Investigating the inner circumstellar envelopes of O-rich stars with ALMA observations of high-*J* SiO masers

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Introduction

SiO masers found within the extended stellar atmospheres are useful for probing the inner regions of circumstellar envelopes (CSE) where convection and pulsation shocks are damped and dust formation occurs around evolved stars.

The ATOMIUM (ALMA Tracing the Origins of Molecules In dUst-forming oxygen-rich M-type stars) Large Programme[1],[2] (PI: L. Decin) observed 17 O-rich AGB and RSG stars covering a range of (circum)stellar parameters in these late stages of stellar evolution.

Here we highlight a few interesting results from:

ALMA Band 6 observations of high-*J* SiO masers

- ❖ Focus on π[1] Gru, R Hya, and detected *v*=0 masers
- ❖ Investigation of mass-loss rates vs flux-weighted mean radii of fitted maser components in the ATOMIUM data set

Supplementary APEX observations

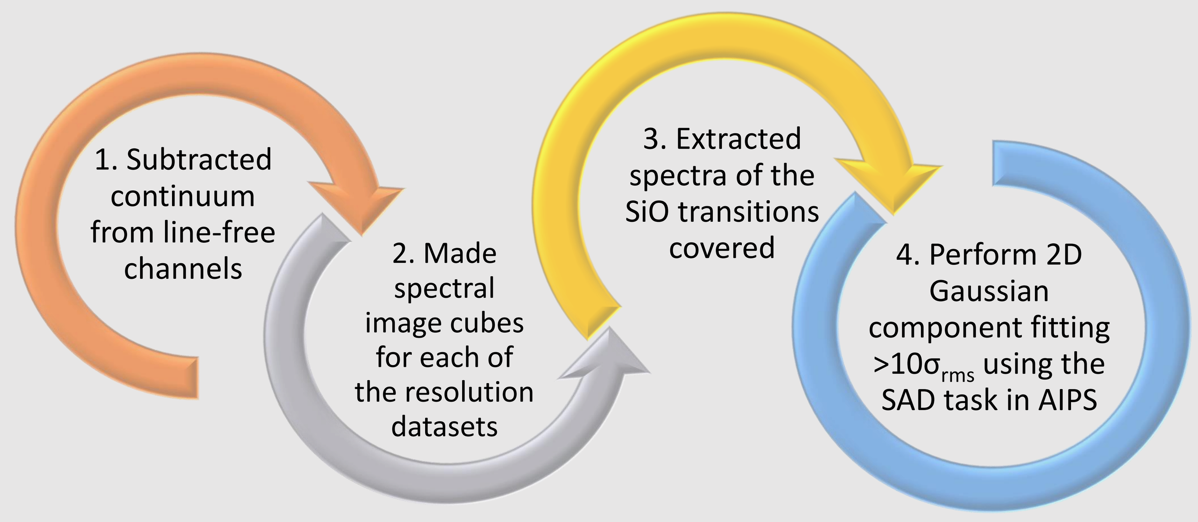
- ❖ Clear evidence of maser variability in some ATOMIUM AGB stars

Observations

ATOMIUM data were obtained using ALMA:

- ❖ Frequency range 213.83-269.71 GHz, observed between 2018-2020.
- ❖ Mid (0".2, sensitive to thermal emission) and high (0".02, comparable to 2-4 AU for the closer targets) resolutions; low resolution data not necessary for the maser study.
- ❖ Contain high-frequency (*J*=5-4 and *J*=6-5) SiO transitions.

Figure 1. Diagram showing the process of data reduction and analysis. Adapted from the description provided in [2].



Single-dish observations of the *J*=5-4 and *J*=6-5 SiO lines were taken with APEX:

- ❖ Equipped with the nFLASH320 receiver, full resolution ~0.086 km/s
- ❖ Target rms = 925 mJy (25 mK in T_a).
- ❖ Two epochs of observations obtained in 2022 (either Jul-Oct or Oct-Dec)

Results

In general:

- ❖ More complex compared to the well-studied 43 (*J*=1-0) and 86 (*J*=2-1) GHz often seen in rings.
- ❖ The masers form clumps of typical size ~R* and are mostly distributed between ~2-4 R*.

