain. With this convention, the boundary condition can be defined through a background brightness temperature, $T_{BG}$

$$I^+(V) = \frac{2kV_0^2}{c^2} T_{BG}(V), \quad (6)$$

$I^+$ referring to the incoming intensity on the rear side of the shell.

The background is the sum of the 3-K cosmic emission, the synchrotron emission from the Galaxy and the H I emission from the ISM located beyond the circumstellar shell with respect to the observer. The first component is a continuum emission, which is smooth, angularly and spectrally. The second component is also smooth spectrally, but it presents a strong dependence with galactic latitude, and shows also some substructures. The sum of these two components has been mapped with a spatial resolution of 0.6 by Reich (1982), Reich & Reich (1986) and Reich, Testori & Reich (2001). The third component (HI emission from the ISM) shows both strong spatial and spectral dependences, which make it a serious source of confusion. It has been mapped with a spatial resolution of 0.6 and a spectral resolution of 1.3 km s$^{-1}$ by Kalberla et al. (2005; Leiden–Argentina–Bonn, LAB, survey). Surveys of selected regions of the sky, in particular along the Galactic plane, have been obtained at a resolution down to 1 arcmin, and show spatial structures, like filaments or clouds, at all sizes (e.g. Stil et al. 2006).

Away from the Galactic plane, typical values range from $T_{BG} \sim 3$–5 K, outside the range of interstellar H I emission, to $T_{BG} \sim 10$–20 K inside an interstellar H I emission. Close to the Galactic plane, the continuum may reach $T_{BG} \sim 10$–20 K, and, including the interstellar H I emission, the background may reach $T_{BG} \sim 100$ K. Note that the background temperature, $T_{BG}$, is not directly related to the kinetic temperature of the surrounding ISM.

In addition, in some cases, a radio source may be seen in the direction of a circumstellar shell. In such a case, we have an unresolved continuum emission (see e.g. Matthews et al. 2008). Such a source may be useful to probe the physical conditions within the circumstellar shell in a pencil-beam mode.

### 4 SIMULATIONS

For this work, we adapted the code developed by Hoai et al. (2014). It is a ray-tracing code that takes into account absorption and emission in the line profile. It can handle any kind of geometry, but for the purpose of this paper we restricted our simulations to circumstellar shells with a spherical geometry as described in Section 2. We assume that, in each cell, the gas is in equilibrium and that the distribution of the velocities is Maxwellian.

In this section, we explore the line profiles for a source that is not resolved spatially by the telescope, and assume a uniform response in the telescope beam (boxcar response, cf. Gardan, Gérard & Le Bertre 2006). We also assume that the line profiles can be extracted from position-switched observations, i.e. that there is no spatial variation of the background. The flux densities are expressed in the units of Jansky (Karl Jansky), where 1 Jy = $10^{-26}$ W m$^{-2}$ Hz$^{-1}$.

We performed various tests in order to evaluate the accuracy of the simulations. It depends mainly on the mass-loss rate of the central source and on the size of the geometrical steps adopted in the calculations. For the results presented in this section, the relative error on the line profile ranges from $\sim 10^{-6}$, for mass-loss rates of $10^{-7}$ $M_\odot$ yr$^{-1}$, to a few $10^{-5}$, for mass-loss rates of $10^{-4}$ $M_\odot$ yr$^{-1}$.

#### 4.1 Freely expanding wind (scenario 1)

We consider a spherical wind in free expansion at $V_{exp} = 10$ km s$^{-1}$. The distance is set at 200 pc, and the mass-loss rate is varied from $10^{-7}$ to $10^{-4}$ $M_\odot$ yr$^{-1}$. We assume that the gas is composed, in number, of 90 per cent atomic hydrogen and 10 per cent $^4$He. We assume a temperature dependence proportional to $r^{-0.7}$, $r$ being the distance to the central star, to the external boundary (0.17 pc) where the temperature drops to 5 K. This temperature of 5 K is probably underestimated as the photoelectric heating by grains absorbing UV photons is expected to raise the temperature of the gas in the cool external layers of shells around stars with high mass-loss rate (Schöier & Olofsson 2001). On the other hand, temperatures as low as 2.8 K have been reported in some high mass-loss rate sources (e.g. U Cam; Sahai 1990). Such low temperatures are only expected in the freely expanding regions of the circumstellar shells.

