ALMA observations and 3D modelling of high-*J* SiO masers towards oxygen-rich evolved stars

Bannawit Pimpanuwat*[1], Malcolm D. Gray[1], Anita M. S. Richards[1], Sandra Etoka[1] and the *ATOMIUM* consortium (Decin, Gottlieb et al.)

[1]Jodrell Bank Centre for Astrophysics, The University of Manchester, Oxford Road, Manchester, UK M13 9PL

ABSTRACT

We report the results of high-*J* SiO maser observations towards oxygen-rich AGB stars which were carried out as a part of the ALMA *ATOMIUM* Large Program between Autumn 2018 and Spring 2020. Analysis of high-resolution channel maps of three of the targets, π^1 Gru, R Hya and IRC+10011, show the following: (1) π^1 Gru likely has a spiral, based on the flow of wind material caused by binary interaction; (2) the positions of the SiO fitted components with most extreme velocities suggests a compact disk in the inner circumstellar environment, agreeing with CO observations; and (3) there may be streamers of dust precursors in IRC+10011. Recent development of three-dimensional (3D) modelling of masers and the results of the latest model are shown and discussed. Future work will be comparisons between the SiO maser observations and the 3D models, which will lead to better understanding of maser emission produced in the inner circumstellar envelopes of oxygen-rich evolved stars.

REFERENCES

[1] Decin et al. 2020, Science, 368, 6510, p.1497-1500.
[2] Gray M., Mason L., Etoka S., 2018, MNRAS, 477, 2628.
[3] Gray M., Baggott L., Westlake J., Etoka S., 2019, MNRAS, 486, 4216.
[4] Gray M., Etoka S., Travis A., Pimpanuwat B., 2020, MNRAS, 493, 2472.
[5] Gottlieb et al. 2021, *submitted*.
[6] Richards, A. M. S., Elitzur, M., & Yates, J. A. 2011, A&A, 525, A56.
[7] Homan et al., 2020, A&A, 644, A61.
[8] Chapman, J. M. & Cohen, R. J. 1985, MNRAS, 212, 375.
[9] Homan et al. 2021, *submitted*.
[10] Gonidakis I., Diamond P., Kemball A. J., 2013, MNRAS, 433, 3133.
[11] Ireland M. J., Scholz M., Wood P. R., 2011, MNRAS, 418, 114.

*CONTACT

Email: bannawit.pimpanuwat@postgrad.manchester.ac.uk

INTRODUCTION

SiO masers are common in the circumstellar envelopes (CSEs) of oxygen-rich stars and are instrumental to probing the regions close to the stellar surface. In the ALMA *ATOMIUM* (ALMA Tracing the Origins of Molecules In dUst-forming oxygen-rich M-type stars) program [1], a sample of 17 oxygen-rich AGB stars which covers a range of (circum)stellar parameters and evolutionary stages was observed.

A 3D maser code [2][3][4] has been in development to construct maser models with realistic physical conditions and recent advances including e.g. multi-cloud systems, 3D velocity profiles and additional sources of radiation. Comparing the models to observations will shed some light on how masers are generated in the CSEs.

This presentation shows results of high-*J* SiO *v*=1,2 masers observed towards some of the ATOMIUM sources, namely π^1 Gru, R Hya and IRC+10011, as well as a simulated image of a ring-like arrangement of maser features produced by the 3D maser code.

OBSERVATIONS

ATOMIUM observations were taken between Autumn 2018 and Spring 2020 in three ALMA array configurations, sensitive to scales ranging from 0.4 arcsecs to 10 arcsecs. The frequency range covered is between 213.83 GHz and 269.71 GHz and the data were processed using the ALMA calibration and imaging pipelines implemented in CASA [1][5]. Specific information on the calibration for individual stars will be available in the ATOMIUM data release.

SIO MASERS IN ATOMIUM TARGETS

We fitted 2D Gaussian components to each patch of emission above $20\sigma_{rms}$ 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", or, if larger, the position errors (0.5*(synthesised beam)/(signal to noise ratio) [6]) of their counterparts in adjacent channels were selected to ensure strongest signal pickup.