π[1] Gru:

- ❖ Shows a curved trail of entirely blue-shifted components towards the companion (Fig. 2a).
- ❖ With the fitted *v*=0 lines, we can infer the flow pattern of the wind material subjected to the conditions caused by binary interaction; evidence of a spiral[3].
- ❖ Components with speeds close to V_{LSR}; suggests tangential beaming due to an accelerating outflow caused by stellar pulsations[4].

R Hya:

- ❖ ^{28}SiO (and its isotopologues) *v*=1 *J*=5-4 and *J*=6-5: most extreme projected speeds along the NE-SW axis of position angle (PA) about 70° (dashed line in Fig. 2b).
- ❖ ~PA of the projected semi-major axis of the equatorial density enhancement (EDE) deduced from CO observations, suggesting a compact differentially rotating disk in the inner CSE[5].

v=0 masers:

- ❖ Detected in 7 sources in ATOMIUM: AH Sco, KW Sgr, VX Sgr, V PsA, W Aql, IRC+10011 and IRC-10529 (the last two relatively strong)
- ❖ ^{28}SiO *J*=5-4 and ^{29}SiO *J*=5-4 are the two observed vibrational ground-state lines

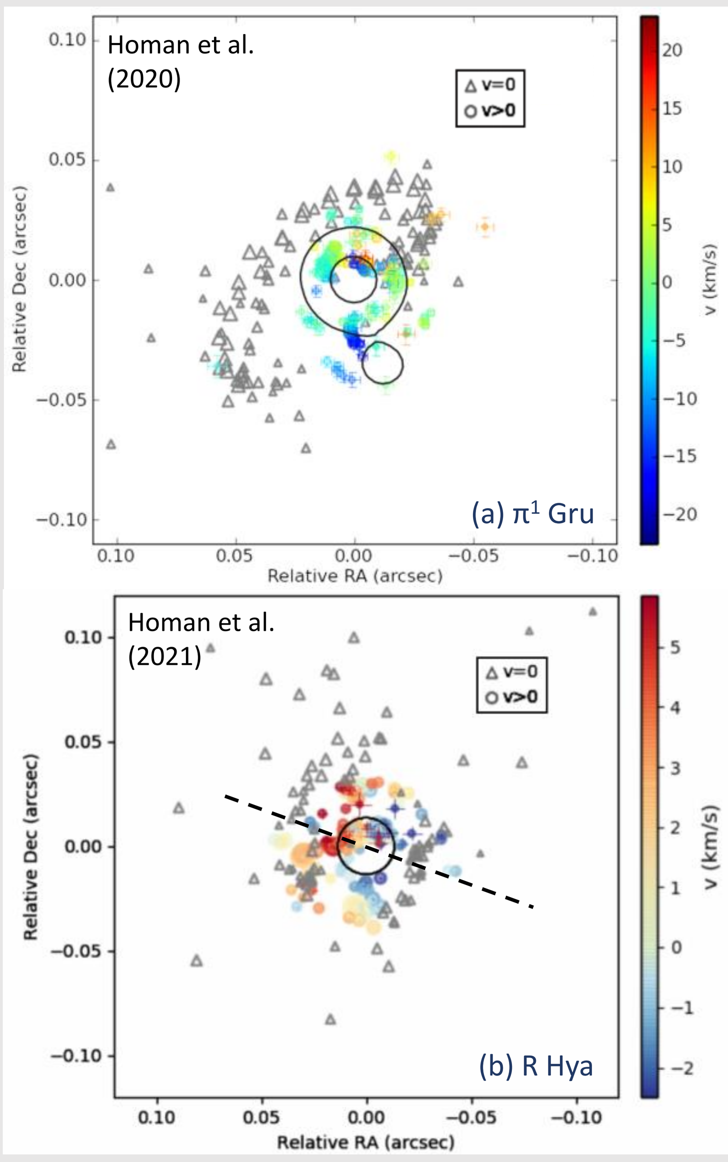


Figure 2. Position and velocity of the Gaussian-fitted components of the SiO *v*=1,2 *J*=5-4 and *J*=6-5 emission lines of the high-resolution dataset observed towards π[1] Gru (a) and R Hya (b). For π[1] Gru, contours of the 120 and 768 times the continuum rms noise value (1.5×10^{-5} Jy/beam) are shown while the black circle in (b) represents the stellar photosphere of R Hya. The marker size scales as log$_{10}$ of the integrated flux and the velocities are shifted to their corresponding V_{LSR}. The grey triangles mark the positions of the mid-resolution components of *v*=0 transitions. Note the different colour bars used in the plots.

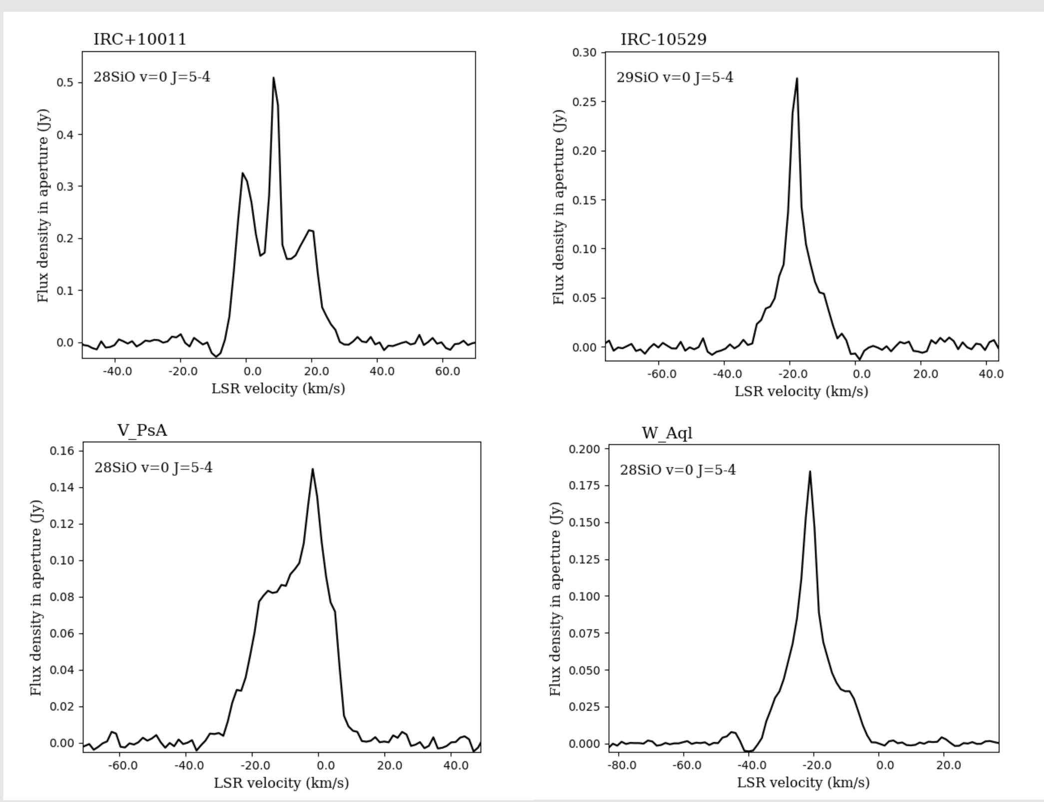


Figure 3. Examples of *v*=0 maser spectra observed towards IRC+10011, IRC-10529, V PsA, and W Aql. The characteristic narrow spikes of masers can be seen on top of the thermal profiles.