The density and temperature profiles are illustrated in Fig. 1 for the $10^{-4} M_\odot$ yr$^{-1}$ case.

In a first set of simulations (Fig. 2), we calculate the integrated emission (within a diameter, $\phi = 6$ arcmin) with no background, in order to estimate the effect of self-absorption (in fact the background should have a minimum brightness temperature of 3 K, cf. Section 3). Self-absorption starts to play a clear role for $10^{-6} M_\odot$ yr$^{-1}$, with an intensity that is reduced, and a profile that changes its shape from almost rectangular to parabolic. A slight asymmetry of the line profile is also present (although not discernible by eye in the figure), with more absorption on the blue side, due to the outwardly decreasing temperature, an effect which has already been described in the case of molecular emission from expanding circumstellar envelopes (Morris, Lucas & Omont 1985).

In a second set of simulations, the mass-loss rate is kept at $10^{-5} M_\odot$ yr$^{-1}$, and the background is varied from 0 K (as above) to 10 K (Fig. 3). The effects noted previously are amplified by the background, in particular with an absorption developing on the blue side of the profile, and then extending to the complete spectral domain when the background temperature reaches 10 K.

We adopted a temperature dependence proportional to $r^{-0.7}$ which fits the results obtained with a radiative transfer model by
4.2 Single detached shell (scenario 2)

We adopt the model developed by Libert et al. (2007). It has been shown to provide good spectral fits of the H i observations obtained on sources with mass-loss rates $\sim 10^{-7} M_\odot$ yr$^{-1}$ (cf. Section 2).

As in Section 4.1, we assume a spatially unresolved source at 200 pc with a mass-loss rate of $10^{-7} M_\odot$ yr$^{-1}$. The internal radius of the detached shell is set at 2.5 arcmin (or 0.15 pc). Similarly, we examine the dependence of the line profile for models with various masses in the detached shell ($M_{DT, CS}$) and various background levels (Figs 4 and 5). The parameters of the four cases illustrated in Fig. 4 are given in Table 1. The free-wind expansion velocity is taken to be $V_{\exp} = 8$ km s$^{-1}$. At the termination shock

Schöier & Olofsson (2001). A shallower dependence would increase the temperature in the outer layers of the circumstellar shell and thus reduce the effects of self-absorption, as well as the absorption of the background radiation. An external source of heating (e.g. by photoelectric heating) would have the same influence.
temperature is given by $T_f \sim (3 \mu m_H)/(16 k) V_{\exp}^2 \sim 1800 K$ (equation 6.58 in Dyson & Williams 1997) with $m_H$ the mass of the hydrogen atom and $\mu$ the mean molecular weight. For the temperature profile inside the detached shell we use the expression 9 in Libert et al. (2007) with a temperature index, $a = -6.0$. The temperature is thus decreasing from $\sim 1800 K$, to $T_f$, at the interface with ISM, $r_f$. The density, velocity and temperature profiles are illustrated in Fig. 6 for case D.

Self-absorption within the detached shell has a limited effect, with a reduction ranging from 1 per cent (model A) to 20 per cent (model D), as compared to the optically thin approximation (Fig. 4). However, taking into account the background introduces a much larger effect (Fig. 5).

The results depend on the adopted parameters in the model (mainly internal radius, expansion velocity and age). Smaller internal radius and expansion velocity, and/or longer age would lower the average temperature in the detached shell. This would increase the effect of self-absorption, as well as that of the background absorption. The line profiles simulated with the A and B-cases represented in Fig. 4 provide a good approximation to several observed H I line profiles (Libert et al. 2007, 2010; Matthews et al. 2013).

As an illustration, we reproduce on Fig. 7 the spatially integrated profile of Y CVn observed by Libert et al. (2007) together with a recent fit obtained by Hoai (in preparation). For this fit, a distance of 321 pc (van Leeuwen 2007), a mass-loss rate of $1.3 \times 10^{-7} M_\odot$ yr$^{-1}$, and a duration of $7 \times 10^5$ yr have been adopted. These parameters differ from those adopted by Matthews et al. (2013), who assumed $1.7 \times 10^{-7} M_\odot$ yr$^{-1}$ and a distance of 272 pc (Knapp et al. 2003). However, by adopting a lower mass-loss rate, and conversely, a longer duration, Hoai (in preparation) can fit the spatially resolved spectra obtained by the VLA and solve the problem faced by Matthews et al. at small radii. A difference between the mass-loss rate estimated from CO observations and that adopted in the model may have several reasons, for instance an inadequate CO/H abundance ratio.

