Cosmic Masers: Proper Motion toward the Next-Generation Large Projects
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(Sub)mm Observations of Evolved Stars

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Abstract. Evolved stars on the asymptotic giant branch and red supergiants have multiple processes that can be studied in the (sub)mm, including stellar surfaces, circumstellar thermal gas and dust, and masers. Telescopes such as APEX and ALMA have opened the possibility to perform studies that are revealing new information on these, as well as on the role of binaries in shaping stellar winds and the evolution to planetary nebulae. Here, we discuss some recent results for (sub)mm observations towards evolved stars focusing particularly on masers. This includes SiO and water masers, as well as ALMA high angular resolution observations of HCN masers towards a carbon-rich star.

Keywords. Masers, stars: AGB and post-AGB, submillimeter

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1. Introduction

Since the last maser IAU in 2017, there have been multiple exciting results for (sub)mm masers. In addition to those reported elsewhere in these proceedings, a CO maser was detected using ALMA towards oxygen-rich AGB star W Hya (Vlemmings *et al.* 2021). For water masers, results have included those for terahertz masers (Neufeld *et al.* 2021) and 658 GHz masers (Baudry *et al.* 2018). For HCN masers, recent results have included those of Menten *et al.* (2018), Wong *et al.* (2019), Fonfría *et al.* (2019) and Jeste *et al.* (2022). SiS masers have been imaged using ALMA towards IRC+10216 (Fonfría *et al.* 2018). Using the ALMA Large Programme ATOMIUM dataset, multiple interesting results have arisen for SiO and water masers (Homan *et al.* 2020, Homan *et al.* 2021, Etoka *et al.* 2022, Richards *et al.* 2022). In the remainder of this article we focus on three (sub)mm observations of evolved stars since the last maser IAU related to SiO masers/thermal CO, HCN masers and water masers respectively.

2. ALMA CO and SiO Observations towards GX Mon

Using ALMA, Randall *et al.* (2020) observed Mira variable GX Mon with the aim of targeting CO (2-1) emission and SiO maser emission. The CO map (Figure 1) reveals a complex circumstellar spiral arc structure. This structure is consistent with hydrodynamical models for an AGB star with a binary companion in an eccentric orbit (orbital separation 7 – 61 AU). While several other species (including SiO, SiS, SO_2, and CS) are detected in the data, only the SO (5–4) map shows a similar, but much weaker,

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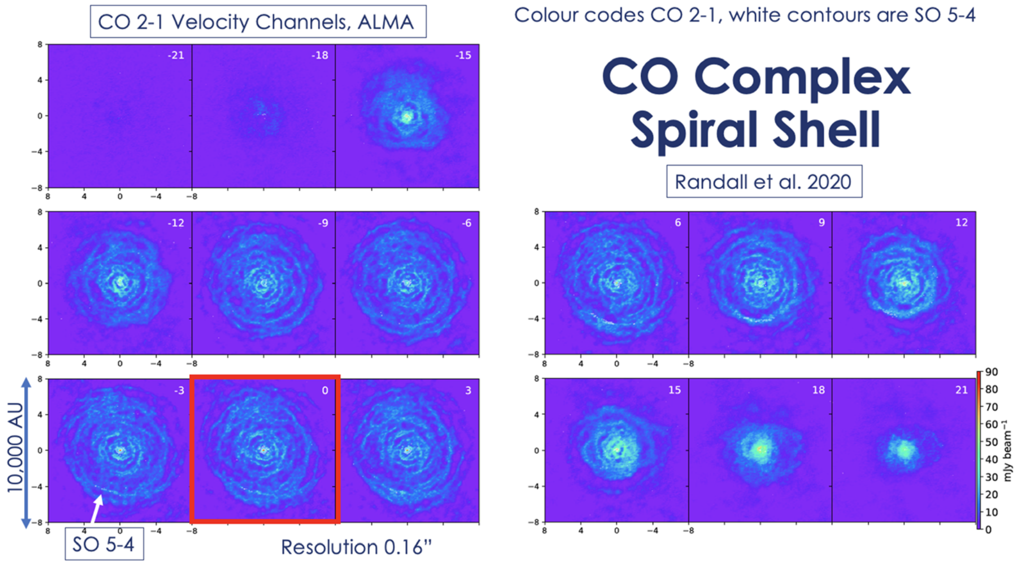

