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Observed properties of red supergiant and massive AGB star populations

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Abstract. This brief review describes some of the observed properties of the populations of massive asymptotic giant branch (AGB) stars and red supergiants (RSGs) found in nearby galaxies, with a focus on their luminosity functions, mass-loss rates and dust production. I do this within the context of their role as potential supernova (SN) progenitors, and the evolution of SNe and their remnants. The paper ends with an outlook to the near future, in which new facilities such as the James Webb Space Telescope offer a step change in our understanding of the evolution and fate of the coolest massive stars in the Universe.

Key words. Stars: evolution – Stars: massive – Stars: mass-loss – Galaxies: stellar content

1. Introduction

In the final stages of their evolution, stars in the birth mass range $\sim$ 1–7 $M_\odot$ ascend the AGB, reaching luminosities of order 10^4 $L_\odot$ due to hydrogen and helium shell burning; Hot Bottom Burning (HBB) at the bottom of the convection zone in the most massive AGB stars can further raise the luminosity, approaching 10^5 $L_\odot$ (Iben & Renzini 1983). The nuclear evolution of AGB stars is truncated by mass loss (van Loon et al. 1999), leaving behind a carbon–oxygen white dwarf. Stars in the birth mass range $\sim$ 11–30 $M_\odot$ do not develop core degeneracy and instead become core helium burning RSGs (Maeder & Meynet 2012). RSGs also evolve along a (short) branch, and their mass loss may or may not change their appearance (van Loon et al. 1999) before they explode as a core-collapse supernova (Smartt 2015). This leaves a range $\sim$ 7–11 $M_\odot$ unaccounted for; these are the super-AGB stars, which behave very much like massive AGB stars but ignite carbon burning in the core before leaving an oxygen–neon–magnesium white dwarf or undergoing electron-capture core-collapse (Doherty et al. 2017). The actual mass range is much narrower, but the boundaries are uncertain. Understanding the fate of super-AGB stars, and recognising them in nature, presents one of the greatest challenges in contemporary astrophysics.

2. Do we know any super-AGB star?

No. Claims are sometimes made, on the basis of surface abundances (rubidium, lithium) or luminosities (above the classical AGB limit), but we lack a way to unequivocally distinguish super-AGB stars from massive AGB stars experiencing HBB. Nonetheless, we should keep a record of candidates for when we have a way to confirm, or refute, their super-AGB nature. Until then, "discoveries" of super-AGB stars are steeped in controversy.

A fascinating example is the bright Harvard Variable, HV 2112 in the Small Magellanic Cloud (SMC). It is a little more luminous than the classical AGB limit, sometimes as cool as spectral type M7.5, and has a relatively long pulsation period (Wood, Bessell & Fox 1983) – commensurate with being such a large star. Things got more exciting when Smith & Lambert (1990) detected lithium, which indicated some level of HBB even if not clinching its status as a super-AGB star. In that same year, however, Reid & Mould (1990) showed lithium to be absent.

Nothing much happened, until Levesque et al. (2014) proposed that HV 2112 could also be a Thorne–Żytkow object – a neutron star which ended up inside a stellar mantle. This conjecture was immediately put to the test by Tout et al. (2014), who note the difficulty in distinguishing between the different origins of similar peculiarities – the calcium abundance might be the discriminating feature, in favour of a Thorne–Żytkow object.

But does HV 2122 in fact reside in the SMC, and is a relatively massive star? Maccarone & de Mink (2016) concluded on the basis of proper motion measurements that HV 2112 must instead belong to the Galactic Halo, and be an extrinsic S-type star upon which the anomalous abundances had been imprinted by a companion AGB star. This would explain the calcium abundance, which is generally high in the Halo. The radial velocity, whilst not excluding Halo membership, is however consistent with that of the SMC (González-Fernández et al. 2015). Revisiting the proper motion, Worley et al. (2016) reinstate its SMC membership. The saga continues.

