The Origin of Outflows in Evolved Stars
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Tracing the inner regions of circumstellar envelopes via high-excitation water transitions

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Abstract. Water is a ubiquitous molecule in circumstellar envelopes (CSEs). Its emission has been detected at a wide range of distances from the central oxygen-rich evolved star. In particular, the water maser transition at 22 GHz, typically extending from about 5–20 stellar radii to as far as several hundred stellar radii from the star, has been commonly used to probe the structure and dynamics of the intermediate regions of the CSE where dust is condensing and the inner wind is being accelerated. The advent of ALMA has opened the door to high-angular resolution mapping of much higher excitation transitions of water, probing the inner regions of the CSEs, some of which are anticipated to exhibit maser action. The ALMA ATOMIUM large program observed many such transitions towards a sample of AGB stars & red supergiants. The preliminary results show that while some transitions depart only slightly from LTE, others clearly show signs of maser action. The Gaussian fitting of the non-diffuse/compact part of some of the (quasi) thermal & maser transitions reveal interesting velocity gradients, signatures of outflowing and infalling motions hence providing important constraints for stellar wind models.

Keywords. stars: AGB and post-AGB, stars: late-type, (stars:) supergiants, (stars:) circumstellar matter, molecular data, radiation mechanisms: thermal, radiation mechanisms: nonthermal, masers, methods: data analysis, techniques: interferometric

1. Introduction

Oxygen-rich stars entering the late stages of their evolution, produce a wide range of oxygen bearing molecules in their circumstellar envelopes (CSEs). Water in particular, can be found throughout the CSE and can consequently be used to investigate both the structure and the dynamics from only a few stellar radii to farther out past the dust formation region, provided that high enough angular resolution is reached.

The work presented here is based on the sample of 17 oxygen-rich Asymptotic Giant Branch (AGB) stars and red supergiants (RSGs) observed as part of the Large program entitled ATOMIUM (standing for "ALMA Tracing the Origin of Molecules in dUst-forming oxygen-rich M-type stars; Decin et al. 2020, Gottlieb et al. 2022) down to an angular resolution of 25–50 mas. The aim of the program is to unravel the molecular pathways leading to the formation of the dust precursors and to study the morphology and shaping of the wind. In order to do so, the sample was selected in such a way that it

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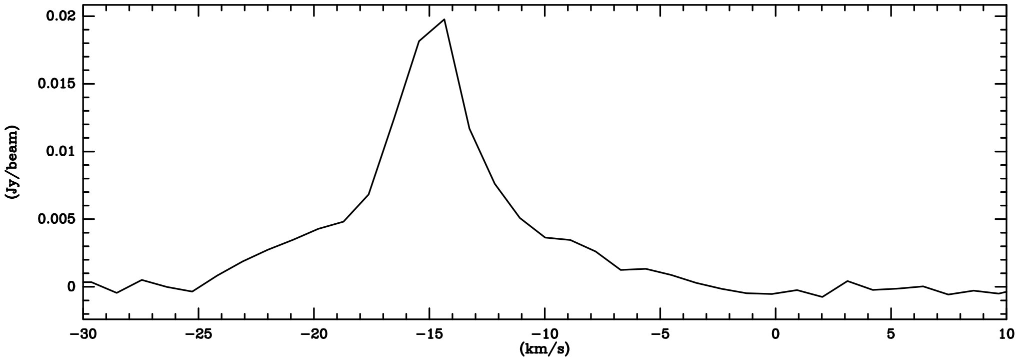

Figure 1. Spectrum of the 268.15-GHz H_2O transition of U Her.

is encompassing a wide range of physical properties (in terms of stellar masses, pulsation behaviours and evolutionary stages) and, in particular mass-loss rates which are ranging from 8×10^{-8} to 6×10^{-5} $M_{\odot}$ yr^{-1}.

