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# Mass loss in advanced evolutionary phases

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**Abstract.** The recent availability of large area deep infrared surveys has provided a new tool to study mass loss in evolved stellar populations. We discuss here how these investigations can help our understanding of stellar mass loss, and the role it plays in the dust and gas budget of entire galaxies, with particular emphasis to the Magellanic Clouds.

**Key words.** Stars: mass-loss – Stars: AGB and post-AGB – Stars: variables: general

## 1. Introduction

Mass loss is a fact of life for most stars. While a small to moderate stellar wind is always present in all stages of stellar evolution, it is at the end of a star's life that a significant fraction of its mass is finally returned to the InterStellar Medium (ISM). This phenomenon has long since been recognized as a crucial step to close the loop in galactic ecosystems, allowing new episodes of star formation and driving the chemical evolution of galaxies (see e.g. Tinsley 1968; Chiosi & Maeder 1986).

The basic principles driving mass loss in evolved stars are well recognized (Salpeter 1974; Kwok 1975; Goldreich & Scoville 1976): as stars switch to more efficient shell burning after leaving the main sequence, they swell to giant or supergiant radius, leading to high luminosity, low gravity and cool atmospheres. Radial pulsations induced by crossing the Long Period Variables (LPV) instability strip further destabilize these atmospheres. Pulsations make available mechanical energy for levitating and compressing the atmosphere to the point in which particulate condensation (astronomical dust) is possible (Sedlmayr 1994). Radiation pressure acting on these newly formed dust grains further enhance the outward flow, leading to strong stellar winds that ultimately deplete these stars of the convective layers surrounding their inert cores (see reviews by Habing 1996 and Willson 2000).

The fine details of these processes are however poorly known. While numerous empirical laws are available to estimate mass loss rate as a function of stellar parameters (see e.g. Reimers 1975; Vassiliadis & Wood 1993; Baud & Habing 1983; Nieuwenhuijzen & De Jager 1990), these relations cannot predict the actual mass loss for individual stars. They also generally fail to reproduce the high mass loss rates observed at the very end of the Asymptotic Giant Branch (AGB, for low and intermediate mass stars), Supergiant (RSG) and Wolf Rayet (WR) phase (high mass stars). Despite progress, what we are still missing is a comprehensive theory of mass loss in evolved stars.

This lack of knowledge poses severe limitations to our understanding of the last phases of stellar evolution: while late evolutionary phases are driven by the mass of the inert core (Paczyński 1970), the end point is determined by the efficiency of mass loss processes in depleting their convective envelopes. Even a basic parameter like the mass above which a star ends its life as core-collapse supernova (SN), rather than as an AGB, is very uncertain. The long held assumption that all AGBs are progenitors of White Dwarfs was recently cast in doubt, with the hypothesis that *super-AGBs* (AGB stars with mass in the 5–10 $M_{\odot}$ range) could be the progenitors of dust-enshrouded SN (Javadi et al. 2011). This poses serious difficulties for stellar population simulations requiring accurate estimates of stellar yields for galactic chemical evolution models.

On the theoretical front, progress is slowly being made by including better pulsation physics and better dust condensation chemistry in time-dependent hydrodynamic models (see e.g. Bladh & Höfner 2012; Mattsson & Höfner 2011; Mattsson et al. 2010; Freytag & Höfner 2008). Observationally, however, advancement is hampered by the difficulty of precisely measuring the parameters of mass losing stars, the mass loss rate in the first place. The most accurate determination of mass loss rates from evolved stars are obtained from radio molecular line observations, that can simultaneously provide the total mass of the gas in the outflow and the wind velocity, from which $\dot{M}$ can be determined. The high $S/N$ ratio and velocity resolution required by these observations, however, pose limitations to the number of targets that can be probed with these techniques.

Mass loss rates for a much larger sample of galactic and extragalactic mass losing evolved stars can be estimated from their infrared excess. Infrared measurements, however, require a priori knowledge of the wind velocity and gas to dust mass ratio. These can only be estimated when the same target can be studied at *both* radio and infrared wavelengths, and are highly uncertain (see e.g. Loup et al. 1997; Guandalini & Busso 2008; Guandalini et al. 2006). All these issues are compounded by the clumpy and time-variable nature of evolved stars' outflows. It is not surprising, therefore, that current estimates of mass loss rates have order-of-magnitude uncertainty, and can result in discrepant measurements by techniques probing different time scales.

The uncertainty in individual mass loss rate measurement can somewhat be mitigated by studying large homogeneous samples or, even better, complete populations of evolved stars in a galaxy. This approach has only become recently possible with the availability of large area infrared and optical deep surveys, capable to detect individual stars above the Red Clump in local group galaxies. The largest current efforts concern the two closest satellites of the Milky Way, the Large and Small Magellanic Clouds (LMC and SMC).