3. Converting luminosity functions into star formation histories

As stars of different birth masses attain different luminosities during their lives as AGB stars, super-AGB stars or RSGs, their luminosity distribution reflects the star formation history (SFH). However, the evolutionary tracks are difficult to separate especially if there is a spread in metallicity, and so the luminosity distribution will be a blend of the luminosity evolution of stars of a range of birth masses, especially on the AGB. Evolution in luminosity is curtailed, though, once stars lose mass at very high rates, so if one could identify stars in that extreme final phase the luminosity distributions would map much more cleanly onto the SFH. Luckily, these stars develop strong, long-period variability (LPV) as their atmospheres pulsate and (help) drive the mass loss (Wood, Bessell & Fox 1983).

A method was devised to determine the SFH from the luminosity distribution of LPVs by Javadi, van Loon & Mirtorabi (2011b), and applied to a near-infrared monitoring survey of LPVs in the Local Group spiral galaxy M 33 (Javadi, van Loon & Mirtorabi 2011a). If $dn'(t)$ is the number of LPVs associated with all stars that formed within a timespan dt around lookback time t, then the star formation rate around that time is

$$\xi(t) \;=\; \frac{dn'(t)}{\delta t}\,\frac{\int_{\rm min}^{\rm max} f_{\rm IMF}(m) m\, dm}{\int_{m(t)}^{m(t+dt)} f_{\rm IMF}(m)\, dm}, \qquad (1)$$

where $f_{\rm IMF}$ is the initial mass (m) function and δt the LPV lifetime.

The method relies on stellar evolution models; only the Padova group predicts all of the essential information (Marigo et al. 2017). This is a problem, as different models predict a different final luminosity for a given birth mass, and different lifetimes before and during the LPV phase (Marigo et al. 2017). It is also a blessing *because* it is model dependent, as it opens an avenue into calibrating the models and thus offers insight into the physics. This became apparent very soon, when Javadi et al. (2013) found that the inferred integrated mass loss exceeded the birth mass. If we define

$$\eta \;=\; \frac{\Sigma_{i=1}^{N}\left(\dot{M}_i \times (\delta t)_i\right)}{\Sigma_{i=1}^{N} M_i}, \qquad (2)$$

then $\eta(m) = 1 - m_{\rm final}/m_{\rm birth} < 1$ always, but the measurements yielded $\eta > 1$. At least part of the solution had to be a downward revision of the LPV lifetimes, which was later confirmed independently by the Padova group themselves (Rosenfield et al. 2016). The revised lifetimes were used to derive a more reliable SFH for M 33 (Javadi et al. 2017).

4. Mass loss from dusty AGB stars and red supergiants

Mass-loss rates can be determined from dusty AGB stars and RSGs by modelling the spectral energy distribution (SED) using a radiative transfer model. The first such systematic analysis for stars with known distances was performed for populations within the Large Magellanic Cloud (LMC) by van Loon et al. (1999), who found that mass-loss rates exceeded nuclear consumption rates for most of the AGB evolution but not for much of the RSG evolution. This means that AGB stars avoid SN but RSGs do not.

They also found evidence that the mass-loss rate increases during the evolution along the AGB as the luminosity increases and the photosphere cools, though RSGs in particular seem to exhibit more abrupt variations between mild and possibly short episodes of much enhanced mass loss. This was put on a more quantitative footing by van Loon et al. (2005) who parameterised the mass-loss rate during the dusty phase of (massive) AGB and RSG evolution as

$$\log \dot{M} = -5.65 + 1.05 \log(L/10\,000\,\mathrm{L_\odot}) - 6.3 \log(T_{\rm eff}/3500\,\mathrm{K}), \tag{3}$$

with no evidence for a metallicity dependence. The dependence on temperature seems very strong but it must be realised that the temperatures among these kinds of stars fall within a limited range ($\sim$ 2500–4000 K).