The observations were made in tunings covering about half of the [214–270] GHz band, at a spectral resolution ranging from 1.1 to 1.3 km s^{-1}, in which 14 high-excitation H_2O transitions (i.e., with excitation temperatures 4000-9000 K) were identified. These excitation temperatures are much higher than those explored at cm wavelengths (i.e., 470-2400 K). As a consequence, these high-excitation H_2O transitions are expected to probe the inner regions of the CSE. A more general detailed analysis of the findings, including refinements of the rest frequencies of the detected transitions as well as statistics in terms of H_2O source properties is currently underway (Baudry et al. *in prep.*). Here we present preliminary results of this analysis with a focus on the non-diffuse/compact part of the emission.

2. Results

Out of the 14 transitions present in the part of [214-270] GHz band explored by our observations, 10 were detected on the basis of a quasi coincidence of an observed spectral feature with a transition in the JPL catalog† (Pickett et al. 1998) or the W2020 database (Furtenbacher et al. 2020). Fifteen out of the 17 sources show at least two transitions, with the 2 non-detected (“S-type”) sources having a C/O very close to 1. The highest rate of detection is for the transition at 268.15 GHz which was detected towards all 15 sources. It is followed by the 262.90-GHz transition detected towards 12 sources and the 259.95-GHz transition detected towards 10 sources.

On top of being the most commonly detected, the 268.15-GHz transition is also always the strongest transition towards a given source when other transitions are also detected. Even in our relatively low-spectral transition datasets (i.e., $\sim$1.1 km s^{-1} at this frequency), the spectral profile of this transition shows clear signs of maser action towards some sources. An example of such a clear signature is presented in Fig. 1 showing the spectrum of U Her in this transition.

It has to be noted that the 2 other widespread transitions (i.e, at 262.90 and 259.95 GHz), though predicted to be also significantly inverted (Gray et al. 2016) do not show conclusive sign of maser action in their spectral profile, though admittedly such a signature could have been hampered by the low spectral-resolution of the datasets.

In order to investigate more precisely the structure and dynamics of the regions where the non-diffuse emission of the detected high-excitation H_2O transitions is emanating from, we performed Gaussian fittings. This analysis confirms the departure from LTE for

