Astro2020 Science White Paper

Unlocking the Secrets of Late-Stage Stellar Evolution and Mass Loss through Radio Wavelength Imaging

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: During the late phases of evolution, low-to-intermediate mass stars like our Sun undergo periods of extensive mass loss, returning up to 80% of their initial mass to the interstellar medium. This mass loss profoundly affects the stellar evolutionary history, and the resulting circumstellar ejecta are a primary source of dust and heavy element enrichment in the Galaxy. However, many details concerning the physics of late-stage stellar mass loss remain poorly understood, including the wind launching mechanism(s), the mass loss geometry and timescales, and the mass loss histories of stars of various initial masses. These uncertainties have implications not only for stellar astrophysics, but for fields ranging from star formation to extragalactic astronomy and cosmology. Observations at centimeter, millimeter, and submillimeter wavelengths that resolve the radio surfaces and extended atmospheres of evolved stars in space, time, and frequency are poised to provide groundbreaking new insights into these questions in the coming decade.

Related White Papers:
L. D. Matthews et al., “Molecular Masers as Probes of the Dynamic Atmospheres of Dying Stars”
S. Ridgway et al., “Precision Analysis of Evolved Stars”
R. Roettenbacher et al., “High Angular Resolution Stellar Astrophysics: Resolving Stellar Surface Features”

1 Background

Evolution onto the asymptotic giant branch (AGB) marks the final thermonuclear burning phase in the lives of stars of low-to-intermediate mass ($0.8 \lesssim M_* \lesssim 8\ M_\odot$). Hallmarks of the AGB stage include a dramatic increase in the stellar luminosity (to $\sim 10^4 L_\odot$), radial pulsations with periods of order hundreds of days, and periods of intense mass loss ($\dot{M} \sim 10^{-8}$–$10^{-4}\ M_\odot$ yr^{-1}) through dense, low-velocity winds ($V_{\rm out} \sim 10$ km s^{-1}). These winds expel up to 80% of the star's initial mass (see review by Höfner & Olofsson 2018) and consequently have a profound effect on the stellar evolutionary track. Because AGB winds are dusty and enriched in heavy elements, AGB mass loss also serves as primary source of dust and chemical enrichment in the Galaxy (Schröder & Sedlmayr 2001; Karakas 2014 and references therein).

We presently lack a comprehensive and self-consistent picture of evolution and mass loss along the AGB (Marengo 2009; Höfner & Olofsson 2018). Indeed, multiple aspects of the physics of late-stage stellar evolution remain poorly understood, including the wind launching mechanism, the mass-loss geometry and timescales, and the evolutionary pathways for stars of various initial masses. A detailed understanding of these issues is crucial for stellar astrophysics and knowledge of the ultimate fate of our Sun, but also for fields including extragalactic astronomy and cosmology, which make use of stellar population synthesis (e.g., Salaris et al. 2014) and prescriptions of gas recycling and chemical evolution in galaxies (e.g., Tosi 2007; Leitner & Kravtsov 2011), which in turn rely critically on the accuracy of stellar evolutionary tracks and their predictions for mass loss and dust and heavy element formation in AGB stars.

Dust has long been thought to be a crucial ingredient for powering the winds of AGB stars (Kwok 1975). When grains form in the cool outer atmospheres ($r > 2R_*$), they can be accelerated by radiation pressure, transferring momentum outward to the gas and leading to mass loss. However, in warmer AGB stars, conditions are too hot for dust formation interior to several $R_\star$ ($r \sim$6–7 AU). Thus some additional mechanism(s) is required to transport material from the stellar "surface" to the wind launch region (Woitke 2006; Höfner 2011). Pulsations are also expected to play a critical role in the mass-loss process (Bowen 1988; Yoon & Cantiello 2010; Neilson 2014). For example, models suggest that the levitation of material through pulsationally-induced shock waves can act as a facilitator for dust formation in oxygen-rich (M-type) AGB stars, leading to more efficient mass loss (Höfner & Andersen 2007; Freytag & Höfner 2008; Bladh & Höfner 2012). The details of how pulsation and mass loss are linked, however, remain poorly constrained. 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), but the interplay between these various processes is still not well understood.

