The Origin of Outflows in Evolved Stars
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Detailing evolved star wind complexity: comparing maser and thermal imaging

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Abstract. Maser properties can be measured with milli-arcsec precision over multiple epochs using ALMA, cm- and mm-wave VLBI and e-MERLIN. This allows: (i) Tracing SiO maser proper motions in the pulsation-dominated zone; (ii) Quantifying clumpiness, variability and asymmetry of the wind traced by masers; (iii) Contrasting behaviour from OH masers even at similar distances from the star; (iv) Measuring magnetic fields. Mass lost from the star, traced by SiO masers, is likely to take decades to reach ∼5 stellar radii. At 5–50 stellar radii, once dust is well formed, 22-GHz H_2O masers show the wind accelerating through the escape velocity; its overall direction is away from the star but the velocity field is complex. In a few cases (so far), highly-directed, localised ejecta are seen. Magnetic fields appear to be stellar-centred and strong enough to influence wind kinematics. Recent ALMA and other observations have shown that otherwise inconspicuous companions shape a majority of evolved star winds, whilst advanced models demonstrate how, for some situations, this is compatible with masers showing negligible rotation proper motions. The long-term monitoring achievable at radio frequencies complements the multi-transition maser studies and analysis of thermal lines and dust at shorter wavelengths.

Keywords. stars: AGB, stars: supergiants, masers, stars: mass loss, winds, outflows

1. Introduction

ATOMIUM (ALMA Tracing the Origins of Molecules In dUst forMing winds, Gottlieb et al. 2021), is a Large Programme which observed 17 O-rich evolved stars (AGB and RSG) using 3 ALMA configurations with a spectral resolution ~ 1.2 km s^{-1} and angular resolutions down to ∼20 milli-arcsec (mas), comparable to the stellar diameters. The frequency range covers about half of the 214–270 GHz band, including transitions of the main accessible molecules involved in dust formation and tracers of the wind from the stellar surface to the interstellar medium. This enables investigation of links between chemical processes and dynamics in the wind and resolves the kinematics in detail. This showed that the winds have complex structures with acceleration continuing far beyond the dust formation zone (from a few to ∼10 $R_\star$, stellar radii). Moreover, all stellar winds showed different degrees of axisymmetry or asymmetry, in most cases almost certainly due to interactions with companions from planetary mass upwards (Decin et al. 2020). The aim of this paper is to demonstrate the role of masers in tracing the winds on even smaller scales and exploit years of monitoring data for some objects.

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†See Gottlieb et al. 2022 for list.

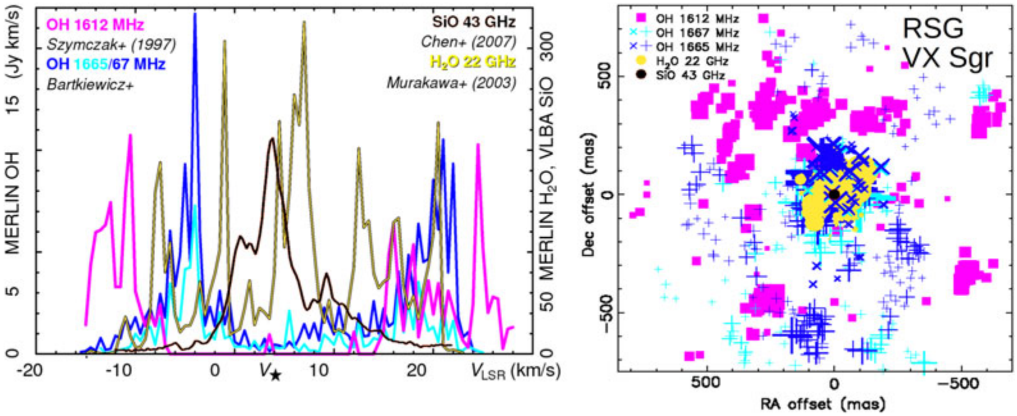

Figure 1. Velocity profiles and locations of common masers around red supergiant VX Sgr. The star is at $V_{\rm LSR}$ 5.3 km s^{-1}, position (0,0) (within the black circle of SiO masers).

