The Origin of Outflows in Evolved Stars
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The onset of mass loss in evolved stars

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Abstract. To look at propagating winds from evolved stars into the interstellar medium is to look at how they are sustained. To understand their origins, we must look to the circumstances that create them in the first instance. In this article, I examine the physical conditions under which pulsation-enhanced, dust-driven winds are first generated. These initial conditions can help constrain the late evolutionary stages of these stars and provide insight into the mechanisms that cause the mass loss itself.

Keywords. stars: AGB and post-AGB, circumstellar matter, stars: fundamental parameters, stars: late-type, stars: mass loss, stars: Population II, stars: winds, outflows, stars: variables: other, globular clusters: general

1. Introduction

The pulsation-enhanced, dust-driven wind of thermally pulsating asymptotic giant branch (TP-AGB) stars is the last in a series of mechanisms by which low- and intermediate-mass ($0.6 \lesssim M \lesssim 8$ M$_\odot$) stars lose mass (e.g., S. Höfner, this proceedings). It replaces chromospheric mass loss, the dominant wind-driving mechanism on the red giant branch (RGB) and early AGB (e.g., Dupree, Hartmann & Avrett 1984). This transition co-incides with several points in stellar evolution: the increase in mass-loss rate it provides generally leads to the mass-loss rate exceeding the nuclear-burning rate; while strong surface pulsations begin at a similar time as the much longer (and unrelated) thermonuclear pulsations of the helium shell and the associated (third) dredge-up of nuclear-processed material to the stellar surface (e.g., Pastorelli et al. 2020). Decorrelating and disentangling cause and effect in these mechanisms and their observational tracers can therefore be difficult, and must be done over a wide range of stellar environments.

2. RGB mass loss

To understand mass loss on the TP-AGB, we need to first understand the chromospheric mass loss that precedes it. It is generally thought that magneto-acoustic waves propagate to a stellar chromosphere, where their energy disperses and drives a warm (∼5000–10 000 K), fast (∼10–100 km s^{-1}) wind from the star (Dupree, Smith & Strader 2009; Cranmer & Saar 2011; Rau et al. 2018). It is normally parameterised using some form of Reimers (1975) law, $\dot{M} = 4 \times 10^{-13}\, \eta LR/M$, for mass M, luminosity L and radius R in solar units, with a normalisation constant η.

Calibrating this law is difficult, because it is hard to measure the mass-loss rates of individual RGB stars. Chromospheric estimates are difficult and have significant uncertainty in their modelling. Instead, estimates of η are based on integrated mass loss, normally

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from a point on the RGB to either the horizontal branch or the early AGB. The RGB-integrated value of η has been well-constrained at $\eta \approx 0.4 - 0.5$ in globular clusters, both directly by McDonald, Johnson & Zijlstra (2011), and indirectly by McDonald & Zijlstra (2015) and, recently, by Tailo et al. (2020 and this proceedings). The latter performs the most self-consistent analysis, though defines a metallicity dependence on η (predicting $\eta \approx 0.7$ for solar metallicity). This conflicts with observations of solar-metallicity open clusters, which suggest $\eta \ll 0.3$ (Miglio et al. (2012); Handberg et al. (2017)). Consequently Tailo et al.'s may not be the most effective description of RGB mass loss in general, but remains our best description for Population II stars at this time. An alternative parameterisation,

$$\dot{M} \sim 5 \times 10^{-20}\ \mathrm{M_\odot\ yr^{-1}}\ \frac{L^{10/3} R^{1/2}}{M^{5/2}}, \tag{2.1}$$