## 2. Mass loss in stellar populations: the Magellanic Clouds

The LMC and SMC, thanks to their proximity to the Milky Way, offer the best available case for studying the role of stellar mass loss in the dust and gas budget of an entire galaxy. They are close enough that giant and supergiant stars can be individually detected, and far enough to allow a "bird's view" of their entire ISM and stellar content. Their well determined distances (50 kpc, e.g. Schaefer 2008 and 61 kpc, e.g. Szewczyk et al. 2009 respectively) allow a precise estimate of stellar luminosities.

For these reasons the LMC and the SMC have been the subject of extensive surveys covering a wide wavelength and temporal domain. In the optical, the MCPS (Zaritsky 2004), MACHO (Alcock et al. 1996) and OGLE (Paczyński et al. 1994) surveys. In the near-IR ($JHK_s$ bands), the 2MASS (Skrutskie 2006), IRSF (Kato et al. 2007) and VMC (Cioni et al. 2011) surveys. In the infrared, the SAGE (Meixner et al. 2006), AKARI LMC (Ita et al. 2008) and HERITAGE (Meixner et al. 2010) surveys. These surveys have generated extensive catalogs providing the Spectral Energy Distributions (SEDs) of millions of point sources ($\approx 8 \times 10^6$ sources in the combined SAGE/2MASS/MCPS catalog).

These multi-wavelength photometric catalogs allow to dissect the LMC and SMC stellar populations in their constituents. This is generally accomplished with appropriate color-magnitude cuts (see e.g. Blum et al. 2006; Cioni et al. 2006; Matsuura et al. 2009; Boyer et al. 2011). These cuts are defined on the basis of sources identified spectroscopically (e.g. Gruendl et al. 2008; Woods et al. 2011) or

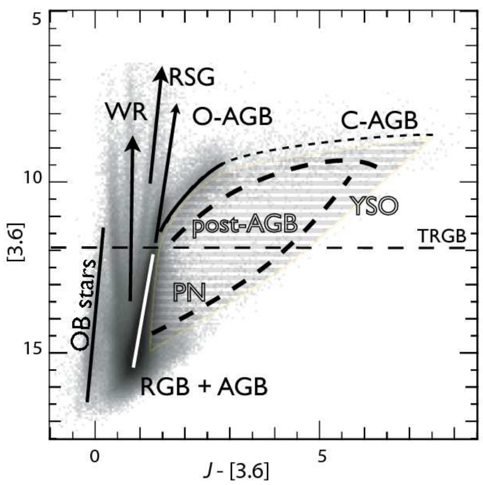


**Fig. 1.** Source density color-magnitude diagram of SAGE catalog LMC sources (Meixner et al. 2006) with main source types identified. Unlabeled vertical sequences are due to foreground contamination from Galactic sources. The dashed area is the locus of bright massive YSOs, overlapping with PN and post-AGB stars. The horizontal dashed line marks the RGB tip magnitude for the LMC.

based on stellar evolution models (e.g. Marigo et al. 2007, 2008). The main limitation of this technique is due to significant overlaps between sources in different evolutionary stages (e.g. bright Young Stellar Objects, having very similar colors and magnitudes of post-AGB and PNe), or with foreground (Milky Way stars) and background (reddened quasars) contaminants. A careful assessment of the result, and comparison with smaller samples identified spectroscopically, is necessary to validate these catalogs classified photometrically.

Figure 1 shows a color-magnitude diagram of the LMC point sources in the SAGE catalog. The main types of evolved stars are identified, including WR, RSG, AGB and RGB stars. In absence of circumstellar dust these sources would trace slanted lines on the diagram, following the arrows plotted in the figure. The infrared excess due to dusty mass loss broadens these tracks, causing some sources to extend toward redder colors. This effect is especially dramatic for the so-called *extreme* AGB stars that can reach very red colors (as much as $J - [3.6] \approx 8$). The mass loss rate and chemical signature of these sources can be determined either by fitting the SED on a source-by-source basis (e.g. Gullieuszik et al. 2012; Riebel et al. 2012), or by adopting a color – mass loss relation (e.g. Groenewegen 2007; Groenewegen et al. 2009; Gruendl et al. 2008). This allows to quantify the total mass loss yield from evolved stars in the galaxy, and estimate the relative contribution of different classes of stars.

**Table 1.** LMC/SMC gas stellar yields$^{a,b}$

| Sources | LMC | SMC |
|---|---|---|
| C-AGBs | 0.7 | 0.08 |
| O-AGBs & RSGs | 0.8 | 0.06 |
| WR stars | ~ 0.1 | ~ 0.01 |
| Type-II SNe | 6–13 | 2–4 |
| OB stars | 0.1–1 | ~ 0.03-0.3 |

(a) in units of $10^{-2}$ $M_\odot$ yr$^{-1}$
(b) from Matsuura et al. (2012)

Table 1 from Matsuura et al. 2012 shows an example of what these analysis can achieve. Among evolved stars, AGBs provide the largest return of gas and dust to the ISM, for both galaxies. The contribution from WR stars is one order of magnitude smaller, comparable to the yield from OB stars. The yield of O-rich stars (O-AGBs and RSGs) is comparable to the total mass loss from C-stars. This is in contrast to previous estimates (see e.g. Boyer et al. 2012; Riebel et al. 2012; Matsuura et al. 2009) that attribute a smaller role to O-rich stars. The discrepancy is probably attributable to the difficulty to correctly identify the chemistry of the reddest sources, where the silicate feature can be missed due to self absorption. All authors, however, found that most of the mass loss from AGB and RSG stars comes from the *extreme* AGBs, reaching individual mass loss rates as high as ~ $10^{-4}$ $M_\odot$ yr$^{-1}$. Riebel et al. (2012) found that the reddest 4% of all AGBs contributes for ~75% of the total mass lost.