Crucial to resolving these questions are detailed model predictions that can be confronted with measurements that directly probe AGB star atmospheres on sub-$R_\star$ scales. Modeling of AGB star atmospheres is extraordinarily challenging owing to their complex physics and non-LTE conditions. However, 3D models that incorporate the effects pulsation, convection, shocks, and dust condensation are finally becoming possible (Freytag et al. 2017; Höfner & Freytag 2019), supplying detailed predictions that can be directly compared with observations. For example, these models predict that the interplay between shocks, pulsation, and convective cells of various sizes will produce stellar surfaces very different in appearance from the small convective cells seen on the Sun (Fig 1). They also predict highly irregular stellar "surfaces" and non-spherical shapes that

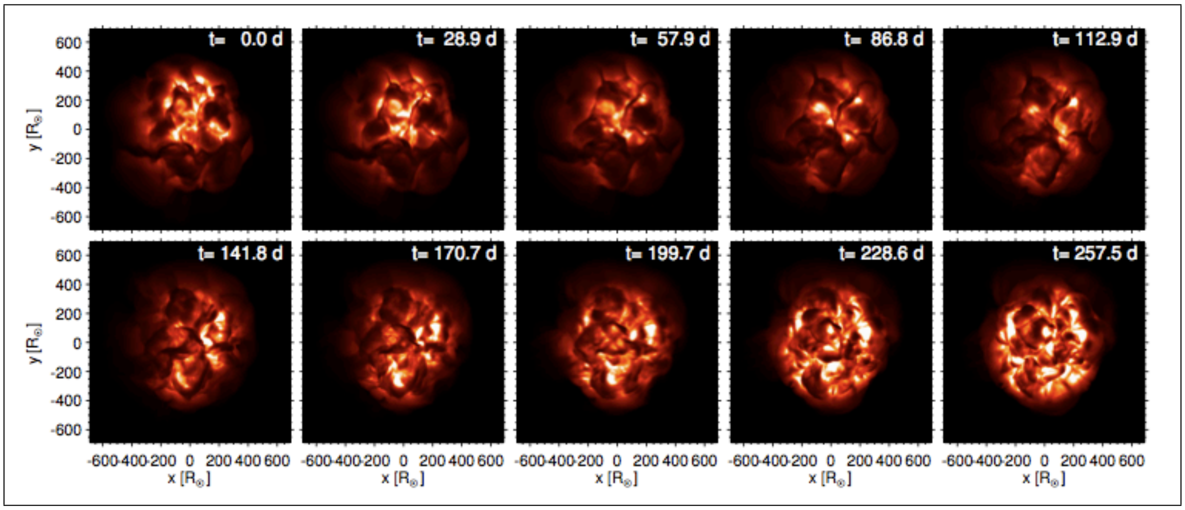

Figure 1: Monthly time sequence of bolometric intensity from a model of a $1 M_{\odot}$ AGB star over the course of a single stellar pulsation cycle. Changes in the appearance of the stellar size, shape, and surface features are apparent from month to month. From Freytag et al. (2017).

perceptively evolve over timescales ranging from days to years. *Empirically testing the exquisitely detailed predictions of these new models will demand new types of ultra high-resolution measurements of diverse samples of AGB stars.*

2 Resolved Imaging of Evolved Giants: Recent Progress

Observational studies aimed at probing AGB mass loss have traditionally targeted tracers of the extended circumstellar ejecta such as infrared (IR) emission from dust or thermal radio lines (e.g., CO), which sample material $\sim$ 10–10^5 AU from the star (see reviews by Castro-Carrizo 2007; Stencel 2009; Höfner & Olofsson 2018). Historically, such observations have provided invaluable constraints on mass-loss rates and wind speeds for large samples of AGB stars (e.g., Young et al. 1993; De Beck et al. 2010). However, addressing many of the outstanding puzzles related to the launch and geometry of AGB winds and their relationship to stellar pulsations, shocks, convection, and other dynamic phenomena requires observations that sample within a few stellar radii (r <10 AU)—and that *spatially, temporally, and spectrophotometrically resolve* the stellar photosphere and its surrounding molecular layers and dust formation zone.

At optical/IR wavelengths, advances in techniques and instrumentation have recently made great strides toward this goal, leading to observations of nearby evolved giants that in some cases reveal surface features (e.g., Paladini et al. 2018), and even gas motions (e.g., Ohnaka & Morales Marín 2018). The potential for exciting growth in this area is discussed in Astro2020 White Papers by Roettenbacher et al. and Ridgway et al. However, the changes in temperature, density, and chemistry that occur as a function of radius in the atmosphere of an AGB star imply that a complete picture cannot be obtained from optical/IR observations alone. Indeed, probing the crucial atmospheric regions in AGB stars within a few stellar radii (roughly from the optical photosphere to the chromosphere)—where the dust is formed and the wind is accelerated and launched—is cru-

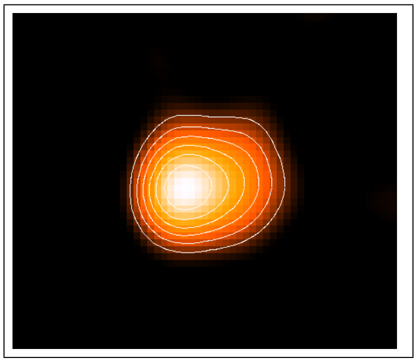

Figure 2: Resolved image of the radio photosphere of the nearby AGB star R Leo (d ≈95 pc) at λ7 mm, obtained with the VLA (Matthews et al. 2018). The star appears non-spherical, with evidence for a non-uniform surface. The peak flux density is ∼4 mJy beam^{-1}. This image was produced using a "sparse model" reconstruction algorithm, enabling super-resolution of the ∼38 mas dirty beam by a factor of ∼0.75. Nonetheless, the stellar surface remains only marginally resolved with current VLA baselines.

cial for a comprehensive understanding of the atmospheric physics and the origin of mass loss in these stars. It is in this region that high-resolution observations at cm, mm, and sub-mm (hereafter "radio") wavelengths provide unique and fundamental information.

