PROCEEDINGS OF SCIENCE

Stellar Evolution Studies Using Masers

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Masers probe a number of stages of stellar evolution including star-formation, asymptotic giant branch stars, pre-planetary nebulae, red supergiants and supernova remnants. High-angular resolution studies using VLBI are revealing information on the accretion process in high-mass stars, the mass-loss process of AGB stars and on the role of magnetic fields. In addition, large projects observing masers associated with star-formation and evolved stars are mapping out galactic structure and probing galactic dynamics. Here, I outline recent results for masers in the area of stellar evolution highlighting the contributions of VLBI and EVN observations, and the synergies of these with data from other telescopes such as ALMA.

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1. Introduction: Masers

Masers (Microwave Amplification by Stimulated Emission of Radiation) i.e., microwave lasers, result from population inversions in non-Local Thermodynamic Equilibrium (non-LTE) conditions. Seed radiation at the corresponding frequency can then stimulate emission and cause exponential amplification through a gas cloud [see e.g., Figure 1 in 1, 2]. Masers are found in a variety of regions including evolved stars, star-formation, active galactic nuclei, supernova remnants, comets and planetary atmospheres. A variety of species can give rise to maser emission including SiO, H_2O, OH, CH_3OH, HCN, SiS, NH_3, H_2CO (formaldehyde) and H recombination masers.

Maser uses include: (i) determination of gas physical conditions; (ii) tracing gas kinematics; (iii) magnetic field estimation via the Zeeman effect; (iv) distances, for example using trigonometric parallax. Accurate stellar line-of-sight velocities can also be measured in the case of SiO masers in evolved stars. Several large projects make use of these aspects of masers including KaVA[1] ESTEMA [3], BeSSEL [4] and the BaADE project [5].

At high-angular resolution, e.g., milli-arcsecond scales, maser emission appears to originate from individual maser clouds/cloudlets. Taking as an example water masers in evolved stars, maser emission from multiple transitions/frequencies can originate from the same cloud in radiative transfer modelling, for example at 22, 183, 321 and 325 GHz [e.g., 6]. Individual cloud(let)s have velocity-flux density line profiles in which the full-width half-maximum (FWHM) is governed by multiple factors, but which could be around the thermal line-width (1.5 km s^{-1} for 22 GHz water maser emission in evolved star conditions). As for the size of the cloud(let)s, MERLIN was used to measure the size of 22 GHz water maser clouds in evolved stars. For asymptotic giant branch (AGB) stars the cloud(let) sizes were in the range 0.5–2 AU and for red supergiants (RSG) in the range 5–10 AU [7]. Note that in some high-angular resolution observations, e.g., for VLBI observations of SiO masers in evolved stars, there is significant maser flux resolved out [8].

Maser observations tend to have the following characteristics: (i) masers at different frequencies are often observed towards the same target e.g., SiO masers from the v=1 J=1-0 (43 GHz), 2-1 (86 GHz), 3-2 (129 GHz), 4-3 (172 GHz) and more; (ii) single-dish spectra are usually blended emission from multiple maser cloud(let)s and can display narrow spectral features; (iii) variability.

2. Masers in Star-Formation

Masers can occur in both low-mass and high-mass star formation, however their incidence is higher in high-mass star formation due to the higher luminosities and more energetic outflows involved [9]. Generally the masers trace hot, dense molecular gas associated with accretion disks, jets and shocks. The most commonly-found masers in star-formation are CH_3OH, OH and H_2O. Rarer masers in this context include SiO, H_2CO and NH_3. In addition to the work described below, recent papers from the EVN [10, 11], VLBA [12], VERA & ALMA [13], MERLIN [14, 15] and modelling [16] are noted. Maser polarization in star-forming regions is reviewed by [17].

[1]A combined array of the KVN (Korean VLBI Array) and VERA (VLBI Exploration of Radio Astrometry). Other arrays/telescopes mentioned in this article include the European VLBI Network (EVN), the Very Long Baseline Array (VLBA), the Atacama Large Millimeter/Submillimeter Array (ALMA), the Multi-Element Linked Radio Interferometer Network (MERLIN), the Hartebeesthoek Radio Observatory (HartRAO), the Very Large Telescope Interferometer (VLTI), the Very Large Array (VLA) and the Square Kilometre Array (SKA).

