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# High resolution ALMA imaging of $H_2O$, SiO, and $SO_2$ masers in the atmosphere of the AGB star W Hya

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**Abstract.** The mass-loss mechanism in asymptotic giant branch (AGB) stars is not yet fully understood. We present 20-milliarcsecond resolution ALMA imaging of the well-studied AGB star W Hya in multiple molecular lines at 250–269 GHz, including masers from SiO, $H_2O$, and $SO_2$. The images show complex plumes, arcs, and clumps over the stellar disk and in the atmosphere extending to several stellar radii. We detected prominent emission components over the stellar disk—instead of pure absorption as expected—in some $Si^{17}O$, $^{30}SiO$, $H_2O$, and $SO_2$ lines. The surface emission seen in the $Si^{17}O$ and vibrationally excited $H_2O$ lines is particularly strong, indicating maser actions. The masers seen over the stellar disk indicate radial amplification.

**Keywords.** Asymptotic Giant Branch, mass loss, masers, stellar imaging

## 1. Introduction

Despite its importance in stellar evolution and the chemical enrichment of galaxies, the mass-loss mechanism in asymptotic giant branch (AGB) stars is not yet well understood. It is often considered that the radiation pressure on dust grains due to absorption or scattering of stellar photons drives mass outflows (Höfner & Olofsson 2018). However, dust grains that form in oxygen-rich AGB stars are too transparent to absorb sufficient photons, and thus cannot drive the mass loss (Woitke 2006; Höfner 2007). As an alternative, Höfner (2008) proposes that the scattering—instead of absorption—of stellar photons by large (0.3–1.0 $\mu$m) transparent grains may drive mass outflows.

To shed light on the long-standing problem of mass loss from AGB stars, it is indispensable to probe the region within a few $R_\star$, where dust forms and the wind accelerates. For this goal, we focus on the well-studied oxygen-rich AGB star W Hya. Its light curve clearly shows a period of 389 days, and the radial velocities measured from the infrared spectral lines show pulsation (Hinkle *et al.* 1997; Lebzelter *et al.* 2005). Thanks to its proximity (98pc, Vlemmings *et al.* 2003), it has been studied with various observational techniques from the visible to the infrared to the radio (e.g., Zhao-Geisler *et al.* 2011; Khouri *et al.* 2015, and references therein). Therefore, W Hya is one of the best targets to study the mass-loss mechanism in great detail.

The recent polarimetric imaging of W Hya at five wavelengths from 645 to 820 nm with spatial resolutions of 23–30 mas using VLT/SPHERE-ZIMPOL (Ohnaka *et al.* 2016, 2017) reveals clumpy dust clouds very close to the star at an angular distance of ∼50 mas, corresponding to just ∼2 $R_\star$. Their 2-D radiative transfer modeling suggests the predominance of large (0.4–0.5 $\mu$m), transparent grains of $Al_2O_3$, or $Mg_2SiO_4$, or $MgSiO_3$

in the clumpy clouds, lending support to the aforementioned scenario of the scattering-driven mass loss. While the SPHERE-ZIMPOL data do not allow us to distinguish the specific grain species, Takigawa *et al.* (2017) found excellent agreement in the spatial distribution of gas-phase AlO emission at 344 GHz as observed with ALMA and that of the clumpy dust clouds. These authors conclude that the clumpy clouds within $\sim$3 $R_\star$ predominantly consist of $Al_2O_3$ grains.

## 2. ALMA observations

We observed W Hya with ALMA at 250–269 GHz in Band 6 using the C43-10 configuration with a maximum baseline of 16 km. The observational set-up provided spatial resolutions of 16–20 mas and velocity resolutions of 1.1–1.2 km $s^{-1}$. Our ALMA observations took place on 2019 June 8, when W Hya was at minimum light with a variability phase of 0.53. The millimeter continuum images can be fitted with a nearly circular disk with an angular diameter of $\sim$60 mas, which is about 1.5 times larger than the stellar angular diameter of $\sim$40 mas measured in the near infrared (Woodruff *et al.* 2009). In contrast to the previous 338 GHz observation by Vlemmings *et al.* (2017), no signature of a hot spot is seen in our ALMA continuum images.