### Table 1. Model parameters (scenario 2), $d = 200$ pc, $V_{\exp}= 8$ km s$^{-1}$ and $M = 10^{-7} M_\odot$ yr$^{-1}$.

| Case | Age (yr) | $r_f$ (arcmin) | $T_f$ (K) | $M_{\rm DT, CS} (M_\odot)$ |
|------|----------|---------------|-----------|---------------------------|
| A    | $5 \times 10^5$ | 3.85 | 135 | 0.05 |
| B    | $10^6$       | 4.14 | 87  | 0.1  |
| C    | $2 \times 10^6$ | 4.47 | 55  | 0.2  |
| D    | $4 \times 10^6$ | 4.83 | 35  | 0.4  |

#### Figure 6. Density, velocity and temperature profiles for a detached shell model (scenario 2, case D).

#### Figure 7. Y CVn integrated spectrum (Libert et al. 2007) and fit obtained by Hoai (in preparation) with scenario 2 ($d = 321$ pc, $M = 1.3 \times 10^{-7} M_\odot$ yr$^{-1}$, age $= 7 \times 10^5$ yr).

### 4.3 Villaver et al. model (scenario 3)

Villaver et al. (2002) have modelled the dynamical evolution of circumstellar shells around AGB stars. The temporal variations of the stellar winds are taken from the stellar evolutionary models of Vassiliadis & Wood (1993).

For our H I simulations, we used the 1.5-$M_\odot$ circumstellar shell models of Villaver et al. (2002) at various times of the TP-AGB evolution. We selected the epochs at 5.0, 6.5 and $8.0 \times 10^3$ yr, which correspond to the first two thermal pulses, and then to the end of the fifth (and last) thermal pulse. The density, velocity and temperature profiles are illustrated in Fig. 8. For these models, which can reach a large size (with radii of 0.75, 1.66 and 2.5 pc, respectively), we adopt a distance of 1 kpc (implying a diameter of up to 17 arcmin).

The results are shown in Fig. 9. In this scenario, the temperature in the circumstellar environment is maintained at high values due to the interactions between the successive shells (Fig. 8). The shape of the line profile is thus dominated by thermal broadening, and does not depend much on the epoch which is considered (although the intensity of the emission depends strongly on time, together with the quantity of matter expelled by the star).

For the same reason, these results do not depend much on the background ($< 5$ per cent for $T_{\text{bg}} = 100$ K). Indeed in the models the temperature of the gas in the circumstellar shell always stays at a high level ($> 10^5$ K, except close to the central star in the freely expanding region).

The predictions obtained with this scenario, in which wind–wind interactions are taken into account, differ clearly from those
obtained with the previous scenario, in which the detached shell is assumed to result from a long-duration stationary process, by a much larger width of the line profiles (full width at half-maximum, FWHM ~ 16 km s\(^{-1}\)). This large width in the simulations for scenario no. 3 results mainly from the thermal broadening, and also, but to a lesser extent, from the kinematic broadening (cf. Fig. 8).

5 DISCUSSION

5.1 Optically thin approximation

If absorption can be neglected, the intensity becomes proportional to the column density of hydrogen. For a source at a distance \(d\), the mass in atomic hydrogen \(M_{\text{H}}\) can be derived from the integrated flux density through the standard relation (e.g. Knapp & Bowers 1983):

\[
M_{\text{H}} = 2.36 \times 10^{-7} d^2 \int S_{\text{HI}} dV,
\]

in which \(d\) is expressed in pc, \(V\) in km s\(^{-1}\), \(S_{\text{HI}}\) in Jy and \(M_{\text{H}}\) in solar masses (M\(_{\odot}\)).