Because the mass-loss rate that is derived from the SED depends on how much the dust is diluted it has a dependence on the wind speed, $v_{\rm exp}$. What is really seen directly is the optical depth of the dusty envelope:

$$\tau \propto \frac{\dot{M}}{r_{\rm gd} v_{\rm exp} \sqrt{L}}, \tag{4}$$

where $r_{\rm gd}$ is the gas:dust mass ratio. However, if the wind is driven by radiation pressure upon the dust, then

$$v_{\rm exp} \propto \frac{L^{1/4}}{r_{\rm gd}^{1/2}}. \tag{5}$$

By measuring $v_{\rm exp}$ directly, for instance from the double-horned hydroxyl maser line profile, its value can be reconciled with the SED modelling by tuning the value for $r_{\rm gd}$. This led Goldman et al. (2017) to determine a more sophisticated formula for the mass-loss rates from AGB stars and RSGs in the LMC, Galactic Centre and Galactic Bulge with known pulsation periods P:

$$\log \dot{M} = -4.97 + 0.90 \log(L/10\,000\,\mathrm{L_\odot}) + 0.75 \log(P/500\,\mathrm{d}) - 0.03 \log(r_{\rm gd}/200). \tag{6}$$

This time P instead of $T_{\rm eff}$ measures the size of the star (in combination with L), but the resemblance to the formula found earlier is striking. There is no dependence on the gas:dust ratio and, by inference, on the metallicity.

The mass loss probed in the dusty phases may only be part of the story. If sustained over an extended period of time, moderate mass loss may matter too. Likewise, the metallicity of massive AGB stars and RSGs in the SMC is only $\sim 0.2\ \mathrm{Z_\odot}$ (as opposed to $\sim 0.5\ \mathrm{Z_\odot}$ in the LMC), and stars become dusty later in their evolution, possibly having lost more mass in other ways before. Bonanos et al. (2010) indeed found that most RSGs exhibit moderate mass-loss rates, $\sim 10^{-6}\ \mathrm{M_\odot\ yr^{-1}}$, which agrees with the study by Mauron & Josselin (2011) of Galactic RSGs among which only few exhibit mass-loss rates $> 10^{-5}\ \mathrm{M_\odot\ yr^{-1}}$. While this confirms the earlier findings by van Loon et al. (1999), no clear bimodality was seen.

Larger populations of massive AGB stars and RSGs are needed to be more conclusive about the rarest, but most intense phases of mass loss in comparison to the more common, gentler phases. To that aim, following from Javadi et al. (2013) and the extended survey by Javadi et al. (2015), Javadi et al. (in prep.) have measured mass-loss rates for thousands such stars in M 33. They confirm the gradual evolution in mass loss along the AGB and the bimodal mass loss on the RSG, with the rates increasing in proportion to luminosity.

These studies show no evidence for anything peculiar to be happening to super-AGB stars. If anything, they are most likely to follow the extension of the AGB sequence and attain exuberant mass-loss rates of $\sim 10^{-4}\ \mathrm{M_\odot\ yr^{-1}}$.

An accurate assessment of the integrated mass loss might lead us to exclude – or allow – their possible fate as electron-capture SN.

An alternative route to mapping the evolution of mass loss along the AGB or RSG branch is based on the fact that populous clusters may show more than one such example. Given the fast evolution in those advanced stages, we are essentially watching a star of the same mass at different moments in its evolution, as snaphots in a movie. Davies et al. (2008) pioneered this approach in the Galactic cluster RSG C1, and more recently Beasor & Davies (2016) applied the same principle to the LMC cluster NGC 2100. They both confirm the increase in mass loss along the RSG branch. Such studies in clusters in which we *know* super-AGB stars should form may elucidate the properties, evolution and fate of super-AGB stars where field studies struggle to recognise them. Apart from the difficulty in finding such clusters, it may be difficult to catch them at their most extreme.