For π^1 Gru, an interesting region is identified to the south of the star, where there is a curved trail of entirely blue-shifted components (Fig. 1). With the fitted results of vibrational ground-state lines, we can infer the flow pattern of the wind material subjected to the conditions caused by binary interaction, which suggests the existence of a spiral [7]. Most of the masers are seen in a ring around the star with speeds close to V_{LSR}. This is evidence of an accelerating outflow, caused by stellar pulsations, producing tangential beaming [8].

The ^{28}SiO (and its isotopologues) *v*=1 *J*=5-4 and *J*=6-5 fitted components of R Hya are detected to have their most extreme projected speeds along the NE-SW axis of position angle roughly 70°. The result is consistent with the PA of the projected semi-major axis of the equatorial density enhancement (EDE) deduced from the CO observations, suggesting a possible presence of a compact disk in the inner CSE [9].

Fig. 1 Position and velocity of the peak positions 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 (top left), R Hya (top right) and IRC+10011 (bottom). 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 R Hya and IRC+10011 plots) represents the size of the stellar photosphere. The marker size scales as $\log_{10}$ of the integrated flux and the velocities have been shifted to their corresponding V_{LSR}. The grey triangles mark the positions of the mid-resolution components of *v*=0 transitions. Note the different spatial scales and colour bars used in the plots.