## 3. Detection of emission over the stellar disk

We detected a total of 40 molecular lines from the following species: $^{29}$SiO, $^{30}$SiO, Si$^{17}$O, $H_2O$, $SO_2$, $^{34}SO_2$, SO, AlO, AlOH, TiO, and HCN. The large angular diameter of W Hya and ALMA's high angular resolution allow us to spatially resolve the emission extending to $\sim$100 mas ($\sim$5 $R_\star$) as well as the absorption over the stellar disk. The emission is irregularly shaped with a plume extending in the NNW, a tail extending in the SSE, and an extended atmosphere elongated in the ENE–WSW direction. However, we found that approximately a third of the identified lines show emission—instead of pure absorption as expected—over the stellar disk. They are the lines of $^{30}$SiO ($v = 2$), Si$^{17}$O ($v = 0$), $H_2O$ ($v_2 = 2$), $SO_2$ (many lines), and AlO, although the emission of this last line is weak. It should be noted that not all lines of a given molecular species show the emission over the stellar disk. For example, while the $^{30}$SiO ($v = 2$) and Si$^{17}$O ($v = 0$) lines show emission, the $^{29}$SiO ($v = 3$) and $^{30}$SiO ($v = 1$) lines show clear absorption over the stellar disk as expected. Likewise, not all detected $SO_2$ lines show emission over the surface, although some of them have similar energy levels. Therefore, the emission cannot be explained by the presence of hot gas in front of the star, because all lines of the same molecular species would show emission in that case.

The vibrationally excited $H_2O$ line ($v_2 = 2$, $6_{5,2}$–$7_{4,3}$) at 268 GHz shows particularly strong emission over the stellar disk in spite of its high upper level energy of 6039 K. Its peak intensity is twice as strong as the continuum intensity. This strongly indicates maser actions. This line has also been reported in multiple AGB stars and red supergiants, suggesting that excitation of this line is widespread among oxygen-rich evolved stars (Baudry *et al.* 2023, and references therein). Some of the detected sources exhibit evidence of strong maser actions.

The maser emission is confined within a radius of $\sim$50 mas ($= 2.4$ $R_\star$). The peak of the $H_2O$ maser emission observed over the stellar disk are found at redshifted velocities between 3 and 5 km $s^{-1}$ with respect to the systemic velocity. However, the line profiles extracted over the stellar disk are broad, ranging from about $-10$ km $s^{-1}$ to 14 km $s^{-1}$. This suggests the presence of a wide range of velocity components between $\sim$1.5 $R_\star$ (millimeter continuum radius) and $\sim$2.4 $R_\star$. The dynamical models for AGB stellar winds (e.g., Höfner *et al.* 2022) show that the velocity of pulsation-driven shocks can reach the magnitude of ∼10–15 km $s^{-1}$. This is in broad agreement with the observed velocity width of the $H_2O$ masers.

Based on the radiative transfer models of Gray *et al.* (2016), Baudry *et al.* (2023, and this symposium) show that, in the presence of warm dust of ∼1300 K, maser emission can occur in the 268 GHz $H_2O$ transition if the $H_2O$ density is higher than $\sim 10^4$ $cm^{-3}$ and the kinetic temperature is lower than ∼900 K. A lower kinetic temperature ($< 500$ K) is required for a lower dust temperature (900 K). This suggests that $H_2O$ maser emission may trace pockets of dense, cool regions in the inner wind of oxygen-rich stars, where dust formation can take place.

The emission over the surface in other molecular lines can also be interpreted as maser actions. This naturally explains that some lines of a given molecular species show the emission over the stellar disk, while other lines of the same species show pure absorption as expected.

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