As first described by Reid & Menten (1997), AGB stars emit optically thick continuum radiation from a "radio photosphere" lying at $\sim 2R_\star$ (∼4 AU in a typical M-type AGB star). Its emission has a spectral index α ≈2, and the characteristic density and temperature at optical depth unity are $\sim 10^{12}$ cm^{-3} and ≈ 1600 K, respectively. The radio photosphere arises near the outskirts of the so-called molecular layer or "MOLsphere" (Tsuji 2000, 2001), just interior to the dust-formation zone where the wind is believed to be launched (Kwok 1975; Höfner 2015). Observations of radio photospheres consequently sample a crucial region of the AGB star atmosphere where pulsation, convection, shocks, and other key processes responsible for the transport of material from the stellar surface to the outflowing wind will be manifested.

The longest baselines of the Karl M. Jansky Very Large Array (VLA) and the Atacama Large Millimeter/submillimeter Array (ALMA) currently provide angular resolutions of tens of mas, enabling resolution of a handful of the nearest AGB stars ($d \lesssim$150 pc) at $\lambda \lesssim$1 cm. Such observations allow measurements of fundamental stellar parameters including radius, brightness temperature (T_B) and bolometric luminosity (Reid & Menten 1997, 2007; Menten et al. 2012). Recently, such observations have also led to tantalizing evidence for non-uniformities on the radio surfaces of some stars, as well as evolution in the photospheric shapes over time, most likely as a result of pulsation and/or convective phenomena (Matthews et al. 2015, 2018; Vlemmings et al. 2017; Fig. 2). However, not only are current samples severely limited, but even the nearest AGB stars are only crudely resolved, and temporal coverage for resolved objects has been limited to one or two epochs (see Matthews et al. 2018). Furthermore, systematic uncertainties presently preclude measuring predicted subtle changes in radius ($\lesssim$15%) and brightness temperature ($\lesssim$±500 K) during the stellar pulsation cycle.

Recently Vlemmings et al. (2017) analyzed ALMA λ0.8 mm observations of the AGB star W Hya and found evidence for a hot spot consistent with gas at chromospheric temperatures (T_B >53,000 K). Such hot gas cannot be readily explained by current models and potentially has

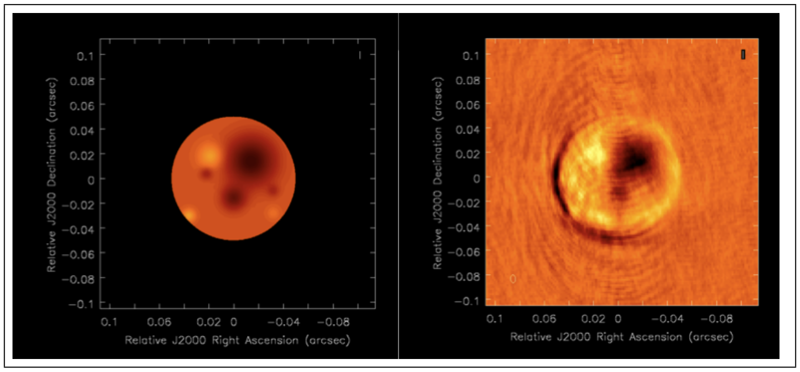

Figure 3: *Left:* Model of the red supergiant Betelgeuse at 38 GHz; *right:* CLEAN image from a simulated 4-hour observation with a Next Generation VLA, after subtraction of a smooth disk model from the visibilities (Carilli et al. 2018). The beam is 6.5mas×4.0mas, the rms noise is 0.25μJy beam^{-1}, and the peak brightness is 8.8μJy beam^{-1}. Imaging with even higher fidelity and resolution will become possible using a new generation of image reconstruction algorithms (cf. Fig. 2 and Section 3).

significant implications for our understanding of the role of shock heating in AGB atmospheres (e.g., Reid & Goldston 2002). However current T_B measurements are subject to large systematic uncertainties and cannot be well constrained at lower frequencies because of insufficient spatial resolution. Compounding these difficulties is the inadequacy of traditional radio imaging techniques such as CLEAN to make high-fidelity images of complex, spatially extended sources such as stellar photospheres (Matthews et al. 2015, 2018; Fish et al. 2016; Carilli et al. 2018; Fig. 3).