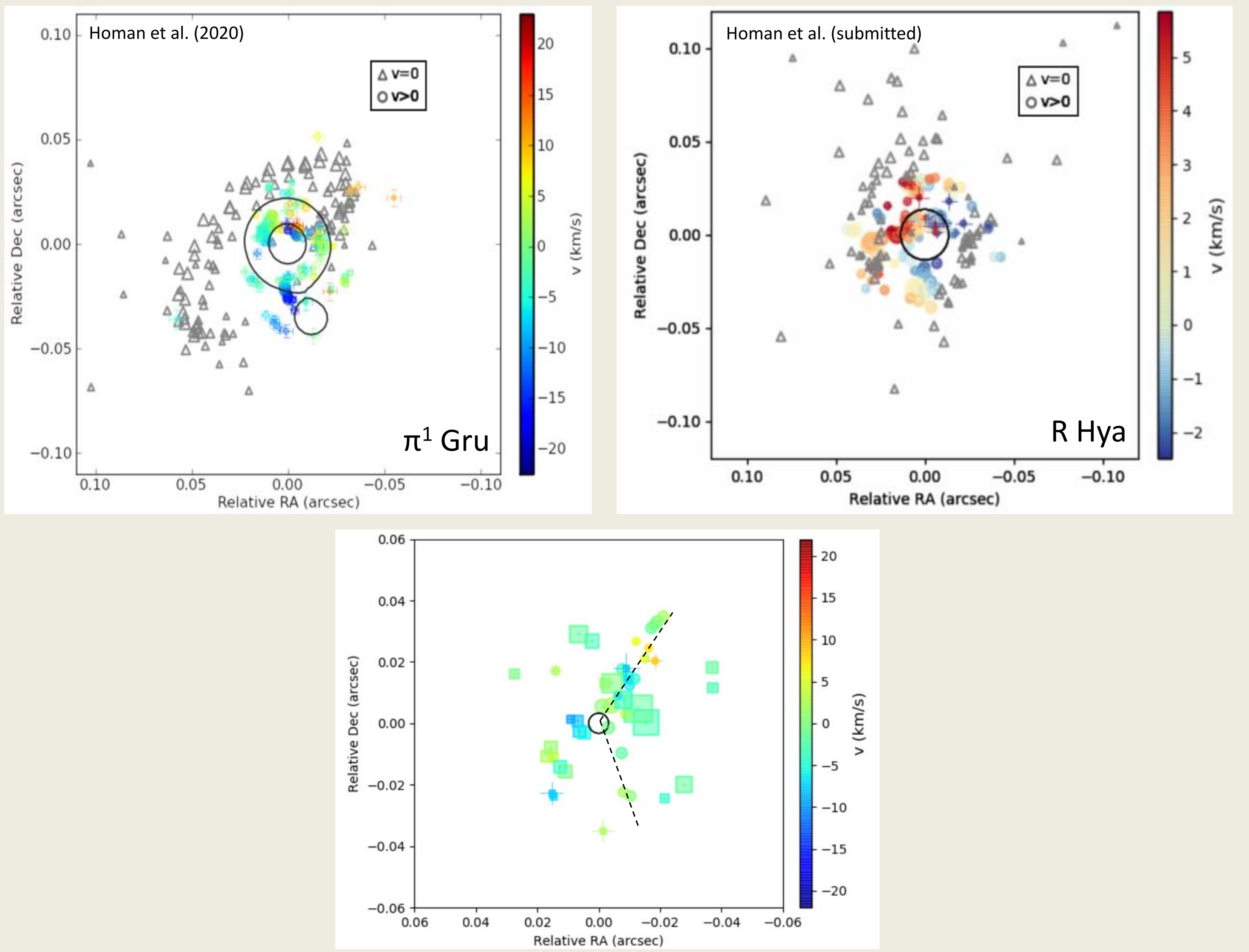
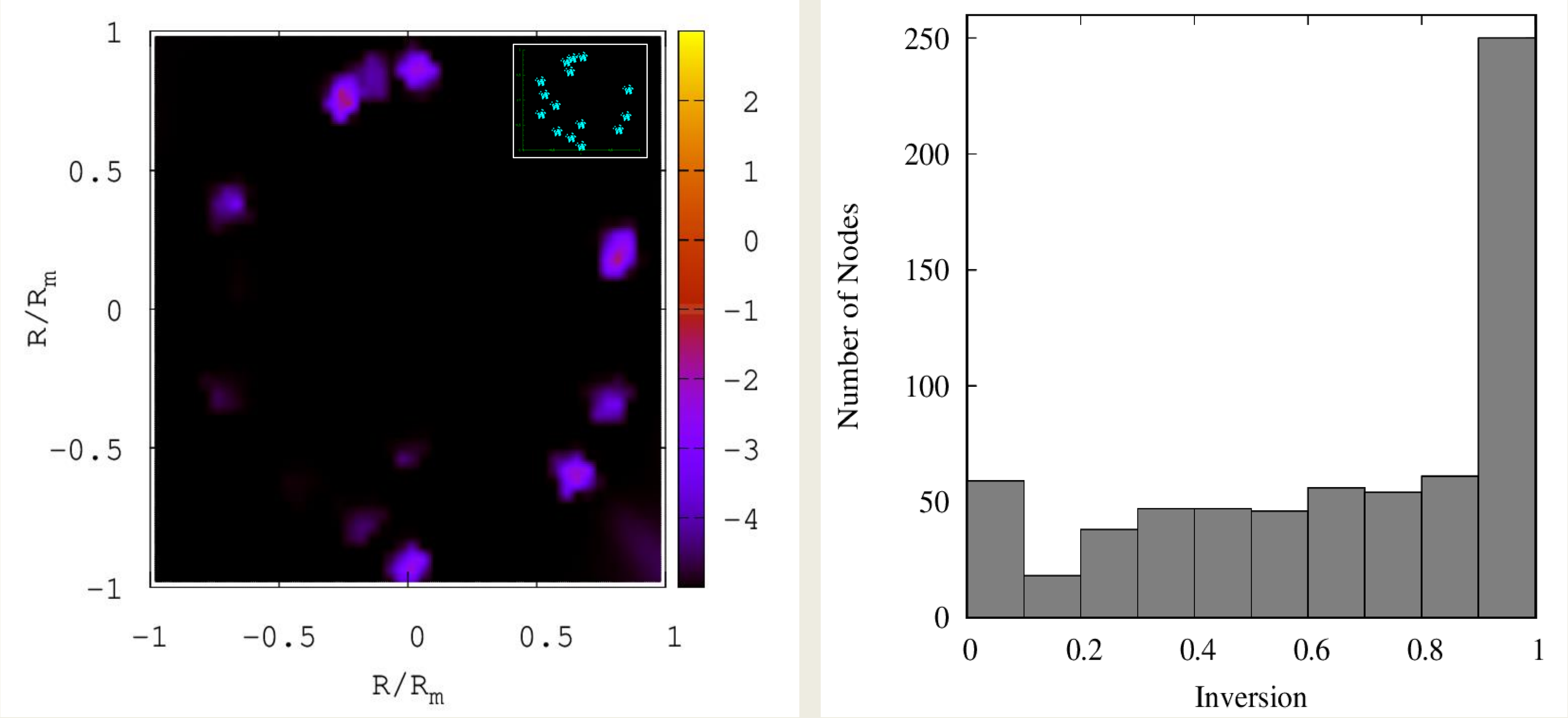