fits the observed data reasonably well, including the open-cluster data. The stronger mass scaling is the only viable method of creating a low η in Galactic open clusters, while retaining high η in globular clusters, particularly the metal-rich clusters that have the lowest initial masses. The stronger luminosity scaling is required to compensate for the differences in RGB-tip luminosity at different metallicities. However, both Tailo's and the above parameterisations are empirical fits to integrated data. What are really needed are direct measurements of RGB mass-loss rates, and a re-examination of Reimers' original law. Since any RGB mass-loss law predicts mass-loss rates should be highest (therefore easiest to measure) near the RGB tip, we must concentrate our measurements of mass-loss rate near the RGB tip, and on early-AGB stars at similar luminosities. However, the prediction of the above law of a rapid rise in $\dot{M}$ with luminosity is potentially important if it can be proven: notably this parameterisation still gives the canonical $\dot{M} \sim 10^{-7}$ $\mathrm{M_\odot}$ $\mathrm{yr^{-1}}$ near the RGB tip.

3. The onset of AGB mass loss

The transition to a pulsation-enhanced, dust-driven wind requires several factors: pulsations to lift material from the stellar surface; a cool, dense environment in which dust can form close to the star; and sufficient radiation pressure on that dust that it can be ejected from the system.

This onset of late-AGB mass loss can be traced in two ways: by searching for mid-infrared excess, which traces the circumstellar dust, and is effective out to distances of a few Mpc; or (more accurately) by tracing molecular outflows through sub-mm rotational lines of CO, which (for low-$\dot{M}$ stars) is only effective within a few hundred pc. To sample a range of environments with confidence, both methods are needed.

One of the striking features defining the onset of AGB mass loss is its strong correlation with pulsation period, whereby stars attaining a period of ∼60 days appear suddenly eligible to produce dust. This is seen in Milky Way field stars (McDonald & Zijlstra 2016), in the Magellanic Clouds (Boyer et al. 2015) and in globular clusters (e.g., Boyer et al. 2009; McDonald et al. 2009 & McDonald et al. 2011). Not all stars begin losing mass at a period of ∼60 days: only low-mass stars do, such as those in globular clusters. The root significance of the 60-day period is that it traces a transition between pulsation sequences B and C', where the long secondary period (LSP) sequence is first initiated, and the strength of the shorter, primary-period pulsations grow significantly (McDonald & Trabucchi 2019). It can be concluded from this strong dependence on pulsation amplitude that the conditions required for dust formation and ejection already exist in such stars, and they wait only for the pulsations to become strong enough for them to initiate the wind. This in turn implies that the chromosphere may have been essentially disrupted (or otherwise negligible) by this point, perhaps by the pulsations

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and consequent increase in scale itself, in order that a cool environment exists close to the star. To examine these hypotheses, we can look to stars of different metallicity, and those below the 60-day transition.

The onset of mass loss in metal-poor stars proceeds in much the same way: stars begin to produce copious dust once they transition across the $B \rightarrow C'$ sequence boundary. Curiously, the aforementioned globular cluster studies plot these stars in the same places in the period–infrared-excess diagram as their metal-rich counterparts. That is, there is the same dust opacity around metal-poor stars as metal-rich stars, despite the lack of dust-producing elements. Strong dust production by oxygen-rich, metal-poor stars is also seen in metal-poor dwarf galaxies (e.g., Boyer et al. 2015 & Boyer et al. 2017) where its onset also appears to correlate with the onset of strong pulsation (McDonald et al. 2014). Few measurements of wind velocities and CO-based mass-loss rates exist for marginally dust-producing, metal-poor stars: those few suggest the dust opacity remains the same partly because the wind is slower (e.g., McDonald et al. 2019 & McDonald et al. 2020). Infrared spectra also show the presence of a different dust species in metal-poor stars, showing only continuum emission, which is posited to be metallic iron (McDonald et al. 2010, 2011). Few measurements exist also at higher metallicities due to lack of sources, but the little evidence we have suggests mass loss is no more effective here (van Loon, Boyer & McDonald 2008). The lack of metallicity response to the onset of strong dust production adds evidence that the ability to condense and drive dust are not limiting factors for generating AGB winds, but that it is the rate at which material is supplied to the dust-condensation zone by pulsations that largely controls the mass-loss rate.

