Astro2020 Science White Paper

Molecular Masers as Probes of the Dynamic Atmospheres of Dying Stars

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☒ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

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Executive Summary: More than half of the dust and heavy element enrichment in galaxies originates from the winds and outflows of evolved, low-to-intermediate mass stars on the asymptotic giant branch (AGB). However, numerous details of the physics of late-stage stellar mass loss remain poorly understood, ranging from the wind launching mechanism(s) to the geometry and timescales of the mass loss. One of the major challenges to understanding AGB winds is that the AGB evolutionary phase is characterized by the interplay between highly complex and dynamic processes, including radial pulsations, shocks, magnetic fields, opacity changes due to dust and molecule formation, and large-scale convective flows. Collectively, these phenomena lead to changes in the observed stellar properties on timescales of days to years. Probing the complex atmospheric physics of AGB stars therefore demands exquisite spatial resolution, coupled with temporal monitoring over both short and long timescales. Observations of the molecular maser lines that arise in the winds and outflows of AGB stars using very long baseline interferometry (VLBI) offer one of the most powerful tools available to measure the atmospheric dynamics, physical conditions, and magnetic fields with ultra-high spatial resolution (i.e., tens of μs, corresponding to $\sim 0.002R_\star$ at $d \approx$150 pc), coupled with the ability to track features and phenomena on timescales of days to years. Observational advances in the coming decade will enable contemporaneous observations of an unprecedented number of maser transitions spanning centimeter to submillimeter wavelengths. In evolved stars, observations of masers within the winds and outflows are poised to provide groundbreaking new insights into the atmospheric physics and mass-loss process.

Related White Papers: L. D. Matthews et al., Unlocking the Secrets of Late-Stage Stellar Evolution and Mass Loss through Radio Wavelength Imaging

1 Context

For low-to-intermediate mass stars ($0.8 \lesssim M_* \lesssim 8\ M_\odot$), the end stages of stellar evolution are marked by the onset of a range of complex and dynamic atmospheric phenomena. During the asymptotic giant branch (AGB) phase, such stars exhibit dramatic increases in radius ($R_\star \gtrsim$1–2 AU) and luminosity ($L_\star \sim 10^4 L_\odot$) and begin undergoing radial pulsations with periods of order hundreds of days. Over the course of single pulsation cycle the brightness of the star may vary by up to $\sim$ 8 magnitudes (a factor of 1000) in the visible. The latter variations are attributed to the time-dependent formation of metallic oxides in the outer atmosphere (Reid & Goldston 2002).

Another key hallmark of the AGB phase is the onset of periods of intense mass loss ($\dot{M} \sim 10^{-8}$–$10^{-4}\ M_\odot$ yr^{-1}) through cool, dense, low-velocity winds ($V_{\rm out}$ $\sim$10 km s^{-1}). These outflows ultimately expel up to 80% of the star's initial mass (see review by Höfner & Olofsson 2018), leading to profound effects on the stellar evolutionary track. Because AGB winds are dusty and enriched in heavy elements, AGB mass loss also produces more than half of the dust and chemical enrichment in the Galaxy, (Schröder & Sedlmayr 2001; Van Eck et al. 2001; Karakas 2014).

A detailed understanding of AGB mass loss is crucial for stellar astrophysics and knowledge of the ultimate fate of our Sun. But more broadly, AGB stars impact the entire Galactic ecosystem, and prescriptions for the mass loss and dust and heavy element production are crucial for extragalactic astronomy and cosmology, which make use of stellar population synthesis (e.g., Salaris et al. 2014), interpretations of the integrated starlight from galaxies (e.g., Melnick & De Propris 2013), and prescriptions of gas recycling and chemical evolution in galaxies (e.g., Tosi 2007; Leitner & Kravtsov 2011). However, we still lack a comprehensive and self-consistent picture of evolution and mass loss along the AGB. Persistent uncertainties include the wind launching mechanisms for stars of different chemistries, the mass-loss geometry and timescales, and the evolutionary pathways for stars of various initial masses (Marengo 2009; Höfner & Olofsson 2018).