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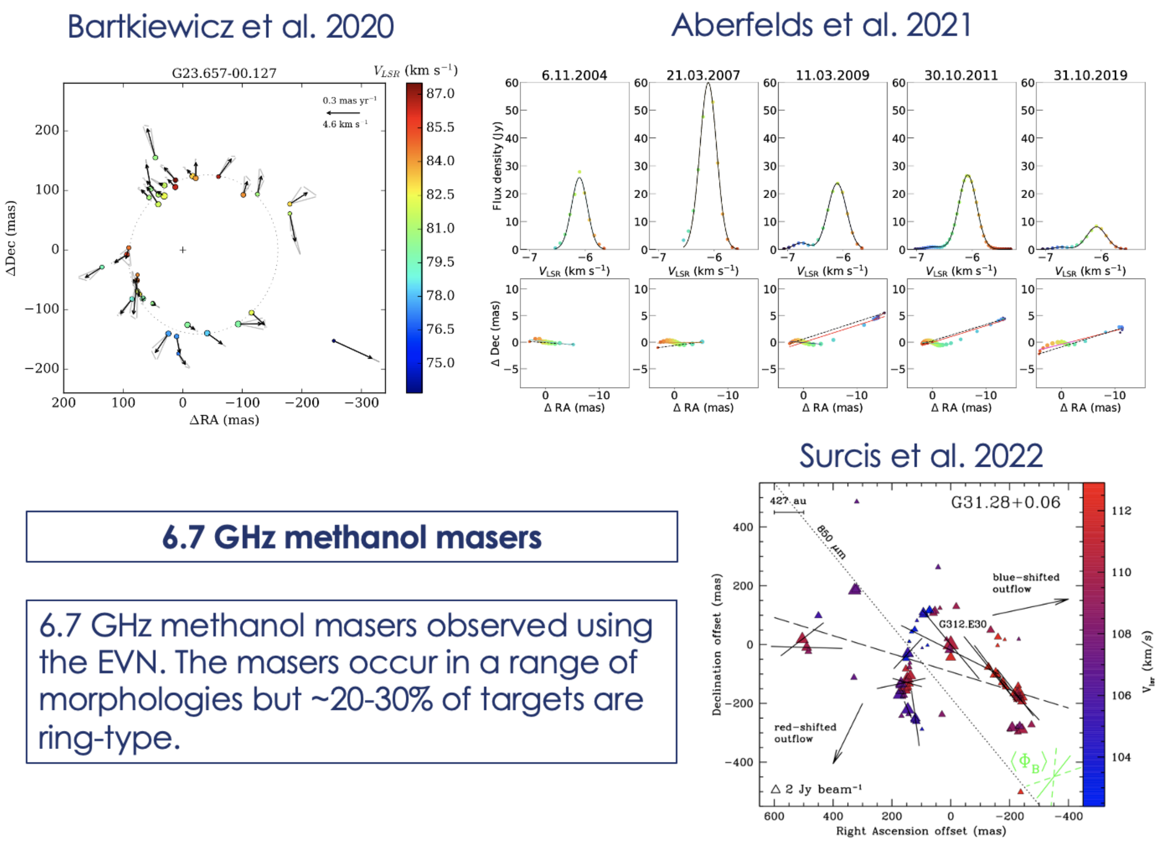

Figure 1: EVN observations of 6.7 GHz methanol maser targets. After [18–20].

2.1 6.7 GHz Methanol Masers

Taking as a case study 6.7 GHz methanol masers, these are uniquely found in high-mass young stellar objects (HMYSOs). The size of the maser cloud(let)s has been measured to be ∼10 AU and they occur within 1000 AU of the HMYSOs. The EVN has been critical to their study e.g., [18–23] (Figure 1).

6.7 GHz methanol masers occur in a range of morphologies, but an interesting morphological sub-set is the ring-type targets. In the case of G23.657-00.127, a 3-epoch EVN study during ∼10 years established that the maser ring was mainly in radial expansion, with a mean velocity of ∼3 km s^{-1} [18]. The observations narrowed down the possible scenarios for this target to the masers either tracing a sphere-like outflow with an almost edge-on disk or tracing a wide-angle wind at the base of a protostellar jet.

A minority of 6.7 GHz methanol masers can also display periodic variability. Twenty-six such targets are currently known with periods in the range 24 – 670 days, however the usual range is between 100 – 300 days. Using the Torun 32 m, two new periodically-varying targets have recently been discovered [24]. Synchronicity of infrared variation and methanol flares in some sources is evidence for pumping mechanism modulation being a leading cause, perhaps linked to accretion

[25, 26]. Note that there is also discovery of anti-correlation between 22 GHz H_2O and CH_3OH flaring towards G107.298+5.639 [26]. See also [27].

