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# AN H I 21-CM LINE SURVEY OF EVOLVED STARS

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**Abstract.** The H I line at 21 cm is a tracer of circumstellar matter around AGB stars, and especially of the matter located at large distances (0.1-1 pc) from the central stars. It can give unique information on the kinematics and on the physical conditions in the outer parts of circumstellar shells and in the regions where stellar matter is injected into the interstellar medium. However this tracer has not been much used up to now, due to the difficulty of separating the genuine circumstellar emission from the interstellar one.

With the Nançay Radiotelescope we are carrying out a survey of the H I emission in a large sample of evolved stars. We report on recent progresses of this long term programme, with emphasis on S-type stars.

Keywords: H I line - evolved stars - AGB - circumstellar matter - interstellar matter - individual sources: OP Her, T Cet, R Gem, W And, RS Cnc

## 1 Introduction

Low- to intermediate-mass stars, at the end of their evolution, become red giants. In this phase they may undergo mass loss at a very large rate ($> 10^{-8}$ $M_{\odot}$ $yr^{-1}$), even so large that it has a decisive effect on their late evolution (Olofsson 1999). Observations show that the rate at which this phenomenon develops varies highly from source to source, so that the balance of mass loss as a function of the initial conditions (mass, metallicity, etc.) and of the stage of evolution is presently not well understood.

The H I line at 21 cm is potentially well suited to determine the history of mass loss because hydrogen is the dominant element in AGB outflows and because atomic hydrogen should be protected from photoionization by the surrounding interstellar medium (ISM). However, the dominant species in the atmospheres of AGB stars is expected to be atomic hydrogen only in relatively "warm" red giants with $T_{eff} > 2500$ K, and by contrast it should be molecular hydrogen in "cool" red giants with $T_{eff} < 2500$ K (Glassgold & Huggins 1983). Nevertheless molecular hydrogen should be ultimately photodissociated by the interstellar radiation field in the external parts of circumstellar shells (Morris & Jura 1983). The distance at which this happens, is expected to depend mainly on the square root of the mass loss rate, but this needs to be proven. Also molecular hydrogen might survive at larger distance, if the outflows are clumpy. Atomic hydrogen should thus be also a useful tracer of the physical conditions in the outer parts of circumstellar shells and in the regions where stellar matter is injected into the ISM. Therefore, H I spectro-imagery of circumstellar environments is expected to bring a wealth of information on the relations between stars and the ISM.

## 2 H I surveys

However the detection of red giants in the H I line at 21 cm happens to be difficult partly due to the weakness of the signal, and even more to the competing emission by the ISM on the same lines of sight. Pionneering efforts in the 1980's led to the detection of only two sources, $\alpha$ Ori and Mira (Bowers & Knapp 1987, 1988). This topic was abandoned until we readdressed it in 2001, after the renovation of the Nançay Radio Telescope (NRT). In a first survey we detected H I in about 20 red giants (Gérard & Le Bertre 2006). The high sensitivity to low surface brightness emission, a good spatial resolution in right ascension ($4'$ at 21 cm) and a well-adapted observing technique (position-switch with increasing east-west offset) contributed to this success.

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The majority of the sources that were detected have a mass loss rate of only a few $10^{-7}$ $M_\odot\,yr^{-1}$. Also the majority have a warm central star with $T_{eff} > 2500$ K. These two results are not independent because, for red giants, there is an inverse correlation between $T_{eff}$ and $\dot{M}$, with warm sources undergoing a relatively low mass loss rate, as compared to cool sources (with $T_{eff} \lesssim 2500$ K) that may have rates as large as $10^{-5}$ to $10^{-4}\,M_\odot\,yr^{-1}$. The line profiles of our detected H I sources are generally narrower than the CO line profiles, implying a slowing down of stellar outflows by surrounding material. The emissions are extended, indicating shell sizes on the order of 1 pc, and suggesting the possibility of tracing the history of mass loss over a few $10^5$ years (see following section).