Figure 1. ALMA CO (2-1) observations of GX Mon with 0.16 arcsecond resolution after Randall *et al.* (2020). The different panels display velocity channels with that of the systemic velocity (adjusted to zero) outlined by the red box. Colour codes the CO 2-1 emission and white contours are SO 5-4 emission (seen more easily in Figure 2). The SO emission appears to be enhanced in an arc-like structure at about 5 arcseconds south of the central star. At the position of the SO arc, there is also an arc-like filament in the ACS/HST image in the F606W and F814W bands.

distribution as that imaged for the CO (Figure 2). Component fitting to the v=1 J=5-4 SiO maser line indicated maser emission distributed in a ring-type morphology near ($<$ 5 R_*) to the central star. There was no evidence for maser emission tracing material shaped by the binary interaction unlike e.g., Humphreys (2018), Homan *et al.* (2020).

3. ALMA High-angular Resolution HCN Maser Observations

Schilke, Mehringer and Menten (2000) and Schilke & Menten (2003) discovered HCN maser lines at 804.751 and 890.761 GHz towards carbon-rich stars. These lines can be very strong, for example towards IRC+10216 in the CSO observations of Schilke & Menten (2003) the peak line flux density was about 800 Jy at 805 GHz and about 8000 Jy at 891 GHz. Energy levels for the 891 GHz maser are >4000 K above ground state, therefore these masers should probe the inner circumstellar envelope. First imaging of these lines by Wong *et al.* (2019) using ALMA with a resolution of 0.1 arcseconds confirmed this. In those observations the extents of the HCN maser regions were found to be ∼10 - 30 AU for V Hya and IRC+10216. New ALMA test data that were taken towards carbon-rich star R Lep, of the 891 GHz HCN maser emission towards that target (Asaki et al. submitted), are soon to be publicly released. The data have an angular resolution of 5 milli-arcseconds, making the image the highest angular resolution image ever made using ALMA to date (ALMA Configuration 10, Band 10).

4. APEX Observations of Water Masers at 437, 439, 471 & 474 GHz

Deguchi (1977) was the first paper, or among the first papers, to make specific predictions about which (sub)mm water lines should be observable. Among the lines predicted is the 474 GHz which was then discovered by Menten *et al.* (2008) and is one of the lines studied by Bergman & Humphreys (2020) towards a sample of 11 evolved stars using

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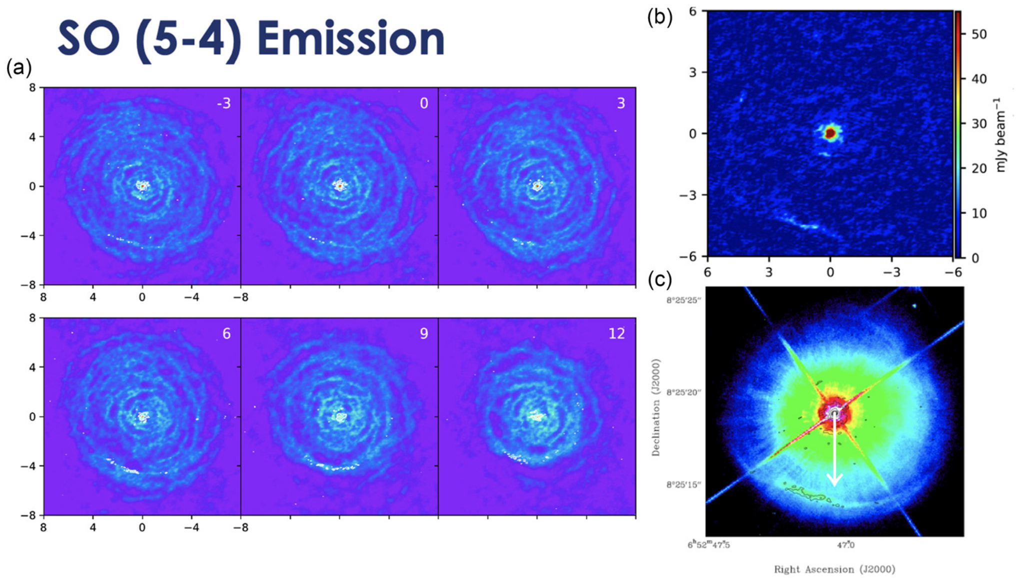