† https://spec.jpl.nasa.gov/ftp/pub/catalog/

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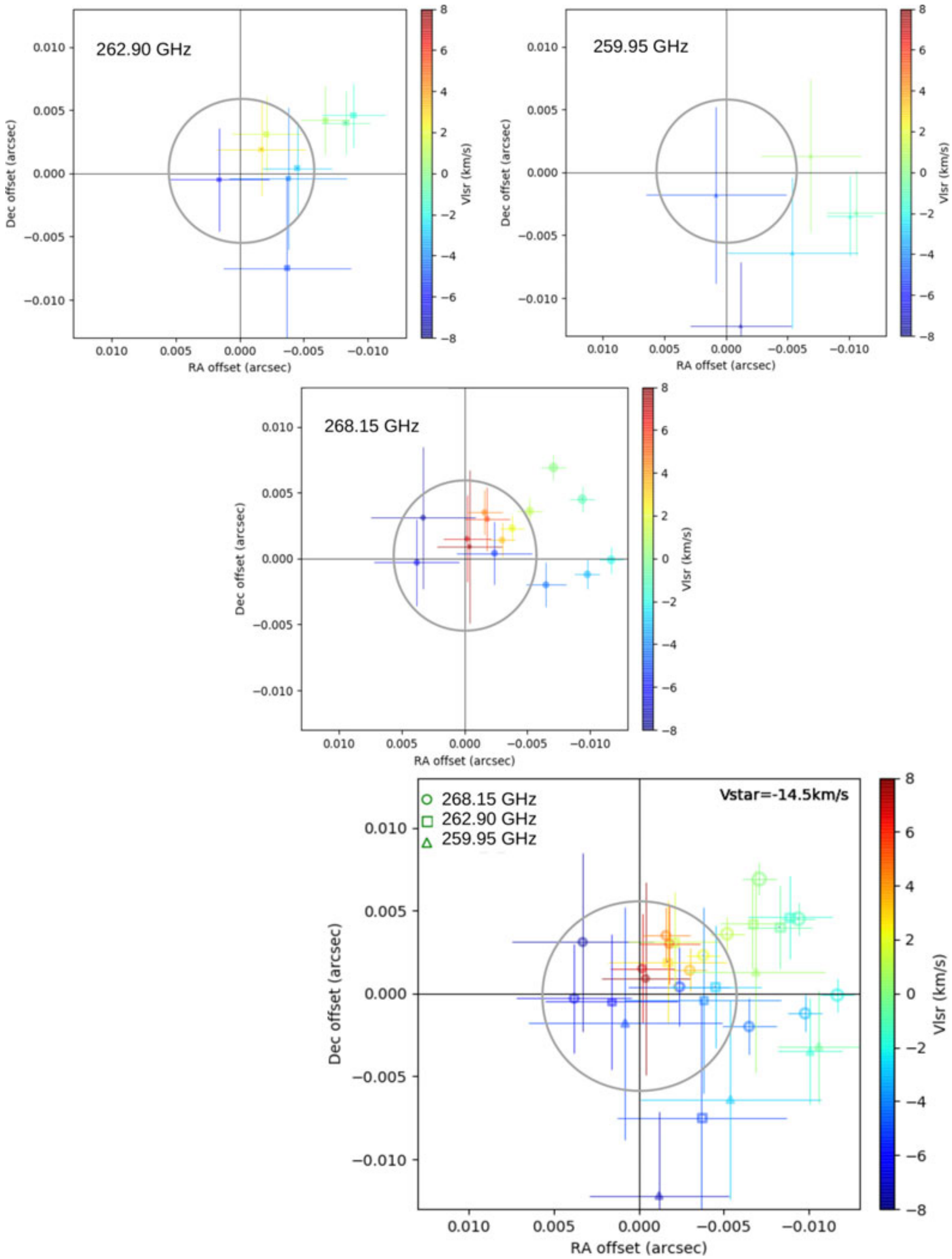

Figure 2. Top and middle: Distribution of the (Gaussian-fitted) features for the 262.90-, 259.95 and 268.15-GHz transitions of U Her. The size of the symbols is proportional to the square root of the intensity of the features while the cross give their positional uncertainty and their colour their velocity information (relative to the stellar velocity) as given by the right-hand side bar. The grey circle represents the stellar diameter as measured in the optical. bottom: The 3 transitions together.

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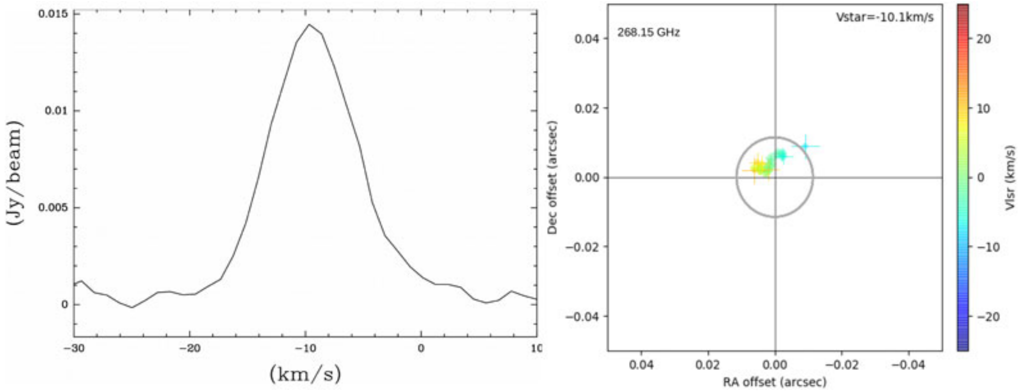

Figure 3. Left: Spectrum of the 268.15-GHz H_2O transition of R Hya. Right: Distribution of the fitted features in this transition.