Our calculations allow us to estimate the error in the derived H\(_{\text{i}}\) mass of circumstellar envelopes that is incurred from the assumption that the emission is optically thin and not affected by the background. As an example, in Fig. 10, we show the ratio between the estimated mass (using the standard relation) and the exact mass in atomic hydrogen. The case without background illustrates the effect of self-absorption within the circumstellar shell for different mass-loss rates. We adopt a freely expanding wind with a

Figure 8. Density, velocity and temperature profiles for the Villaver et al. (2002) model (scenario 3) at three different epochs \(5.0 \times 10^5\) yr (left), \(6.5 \times 10^5\) yr (centre), \(8.0 \times 10^5\) yr (right).

Figure 9. \(\text{H} \text{i}\) line profiles of a circumstellar shell model around a 1.5 M\(_{\odot}\) star during the evolution on the TP-AGB phase \(5.0, 6.5, 8.0 \times 10^5\) yr; Villaver et al. 2002), no background. The distance is set at 1000 pc. The first two profiles have been scaled by 37.7 and 3.87, respectively, in order to help the comparison between the different line profiles.

Figure 10. Ratio between the ‘estimated’ mass in atomic hydrogen and the real mass for the freely expanding wind case (scenario no. 1) with mass-loss rates ranging from \(10^{-7}\) to \(10^{-4}\) M\(_{\odot}\) yr\(^{-1}\) (see Section 5.1) and different cases of temperature dependence (see text). Upper panel: no background. Lower panel: with a 5 K background.
temperature profile in \( r^{-0.7} \) (as in Section 4.1), with \( r \) expressed in arcmin., or a constant temperature (5, 10, 20 K). The ratio clearly decreases with decreasing temperature in the circumstellar shell, increasing mass-loss rate and increasing background temperature.

In the constant temperature case with \( T = 5 \text{ K} \) and \( T_{BG} = 5 \text{ K} \), the line profiles should be flat (cf. radiative transfer equation in Section 3), and thus the ‘estimated’ masses, exactly null. Our numerical calculations agree with this prediction to better than \( 3 \times 10^{-1} \), for mass-loss rates up to \( 10^{-4} \, M_\odot \, \text{yr}^{-1} \).

The standard relation used for estimating the mass in atomic hydrogen should obviously be handled with caution in the case of the freely expanding wind scenario (no. 1). On the other hand, our calculations show that the deviation is much smaller for the two other scenarios (and basically negligible for scenario no. 3). This is mainly an effect of the high temperature in the detached shells resulting from the wind–wind interactions.

### 5.2 Spectral variations of the background

The H\(_{\alpha}\) absorption produced by cold galactic gas in the foreground of bright background emission may be shifted towards the velocity with highest background (cf. Levinson & Brown 1980). To illustrate this effect in the case of circumstellar shells, in Fig. 11, we show the results of our simulations for a \( 10^{-3} \, M_\odot \, \text{yr}^{-1} \) freely expanding wind, as in Section 4.1, and a background temperature varying linearly between \( 10 \) K at \(-10 \, \text{km s}^{-1}\) and \( 5 \) K at \(+10 \, \text{km s}^{-1}\). The absorption is clearly shifted towards velocities with highest background. One notes also that the emission is shifted towards velocities with lowest background.

In the case of an intense and spectrally structured background, some care should be exercised when comparing the H\(_{\alpha}\) line centroids with the velocities determined from other lines.

![Figure 11](https://example.com/fig11.png)

**Figure 11.** Effect of a background intensity varying linearly from 10 to 5 K across the line profile for a scenario 1 model with \( M = 10^{-5} \, M_\odot \, \text{yr}^{-1} \). The curves labelled ‘\( T_{BG} = 5 \text{ K} \)’, and ‘\( T_{BG} = 10 \text{ K} \)’, are reproduced from Fig. 3.

### 5.3 Comparison with observations

Freely expanding winds have been definitively detected in the H\(_{\alpha}\) line in only two red giants: Y CVn (Le Bertre & Gérard 2004) and Betelgeuse (Bowers & Knapp 1987). The corresponding emission is relatively weak and difficult to detect. Data obtained at high spatial resolution reveal a double-horn profile (e.g. Bowers & Knapp 1987). It is worth noting that a high-velocity expanding wind (\( \left< v\right> \sim 35 \, \text{km s}^{-1} \)) has also been detected around the classical Cepheid \( \delta \) Cep (Matthews et al. 2012). A pedestal is suspected in a few H\(_{\alpha}\) line profiles that could be due the freely expanding region (Gérard & Le Bertre 2006; Matthews et al. 2013). The first scenario might also be interesting for interpreting sources in their early phase of mass-loss, or for sources, at large distance from the Galactic plane, embedded in a low-pressure ISM.

