*Cosmic Masers: Proper Motion toward the Next-Generation Large Projects*
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# Investigating the inner circumstellar envelopes of oxygen-rich evolved stars with ALMA observations of high-$J$ SiO masers

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**Abstract.** We highlight a few results from ALMA Band 6 observations of high-rotational transition number ($J$) SiO masers towards oxygen-rich AGB and red supergiant stars carried out as part of the ATOMIUM Large Programme in 2018–2020. A search for a relationship between mass-loss rates and flux-weighted mean angular distances of maser components was inconclusive, as linear regression models for the $^{28}$SiO $v$=1 $J$=5–4 and $J$=6–5 transitions were inconsistent. Supplementary APEX observations towards the ATOMIUM AGB stars also suggest variability at different stellar pulsation phases.

**Keywords.** Masers, Stars: AGB and post-AGB, Stars: circumstellar matter, Stars: mass-loss

## 1. Observations

The observations were taken with ALMA Band 6 (213.83–269.71 GHz) between Autumn 2018 and Spring 2020 in three array configurations sensitive to scales ranging from 0.4–10 arcsecs, as part of the ATOMIUM Large Programme (Decin *et al.* 2020). The data were processed in CASA using the ALMA calibration pipeline and dedicated scripts for self-calibration and imaging (Gottlieb *et al.* 2022).

We fitted two-dimensional Gaussian components to each patch of emission above $10\sigma_{rms}$ in each of the channel maps covering SiO $v$=1,2 $J$=5–4 and $J$=6–5 lines, using the SAD task in the AIPS package. Only the Gaussians within either 0.01 arcsec, or, if larger, the position errors (0.5×synthesised beam/signal-to-noise ratio) of their counterparts in adjacent channels were selected to ensure strongest signal pickup.

## 2. Mass-loss rates *vs* mean angular separations from the star

The determination of mean angular separations from the star ($R$) of maser components was adapted from the method described in Assaf *et al.* (2011). For each candidate position, we determined the angular distances of all SiO maser components. We then calculated the radius that encloses 90% of the total emission. A subset of sources with >10 fitted components (for that particular transition) was analysed to minimise bias due to the sporadicity of high-$J$ SiO maser components. The uncertainty in $R$ was taken to be the standard deviation of the mean.

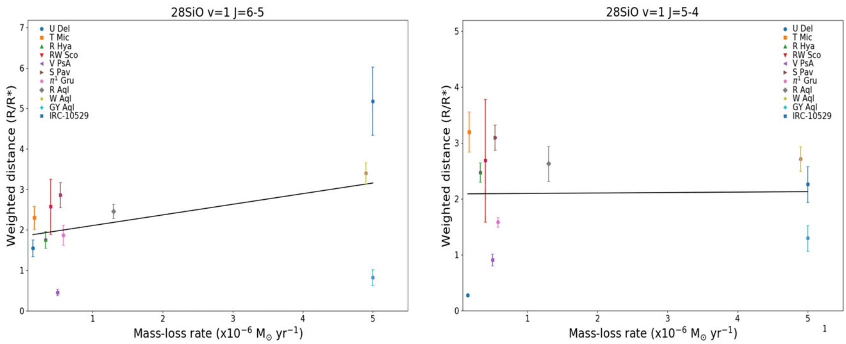


**Figure 1.** Plots of flux-weighted mean angular separation of fitted maser components against mass-loss rate for $^{28}$SiO $v$=1 $J$=6–5 (left) and $^{28}$SiO $v$=1 $J$=5–4 (right). The solid lines represent the best-fit linear regression models. Only the sources with considerable maser action are included in the analysis.

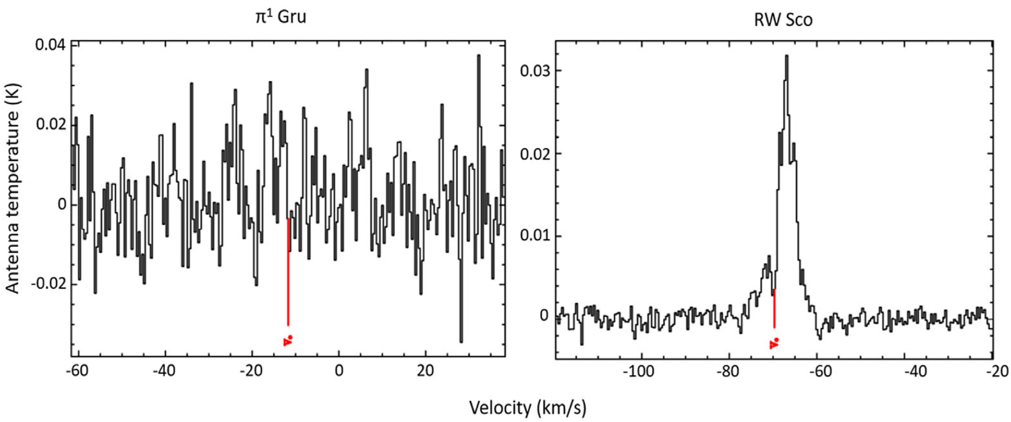


**Figure 2.** Preliminary spectra of $^{28}$SiO $v$=1 $J$=5–4 emissions towards $\pi^1$ Gru (left) and RW Sco (right) in the first epoch of APEX observations; these show zero maser action in $\pi^1$ Gru and strong masers in RW Sco. The vertical lines labelled $v_0$ mark the stellar velocity. Note that the y-axis is still in units of K (courtesy of S. Etoka).

The plots of flux-weighted $R$ against mass-loss rate for the two most frequently detected high-$J$ SiO masers in the ATOMIUM sample are shown in Fig. 1. It is unclear whether a correlation exists between both observables as the coefficients of the linear regression model are 0.43 and 0.02 for $^{28}$SiO $v$=1 $J$=6–5 and $^{28}$SiO $v$=1 $J$=5–4 lines. This discrepancy could be due to intrinsic properties of the maser transitions or competitive gain (Doel *et al.* 1995 and references therein). However, the current approach lacks any information in the line-of-sight direction which skews the results towards small radii as many bright maser components lie close to or in front of the star. Further analysis is required to verify these results.

## 3. Variability

Two epochs of supplementary single-dish observations of the SiO $v$=1 $J$=5–4 and $J$=6–5 lines towards a selected subset of ATOMIUM targets were taken using APEX between June–December 2022. Fig. 2 shows two preliminary spectra of the $^{28}$SiO $v$=1

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$J$=5–4 line towards $\pi^1$ Gru (phase = 0.5) and RW Sco (phase = 0.0). When compared to the ATOMIUM observations (Homan *et al.* 2020; Pimpanuwat *et al. in prep.*), both sources show evidence of maser variability, especially $\pi^1$ Gru where the previously detected maser has subsided.

## Supplementary material

To view supplementary material for this article, please visit http://dx.doi.org/10.1017/S1743921323002235

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