Mass-loss rate *vs* mean angular separation of maser components:

- ❖ The flux-weighted mean radius of the fitted maser components for each maser source is defined as the angular distance from the star in which 90% of the total emission is enclosed[6].
- ❖ Plotted against the mass-loss rate of its respective star (Fig. 4).
- ❖ Unclear whether there is a relationship: the correlation coefficients of the linear regression model for ^{28}SiO *v*=1 *J*=6-5 (0.43) and ^{28}SiO *v*=1 *J*=5-4 (0.02) are inconsistent.
- ❖ Need to determine the flux-weighted radius in 3D as many bright maser components lie close to or in front of the star in the line-of-sight direction.
- ❖ May also be intrinsic to the nature of the maser transitions. Further analysis is necessary.

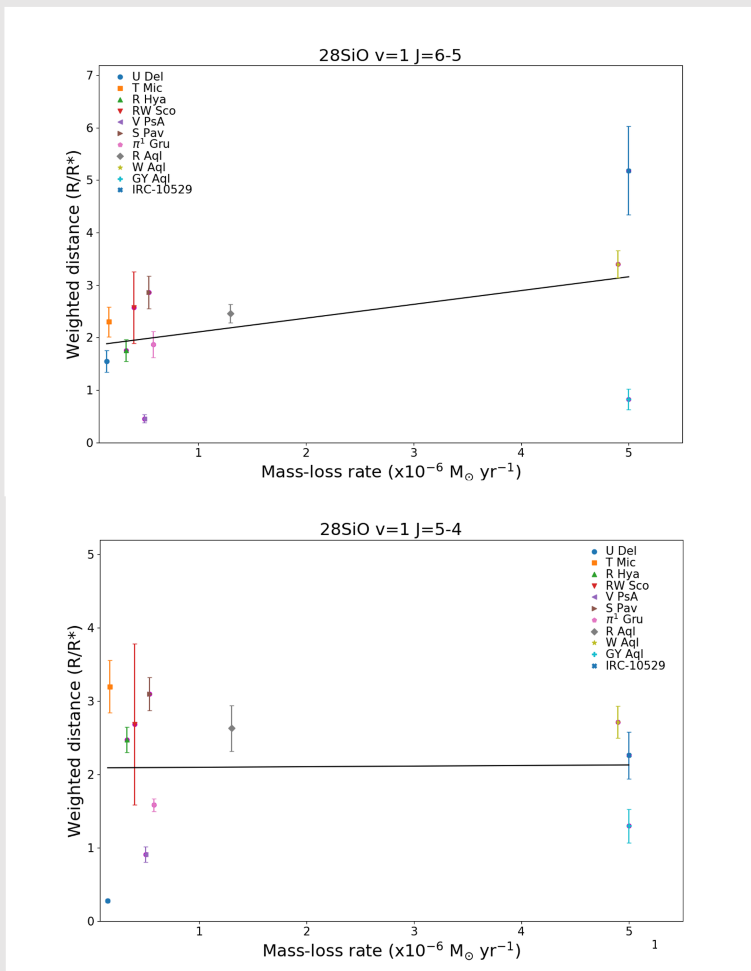


Figure 4. Plots of flux-weighted angular distance of fitted maser components against mass-loss rate for ^{28}SiO *v*=1 *J*=6-5 (*top*) and ^{28}SiO *v*=1 *J*=5-4 (*bottom*). The solid lines represent the best-fit linear regression models where the correlation coefficient is 0.43 and 0.02 for the *J*=6-5 and *J*=5-4 transition, respectively. Only the AGB sources with considerable maser action are included in the analysis.