In general, sources which, up to now, have been detected in H\(_{\alpha}\) show quasi-Gaussian line profiles of FWHM \( \sim 2–5 \, \text{km s}^{-1} \) (Gérard & Le Bertre 2006; Matthews et al. 2013), a property which reveals the presence of slowed-down detached shells. These profiles are well reproduced by simulations based on the scenario no. 2 presented in Section 4.2, assuming mass-loss rates of a few \( 10^{-7} \, M_\odot \, \text{yr}^{-1} \) and durations of a few \( 10^7 \) yr. In particular, for Y CVn and Betelgeuse, the main H\(_{\alpha}\) component has a narrow line profile (~3 km s\(^{-1}\)) and is well reproduced by this kind of simulation (Libert et al. 2007; Le Bertre et al. 2012).

Sources with large mass-loss rates (>\( 5 \times 10^{-7} \, M_\odot \, \text{yr}^{-1}\)) have rarely been detected (with the notable exceptions of IRC +10216 and AFGL 3068, see below). The simulations presented in Section 4.3 show the line profiles that sources, such as those predicted by Villaver et al. (2002), should exhibit at the end of the thermal-pulse phase, with large mass-loss rates, and with interaction with the local ISM. In these models, in which the evolution of the central star is integrated, the circumstellar envelopes result from several interacting shells, as well as from the ISM matter which has been swept-up. Shocks between successive shells maintain a high gas temperature (~4000 K).

For these models the calculated line profiles are not seriously affected by the background level, and the flux densities are large enough for allowing a detection up to a few kpc. For instance, in the GALFA-H\(_{\alpha}\) survey (Peek et al. 2011), the 3\( \sigma \) detection limit for a point source in a 1 km s\(^{-1}\) channel is ~30 mJy. Saul et al. (2012) have detected many compact isolated sources in this survey. However, at the present stage, none could be associated with an evolved star (Begum et al. 2010).

Furthermore, several sources with high mass-loss rates, such as IRC +10011 (WX Psc), IK Tau (NML Tau) or AFGL 3099 (IZ Peg) which are observed at high galactic latitude, with an expected low interstellar H\(_{\alpha}\) background, remain undetected (Gérard & Le Bertre 2006; Matthews et al. 2013). The simulations that we have performed based on the three different scenarios considered in this work cannot account for such a result. It seems therefore that, in sources with large mass-loss rates (>\( 5 \times 10^{-7} \, M_\odot \, \text{yr}^{-1}\)), hydrogen is generally not in atomic, but rather in molecular form.

Glassgold & Huggins (1983) have discussed the H\(_{\alpha}\)/H\(_{\alpha}\) ratio in the atmospheres of red giants. They find that for stars with photospheric temperature \( T_e \geq 2500 \) K, most of the hydrogen should be in atomic form, and the reverse for \( T_e \leq 2500 \) K. Winters et al. (2000) find that there is an anti-correlation between \( T_e \) and the mass-loss experienced by long period variables. It seems likely that stars having a mass-loss rate larger than a few \( 10^{-7} \, M_\odot \, \text{yr}^{-1}\) have also generally a low photospheric temperature, with \( T_e \leq 2500 \) K, and thus a wind in which hydrogen is mostly molecular.
Recently, Matthews, Gérard & Le Bertre (2015) have reported the detection of atomic hydrogen in the circumstellar environment of IRC +10216, a prototype of a mass-losing AGB star at the end of its evolution with $M \sim 2 \times 10^{-3} \, M_\odot \, \text{yr}^{-1}$. The observed morphology, with a complete ring of emission, is in agreement with the predictions of Villaver et al. (2002, 2012). They find that atomic hydrogen represents only a small fraction of the expected mass of the circumstellar environment (<1 per cent), supporting a composition dominated by molecular hydrogen. Unfortunately, a reliable line profile could not be extracted due to the low level of the emission and to a patchy background. The detection of H\textsc{i} over a spectral range $\sim 10 \, \text{km s}^{-1}$ suggests a line width larger than commonly observed in evolved stars, which would make it compatible with scenario no. 3. Gérard & Le Bertre (2006) have reported the possible detection of AFGL 3068, another carbon star with high mass-loss rate ($\sim 10^{-4} \, M_\odot \, \text{yr}^{-1}$). In this case, also, the line width ($\sim 30 \, \text{km s}^{-1}$) is larger than expected for scenario no. 2, and might be better explained by scenario no. 3. Another possibility for this source which is at a large distance from the Galactic plane ($z \sim 740 \, \text{pc}$) would be that we are mostly detecting a freely expanding wind not slowed down by its local ISM (i.e. scenario no. 1).