5. Beyond the red supergiant and asymptotic giant branches

Massive AGB stars and RSGs can undergo a blueward excursion as a result of core expansion before returning to the cool giant branch – a "blue loop". This is a much slower transformation than the "jump" from the main sequence to the giant branch, and is responsible for populating the Cepheid instability strip (Valle et al. 2009). Cepheid variables therefore could be extremely valuable probes of what may already have happened to these stars on the cool giant branch, such as any mass loss, especially as their pulsational properties depend on their current mass. It also means that the cool giant branches are populated by stars that have, and those that have not undergone a blue loop – again, these may differ as a result of the mass loss during their lives as blue (or yellow) supergiants. Typically, much fewer warm supergiants are seen than are predicted by the models (Neugent et al. 2010), which suggests that the models do not yet adequately account for certain processes that happen inside RSGs.

Pulsation periods lengthen as a star expands when it is reduced in mass, so period–luminosity diagrams of AGB and RSG LPVs have the potential to trace mass loss and possibly the effects of blue loops. Also, the mode in which the pulsation is excited depends on stellar structure. Yang & Jiang (2012) charted this parameterspace for RSGs in the Magellanic Clouds, M 33 and the Milky Way but their combination with similar information for AGB stars left an unfortunate gap right around where super-AGB stars could be found. This must – and can – be remedied.

AGB stars and RSGs may also move irreversibly towards hotter photospheres, due to mass loss (by a wind or stripping in a binary system). The luminosity distribution over post-AGB stars and post-RSGs must be devoid of the birth masses associated with the electron-capture SN demise of the more massive among super-AGB stars, and depleted of those RSGs which encountered their end in a SN. Again, a concerted analysis is required, where in the past different communities have often concentrated on just the lower-mass (post-)AGB stars or on just the higher-mass (post-)RSGs.

6. The progenitors and remnants of core-collapse supernovæ

Having established that many RSGs most likely do not lose their envelope before the core collapses, it is comforting that all of the SN type II-P progenitors that have been discovered so far are RSGs (Smartt 2015). Their birth mass range is estimated to be ~ 9–17 $M_\odot$ (Smartt 2015), though the upper limits could allow dusty RSGs as massive as ~ 21 $M_\odot$ to have resulted in II-P SNe. This would also be more consistent with the above findings about the mass-loss rates of RSGs, where a proportion of core-collapsing RSGs should experience high mass-loss rates. The confirmed RSG progenitors tend to be of relatively early spectral type and thus constitute those RSGs that have lost relatively little of their mantle.

What exactly determines the difference in rate of evolution of the core – setting the timing of core collapse – and of the mantle – setting the mass loss, is unclear, but larger sam-

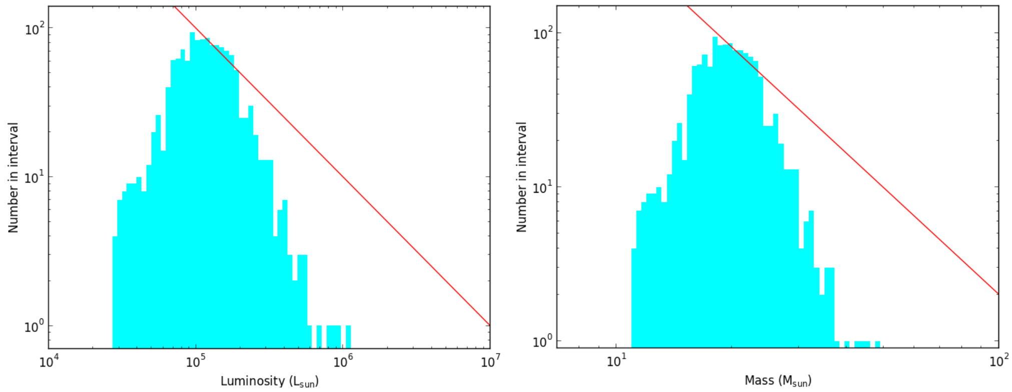

Fig. 1. Luminosity (left) and birth mass (right) distribution of RSGs in the grand-design spiral galaxy M 101 at 7 Mpc distance based on groundbased and *Spitzer*-IRAC infrared imaging (courtesy of James Bamber). The luminosity-to-mass conversion is based on a fit to Padova models (Marigo et al. 2017): $\log L = 2.49 \log M + 1.84$. The initial mass function, with a slope of -2.3, is overplotted; the distributions are depleted on the low and high sides due to incompleteness and diminished RSG lifetimes, respectively.

ples of discoveries and limits on progenitors of II-P SNe should help elucidate this: their lightcurves and spectral evolution may reveal differences in the mantle mass and circumstellar density, whilst their galactic environments may reveal a dependence on metallicity. Likewise, a connection between RSG evolution and mass loss on the one hand, and SNe of types II-L and Ib on the other, may be made if the more massive RSGs ($\sim$ 20–30 M$_\odot$) lose most of their mantle before exploding.

