Why Galaxies Care About AGB Stars: A Continuing Challenge through Cosmic Time
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The onset of mass loss in AGB stars

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Abstract. The factors controlling strong mass loss from evolved stars remain elusive, frustrating efforts to parameterise mass loss in models of evolved stars. We herein describe evidence we have collected to show that the mass-loss rate of stars is controlled by stellar pulsations, and that we are close to providing improved prescriptions for mass-loss rates from many kinds of evolved stars.

Keywords. stars: mass loss, stars: AGB and post-AGB, stars: variables: other, circumstellar matter, stars: evolution, stars: late-type, stars: chromospheres, stars: magnetic fields, stars: Population II, stars: winds, outflows

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Strong mass loss from asymptotic giant branch (AGB) stars is thought to occur via a combination of atmospheric levitation by long-period stellar pulsations, and radiation pressure on dust forming in that levitated atmosphere. The conditions required to initiate that mass loss, however, remain a problematic source of uncertainty for models of stellar structure and evolution (Höfner & Olofsson 2018). While we observe the effects of dust formation and wind acceleration, it is not clear what determines the rate at which mass is lost, meaning it cannot be described by stellar evolution modellers (J. Lattanzio, this proceedings). The distinction becomes important when one applies these rules to stars of differing metallicity: if pulsation sets the mass-loss rate, mass loss should be largely independent of metallicity; if radiation pressure on dust sets the mass-loss rate, mass loss should be strongly metallicity dependent. A third option also exists: the weaker mass loss promoted by magnetically driven winds may continue to play a role on the AGB (e.g. Dupree, Hartmann & Avrett 1984).

Mass-loss rates from evolved stars have historically been estimated via empirical laws. These notably include Reimers (1975), a function of luminosity (L), radius (R) and mass (M) described by $\dot{M} = 4 \times 10^{-13} \eta LR/M$ M$_\odot$ yr^{-1}, where $\eta \approx 0.477$ (McDonald & Zijlstra 2015) is a scaling constant, normally calibrated on globular clusters. This is well-known to under-predict mass-loss rates from intermediate-mass evolved stars, which are undergoing this dust-driven "superwind" (Renzini & Voli 1981). However, it also *over*-estimates mass-loss rates of many open cluster and field stars that are not yet undergoing a superwind (Miglio *et al.* 2012, Handberg *et al.* 2017, Groenewegen 2014): Reimers' law (with $\eta \approx 0.4$) predicts a mass-loss rate of $\sim 10^{-7}$ M$_\odot$ yr^{-1} for RGB-tip stars; yet where such mass-loss rates are observed, stars invariably show infrared excess indicative of strong dust production, which is not typically observed for RGB-tip stars in clusters or the field (e.g. McDonald *et al.* 2011, McDonald *et al.* 2014, McDonald & Zijlstra 2016).

Infrared excess, indicating strong mass loss ($\gtrsim 10^{-7}$ M$_\odot$ yr^{-1}), seems confined to the AGB. It typically begins close to the RGB tip, and is present only in variable stars (McDonald, Zijlstra & Boyer 2012; McDonald, Zijlstra & Watson 2017). A critical point appears to be when stars reach a 60-day period, when $K_{\rm s} - [22]$ colour increases from ~ 0

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mag to 1–2 mag: this corresponds approximately to the point at which low-mass stars transit onto the C' sequence in the period–luminosity diagram (McDonald & Ziljstra 2016), and is associated with an increase in pulsation amplitude (Trabucchi *et al.* 2017 & these proceedings).

The cause of this increase in excess infrared flux has been unclear. It may represent a real increase in mass-loss rate driven by radiation or pulsation, or simply an increase in dust-production efficiency in a magnetically supported wind. To investigate, we obtained spectra of carbon monoxide J=3–2 lines towards 11 nearby, oxygen-rich stars that straddle the 60-day boundary, using the Atacama Pathfinder Experiment (APEX) telescope (McDonald *et al.*, in press). Stars with infrared excess ($K_s - [22] > 0.55$ mag) were detected with APEX (estimated average $\dot{M} \sim 3.7 \times 10^{-7}$ M$_\odot$ yr^{-1}); stars without infrared excess were not detected ($\dot{M} \lesssim 1 \times 10^{-7}$ M$_\odot$ yr^{-1}), and $K_s - [22]$ colour is shown to correlate with mass-loss rate within a factor of ∼6 between $0 \leqslant K_s - [22] \lesssim 5$ mag. Wind velocity shows little change, maybe slowing slightly across this transition, from ∼10–12 km s^{-1} (Groenewegen 2014; McDonald *et al.* 2016) to ∼3–11 km s^{-1} for stars above the $K_s - [22] = 0.55$ mag transition. The transition is near-instantaneous in evolutionary terms, so is unlikely to be tied to stellar luminosity, hence radiation pressure on dust. Thus, the transition around 60 days corresponds to a real increase in mass-loss rate, tied to pulsations and not either more efficient dust condensation, or a change in the star's magnetic wind driving. We estimate the increase to be by a factor of ∼100.

The substantial increase in mass-loss rate when stars begin strong pulsation strongly implies that mass-loss rate is set predominantly by the pulsation properties of the star, not radiation pressure on dust. In turn, this implies that radiation pressure on dust should not greatly influence the mass-loss rate, setting only the terminal velocity of the wind. To investigate this, we must observe outflow velocities of stars in metal-poor systems. Observations in the Magellanic Clouds are possible but difficult, due to the distance (e.g. Groenewegen *et al.* 2016), as are observations in globular clusters, due to the strong irradiation (e.g. McDonald *et al.* 2015). Recently, we have obtained detections of a wind from a star in a globular cluster and a Galactic Halo star, using the Atacama Large Millimetre Array. Initial analysis of these observations support the idea that the winds of these metal-poor stars are still driven by radiation pressure on dust (McDonald *et al.*, in prep.).

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