Figure 2. SO (5-4) observations of GX Mon after Randall *et al.* (2020). *a)* Selected velocity channels of CO 2-1 emission (colourscale) and SO 5-4 emission (white contours) from Figure 1; *b)* SO (5-4) image for velocity range -11.4 to -4.9 km s^{-1}, chosen to emphasise the morphology of the weak ring and arc-like emission; *c)* Composite ACS/HST image of GX Mon in the F606W and F814W bands, overlaid with the SO (54) emission from the above panel. The white arrow indicates the direction of the stellar proper motion (from Gaia DR2 via Simbad).

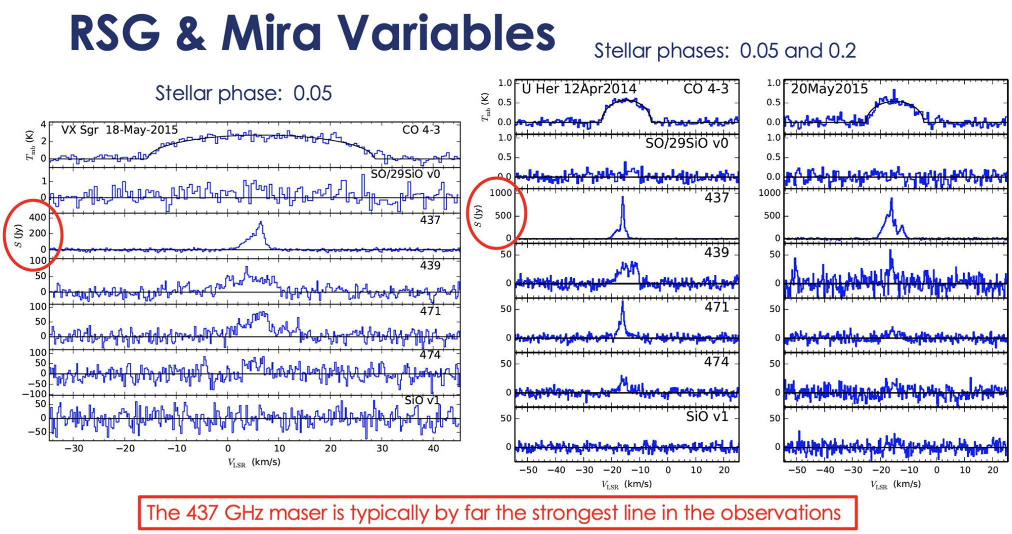

Figure 3. APEX observations towards Red Supergiant VX Sgr and Mira Variable U Her (2 epochs) after Bergman & Humphreys (2020). The observations of CO, SO, and ^{29}SiO are reported in main beam temperature using a velocity resolution of 0.5 km s^{-1}. Observations of the water lines and SiO v = 1 J = 11 - 10 are reported in flux density and are shown with a spectral resolution of 0.25 km s^{-1}. Of the water masers studied here towards 11 objects - at 437, 439, 471 & 474 GHz - the 437 GHz maser is typically by far the strongest in the observations which is not reproduced in the modelling.