SiO maser variability in AGB stars

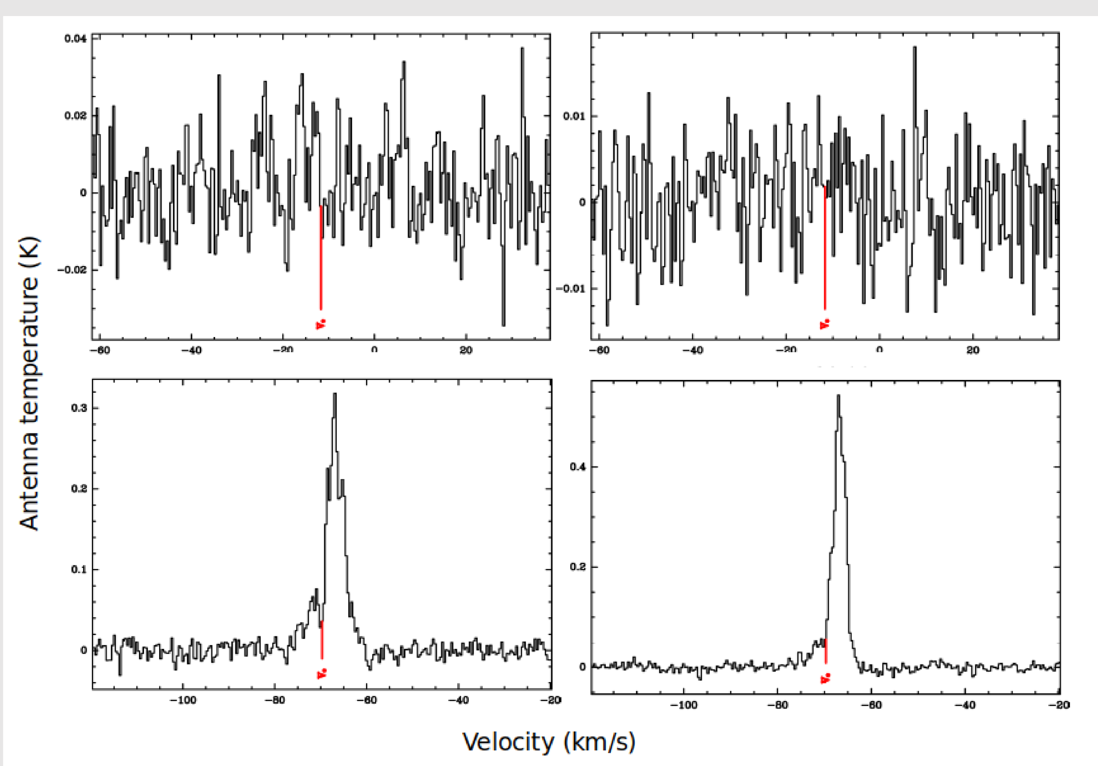


Figure 5. Preliminary spectra of ^{28}SiO *v*=1 *J*=5-4 emissions towards π[1] Gru (*top*) and RW Sco (*bottom*) in the two epochs of APEX observations; these show zero maser action in π[1] Gru and strong masers in RW Sco. The vertical lines mark V_{LSR}. Note that the y-axis is still in K (courtesy of S. Etoka).

Example:

^{28}SiO *v*=1 *J*=5-4 detected in most sources during ATOMIUM observations

Two extreme cases of variability in 2022:

- ❖ π[1] Gru: non-detection (phase = 0.5 and 0.1)
- ❖ RW Sco: bright maser in both epochs (phase = 0.0 and 0.3)

Summary

- ❖ Some of the recent results of the analysis of ATOMIUM SiO masers, observed between Autumn 2018 and Spring 2020 by ALMA, are presented and properties of the CSE of π[1] Gru, R Hya and IRC-10529 are briefly discussed.
- ❖ The relationship between mass-loss rates and flux-weighted mean radii is unclear due to the exclusion of the line-of-sight direction in the analysis.
- ❖ APEX observations of *J*=5-4 SiO lines show clear evidence of maser variability at different phases of stellar pulsations.

References

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