the strongest and most compact fitted feature of the peak reaching a brightness temperature of $T_B \sim 10^4$ K. Figure 2 top and middle panels present the distribution of the (fitted) features for the 268.15-, 262.90- and 259.95-GHz transitions of U Her. While the three transitions probe similar radii, it can be seen from the figure that each transition probes for the most part, different regions though with a common overall velocity field signature. This later finding is evident in the bottom panel of Fig. 2 presenting the combination of the 3 transitions. This figure also highlights not only a East-West asymmetry but also reveals clear velocity gradients as well as "blue" and "red" shifted material superimposed on the stellar diameter, signatures of ouflowing and infalling motions.

R Hya is one of the sources which shows a substantial number of reasonably strong high-excitation H_2O transitions. It has to be noted that is spite of the strength of the 268.15-GHz transition towards this source, its spectral profile presented on the left panel of Fig. 3, does not show any sign of maser action. On the other hand, here again a clear velocity gradient can be observed in this transition (cf. right panel of Fig. 3). Figure 4 presents the distributions of the non-diffuse emission of the other high-excitation H_2O transitions strong enough to pass the 5σ threshold set as a minimum requirement for the Gaussian fitting. For this source too, the combination of the features reveals the presence of a quasi-linear position-velocity structure extending along a SE-NW axis and signatures of ouflowing and infalling motions particularly well traced by the 268.15-GHz transition showing all but one of the fitted features gradually changing from "blue" and "red" shifted material along the axis aforementioned superimposed on (Northern hemisphere of) the stellar diameter (cf. right panel of Fig. 3).

3. Conclusion

The ATOMIUM datasets observed towards 17 oxygen-rich evolved stars in the [214-270]-GHz band confirmed the presence of 10 out of the 14 high-excitation H_2O transitions identified as present in the part of the band in which the observations were performed. All but two sources (namely the "S" type ones, for which the C/O ratio is nearly 1), show the presence of at least two transitions.

The 268.15-GHz transition is by far the most common, since observed towards all the 15 sources. It is also always the strongest transition when more than one transition is detected towards the same source and in some of the sources, it shows signs of maser action.

Though predicted to be also significantly inverted, the low-spectral-resolution spectra of the 262.90- and 259.95-GHz transitions do not reveal any conclusive sign of

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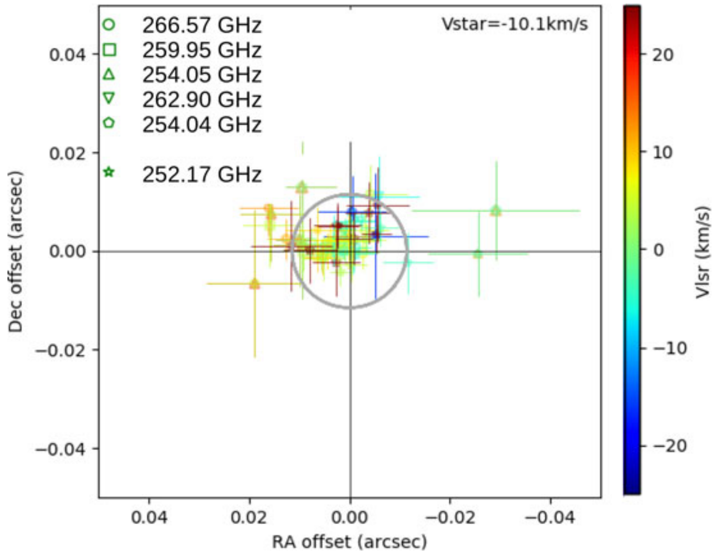

Figure 4. Distribution of the fitted features of the strongest high-excitation H_2O transitions excluding the 268.15-GHz transition of R Hya.

maser action. Higher spectral-resolution observations are needed to further analyse any potential sign of departure from LTE for these transitions.

Finally, clear velocity gradients and signatures of infalling and outflowing motions are observed towards some sources.

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