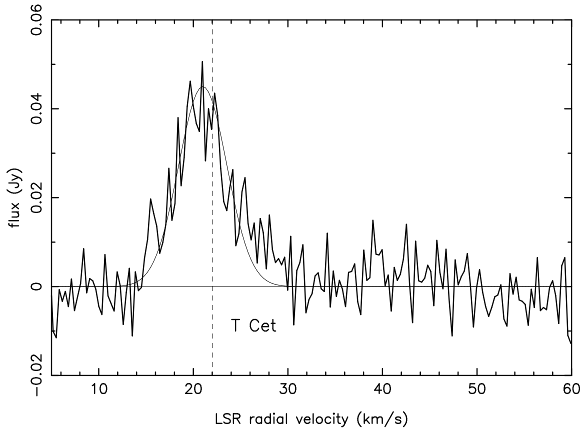


**Fig. 1.** H I spectrum of T Cet. The vertical dashed line marks the radial velocity determined from circumstellar CO lines by Ramstedt et al. (2009). The thin line is a gaussian fit to the H I profile.

In collaboration with L.D. Matthews, the most promising sources are then imaged with the Very Large Array (VLA; e.g. Matthews et al. 2008, 2011). These images allow us to study in more detail the geometry of the circumstellar shells which tend to exhibit signatures of ISM interaction due to the motion of the central stars with respect to the local ISM (Villaver et al. 2003; Libert et al. 2008).

The observation of H I in cool sources ($T_{eff} \lesssim 2500$ K) is more difficult because atomic hydrogen is not expected to peak on the central star, but rather to be found only at some distance as a daughter species of molecular hydrogen. For nearby sources we therefore need to cover large areas on the sky in order to detect the putative H I emission (that may or may not be present depending on the history of mass loss, clumping,...). Although more difficult to study, we cannot ignore these sources which may in fact dominate the replenishment of the interstellar medium by stellar matter (Sedlmayr 1994).

It thus appears necessary to survey systematically evolved stars for their H I emission. We have already performed systematic observations of a sample of 60 carbon stars (Gérard et al. 2011), and presently study a sample of 20 S-type stars, i.e. AGB stars with a photospheric C/O abundance ratio close to 1 or slightly less, mainly selected from the work of Ramstedt et al. (2009). These authors have obtained CO radio observations that allow them to derive accurate radial velocities which, for us, are a useful guide to identify the circumstellar H I lines.

In Fig. 1, we show the H I profile of T Cet, a S-type semi-regular variable (SRb), with a mass loss rate of 0.4 $10^{-7}$ $M_\odot\,yr^{-1}$ (for a distance of 240 pc, Ramstedt et al. 2009). The H I line is slighly offset in velocity ($\sim 1\,km\,s^{-1}$) with respect to the CO lines. As usual, this offset is towards the zero-velocity of the local standard-of-rest (LSR) frame which suggests a dragging of the circumstellar envelope by the ambient ISM (Gérard & Le Bertre 2006). In Fig. 2 (left), we show the spectrum of OP Her, an irregular variable (Lb) of type S for which no radio CO detection has been reported. Famaey et al. (2005) give a LSR radial velocity of 29.5 $km\,s^{-1}$, whereas we find an H I line centered at 27 $km\,s^{-1}$.

T Cet and OP Her are rather warm sources at high galactic latitudes, and we easily detect their H I emissions. On the other hand the S-type Mira variable R Gem is barely detected in H I (Fig. 2 right), although it is a strong CO emitter, with a substantial mass loss rate (4.4 $10^{-7}$ $M_\odot\,yr^{-1}$, for a distance of 710 pc, Ramstedt et al. 2009). As its radial velocity is large ($-60$ $km\,s^{-1}$), confusion remains weak, and we could obtain a marginal detection of $\sim 7$ mJy. We presently do not fully understand the reason for the weakness of the H I emission of many Miras. Hydrogen could be mainly in molecular form, and preserved from photo-dissociation in the outer layers of their circumstellar shells (self-shielding in high density regions ?). Alternatively the duration of the mass loss phenomenon could be too short to allow for the presence of a detectable quantity of atomic hydrogen. It is noteworthy that, in their IRAS survey of evolved stars, Young et al. (1993) found that Mira variables tend to have been losing mass for a shorter period than semi-regular variables, and have smaller infrared diameters. This questions the often cited argument that semi-regular variables might evolve into Mira variables.