In broad terms, AGB winds are thought to be dust-driven (e.g., Kwok 1975): dust formation occurs in the cool, outer atmosphere ($r > 2R_\star$) and radiation pressure on these grains transfers momentum outward to the gas, leading to mass loss. However, in warmer and/or oxygen-rich (M-type) stars, conditions are too hot for dust formation interior to r $\sim$6–7 AU. Thus some additional mechanism is required to transport material from the stellar "surface" to the wind launch region (Woitke 2006; Höfner 2011). Pulsations are suspected of playing a critical role in this process (Bowen 1988; Yoon & Cantiello 2010; Neilson 2014), but the details are still poorly understood. Magnetic fields, acoustic waves, and/or Alfvén waves are also candidates for shaping and regulating mass loss (e.g., Blackman et al. 2001; Harper 2010), possibly in conjunction with large-scale convective processes (e.g., Lim et al. 1998; O'Gorman et al. 2017). However, the intricate interplay between these various processes is still poorly constrained. Significant progress in this field will require empirical constraints that combine: (1) the ability to *spatially resolve* the stellar atmosphere on the relevant physical scales ($\ll R_\star$); (2) *temporal resolution* of the characteristic dynamical timescales; and (3) the ability to *directly measure gas motions*.

Fortuitously, the molecule-rich atmospheres of evolved giants frequently give rise to *molecular masers* that can be exploited for this purpose (e.g., Gray 2012). Though stellar masers were discovered $\sim$50 years ago (Wilson & Barrett 1968; Snyder & Buhl 1974), technological advances, coupled with advances in maser theory (Gray et al. 2016) and the modeling of AGB star atmospheres (Freytag et al. 2017; Höfner & Freytag 2019), are poised to allow masers to supply tremendous new insights into the physics of evolved stars and stellar mass loss in the coming decade.

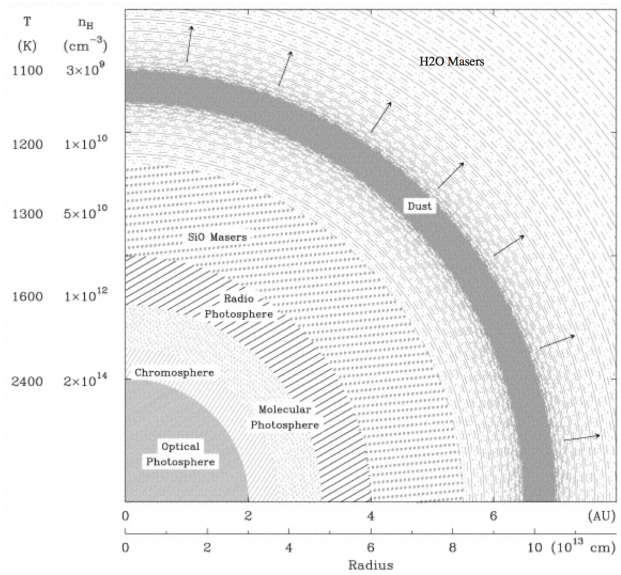

Figure 1: Schematic illustrating the various atmospheric layers of an M-type AGB star. SiO maser emission arises near the radio photosphere, just interior to the dust formation zone where the stellar wind is launched. H_2O masers arise just outside the dust formation zone. Adapted from Reid & Menten (1997).

2 Molecular Masers in Evolved Stellar Atmospheres: Background and Recent Results

In oxygen-rich (M-type) AGB stars, maser emission from SiO arises within a few $R_\star$, just outside the radio photosphere ($r \sim 2R_\star$), and adjacent to the dust formation zone and molecular layers (Reid & Menten 1997; Fig. 1). The properties of the SiO masers are therefore intricately linked with the atmospheric regions where stellar mass loss originates (Humphreys 2002; Gray et al. 2009). In carbon-rich AGB stars, HCN masers are thought to trace similar regions (Gray 2012; Izumiura et al. 1995; Menten et al. 2018). H_2O masers, in comparison, typically arise just outside the dust formation zone at $r \sim 10$–100 AU.