The exponential nature of maser amplification means that line widths can be narrowed to a few tenths km s^{-1} and maser spot positions can be fitted with an accuracy of 1/10 of the synthesised beam or better – au scales at the distances of most of the ATOMIUM sample. Groups of spots trace clumps which share distinctive physical conditions. ATOMIUM masers are discussed in this Proceedings by Etoka et al. and others; this paper concentrates on complementary observations of masers at frequencies <50 GHz. Fig. 1 shows that masers located at increasing distances from the star extend to progressively higher expansion velocities, also approximately a decreasing order of excitation temperatures. The outermost (1612-MHz OH) masers have a twin-peaked profile characteristic of a fairly smoothly expanding shell at 50–100 $R_\star$. The innermost SiO masers have a central spectral peak characteristic of strong acceleration. The OH mainline and H_2O 22 GHz masers show intermediate behaviour; the 22-GHz masers are found in clumps where the pumping conditions require much higher densities and temperatures than the OH mainline masers emanating from the surrounding gas (Richards et al. 2012).

2. A slow start to the wind

Multi-epoch VLBA monitoring has been performed for 43-GHz SiO masers around a number of Northern sources; whilst R Cas is not in the ATOMIUM sample it is a typical M-type mira. Fig. 2 shows maser clumps have non-linear proper motions. Although the maximum line of sight velocity with respect to the star is ∼6 km s^{-1} this includes infall as well as outflow. The average net proper motion away from the star is 0.4±0.1 km s^{-1}, or up to ∼0.55 km s^{-1} allowing for projection effects. This suggests that the wind takes 45–70 yr to cross the SiO shell, out to 3.5 $R_\star$ (∼5 au), thus providing a long timescale for dust formation and other chemistry. Once dust forms, the wind expands at least 10× faster, covering ∼50 au in the next 50 yr (Assaf et al. 2018). The magnetic field strength measured from Zeeman splitting of masers shows that it could contribute to shaping the wind but not play the main rôle in launching mass loss (Assaf et al. 2013).

3. Arcs and spokes

U Her is a Mira variable at about 266 pc (Vlemmings et al. 2007), stellar velocity $V_\star$ −14.9 km s^{-1}, $R_\star$ 5.5 mas (Ragland et al. 2006). Its OH mainline masers at 1.6 GHz were imaged using the EVN in 1999 (4 epochs) and using e-MERLIN in 2014. Water masers at 22 GHz were imaged with MERLIN in 1994, 2000 and 2001 (Richards et al. 2012). The W side of the shell is brighter/elongated in many species (Fig. 3). The H_2O

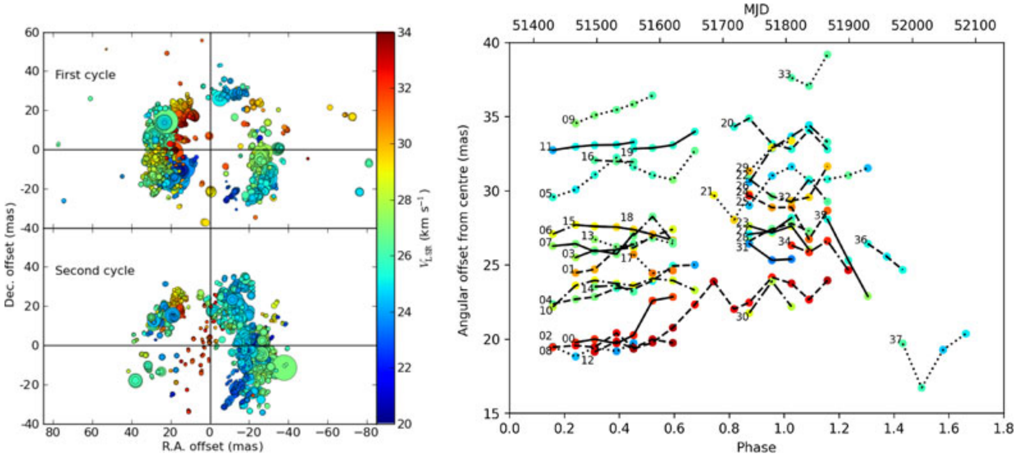

Figure 2. R Cas SiO masers observed 23 times over almost 2 stellar periods (∼2 years). Left: Maser components detected in each cycle. The stellar radius is 12.6 mas (Weigelt et al. 2000). Right: Proper motion trajectories (angular separation from the star v. date and phase) for clumps which can be matched over multiple epochs.