Stars with pulsation periods near the 60-day boundary are another poorly observed class. This is partly because they tend to lie at luminosities close to or below the RGB tip, beyond the observational cutoff of most AGB-star studies, and in a region where RGB and AGB stars cannot normally be cleanly separated. Existing observations come from Groenewegen (2014) (VY Leo), McDonald et al. (2016) (EU Del) and McDonald et al. (2018) (several stars). These observations show that low mass-loss rates† ($\dot{M} \sim 10^{-9}$ to 10^{-8} M$_{\odot}$ yr^{-1}) can be traced from these stars via molecular CO. Interestingly, VY Leo is one of the original stars studied by Reimers (1973), where it was assigned a mass-loss rate from chromospheric indicators (Ca II H&K and Hα) of $\dot{M} = 10^{-7.15}$ M$_{\odot}$ yr^{-1}. Whether this rate survives modern scrutiny remains unclear, as it has not been remeasured.

Dust production by RGB stars is a controversial topic (e.g., Boyer et al. 2010, McDonald et al. 2011), partly because it is impossible to cleanly separate RGB from early-AGB stars in most cases. However, statistical indications are generally that RGB stars do not produce dust, while some AGB stars at the same luminosity do (McDonald & Zijlstra 2016). Consequently, it is an open debate about whether the dust-producing stars near the RGB tip are true RGB stars or the less-numerous early-AGB stars with similar surface properties. The strong mass scaling in the previous section gives rise to the possibility that the mass difference between the lowest-mass RGB and AGB stars could play an important role in generating a dusty wind from AGB but not RGB stars. However, the small-amplitude (SARG) pulsations from RGB-tip stars (e.g., Takayama, Saio & Ita 2013) may speculatively either lead to some enhancement of the wind, or assist in disrupting the chromospheric mass loss.

† We have recently been made aware of an error in McDonald et al. (2018), where R$_{\odot}$ was assumed as the unit of R_* in the scaling law of De Beck et al. 2010, where the appropriate unit was cm. This affects the mass-loss rates that were derived.

4. Discussion

We can therefore paint an evolutionary picture where the mass loss from RGB stars rises sharply towards the RGB tip, being strongest for the lowest-mass stars, and perhaps enhanced by the small-amplitude pulsations that occur there for such stars. That mass loss effectively ceases when the star transitions to the horizontal branch (or blue loop for more-massive stars), but begins to rise again as the star ascends the AGB. When the star becomes unstable to strong long-period pulsations, during the sequence $B \to C'$ crossing when the long-secondary period initiates, a pulsation-enhanced, dust-driven wind can begin in earnest. As the star exits onto the fundamental sequence (C), the pulsations become stronger, and the wind builds in strength until the entire envelope is ejected. While this paints a largely coherent picture of mass loss from low- and intermediate-mass stars, it is based on only a small amount of data.

Obtaining more data on stars undergoing this transition is crucial if we want to chart how, when and why stars initiate their final, dusty winds. This is one of the primary goals of the Nearby Evolved Stars Survey (NESS; Scicluna et al. 2022). The survey is designed as a volume-limited survey, tiered in mass-loss rate and distance. The lower tiers target low-mass-loss-rate, nearby stars, including many of those undergoing this transitionary phase. The results of this survey can be compared with higher-resolution surveys of smaller numbers of more-evolved objects (e.g., DEATHSTAR; Ramstedt et al. 2020; and ATOMIUM; Gottlieb et al. 2022), which are indicating that companions to evolved stars are also important in shaping the properties of the winds we see. It is hoped that the combination of these surveys (plus, of course, new results from the *James Webb Space Telescope*) will provide a much more rounded perspective on the reasons why, when and how AGB stars start to lose mass, with which information we can start to close one of the final unanswered problems in single-star evolution.

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