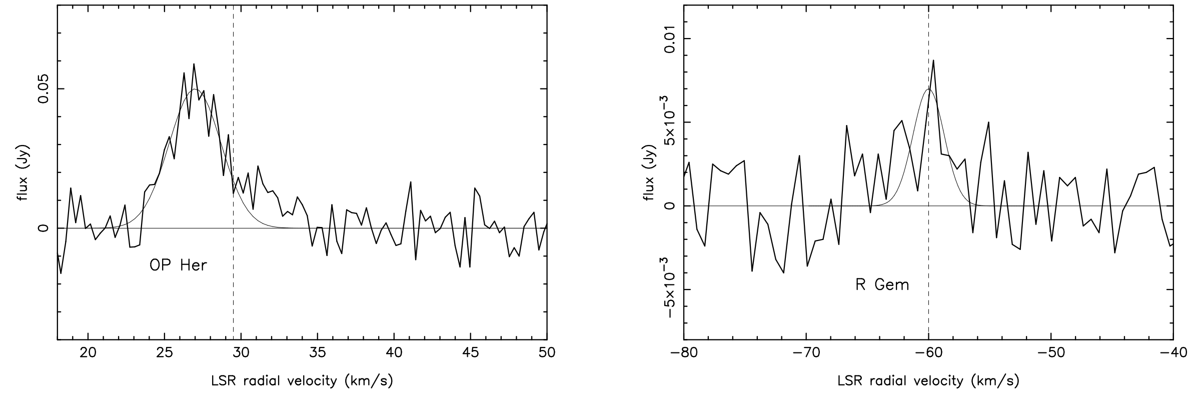


**Fig. 2. Left:** H I spectrum of OP Her. The vertical dashed line marks the stellar radial velocity from Famaey et al. (2005). **Right:** H I spectrum of R Gem. The vertical dashed line marks the radial velocity determined from circumstellar CO lines by Ramstedt et al. (2009). The thin lines are gaussian fits to the H I profiles.

## 3 Detailed studies of individual sources

In our first H I survey (Gérard & Le Bertre 2006) we found that, in general, the emissions of nearby sources are extended, indicating shell sizes on the order of 1 pc, and suggesting the possibility of tracing the history of mass loss over a few $10^5$ years. Also, the H I emissions are sometimes spatially shifted w.r.t. to the central stars in a direction that is often opposite to that of the proper motion. Using the VLA, a "head-tail" morphology has been found in several cases (Matthews & Reid 2007; Matthews et al. 2008, 2011). Thus it appears that, in H I at 21 cm, we are probing a region that is shaped by the motion of the star relative to the ISM. Even though the NRT has a large beam ($4'$ in right ascension and $22'$ in declination at 21 cm) compared to the VLA ($\sim 1'$ in the D-configuration), the circumstellar environments of many sources can be resolved. In the extreme case of Mira, a 2-degree long tail has been discovered in the far ultra-violet by the satellite GALEX (Martin et al. 2007). In that case the H I emission extends clearly beyond the VLA primary beam, and observations with a large size single dish antenna are needed to detect H I in the tail (Matthews et al. 2008). It is in such regions that stellar matter is expected to be injected into the ISM, and observations at high spectral resolution of the H I line at 21 cm allow us to constrain the kinematics in this kind of fascinating, but barely studied, environment.

