Cosmic Masers: Proper Motion toward the Next-Generation Large Projects
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ALMA explores the inner wind of evolved O-rich stars with two widespread vibrationally excited transitions of water

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Abstract. ALMA observations with angular resolution in the range ∼20–200 mas demonstrate that emission at 268.149 and 262.898 GHz in the (0,2,0) and (0,1,0) vibrationally excited states of water are widespread in the inner envelope of O-rich AGB stars and red supergiants. These transitions are either quasi-thermally excited, in which case they can be used to estimate the molecular column density, or show signs of maser emission with a brightness temperature of $\sim 10^3$–10^7 K in a few stars. The highest spatial resolution observations probe the inner few stellar radii environment, up to ∼10–12 $R_\star$ in general, while the mid resolution data probe more thermally excited gas at larger extents. In several stars, high velocity components are observed at 268.149 GHz which may be caused by the kinematic perturbations induced by a companion. Radiative transfer models of water are revisited to specify the physical conditions leading to 268.149 and 262.898 GHz maser excitation.

Keywords. stars: AGB and post-AGB, supergiants, radiation mechanisms: thermal, radiation mechanisms: non-thermal, masers, techniques: interferometric

1. Introduction

Water (H_2O) in the inner gas layers above the photosphere of O-rich evolved stars is an essential oxidizing agent in the formation of gas-phase clusters and, ultimately, dust grains (e.g. Gobrecht et al. 2016). Ten rotational transitions, in the ground or high-lying vibrational states of water with excitation energies ∼4000–9000 K, were recently identified by Baudry *et al.* (2023) in the ALMA Large Program (LP) called ATOMIUM: 'ALMA tracing the origins of molecules in dust-forming O-rich M-tytpe stars'. ATOMIUM is the first ALMA LP in the field of stellar evolution. It included the observations of a sample

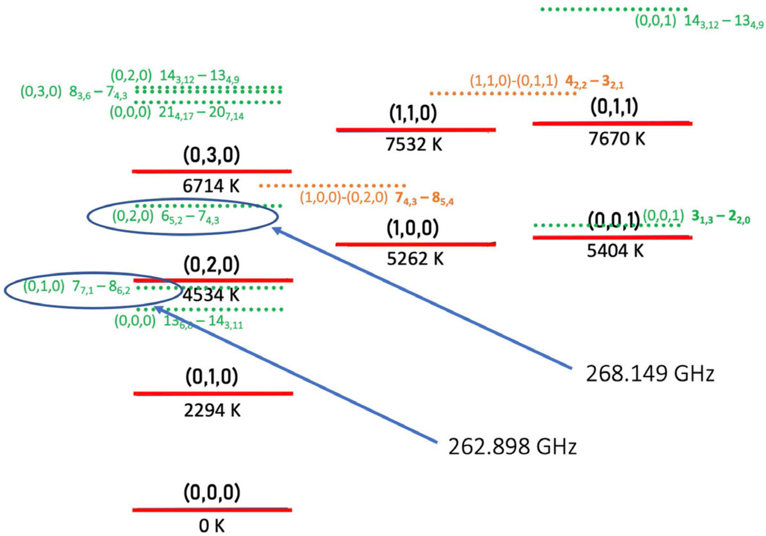

Figure 1. Energy level diagram indicating in red the band origins of the 8 lowest vibrational states of H_2O, with quantum numbers (v_1,v_2,v_3) and associated energy. The 10 transitions observed in the ATOMIUM LP are indicated by green or orange dotted lines (for pure rotational transitions or ro-vibrational transitions). The two most widespread lines of water in this work are observed at 268.149 GHz and 262.898 GHz.

of 14 Asymptotic Giant Branch (AGB) stars and three Red Supergiants (RSGs) aiming at understanding the chemistry of the dust precursors as well as the links between chemistry and the wind dynamics of these stars; see first results in e.g., Decin *et al.* (2020) and Gottlieb *et al.* (2022).

We focus this presentation on the two most widespread transitions of water that were discovered at 268.149 and 262.898 GHz during the ATOMIUM survey together with eight other transitions of H_2O (Figure 1) and several high-lying transitions of OH (Baudry *et al.* 2023).

2. H_2O results at 268.149 and 262.898 GHz

17 stars were observed as part of the ATOMIUM project (Gottlieb *et al.* 2022). The results presented here are taken from main array observations in two configurations separated by ∼8–10 months, giving ∼20–200 mas resolution, probing the wind acceleration region. Sensitivity was ∼1 mJy/beam at the highest angular resolution and our velocity resolution was ∼1.2 km/s. Complementary data at a spectral resolution of ∼0.1 km/s were acquired with the ALMA Compact Array (ACA) for a few stars 26 months later, providing additional variability information.