Because of their high brightness temperatures ($\gtrsim 10^6$ K), masers can be observed with ultra-high spatial resolution using very long baseline interferometry (VLBI). In recent years, VLBI observations with the Very Long Baseline Array (VLBA) of stellar SiO and H_2O masers with angular resolutions of $\sim$0.2–0.5 mas have established the enormous potential of high-resolution studies of masers for understanding the complex atmospheric physics and mass loss of AGB stars. Examples of key results to date include:

Spatial structure Observations with the VLBA have revealed that SiO masers lie in complex ring-like structures centered on the host star, lying just outside the hot molecular layer observable at IR wavelengths ($r \sim$2–4$R_\star$; e.g., Diamond et al. 1994; Cotton et al. 2004, 2006; Wittkowski et al. 2007; Amiri et al. 2012; Fig. 2). Intriguing jet-like features are seen in some cases (Cotton et al. 2006; Amiri et al. 2012), although their origin has remained a puzzle, as they cannot be interpreted as simple outward accelerations. Temporal monitoring and proper motions measurements are needed to establish the true nature of these features.

Variability SiO and H_2O masers in evolved stars are highly time variable (e.g., Pardo et al. 2004; Kim et al. 2014). The availability of the VLBA as a *dedicated* VLBI instrument has thus

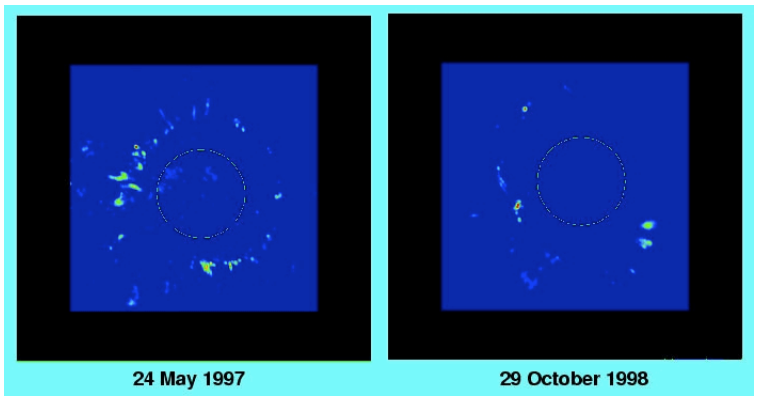

Figure 2: VLBA images of the λ7 mm SiO v=1, J=1-0 masers in TX Cam during two different epochs. Credit: P. J. Diamond and A. J. Kemball (see also Diamond & Kemball 2003; Gonidakis et al. 2013).

been crucial for enabling the regular monitoring of stellar masers with high spatial resolution. One spectacular example is the 78-epoch "movie" of the SiO masers in TX Cam over nearly 5 years (Gonidakis et al. 2013; Fig. 2). These data indicate that a shock with velocity $\sim$7 km s^{-1} is created during each stellar pulsation cycle that in turn affects the intensity and distribution of the masers. Further, the velocity structure suggests a bipolar geometry, contrary to the spherically symmetric outflows that are traditionally assumed for AGB stars (see Höfner & Olofsson 2018). However, as we presently lack similar time-lapse data for other AGB stars, it is impossible to draw general conclusions, and firm links between different components of the atmospheric physics (shocks, pulsation, convection) and the observed maser behaviors are not yet established. Variability studies over a large number of objects are needed to establish the connections between the AGB atmosphere and the mass loss process.

Magnetic fields Full polarization measurements of SiO masers offer a powerful means of constraining the little-understood role of magnetic fields in AGB mass loss (e.g., Vlemmings 2018) and provide a vital link between the "surface" magnetic field measured through infrared lines (Lèbre et al. 2014) with "circumstellar" magnetic fields measured further out via H_2O and OH lines. Using the VLBA, Amiri et al. (2012) obtained full-polarization maps of the SiO masers in the OH/IR AGB star OH 44.8-2.3 and discovered that they are significantly linear polarized ($\sim$100%), underscoring an important role for magnetic fields in the outer atmosphere and circumstellar environment (Fig. 3). The polarization vectors also seem to indicate a dipolar magnetic field morphology, although the relationship between the B-field geometry and the stellar outflow cannot yet be firmly established. An improved understanding of these results requires higher signal-to-noise ratio observations, along with similarly detailed studies for other AGB stars.