In Fig. 3, we show the spectra obtained on and around W And, a Mira variable of type S, with a mass loss rate of $1.7\,10^{-7}$ $M_\odot\,yr^{-1}$ (for a distance of 280 pc, Ramstedt et al. 2009). In the left panel, the position-switch spectra obtained at $\pm 4'$ and at $\pm 6'$ are almost indistinguishable. Thus the source does not appear to be extended in right ascension (diameter size $\leq 4'$). On the other hand the maximum of H I emission is clearly offset south ($\sim 5'$) because the fluxes obtained on the star position and at $11'$ south are almost the same (Fig. 3, right panel).

There is also a practical reason for mapping individual sources. The confusion with interstellar emission can be so intricate that a large size map around the target is needed in order to isolate the genuine circumstellar emission. For example an extended mapping around RS Cnc, a S-type semi-regular variable (SRc), by Libert et al. (2010), revealed a structure of $\sim 18'$ that we could separate from the underlying ISM emission.

## 4 Conclusion and future work

The 21-cm H I emission from evolved stars brings unique information on the kinematics and the physical conditions in the external regions of circumstellar shells. However, it is weak, especially in cool sources where molecular hydrogen may dominate, and its observation often suffers from confusion by the ISM emission. More work is needed to understand the formation of H I lines in circumstellar environments, and to assess the potential contribution of H I studies to the physics of circumstellar shells around evolved stars.

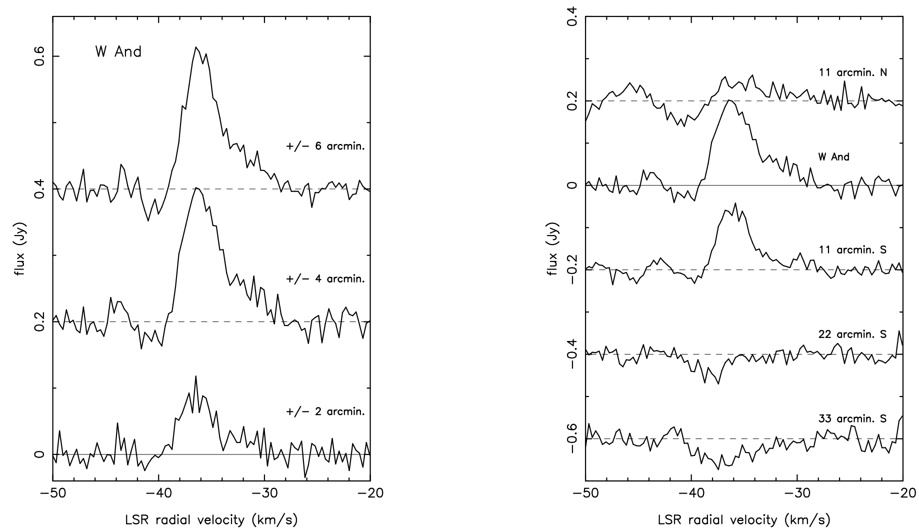


**Fig. 3. Left:** W And spectra obtained in the position-switch mode with the star centered ("on") and the off-positions taken in the east-west direction at $\pm 2'$, $\pm 4'$, and $\pm 6'$. For clarity the spectra have been successively shifted by 0.2 Jy. **Right:** position-switch spectra ($\pm 4'$) with the central beam placed at $+11'$ (half a beam, north), on source (as on the left panel), $-11'$ (half a beam, south), $-22'$ (one beam, south), and $-33'$ (one and half beam, south).

The Square Kilometre Array (SKA) would be ideal to study these weak and extended sources. In the H I line at 21 cm it will be able to image nearby circumstellar environments at all scales needed to probe the history of mass loss and the interaction of stellar outflows with the ISM. Nevertheless, using the observational strategy that we have developed with the NRT we can already begin to explore this field. The EVLA offers also the promising possibility to study these sources at the sub-arcminute scale, as well as will soon the SKA precursors (ATA, MeerKAT, etc.) that are under construction.

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