A metallicity effect on the properties of the SN resulting from the explosion of a RSG (or super-AGB star) is expected even if the mass-loss rate does not change, because the winds are slower at lower metallicity (Goldman et al. 2017). This would increase the circumburst density, with implications for the SN lightcurve (Moriya et al. 2017). It also means that the reverse shock may be stronger.

The SN has a devastating effect on the dust produced by the RSG, even if it did not explode as a RSG as the SN ejecta move at $\sim 10^3$ times the speed of the RSG wind and catch up within a century. The RSG dust, and any ISM dust in the vicinity, is sputtered in the forward shock, whilst the reverse shock sputters much of the dust produced in the SN ejecta. The net effect being that SNe are dust destroyers (Lakićević et al. 2015; Temim et al. 2015).

Because SN remnants (SNRs) can be seen for $> 10^4$ yr they might tell us something about the SN progenitors in their final $< 10^4$ yr that is difficult to capture while they are still alive. The two most prolific SN factories known, NGC 6946 (Sugerman et al. 2012) and M 83 (Blair et al. 2015) exhibit hundreds of SNRs (Bruursema et al. 2014; Winkler, Blair & Long 2017).

7. The next frontier

A naive estimate for a massive spiral galaxy suggests one RSG explodes every century. With a typical RSG lifetime of $\sim 10^3$ centuries, we thus expect to find a population of order 10^3 RSGs. Thus the statistics look extremely promising for studies of the luminosity distribution and the evolution of mass loss of RSGs (and super-AGB stars) in such galaxies.

The next step from the Magellanic Clouds can take us to the nearest spiral galaxies, M 33 (Drout, Massey & Meynet 2012) and M 31 (Massey & Evans 2016) at $\sim$ 0.9 Mpc, or NGC 300 and the metal-poor dwarf Sextans A, both within 2 Mpc. Indeed, the Surveying the Agents of Galaxy Evolution (SAGE) team, who have revolutionised our views of the Magellanic Clouds, are proposing an Early Release Science programme for the James

Webb Space Telescope (JWST) precisely to do that. But how far could we go?

M 101 is the most massive spiral galaxy within 7 Mpc, viewed face on. Bamber et al. (in prep.) have used groundbased and *Spitzer* infrared images, and *Hubble* optical images, to identify RSG candidates across the entire disc. The *Spitzer* data are heavily compromised by the limits in resolution and sensitivity, and JWST will be both necessary and sufficient to quantify the dust production by RSGs in M 101. Likewise, the luminosity distribution suffers from incompleteness at the low end. Still, it reveals a tantalising first glimpse of the evolution of the most luminous RSGs (Fig. 1): a healthy number of RSGs in the $\sim$ 17–22 $M_\odot$ range suggests these could well be the progenitors of SNe, while the sharp drop that sets in at higher masses suggests much diminished RSG lifetimes. The latter is not unexpected if those are the RSGs that become Wolf–Rayet stars, as a result of stronger mass loss.

8. Will we find super-AGB stars?

Yes. We look towards our colleagues who model the structure and dynamical behaviour, and nucleosynthesis and surface enrichment of super-AGB stars to make predictions for the observable signatures that can tell super-AGB stars apart from other massive AGB stars (and RSGs). We also need to reach an agreement on the birth-mass range of super-AGB stars. Meanwhile, we look for peculiarities or more subtle hints of deviations, that indicate we may be dealing with a star of a different kind.

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