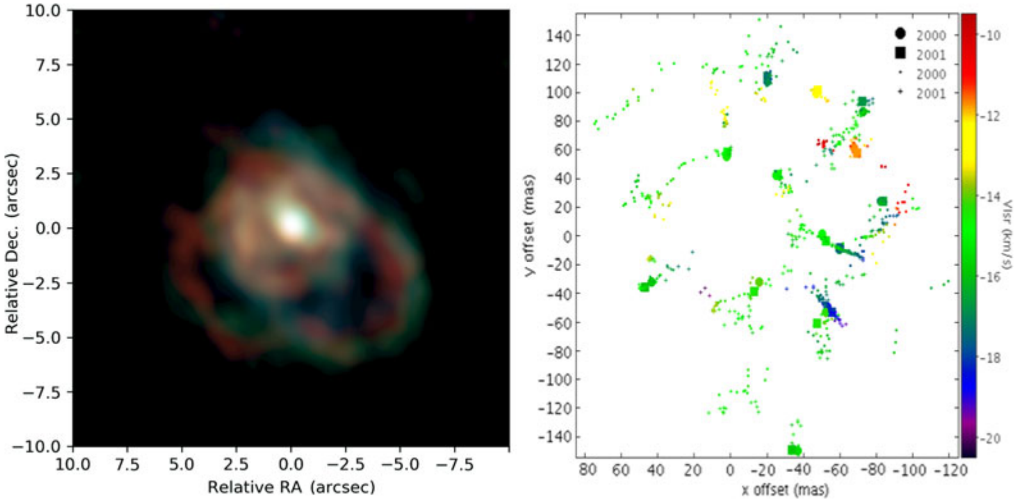

Figure 3. Left: Integrated CO emission from U Her (Decin et al. 2020). Right: The positions of 22 GHz H_2O masers observed in 2000 and/or 2001 (large/small symbols).

maser structure is similar at all epochs and proper motions show overall, accelerating expansion and exhibit radial ‘spokes’ at around (–50, –60) and (–60, –10) mas offset, –16 to –22 km s^{-1}. SiO spokes have been found to be aligned with the local magnetic field, e.g. studies of U Her by Cotton et al. (2010).

Fig. 4, right, shows an H_2O maser spoke in the SW (as seen in Fig 3), superimposed on thermal SiO emission at a similar velocity. The SiO spoke is seen in all the v=0 transitions in ATOMIUM: ^{28}SiO ^{29}SiO and ^{29}SiO J=5-4 and ^{28}SiO J=6-5. The angular separation between the H_2O maser and the SiO spoke is $\sim 0''.1$, which in the 24 yr between observations corresponds to about 5 km s^{-1} proper motion. This is realistic, allowing for projection effects, as the line of sight velocity with respect to $V_\star$ is –7 to –10 km s^{-1}.

Fig. 5 shows a (pale-shaded) OH maser clump further from the star in the same direction as the SW H_2O maser spoke but at a velocity closer to $V_\star$. Left-hand circular