Nine out of the ten H_2O lines detected with ALMA are new discoveries in space. The transition at 268.149 GHz, reported earlier in VY CMa and IK Tau (Tenenbaum *et al.* 2010; Velilla-Prieto *et al.* 2017), is now detected in 15 stars of our sample. It is also detected in W Hya (Ohnaka et al. this symposium). The two strongest and most widespread transitions of water in our sample lie in the (0,2,0) and (0,1,0) vibrational states at 268.149 and 262.898 GHz (15 and 12 sources, respectively). Sources with strong 268.149 GHz emission tend to show relatively strong emission at 262.898 GHz, although there is no clear correlation of the 268.149 GHz line parameters with those of other transitions. However, eight sources in our sample, as well as VY CMa, IK Tau and R Hya, are detected at 658.007 GHz, another most widespread transition in the (0,1,0) vibrational

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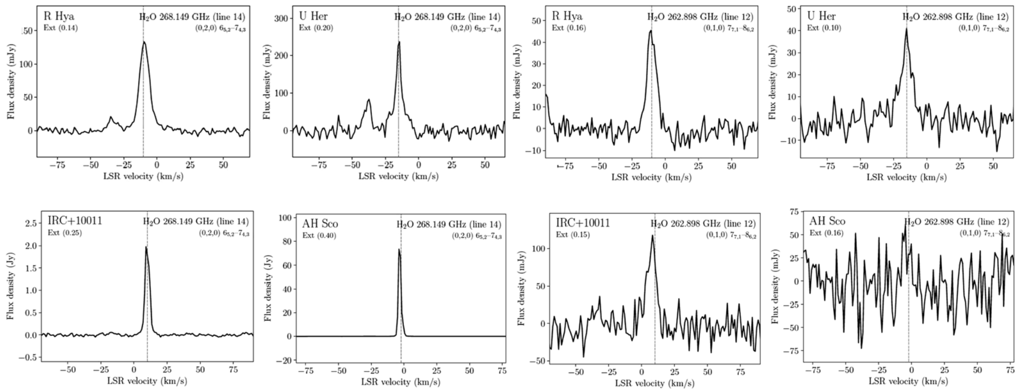

Figure 2. Spectra of the 268.149 and 262.898 GHz water lines in R Hya, U Her, IRC+10011 and AH Sco. The flux density scale at 268.149 GHz in IRC+10011 and AH Sco is expressed in Jy. The blue vertical line indicates the systemic local-standard-of-rest (LSR) velocity.

state (e.g., Baudry *et al.* 2023). Figures 2 and 3 present some spectra and channel maps, respectively, of our 268.149 and 262.898 GHz data.

3. Line excitation in the gas acceleration zone and maser models

We found that, in some stars, the 268.149 and 262.898 GHz transitions are in quasi-Local Thermal Equilibrium (LTE). This is demonstrated by constructing population diagrams from the velocity-integrated line flux densities for a range of excitation energies including at least six H_2O transitions. The 268.149 and 262.898 GHz transitions do not depart substantially from LTE in several sources and, overall, we derive H_2O column densities of $\sim$0.6–6$\times 10^{20}$ cm^{-2}. However, in some sources, such as U Her, IRC+10011 and AH Sco, the lower limit of the brightness temperature, $T_{\rm b}$, is $\sim 10^4$–10^7 K at 268.149 GHz, thereby indicating the likelihood of maser action, which is supported by the narrow line profile and high flux density in IRC+10011 and AH Sco (Figure 2), time variability observed in some sources and the different angular extents mapped at two different epochs in U Her. In contrast with the 268.149 GHz observations, the 262.898 GHz transition does not exhibit strong maser action. The highest value of $T_{\rm b}$ is $\sim$1100 K, although this could just be a lower limit. However, in IRC+10011, we observed time variability (time span of $\sim$0.5 yr) in spectral features across the line profile.

The angular size of the H_2O sources was measured for all observed transitions and stars from our channel maps or integrated intensity maps. Sizes of 10–50 mas are obtained from high resolution images and the emission typically extends $\sim$ 3–12 $R_\star$ from the star, occasionally further (e.g. AH Sco). Water is observed in the wind acceleration zone defined according to the wind velocity profile analyses of multiple lines in the ATOMIUM survey (Gottlieb *et al.* 2022). In this zone, the blue and red wings of the 268.149 GHz line profile often exceeds the velocity range spanned by the CO (2–1) line. This is also observed for the SiO wings that are ($\sim 1.6\times$) larger than the CO velocities and can be explained by turbulence due to the irregular nature of the inner wind and shocks propagating above the photosphere, or by complex kinematics (e.g. binarity). At small spatial scales, velocity gradients were also observed in R Hya and U Her against the photosphere, underlining complex gas motions.