The nature of the *extreme* AGB stars, and the fact that they should be grouped as a separate class, is debated. These sources are mostly comprised of C-rich AGB stars (~97% of the total, in Riebel et al. 2012). This is expected: since mass loss is predicted to increase dramatically at the end of the AGB phase (Willson 2000) the stars in the *extreme* class are likely to be more evolved. In the low metallicity environment of the Magellanic Clouds these stars can more readily experience a sufficient number of third dredge-up episodes to switch their chemistry to $C/O > 1$, thus becoming carbon stars. This explanations may however not hold for the more luminous (more massive, see e.g. Vassiliadis & Wood 1993) *extreme* AGBs. These stars could experience a Hot Bottom Burning process (HBB; Smith & Lambert 1985; Bloecker & Schoenberner 1991; Boothroyd & Sackmann 1992), preventing them from developing a C-rich chemistry. A small number of very bright and red OH/IR stars has indeed been identified among this class (Wood et al. 1992; Groenewegen et al. 2009). According to Matsuura et al. (2012), the high mass loss rate of just a few HBB AGBs, together with the RSGs, is sufficient to raise the contribution of O-rich evolved stars to the same level of C-AGBs.

A result in common among these recent analysis is that the total yield from evolved stars is dwarfed by the total gas mass returned by core-collapse SNe. Despite the uncertainties in estimating the current SN frequency in the Magellanic Clouds (see e.g. Mathewson et al. 1983; Filipovic et al. 1998), the total gas return to the ISM from SNe can be more than one order of magnitude larger than that from AGBs and RGBs combined. This is in contrast with the Milky Way, where AGB stars are the main contributors for both gas and dust to the ISM (see e.g. Tielens et al. 2005). The larger role played by SNe in the Magellanic Clouds is most likely a consequence of the recent episodes of enhanced star formation experienced by both galaxies (Harris & Zaritsky 2004, 2009), the SMC in particular. In addition, the lower metallicity of the Magellanic Clouds can lead to weaker dust-driven winds (Bowen & Willson 1991; Marshall et al. 2004), that could reduce the yield of O-rich AGB and RSG stars in the gas budget of the two galaxies.

AGB stars, however, are still presumed to be the main source of dust for the ISM. Even though recent HERITAGE analysis of SN 1987A (Matsuura et al. 2011) has shown that SNe can produce significant amount of dust, following similar determinations in Galactic SN remnants (Barlow et al. 2010), SN dust grains are likely destroyed at later stages by ISM and SN wind collisions.

Finally, multiple epochs surveys like MACHO and OGLE provide light curve and period of optically bright LPVs. Period-luminosity diagrams at optical (Wood et al. 1999) and infrared (Riebel et al. 2010) wavelengths using these datasets show that the LMC and SMC LPVs are distributed in a number of sequences corresponding to different pulsation modes (plus the odd and mysterious long secondary period "*D*" sequence). Riebel et al. (2012) have shown that these sequences correlate with mass loss rates and chemical type. Variables with higher $\dot{M}$ are primarily fundamental mode and first overtone pulsators, with higher overtone variables characterized by very low $\dot{M}$. Carbon stars occupy the high luminosity section of these sequences, and are fundamental pulsators by a factor 2:1 (while O-rich AGBs are equally distributed among all sequences). Only a minority of *extreme* AGBs can be analyzed with this technique (they are too dust-obscured to be picked-up by optical surveys), and they appear all grouped at the top of the fundamental mode sequence.

## 3. Conclusions

The transition of astronomy to a *big science* enterprise has enabled deep surveys of nearby galaxies, providing a new diagnostic tool to undertand mass loss in whole stellar populations, and the stellar feed-back to galactic chemical evolution. The examples discussed above for the LMC and SMC show how progress has been made in determining the relative yield of evolved stars of different masses, and with different chemical and variability characteristics. The next generation of space and ground infrared telescopes will extend our reach to stars in more distant local group galaxies. The acquisition of precise parallaxes for large samples of galactic evolved stars with GAIA will allow a similar detailed analysis for the Milky Way (Feast 2003).

At the same time, the theoretical interpretation of these results is gaining ground, with the ultimate goal of simulating the photometry, chemistry, mass loss and pulsational properties of the stellar populations of entire galaxies (see e.g. Girardi & Marigo 2007).

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