If the atomic hydrogen is of atmospheric origin (a fraction of 1 per cent is expected for a star with an effective temperature of 2200 K; Glassgold & Huggins 1983), its abundance should correspondingly be scaled down in our radiative transfer simulations. The effect of the optical depth on the line profiles could be considerably reduced for such a case. For stars with lower effective temperature ($T_e \leq 2200 \, \text{K}$), atomic hydrogen might also be present in the external regions of circumstellar envelopes as a result of the photodissociation of molecular hydrogen by UV photons from the ISRF (Morris & Jura 1983).

### 5.4 Case of a resolved source

We have concentrated our study on the prediction of spatially integrated spectra. However, circumstellar envelopes may reach a large size ($\sim 2-3 \, \text{pc}$; Villaver et al. 2002), and thus have a large extent over the sky. Also, interferometers provide a larger spatial resolution than single-dish antennas. It is thus interesting to examine how the line profile may vary as a function of position. As an example, in Fig. 12, we show a spectral map that would be obtained for a detached shell observed over a background with $T_{\text{bg}} = 50 \, \text{K}$ (scenario 2). The line appears mostly in emission and, as expected, delineates the detached shell. However, in the case of a high background level, the line appears also in absorption, in particular in the external part of the detached shell where the lines of sight cross regions with gas at low temperature.

Spatially resolved H\textsc{i} studies, with a careful subtraction of the background emission, may thus reveal spectral signatures that hold information on their physical conditions. Such signatures could help to constrain the physical properties of the gas in a region where molecules are absent or not detectable.

### 6 PROSPECTS

We have simulated H\textsc{i} 21-cm line profiles for mass-losing AGB stars expected for different scenarios assuming spherical symmetry. However, AGB sources are moving through the ISM and their shells may be partially stripped by ram pressure (Villaver, García-Segura & Manchado 2003; Villaver, Manchado & García-Segura 2012). As a consequence of the interaction a bow-shock shape appears in the direction of the movement, but also a cometary tail is formed which is fed directly from the stellar wind and from material stripped away from the bow shock. The cooling function and the temperature assumed for the wind have an important effect on the formation of the tail as shown in Villaver et al. (2012). Higher density regions formed behind the star will cool more efficiently and will collapse against the ISM pressure, allowing the formation of narrow tails.

Gérard & Le Bertre (2006) have reported shifts of the H\textsc{i} emission in velocity as well as in position for several sources. Matthews et al. (2008) have reported a shift in velocity for different positions along the tail of Mira (see also X Her, Matthews et al. 2011). These effects can also affect the H\textsc{i} line profiles, and thus the detectability. In addition, material lost by the AGB star should be spread along a tail that may reach a length of 4 pc, as in the exceptional case of Mira. On the other hand, Villaver et al. (2012) show that for sources with large mass-loss rates at the end of their evolution, dense shells could still be found close to the present star position.

We have assumed a background with a constant brightness. Of course, as explained in Section 3, this applies only to the cosmic background, and to a lesser extent to the galactic continuum emission. It does not apply to the galactic H\textsc{i} emission which may show spatial structures of various kinds. The resulting effect may be more complex than that simulated in Section 4. For instance, an absorption line could form preferentially at the position of a peak of galactic H\textsc{i} emission (a radiative transfer effect). Such a phenomenon may affect the predictions presented in Section 5.4. Therefore, a good description of the background will also be needed to model the observed line profiles. Such input may be obtained through frequency-switched observations for the galactic H\textsc{i} component, and through the surveys of the continuum at 21 cm which are already available (see Section 3).