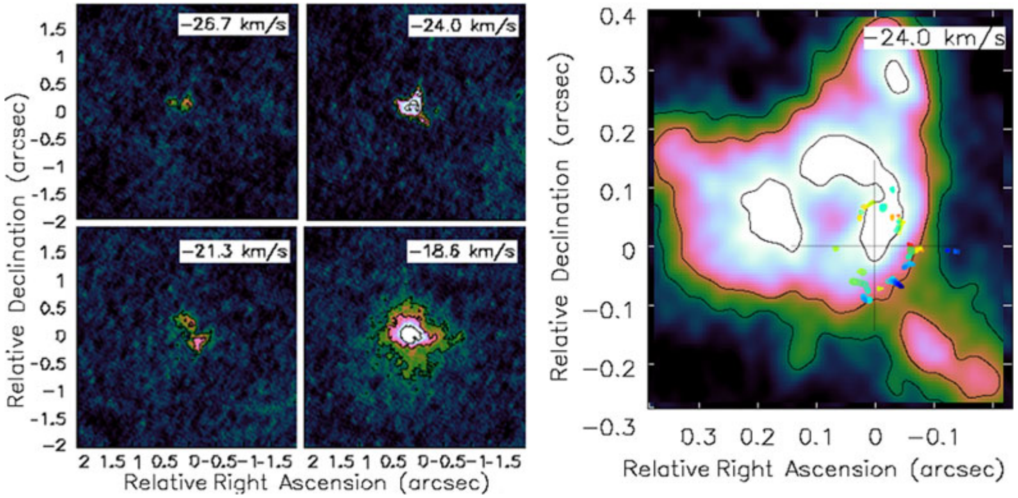

Figure 4. Left: U Her thermal ^{28}SiO J=5-4 v=0 emission, selected channels (ATOMIUM), observed in 2018. A spoke is seen at $V_{\rm LSR}$ $\sim$–24 km s^{-1}. Right: Zoom into the SiO spoke, overlaid with the positions of 22 GHz H_2O masers (see also Fig. 3), spoke components are darkest).

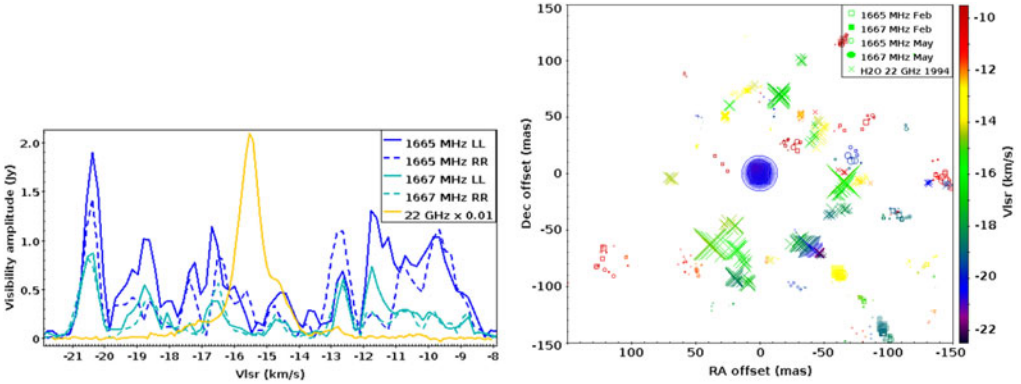

Figure 5. Left: U Her maser spectra. OH RR is only brighter than LL at $\sim$–12.7 km s^{-1}. Right: The –12.7 km s^{-1} feature corresponds to the pale-shaded clump around (–65, –90) mas offset. The centre of expansion, assumed to be the star (behind the most blue-shifted OH), is at (0, 0). Symbols sizes are proportional to flux density.

polarization (LL) is mostly brighter than right-hand circular (RR) (Zell & Fix 1996), implying a magnetic field directed towards the observer Cook (1977) but in the direction of expansion of the H_2O maser spoke the field appears to be reversed. A $\sim$1 G magnetic field was inferred from VLBA H_2O maser observations by Vlemmings et al. (2002) but was not detectable in later observations (Vlemmings et al. 2005). In the absence of absolute astrometry they located the magnetised feature close to the star but we suggest that it is identified with the 22 GHz clump at a similar velocity. A possible explanation is a directed, clumpy or episodic outflow, so that shock compression transiently enhances and distorts the local magnetic field, which may be frozen in to the clumps. OH 1612 MHz masers show unusual flares (Etoka et al. 1977).