2.2 Masers Tracing Accretion Bursts

Single-dish monitoring of NGC 6334I using HartRAO revealed that maser lines from OH, CH_3OH and H_2O underwent a dramatic increase in flux density in 2015 that persisted at least until 2018 [28]. These maser flares, in lines that are radiatively pumped, can be directly associated with bursts of accretion onto the central protostar [9]. Note that the 22 GHz H_2O maser, although generally considered to be collisionally-pumped, also has a radiatively-pumped regime [29]. The Maser Monitoring Organisation (M2O) was formed to perform single-dish monitoring and trigger interferometry observations during flaring events, see https://www.masermonitoring.com.

2.3 Maser Superbursts

There are three regions that are currently known to give rise to maser superbursts i.e., dramatic increases in maser flux density by several orders of magnitude not associated with accretion. These are Orion KL, W49N and G25.65+1.05. In the case of a 2017 superburst in G25.65+1.05, EVN, KaVA and VLBA observations established that the superburst was localised to a sub-milliarcsecond region of the target [30]. The cause is attributed to superposition of maser clouds in the line-of-sight to the observer, creating an increased maser amplification path length.

2.4 Higher-Frequency Masers

Masers in the mm/submm wavelength regime are also being used to study star-formation. Orion Source I was previously studied using SiO and H_2O masers, mainly at 43 and 22 GHz [31–33]. However, water masers at 232, 321, 474 and 658 GHz have now been detected towards Source I using ALMA [34–37]. Other star-forming regions are known to display strong mm/submm water masers, such as W49N [38].

3. Masers in AGB Stars and Red Supergiants

Imaged AGB and RSG stellar surfaces can have inhomogeneous flux density distributions in e.g., ALMA and VLTI observations [40, 41]. This is in line with the models of Höfner and Freytag in which the surface is covered in convective cells [42, 43] and is discussed further in [44].

3.1 Oxygen-rich Stars

In oxygen-rich evolved stars, SiO masers can form in tangentially-amplifying rings about the stars within 5 R_* in the inner circumstellar envelope (CSE) and have been extensively studied at 43 GHz, and somewhat at 86 and 129 GHz, using VLBI [e.g., 45–50]. The masers amplify predominantly along tangential, rather than radial, directions due to the lower velocity gradients (i.e., higher "velocity coherence") along the tangential paths in the inner circumstellar envelope. Proper motion studies reveal outflow, infall and complex non-radial motions [51, 52]. Higher-frequency SiO masers are common in evolved stars [e.g., 53–55]. Polarization of SiO masers has been studied in multiple publications [e.g., 56], see later for a discussion of derived magnetic field estimates.

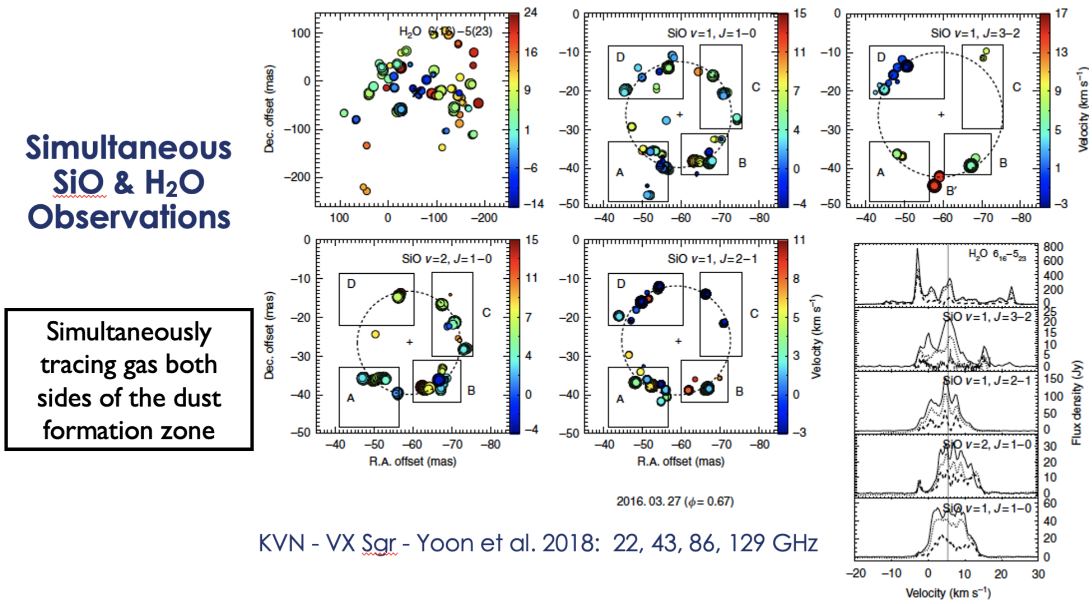

Figure 2: KVN observations of circumstellar SiO and H_2O masers towards VX Sgr. After [39] .