It has to be noted that, in the position-switched mode of observation, the intrinsic line profile of the stellar source can also be spoiled by the patchiness of the galactic background emission (observational artefact). The main source of confusion is the
galactic H\textsc{i} emission which is structured spatially and spectrally. The classical position-switched mode of observation is not always efficient to correct the 21-cm spectra from the emission that is not directly associated with the star. More sophisticated methods with 2D mapping might be needed for subtracting the contaminating emission in these cases. Interferometric observations have the advantage of filtering the large-scale galactic emission. However, one should care that an intrinsic circumstellar emission is not also subtracted in this mode of observation. Also some artefacts may arise from incomplete spatial sampling of the large-scale emission, as illustrated by the case of TX Psc (Matthews et al. 2013). If feasible, an excellent u-v coverage combined with maps from a single-dish telescope providing small spacings has to be obtained. Also, for circumstellar shells angularly larger than the primary beam of the interferometer, mosaicked observations combined with single-dish maps are needed.

Another caveat is that, when the distance to the source becomes larger, the foreground ISM material may play the role of an absorbing layer of growing importance (Zuckerman et al. 1980). The circumstellar shell line profile may thus be distorted by absorption due to the foreground cold material that shares the same radial velocity range.

Sources with high mass-loss rate (\(\sim 10^{-6} - 10^{-5} \text{M}_\odot \text{yr}^{-1}\)) tend to be concentrated towards the galactic plane. They are expected to dominate the contribution of AGB stars to the replenishment of the ISM (Le Bertre et al. 2003). The recent detection of IRC + 10216 by Matthews et al. (2015) shows that atomic hydrogen should be present in these sources and that the H\textsc{i} line at 21 cm can be used to probe the morphology and the kinematics of stellar matter decelerated at large distance from the central star. However, as discussed above, when the background is large, a proper modelling of the line profiles will be necessary.

7 SUMMARY AND CONCLUSIONS

We have simulated H\textsc{i} 21-cm line profiles expected for several different scenarios representing different evolutionary stages of evolved stars, and thus corresponding to different AGB circumstellar structures. We have relaxed the optically thin hypothesis which was assumed in previous works, and included the emission from the background.

Self-absorption may be important in freely expanding circumstellar shells, as well as in some detached shells resulting from the interaction of the stellar winds with the local ISM. The H\textsc{i} line profile may also be affected by the background level and by the spectral profile of this background emission.

The numerical simulations that we have performed show that, under certain conditions, the observed H\textsc{i} 21-cm flux densities from mass-losing stars can be significantly reduced by taking into account optical depth effects and the presence of the background emission, but not to such a level such as to account for the non-detection of several sources. Therefore, one should consider that molecular hydrogen instead of atomic hydrogen likely dominates in sources with high mass-loss rates (\(\gtrsim \text{few} \times 10^{-7} \text{M}_\odot \text{yr}^{-1}\)), probably an effect of their low atmospheric temperature. Still, the recent results of Matthews et al. (2015) show that the H\textsc{i} line at 21 cm can be a useful probe of the outer regions of sources with low stellar effective temperature (\(\sim 2500 \text{K}\)).

For sources with mass-loss rates \(\sim 10^{-7} \text{M}_\odot \text{yr}^{-1}\), which are detected in H\textsc{i}, the global agreement between the observed line profiles and the simulations based on the second scenario suggests that their central stars undergo mass-loss smoothly over several \(10^5 \text{yr}\).

ACKNOWLEDGEMENTS

We thank Pierre Dariuslat and Jan Martin Winters for their continuous support and kind encouragements. We are also grateful to N. Cox and A. J. van Marle, the organisers of the Lorentz workshop on Astropheres (Leiden, 2013 Dec 9–13), where the ideas developed in this paper started to take shape. DTH and PTN thank the French Embassy in Hanoi and the CNRS/IN2P3 for financial support. Financial and/or material support from the Institute for Nuclear Science and Technology, Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number 103.08-2012.34 and World Laboratory is gratefully acknowledged. LDM is supported by grant AST-1310930 from the National Science Foundation. EV acknowledges Spanish Ministerio de Economía y Competitividad funding under grant AYA2013-45347P. TL acknowledges financial support by the CNRS programmes ASA and PCMI.