3 Goals for the Next Decade

Addressing the many questions outlined above will require a suite of new high-resolution, multi-wavelength imaging observations of evolved stars, coupled with innovations in imaging methods. We recommend the following areas as priorities for the coming decade:

The spatial dimension: resolving a statistical sample of AGB stars Increasing current VLA and ALMA baselines by a factor of 10 would provide angular resolution of $\sim$26 mas at 8 GHz and $\sim$1 mas at 345 GHz, permitting resolution of the photospheric surfaces of AGB stars to distances beyond a kpc, and expanding current sample sizes by several orders of magnitude. This would make it possible for the first time to image the surfaces of stars over a representative range of temperature, chemistry, and mass-loss rate.

The frequency dimension: radio tomography The frequency dependency of the radio (free-free) opacity in radio photospheres implies that shorter radio wavelengths probe successively deeper layers in the atmosphere (Reid & Menten 1997). In principle, this enables spatially resolved measurements of radio photospheres to be used for stellar "tomography" (see Harper 2018) and quantifying the run of temperature with depth. Until now, this has been possible only in a few cases (Lim et al. 1998; Matthews et al. 2015; O'Gorman et al. 2015). Interferometric arrays with baselines of up 300 km would make it possible to resolve radio photospheres of nearby AGB stars ($d \lesssim$150 pc) over nearly two decades in frequency, enabling tomography of dozens of the best-known AGB stars.

The time dimension AGB stars are highly time-variable (e.g., Fig. 1), making inferences gleaned by observations at only a single observing epoch inherently limited and potentially misleading. The links between these variations and different components of the atmospheric physics (shocks, pulsation, convection) remain poorly understood, and intra- and inter-pulsation cycle variations have not been explored using data that resolve the stellar photosphere.

Improvements in radio image reconstruction methods Innovative new imaging approaches including sparse model imaging (e.g., Honma et al. 2014; Akiyama et al. 2017a, b; Fig. 2) and maximum entropy methods (e.g., Fish et al. 2014; Chael et al. 2016) have been shown to be able to super-resolve features $\sim$3–4 times smaller than the nominal diffraction limit and hold considerable promise for advancing high-fidelity radio imaging of stellar surfaces (see Matthews et al. 2018).

Probing gas motions The cool temperatures and rich chemistry of AGB stars give rise to rotational transitions from a multitude of molecules at cm through sub-mm wavelengths (e.g., Turner & Ziurys 1988; Menten 2000). When observed with high resolution, many of these lines provide valuable diagnostic information within the warm (T <1000 K) inner envelopes of AGB stars, including physical conditions (temperature, density), chemistry (e.g., determinations of elemental depletion with radius; Menten 2000), and kinematics (including infall and outflow motion; Wong et al. 2016; Vlemmings et al. 2017, 2018; Kervella et al. 2018; Fonfría et al. 2019). Ultra-wide bandwidth continuum studies will enable simultaneous measurements of these lines and allow building a more complete picture of the complex processes that lead to AGB winds and mass loss.

4 Summary of Requirements and Recommendations

Achieving the goal of unlocking the secrets of late-stage stellar evolution and mass loss will require access to radio interferometers with continuous frequency coverage from $\sim$10–400 GHz on sufficiently long baselines ($\sim$30–300 km) to resolve a statistically significant sample of evolved stars ($d \lesssim$1 kpc). Such baselines will bridge the intermediate spatial scales between current connected element interferometers and very long baseline interferometric (VLBI) arrays (Kameno et al. 2013; Selina et al. 2018).

Enabling efficient, high-quality radio imaging of the complex surfaces of cool giant surfaces will require arrays with excellent instantaneous u-v coverage, coupled with ultra-wide instantaneous bandwidths ($\Delta\nu$ $\sim$20 GHz) to ensure high signal-to-noise ratio detections on the longest baselines within modest integration times (e.g., T_B rms $<$ 10 K in 1 hour, assuming FWHM$\sim$10 mas). Interpretation of stellar imaging data will also require investment in the development of advanced radio imaging methods capable of achieving high-fidelity, high dynamic range images of complex and time-variable sources.

The time-variable nature of evolved stars implies that the operations model for next-generation radio arrays must accommodate repeat observations of targets over weeks to months, and allow for monitoring programs that span several years or more. Such arrays must also preserve the flexibility to permit detailed follow-up on targets found to be of special interest or importance.

Ultra-wide bands will enable the simultaneous observation of numerous spectral lines in evolved stars whose study will help to elucidate the complex physics, chemistry, and kinematics in the atmospheres of these stars. However, the radio frequency interference (RFI) environment is expected to grow increasingly hostile in the coming decade (Liszt 2018). Investments in strategies to minimize RFI impacts will therefore be critical.

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