Our maser models (Gray *et al.* 2016) were re-examined (Baudry *et al.* 2023) to show that the 268.149 GHz negative opacity increases with increasing dust temperature, $T_{\rm d}$, as expected near the photosphere, while 658.007 GHz line inversion requires lower values of $T_{\rm d}$ and relatively high values of the kinetic temperature ($T_{\rm K}$, see the left and middle

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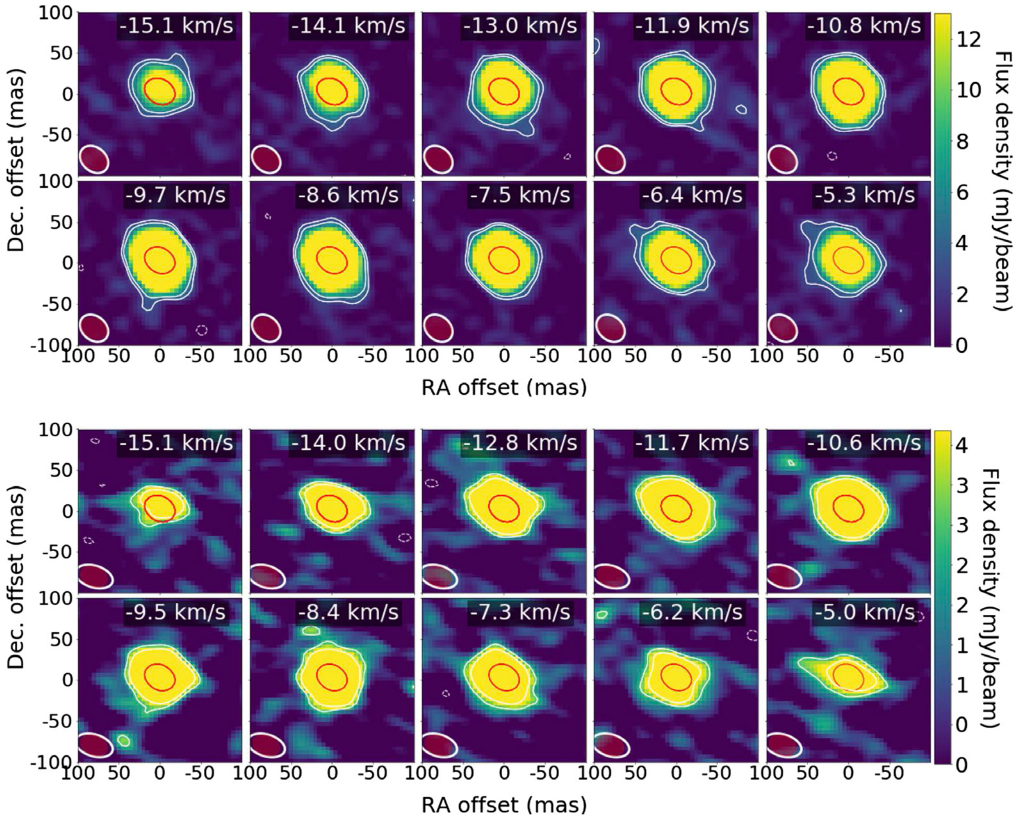

Figure 3. Channel maps of the 268.149 and 262.898 GHz lines in R Hya (upper and lower panels). The red contour near the center delineates the continuum emission at half peak intensity. The line and continuum beams are superimposed in the lower left corner of each panel and shown in white and dark-red, respectively.

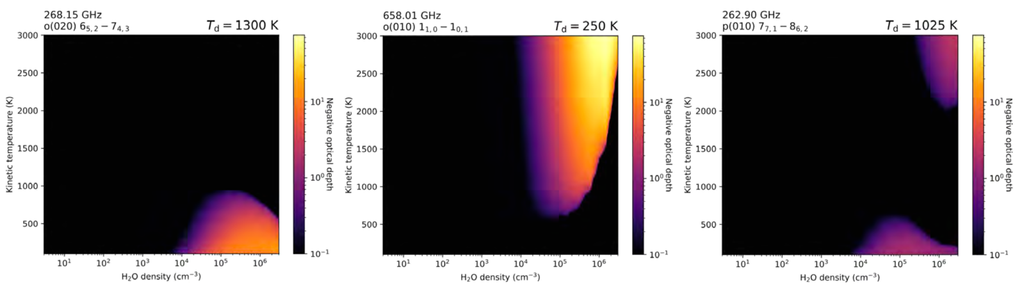

Figure 4. Negative opacity of 268.149 GHz line, in the (0,2,0) state, and 658.007 and 262.898 GHz lines in the (0,1,0) state. The first and third panels are for similar values of the dust temperature, T_d.

panels in Figure 4). The right panel of Figure 4 shows that the 262.898 GHz para-transition in the (0,1,0) state is less strongly inverted than the 268.149 GHz transition for similar physical conditions, as observed; note that the 262.898 GHz transition can also be inverted in the high T_K regime. For all lines, inversion requires H_2 number densities around a few times 10^9–$10^{10}cm^{-3}$.

4. Conclusion

The most common H_2O transitions in our sample of O-rich evolved stars are observed in high-lying levels at 268.149 (6040 K) and 262.898 GHz (4480 K) in the (0,2,0) and (0,1,0) vibrational states, respectively. Maser emission in the 268.149 GHz line was observed with the ALMA main array and the ACA in some stars, whereas thermal emission dominates at 262.898 GHz in most sources. Combined with the OH lines discovered during our survey and described in Baudry *et al.* (2023), we derived an OH/H_2O abundance ratio of around 10^{-2}. Our H_2O maser models were re-examined to specify the physical conditions leading to line inversion near the photosphere.

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