Multi-transition observations Multiple transitions and isotopologues of SiO and H_2O emit in the cm, mm, and sub-mm (Alcolea 2004; Humphreys 2007; Gray 2012). Because these various transitions require different conditions to excite, spatially resolved observations of multiple maser lines within a single star permit measurements of density and temperature within different regions of the atmosphere, the propagation of shocks, and the transfer of material between layers of the star (e.g., Humphreys et al. 2002; Gray et al. 2009, 2016). In particular, *contemporaneous* observations of multiple lines and comparisons of their properties and evolution with those of the optical and radio photospheres offer potent diagnostics of the atmospheric physics. However, several key

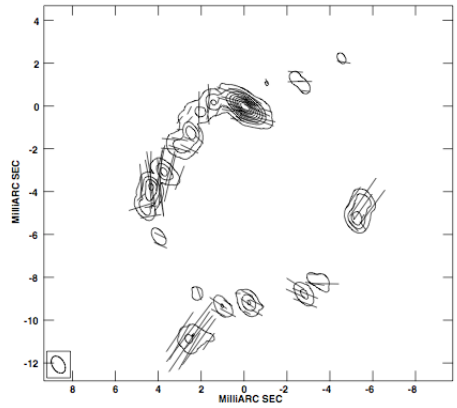

Figure 3: Contour map of the SiO v=1, J=1-0 maser emission in the OH/IR star OH 44.8-2.3 obtained with the VLBA, overplotted with linear polarization vectors. Vector length is proportional to linearly polarized intensity (1 mas = 1.25 Jy beam^{-1}) and position angle corresponds to the EVPA. From Amiri et al. (2012).

lines emit outside the frequency coverage of the VLBA (i.e., ν_0 >90 GHz) or else fall below its brightness temperature limits for line emission [e.g., $T_B \sim 10^8$ K within a 31 kHz spectral channel ($\sim$0.2 km s^{-1} for ν=43 GHz) during a 6-hour integration].

Recently, a novel optics system was installed on the Korean VLBI Network (KVN), enabling simultaneous observations of four bands spanning 21–142 GHz (Han et al. 2008). The promise of this set-up for observing stellar masers has already been demonstrated (Cho et al. 2017; Yoon et al. 2018). However, the KVN lacks the long baselines needed to resolve the true sizes of maser emitting gas clumps and to gauge the fraction of emission emitted on various spatial scales. The longer baselines of the VLBA have the needed resolution, but the limited instantaneous bandwidth largely precludes the contemporaneous observations of multiple lines. A consequence is persistent ambiguity in the astrometric registration between different transitions that significantly complicate the interpretation of maser data (e.g., Phillips et al. 2003; Desmurs et al. 2014; Issaoun et al. 2017; Fig. 4).

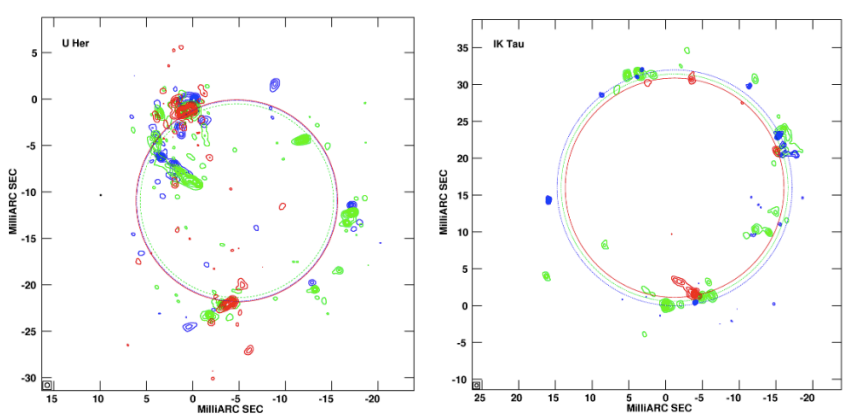

Figure 4: VLBA maps of SiO v = 1 (blue), v=2 (green), and v=3 (red), J=1−0 maser emission in U Her and IK Tau (Desmurs et al. 2014). The relative astrometry of the different lines is currently highly uncertain, limiting our ability to quantitatively constrain models of the maser pumping and atmospheric physics.