Fig. 2 *Left*: Simulated image of masers based on a 3D computational domain (shown as an onset in cyan) representing a projected ring-like structure similar to what we typically see in the CSEs. R_m is the model size and the colour scale is proportional to the base-10 logarithm of the specific intensity divided by the saturation intensity (i_{sat}) *Right*: Histogram of the distribution of domain nodes amongst ten bins representing fractional population inversion ranges, where the lower the value is, the more saturated the node becomes, leading to brighter maser emission.



Preliminary results of the fitted ^{28}SiO *v*=1 *J*=5-4 maser for IRC+10011 show that it may be tracing streamers (shown as dashed lines in Fig. 2) or material with local deviant velocities, while the ^{28}SiO *v*=2 *J*=5-4 components, at speeds close to the systemic velocity, are potentially present in a (partial) ring.

The analysis of ATOMIUM SiO masers is currently ongoing. Apart from wind morphologies and a broad picture of dust-forming regions, we are investigating the potential relationship between mass-loss rates and regions in which masers are emitted (Pimpanuwat et al. *in prep.*).

3D MASER MODELLING

To simulate a system of maser clouds in CSEs, 15 45-node computational domains were produced such that they are arranged in a 3D spherical shell (hereafter, compound domain), based on the observed ^{28}SiO *v*=1, *J*=1-0 masers towards TX Cam [10]. The SiO number density was set to vary in the range of 10^7-10^8 /cm^3 while the stellar envelope velocity profile in 3D was assumed to follow the CODEX models [11] for Mira variables, which form a large portion of the ATOMIUM sample, where a shock layer is present in the CSE. The optical depth multiplier (see [3]) used was close to 10, where the filling factor of this domain is roughly 10-15%.

Fig. 2 shows a simulated VLBI image of maser emission at the central frequency channel with peak flux density. The result reflects what we expect to see from the input physical conditions and the nature of maser pumping as the brightest features near the top of the figure are due to a high level of amplification achieved through cloud overlaps, which increase the maser depth and therefore the distance over which the maser is amplified. The image, alongside the histogram of nodes in decadal bins illustrating the fraction inversion, also supports the clumpy nature of maser features owing to localised dense regions. Differences in maser specific intensities of individual clouds (2-3 orders of magnitude) are caused by initial variable number density and the presence of the shock, which is dependent on radial distances from the centre of the star. More intense masers are also seen more centrally bright and smaller in angular size, a clear indication of beaming effects.

The recent addition of an interior source of radiation at the centre of maser cloud systems together with, for example, the inclusion of molecular fraction and kinetic and dust temperatures, will allow us to replicate the observations of SiO masers in the ATOMIUM sample and thus result in a more realistic look, in 3D, of the properties and processes in CSEs of oxygen-rich AGB stars.

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+10011 are briefly discussed.

3D modelling of masers in the CSEs gives satisfactory results as expected from various input parameters. The new models in the works will be compared with the ATOMIUM observations leading to a deeper constraint/understanding of the inner CSE.