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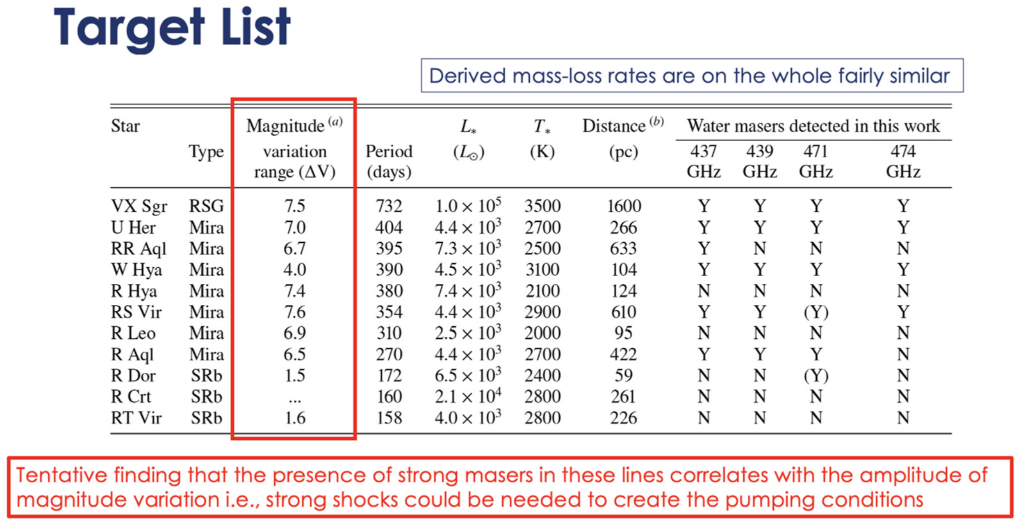

Target List

Derived mass-loss rates are on the whole fairly similar

Star	Type	Magnitude [(a)] variation range (ΔV)	Period (days)	L_* ($L_\odot$)	T_* (K)	Distance [(b)] (pc)	Water masers detected in this work: 437 GHz	439 GHz	471 GHz	474 GHz
VX Sgr	RSG	7.5	732	1.0×10^5	3500	1600	Y	Y	Y	Y
U Her	Mira	7.0	404	4.4×10^3	2700	266	Y	Y	Y	Y
RR Aql	Mira	6.7	395	7.3×10^3	2500	633	Y	N	N	N
W Hya	Mira	4.0	390	4.5×10^3	3100	104	Y	Y	Y	Y
R Hya	Mira	7.4	380	7.4×10^3	2100	124	N	N	N	N
RS Vir	Mira	7.6	354	4.4×10^3	2900	610	Y	Y	(Y)	Y
R Leo	Mira	6.9	310	2.5×10^3	2000	95	N	N	N	N
R Aql	Mira	6.5	270	4.4×10^3	2700	422	Y	Y	Y	N
R Dor	SRb	1.5	172	6.5×10^3	2400	59	N	N	(Y)	N
R Crt	SRb	...	160	2.1×10^4	2800	261	N	N	N	N
RT Vir	SRb	1.6	158	4.0×10^3	2800	226	N	N	N	N

Tentative finding that the presence of strong masers in these lines correlates with the amplitude of magnitude variation i.e., strong shocks could be needed to create the pumping conditions

Figure 4. Target list from Bergman & Humphreys (2020) indicating which sources have maser detections. There is a tentative finding that strong masers in these lines correlates with the amplitude of the stellar magnitude variation.

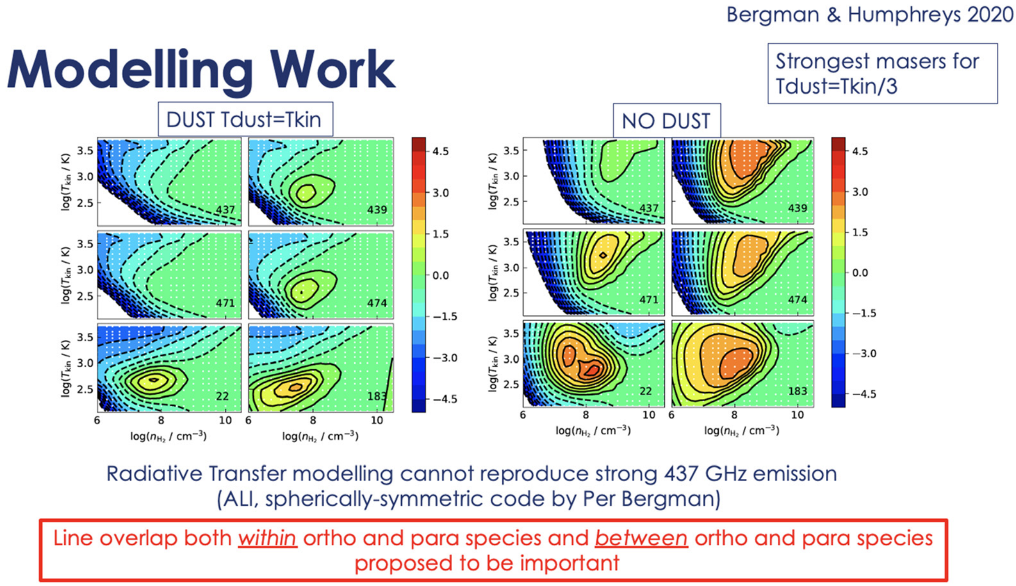

Figure 5. Example modelling results from Bergman & Humphreys (2020). We note that a case with no dust is not realistic for evolved star environments.