3 Goals for the Next Decade: Requirements and Recommendations

Technological innovations during the next decade promise major leaps in our ability to exploit VLBI studies of masers as a tool for understanding stellar evolution and mass loss.

Goal: documenting temporal changes AGB star atmospheres are highly dynamic, making inferences gleaned from observations at only a single observing epoch severely limiting—and potentially misleading. The use of VLBI to obtain high time- and spatial-resolution "movies" of masers in a sample of nearby ($d \lesssim$1 kpc) AGB stars spanning a range in properties would supply vital insights into the physics of AGB outflows. For example, such observations would enable the measurement of shock velocities (e.g., Gonidakis et al. 2013) which are critical to constraining the role of pulsation in AGB mass loss (Reid & Menten 1997; Gray et al. 2009) and for explaining the possible existence of gas at chromospheric temperatures (e.g., Luttermoser 1988; Vlemmings et al. 2017). Such measurements can be compared with independent assessments gleaned from the variability of radio photosphere light curves (see Reid & Menten 1997; Reid & Goldston 2002). Full polarization observations would simultaneously enable constraints on the magnetic field strength and geometry (e.g., Amiri et al. 2012).
Requirements/recommendations: To enable full polarization monitoring of masers over both short and long cadences, it is crucial for the US community to maintain a dedicated VLBI array with improved sensitivity. No other VLBI facility in the world has this capability in combination with the $\sim 10^4$ km baselines needed to provide the angular resolution to fully resolve the structure and motions of individual maser clumps in stellar atmospheres.

Goal: multi-frequency line mapping Building a complete understanding of the physical conditions, chemistry, and gas motions within the atmospheres and envelopes of AGB stars benefits from the ability to detect and simultaneously observe a wide range of maser transitions, including relatively weak ($T_B \sim 10^4$ K) and little explored lines such as SiO v=0 (Bolboltz & Claussen 2004); ^{29}SiO v=0,1, ^{28}SiO v=2, J=2$-$1, ^{28}SiO v=3 (Soria-Ruiz et al. 2005, Desmurs et al. 2014), and HCN (unique to carbon stars; e.g., Izumiura et al. 1995; Menten et al. 2018).
Requirements/recommendations: Enabling contemporaneous VLBI measurements of multiple maser lines requires upgrading VLBA stations to wider instantaneous bandwidths ($\gtrsim$8 GHz) and expanded frequency coverage (to $\nu \gtrsim$100 GHz). While wider bandwidths do not increase spectral line sensitivity, they improve measurements by expanding the available high-frequency calibration sources. Parallel improvements in line sensitivity can be achieved through: (1) inclusion in VLBI arrays additional large apertures such as phased ALMA ($0.8 \lesssim \lambda \lesssim 7$ mm; Matthews et al. 2018), the phased VLA ($0.7 \lesssim \lambda \lesssim 1.3$ cm), and the Robert C. Byrd Green Bank Telescope ($0.3 \lesssim \lambda \lesssim 1.3$ cm); and (2) the addition of many stations on intermediate baselines ($\sim$30-300 km) to bridge the spatial scales and brightness temperature sensitivity of current VLBI arrays and connected element interferometers (see Kameno et al. 2013; Selina et al. 2018). A continuum brightness temperature sensitivity of $< 10^3$ K on the intermediate baselines would enable simultaneous detection and astrometric registration of the stellar continuum and the maser emission with exquisite precision ($\ll R_\star$), providing valuable new insights into the transport of matter and energy in AGB star atmospheres and into the pumping mechanism for masers (e.g., Gray et al. 2009, 2016; Desmurs et al. 2014).

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