REFERENCES

Begum A. et al., 2010, ApJ, 722, 395
Bowers P. F., Knapp G. R., 1987, ApJ, 315, 305
Dyson J. E., Williams D. A., 1997, The Physics of the Interstellar Medium, 2nd edn. IoP Publishing, Bristol
Gardan E., Gérard E., Le Bertre T., 2006, MNRAS, 365, 245
Gérard E., Le Bertre T., 2006, AJ, 132, 2566
Glassgold A. E., Huggins P. J., 1983, MNRAS, 203, 517
Hoai D. T., Matthews L. D., Winters J. M., Nhung P. T., Gérard E., Libert Y., Le Bertre T., 2014, A&A, 565, A54
Kalberla P. M. W., Burton W. B., Hartmann D., Arnal E. M., Bajaja E., Morras R., Pöppel W. G. L., 2005, A&A, 440, 775
Knapp G. R., Bowers P. F., 1983, ApJ, 266, 701
Knapp G. R., Morris M., 1985, ApJ, 292, 640
Knapp G. R., Pourbaix D., Platais I., Jorissen A., 2003, A&A, 403, 993
Le Bertre T., Gérard E., 2004, A&A, 419, 594
Le Bertre T., Tanaka M., Yamamura I., Murakami H., 2003, A&A, 403, 943
Le Bertre T., Matthews L. D., Libert Y., 2012, MNRAS, 422, 3433
Lequeux J., 2005, The Interstellar Medium, Astronomy & Astrophysics Library. Springer, Berlin
Levinson F. H., Brown R. L., 1980, ApJ, 242, 416
Libert Y., Gérard E., Le Bertre T., 2007, MNRAS, 380, 1161
Libert Y., Gérard E., Thum C., Winters J. M., Matthews L. D., Le Bertre T., 2010, A&A, 510, A14
Loupi C., Forveille T., Omont A., Paul J. F., 1993, A&AS, 99, 291
Matthews L. D., Reid M. J., 2007, AJ, 133, 2291
Matthews L. D., Libert Y., Gérard E., Le Bertre T., Reid M. J., 2008, ApJ, 684, 603
Matthews L. D., Libert Y., Gérard E., Le Bertre T., Johnson M. C., Dame T. M., 2011, AJ, 141, 60
Matthews L. D., Marengo M., Evans N. R., Bono G., 2012, ApJ, 744, 53
Matthews L. D., Le Bertre T., Gérard E., Johnson M. C., 2013, AJ, 145, 97
Matthews L. D., Gérard E., Le Bertre T., 2015, MNRAS, preprint (arXiv:1502.02050)
Morris M., Jura M., 1983, ApJ, 264, 546
Morris M., Lucas R., Omont A., 1985, A&A, 142, 107
Olofsson H., 1999, in Le Bertre T., Lebre A., Waelkens C., eds, Proc. IAU Symp. 191, Asymptotic Giant Branch Stars, Astron. Soc. Pac., p. 3
Olofsson H., Bergman P., Lucas R., Eriksson K., Gustafsson B., Bieging J. H., 2000, A&A, 353, 583
Peek J. E. G., Heiles C., Douglas K. A. et al., 2011, ApJS, 194, 20
Reich W., 1982, A&AS, 48, 219

MNRAS 449, 2386–2395 (2015)
Reich P., Reich W., 1986, A&AS, 63, 205
Reich P., Testori J. C., Reich W., 2001, A&A, 376, 861
Sahai R., 1990, ApJ, 362, 652
Saul D. R., Peek J. E. G., Grecich J. et al., 2012, ApJ, 758, 44
Schöier F. L., Olofsson H., 2001, A&A, 368, 969
Stil J. M. et al., 2006, AJ, 132, 1158
van Leeuwen F., 2007, Astrophysics and Space Science Library, Vol. 350, Hipparcos, the New Reduction of the Raw Data. Springer, Berlin
Vassiliadis E., Wood P. R., 1993, ApJ, 413, 641
Villaver E., García-Segura G., Manchado A., 2002, ApJ, 571, 880
Villaver E., García-Segura G., Manchado A., 2003, ApJ, 585, L49
Villaver E., Manchado A., García-Segura G., 2012, ApJ, 748, 94
Winters J. M., Le Bertre T., Jeong K. S., Helling C., Sedlmayr E., 2000, A&A, 361, 641
Young K., Phillips T. G., Knapp G. R., 1993, ApJ, 409, 725
Zuckerman B., Terzian Y., Silverglate P., 1980, ApJ, 241, 1014

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