Rapid variability of the masers is detected [57]. SiO maser results from the BaADE project VLA and ALMA study of 28,000 targets include e.g., [58–60].

Further out in the CSE[2], water masers at 22 GHz are shown to probe the wind acceleration zone in MERLIN observations. The 22-GHz emission occurs in approximately spherical, thick shells where the outflow velocity is found to increase by a factor of 2 or more between the inner and outer shell radii [7]. The fact that it is now possible to perform simultaneous VLBI observations of SiO and H_2O masers at 22 GHz with 43/86/129 GHz is likely to be important for constraining gas conditions either side of the dust formation zone in evolved stars [39, 61] (Figure 2). For water masers at mm/submm wavelengths, ALMA has been used to image water maser emission at 321, 325 and 658 GHz towards VY CMa [62]. Single-dish studies have also been performed [e.g., 53, 63–65, and references therein]. In general these higher frequency masers appear common but more spatially-resolved observations are needed to understand their locations in the CSE.

For main line OH masers at 1665 and 1667 MHz[3], VLBI astrometric observations of circumstellar OH masers can yield the proper motions and parallaxes of AGB stars [66]. The most blue-shifted circumstellar OH maser spot can be the amplified stellar image. Adding in the SKA to VLBI networks means that very many objects within a few kpc would be accessible for this type of work [67]. Note that for OH 1665 MHz maser flaring towards binary system Mira AB, however, the location of the strongest flaring was much closer to Mira A than the typical OH maser zone, more similar to the water maser zone [68]. For OH 1612 MHz masers, these occur at $\sim$1000 R_* and they can be used to provide distances via the phase lag method [69].

[2]Very approximate radii for the location of the water maser emission at 22 GHz is somewhere in range 5 to 50 R_*.

[3]Located somewhere in the range $\sim$100 - 1000 R_*, however there is a caveat that they can also be at the same distance as 22 GHz H_2O masers.

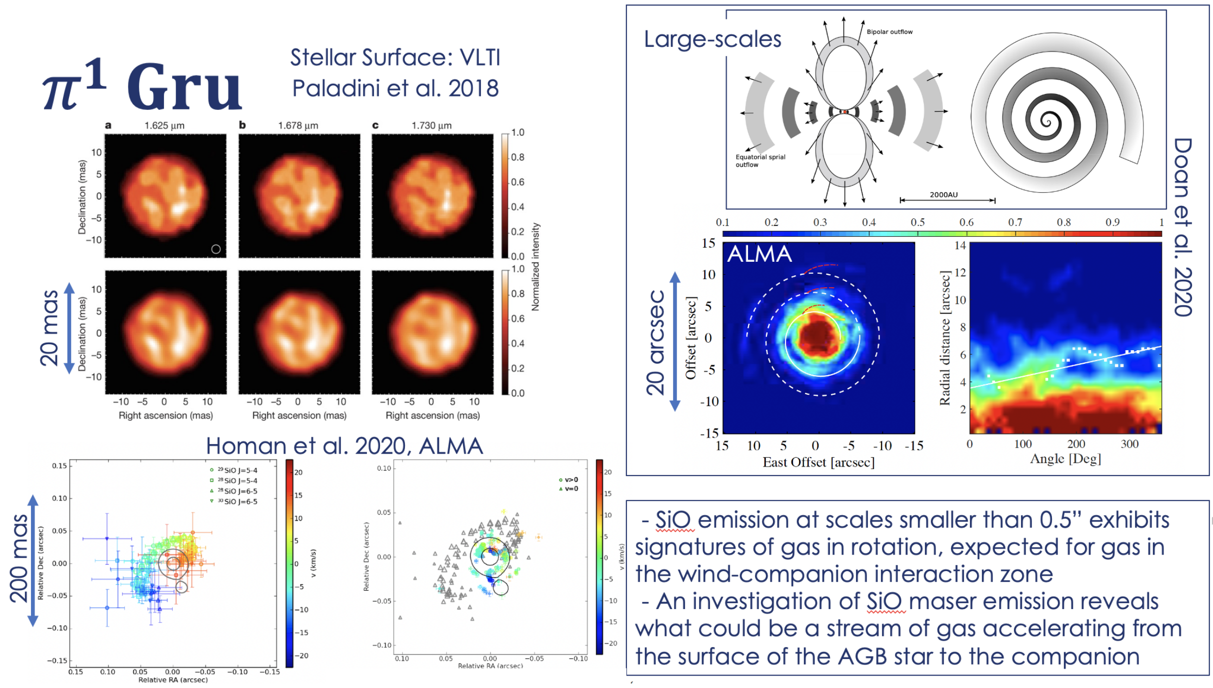

Figure 3: Binary π^1 Gruis at multiple scales using VLTI and ALMA. SiO maser emission could be tracing gas accelerating from the AGB star to the companion. After [73–75].