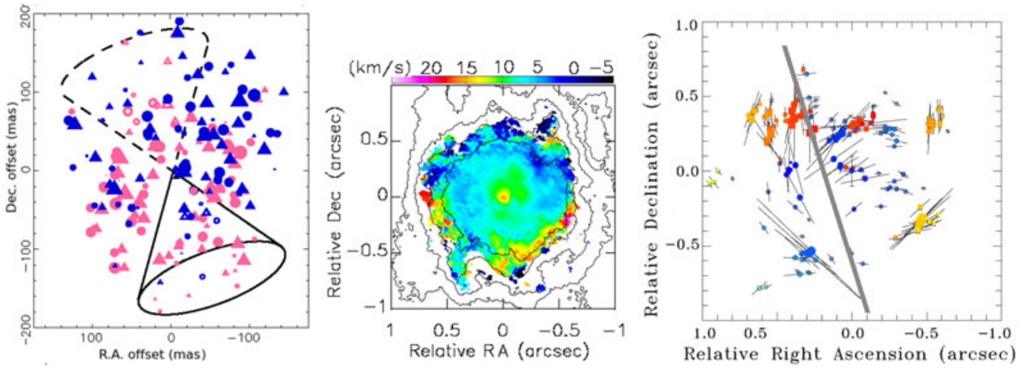

Figure 6. RSG VX Sgr. Left: 22-GHz H_2O maser positions (MERLIN), emission at velocities $<V_\star$ shown by darker (blue) symbols, $>V_\star$ lighter (pink). Masers inside the outlined bicone are weaker than those outside. Middle: Thermal SiO v=0 J=5-4 (ATOMIUM) velocity-weighted integral of emission >0.015 Jy overlaid on contours of total intensity $>3\sigma_{\rm rms}$. Right: OH 1612-MHz masers, symbol colour representing velocity as in middle panel; thin lines show polarization vectors and thick grey line is inferred magnetic dipole axis (Szymczak et al. 2001).

4. Bright 22-GHz water masers trace equatorial density enhancement

Multi-epoch 22 GHz H_2O maser studies of clump proper motions show accelerating expansion, between $\sim$5 to $\geqslant 20\ R_\star$. The 22-GHz masers often show higher expansion velocities than interleaving OH masers which appear to be at the same distance from the star, consistent with the momentum from radiation pressure on dust being transferred more efficiently in denser clumps. There is usually no systematic rotation seen in proper motions; even where the CSE shows an offset between blue- and red-shifted emission this appears to be due to the 22-GHz regions being more extended or brighter in some directions, likely to be an equatorial density enhancement. This is well-demonstrated by the RSG VX Sgr ($V_\star$ 5.7 km s^{-1}) which has 22-GHz H_2O maser proper motions showing that the only systematic flow is accelerating, radial expansion, but Fig. 6 left shows that the masers are brightest in a thick belt and weakest in a biconical region (Murakawa et al. 2003). This is what produces the apparent blue-shifted – red-shifted NE–SW offset as the emission from receding gas (with respect to $V_\star$) is weaker in the NE, whilst the emission from approaching gas is brighter in the SW. This is aligned within uncertainties with the axis of a stellar-centred magnetic dipole, as measured by Vlemmings et al. (2005, 2011) from H_2O and SiO masers, and from OH masers (Szymczak et al. 1999, 2001). Fig. 6 (middle) shows that in a selected velocity range, thermal SiO has a similar red-/blue-shifted offset but OH (right) has the opposite offset, possibly due to the less dense regions or a smaller velocity gradient within the cones favouring its pumping conditions.

5. Conclusions

Imaging masers at <50 GHz complements the ATOMIUM studies of CSE dust formation and dynamics. The slow and irregular progress of mass loss traced by SiO masers in the inner 5 $R_\star$ provides time for complex chemistry to develop. 22 GHz H_2O masers are concentrated in dense clumps between $\sim$5–$\geqslant 20\ R_\star$ where the wind attains escape velocity. In U Her there is an apparent correlation between H_2O maser spokes and thermal SiO clumps, which suggests that some mass is lost as localised ejecta. This has been reported in RSG e.g. VY CMa (Humphreys et al. 2021) but not well-studied previously in AGB stars. Zeeman splitting suggests that the magnetic field strength is not sufficient to drive mass loss but can shape the wind, e.g. the mild axisymmetry of VX Sgr.

Well-studied circumstellar SiO and 22-GHz H_2O masers are usually found in thick shells. These may be poorly filled but extreme-velocity emission is usually seen nearer to the direction of the star, than emission at close to $V_\star$, and long-term monitoring or comparison with other lines shows offsets in different directions, incompatible with systematic rotation. A few AGB stars have 22-GHz masers which do appear to be located in a rotating disc with a Keplerian velocity profile (Szczerba et al. 2006) but these are quite distinct. It is possible that studying the brightest 22 GHz masers selects those with more spherical shells, as strong companion interactions tend to disrupt the velocity coherence or other maser pumping conditions, as modelled for OH by Howe & Rawlings (1994). U Her and VX Sgr are the only ATOMIUM stars with multi-epoch, high-resolution 22 GHz maser imaging although the majority have single-dish detections. We are investigating the morphology and kinematics of 22-GHz masers around other ATOMIUM stars in a programme of single-dish monitoring of the objects at Declination $\geqslant -28°$ using the Medicina and Pushchino radio telescopes, to be followed up by e-MERLIN imaging.

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