APEX (Figure 3). These lines originate from the so-called water "transposed backbone". From the sample of 11 evolved stars, 7 display one or more of the masers at 437, 439, 471, and 474 GHz. The fact that the maser lines are detected near the stellar velocity indicates that they are likely to originate from the inner circumstellar envelopes of the targets. Bergman & Humphreys (2020) tentatively link the presence of masers to the degree of variability of the target star, that is, masers are more likely to be present in Mira variables than in semi-regular variables (Figure 4). Typically, the 437 GHz line is the strongest maser line observed among those studied but that could not be reproduced in radiative transfer modelling (Figure 5). See also Yates, Field & Gray (1997)

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and Gray *et al.* (2016) for radiative transfer modelling results including these lines. Bergman & Humphreys (2020) propose that line overlap *between* ortho and para water may need to be incorporated in models in order to reproduce observations. Some potential overlaps of interest are identified in that paper.

5. Conclusions

Since the last maser IAU in 2017, work on masers is increasingly being performed in the (sub)mm wavelength range. However, there is much we still do not know about these masers in evolved stars and more imaging studies to determine locations in circumstellar envelopes are needed. With ALMA Cycle 10, Band 1 and flexible tuning mmVLBI are offered which may bring new opportunities for evolved star maser study.

References

Bergman, P. & Humphreys, E. M. L. 2020, *A&A*, 638, A19
Baudry, A., Humphreys, E. M. L., Herpin, F., *et al.* 2018, *A&A*, 609, A25
Decin, L., Montargs, M., Richards, A. M. S., *et al.* 2020, *Science*, 369, 1497
Deguchi, S. 1977, *PASJ*, 29, 669
Etoka, S., Baudry, A., Richards, A. M. S., *et al.* 2022, IAU Symposium, 366, 199
Fonfría, J. P., Fernández-López, M., Pardo, J. R., *et al.* 2018, *ApJ*, 860, 162
Fonfría, J. P., Fernández-López, M., Pardo, J. R., *et al.* 2019, IAU Symposium, 343, 398
Gray, M. D., Baudry, A., Richards, A. M. S., *et al.* 2016, *MNRAS*, 456, 374
Jeste, M., Gong, Y., Wong, K. T., *et al.* 2022, *A&A*, 666, A69
Homan, W., Montargs, M., Pimpanuwat, B., *et al.* 2020, *A&A*, 644, A61
Homan, W., Pimpanuwat, B., Herpin, F., *et al.* 2021, *A&A*, 651, A82
Humphreys, E. 2018, in Imaging of Stellar Surfaces, 13
Menten, K. M., Lundgren, A., Belloche, A., Thorwirth, S., & Reid, M. J. 2008, *A&A*, 477, 185
Menten, K. M., Wyrowski, F., Keller, D., & Kaminski, T. 2018, *A&A*, 613, A49
Neufeld, D. A., Menten, K. M., Durán, C., *et al.* 2021, *ApJ*, 907, 42
Randall, S. K., Trejo, A., Humphreys, E. M. L., *et al.* 2020, *A&A*, 636, A123
Richards, A. M. S., Assaf, K. A., Baudry, A., *et al.* 2022, IAU Symposium, 366, 204
Schilke, P., Mehringer, D. M., & Menten, K. M. 2000, *ApJ*, 528, L37
Schilke, P. & Menten, K. M. 2003, *ApJ*, 583, 446
Vlemmings, W. H. T., Khouri, T., & Tafoya, D. 2021, *A&A*, 654, A18
Wong, K. T. 2019, in ALMA2019: Science Results and Cross-Facility Synergies, 55
Yates, J. A., Field, D., & Gray, M. D. 1997, *MNRAS*, 285, 303

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