Note that, towards many evolved stars SiO, H_2O and OH maser emission is observed towards the same target, such that information on the CSE at different radii can be obtained. Circumstellar masers have also been detected towards the Magellanic Clouds [70].

3.2 Carbon-rich Stars

Towards carbon-rich stars, HCN masers are widespread [71] and SiS masers have been detected [72].

4. Masers and the Shaping Process of AGB Winds

A matter of debate has been what is the shaping process of AGB stars, thought to be broadly spherically-symmetric, to Planetary Nebulae that can display complex aspherical morphologies. The major questions have been (i) how this happens - is it due to binarity or magnetic fields; and, (ii) when it happens, is the shaping initiated on the AGB or only in the post-AGB phase?

ALMA CO observations have been instrumental in finding "hidden" companions to AGB stars [76–78] in which arcs and spirals were detected. From these observations it was known, for example, that high mass loss rate targets displayed spiral morphologies and low mass loss rate targets displayed disk structures [78]. ALMA was also used to study known binaries with different characteristics [79–81], seeing similar features in CO. The ALMA Large Program ATOMIUM (ALMA Tracing the Origins of Molecules In dUst-forming oxygen-rich M-type stars) [82] observed a sample of fourteen stars in CO and other molecules, finding that:

• The evolution of a spherical wind from an AGB star into an aspherical Planetary Nebula could be due to binary interactions.
• The same physics shapes both AGB winds and Planetary Nebulae.
• Target morphology and mass-loss rate are correlated, with an evolutionary scenario proposed.

One of the targets of ATOMIUM, π^1 Gruis (a known binary) now has an interesting set of imaging data built up for it (Figure 3). Using VLTI, the stellar surface at 1.6 μm (diameter ~10 milli-arcseconds) was found to have evidence for convective cells [73]. Using ALMA, SiO thermal emission at scales smaller than ~100 milli-arcseconds exhibits signatures of gas in rotation, expected for gas in the wind-companion interaction zone. This appears to link up with a CO spiral observed on larger scales [75]. Also, it appears that SiO maser emission could be tracing a stream of gas accelerating from the surface of the AGB star to the companion [74].

The role of magnetic fields in the shaping process to Planetary Nebulae remains under debate. Both optical spectro-polarimetry and SiO masers indicate there can be Gauss-level magnetic fields close to the stellar surface [83, 84], which would be dynamically significant. Magnetic field estimates using circumstellar masers at different radii in the CSE indicate toroidal or solar-type magnetic fields [84].

5. Masers in Pre-planetary and Planetary Nebulae

Fifteen post-AGB stars/pre-Planetary Nebulae show highly-collimated water maser jets. These "water fountains" [85] could be progenitors of bi-polar Planetary Nebulae. W43A shows magnetic collimation of the jet [86]. Recent ALMA observations of CO isotopologues towards the water fountain targets suggest that they are undergoing common envelope evolution [87] i.e., tight binaries surrounded by a common envelope [88]. As such, there is likely to be heightened interest in these types of sources and other maser tracers could be useful. SiO masers are now known towards at least two of the water fountains [89, 90]. Submillimetre water maser emission has also been detected [91]. Other pre-Planetary Nebulae can also display maser emission, for example OH231.8+4.2 [92, 93]. In addition, maser emission (H_2O and/or OH) is known towards at least eight Planetary Nebulae. Planetary Nebulae that host maser emission are believed to be at a very young stage [94].

6. Conclusions

High-angular resolution observations of masers are making critical contributions to the understanding of stellar evolution e.g., EVN observations of 6.7 GHz methanol masers in high-mass star formation; VLBI and VLA maser observations, in conjunction with single-dish monitoring observations, constraining accretion bursts and maser superbursts; large maser programs such as BeSSeL, BAaDE and ESTEMA probing stellar evolution and galactic structure/dynamics; and, VLBI maser and ALMA observations yielding new information on the shaping process to Planetary Nebulae. With the advent of the SKA, it will also be possible to extend the search for stellar masers to local group galaxies [95]. Overall this is a very active field of research, such that it was not possible to perform a comprehensive description of all recent stellar evolution studies using masers, but rather to highlight some of the different aspects under current study.

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