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Observationally decoding the mechanisms driving mass loss from AGB stars

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Abstract. In this contribution, I discuss recent developments into the mechanisms driving the stellar winds of evolved stars: magneto-acoustic energy transport, stellar pulsations, and radiation pressure on dust. I summarise the observational expectations from these winds, and present the observational evidence showing the regimes in which they may operate.

Key words. stars: mass-loss — circumstellar matter — infrared: stars — stars: winds, outflows — stars: AGB and post-AGB

1. Introduction

Mass loss dictates the death of most stars. The mechanisms driving mass loss from single stars are debated. Mass-loss mechanisms can be thought of as a progressive series, where progression depends on achieving certain criteria while still retaining enough stellar envelope mass to avoid leaving the asymptotic giant branch (AGB). The following symbols are used: luminosity, L; radius, R; mass, M; metallicity, Z; terminal wind velocity v_∞; and pulsation period, P, and amplitude δV, with units of solar units, km s^{-1}, days and magnitudes, as appropriate.

2. Mechanisms

Four main mechanisms are thought to remove mass from single stars:

(1) *Magneto-acoustic mass loss:* It is not clear how well this process scales to more evolved stars. Charged-particle flow, magnetic reconnection, and Alfvén waves may be important heating sources. Above $\sim$10–20 R$_\odot$, stars cannot sustain coronae, but chromospheres are still present (e.g. Suzuki 2007).

(2) *Pulsation-driven mass loss:* Larger, cooler stars have convective cells that occupy a significant fraction of the stellar surface. Convective turnover within these cells is thought to stochastically excite low-harmonic oscillations in the outer layers of the star, with later excitation by the κ-mechanism (e.g. Bedding et al. 2005). These pulsations drive powerful shocks through the outer atmosphere, observable as optical emission lines. These shocks may disrupt the ability of the chromosphere to heat plasma near the stellar surface, perhaps partly because they levitate material in the outer atmosphere, increasing the density in the chromospheric layer and above (e.g. McDonald & van Loon 2007). While pulsation amplitudes are well below the escape velocity, the damping energy released through shocks into the outer atmosphere could promote a multi-stage 'rocket', with each pulsation further levitating a fraction of the material below it, to a point where it can escape at an

atomic level (Jeans escape) or bulk level (turbulent motion) (e.g Freytag 2017).

(3) *Radiation-driven mass loss:* The increase in density in cooler layers allows the plasma layer to become neutral and then molecular. When a certain density is reached, dust can condense: typically at $\sim$1000 K and $\sim$2 R_*. Refractory, transparent dust condenses near the star (e.g. Al_2O_3, Mg_2SiO_4), whereas more volatile, opaque dust may not condense until $\gtrsim$10 R_* (e.g. Fe_2SiO_4), and then only if densities are sufficiently high (Gail & Sedlmayr 1999; Bladh et al. 2015).

Radiation pressure on this dust can force it from the star. Collisions between dust grains and the surrounding gas partly couple the media, driving both from the star, though perhaps with some lag or "drift" velocity between the two (Willson 2000). Around carbon stars, (hydrogenated) amorphous carbon is both opaque and refractory, so these winds are easy to drive. However, theoretical studies of oxygen-rich stars have difficulty creating enough absorption to effectively drive the wind without overheating the grains (Woitke 2006). Scattering of light has been invoked as an alternative way to transfer momentum (Höfner 2008), but this requires the grains to be very large ($\gtrsim$1 μm) compared to expectations ($\lesssim$0.1 μm).

(4) *Supernovae:* If a star is sufficiently massive and/or exhibits sufficiently little mass loss, it will reach the minimum mass required to undergo a supernova, either through electron capture or core collapse (e.g. Karakas & Lattanzio 2014).

While supernovae are too energetic to be otherwise affected, any of the first three mechanisms may be modified by other stellar processes, such as rotation or convective 'overshoot' into the upper stellar atmosphere.

3. Expectations

For a given star or population, we can expect different observables to be present, based on which mechanism(s) are operating:

(1) *Magneto-acoustic mass loss:* As stars evolve, they typically become larger, with lower magnetic flux per unit area. A larger surface area and reduced stellar gravity should promote higher mass-loss rates, but the lower heating rates should decrease the velocity at which this ejecta escapes (Suzuki 2007). Eventually, mass loss should become increasingly patchy and sporadic, the ejecta velocity may decline below the escape velocity of the star, and magnetism should stop being a major driving force of the wind. Mass-loss rates are predicted to follow some formalism like Reimers (1975) law: $\dot{M} \propto LR/M$ (see also Schröder & Cuntz 2005; Cranmer & Saar 2011), and be governed by the magnetic field strength which — while it varies from star to star — should not vary much with metallicity.

(2) *Pulsation-driven mass loss:* Convective cells and harmonic overtone modes may cause departure from a spherically symmetric wind. Although the wind experiences shocks, most of the wind should be sub-sonic, with a velocity and mass-loss rate that may be set by the pulsation properties of the star (amplitude, period and/or mode), rather than stellar properties such as luminosity or metallicity. It may not necessarily be a constant outflow, but episodic, with local fallback onto the star meaning that the wind is only an outflow as a temporally and spatially integrated average.

(3) *Radiation-driven mass loss:* Purely radiation-driven mass loss relies implicitly on radiation pressure from the star acting on dust grains, so we may approximate $\dot{M}v_\infty \propto L/Z$, with some additional inverse relation to the escape velocity at dust-forming radii (e.g. Ivezic & Elitzur 1997). Acceleration below the wind's sonic point results in an increase in mass-loss rate; and, above the sonic point, an increase in terminal velocity. Carbon-based dust can be produced internally by carbon stars, which should have a lower dependence on metallicity than oxygen-rich stars, hence we should see that the dependence of $\dot{M}$ and/or v_∞ with metallicity is lower for carbon stars, and will depend on the amount of free carbon they have (Lagadec & Zijlstra 2008).

(4) *Supernovae:* Whether a star undergoes a supernova depends on its mass-loss history. If radiation-driven mass loss is important, we can expect a lower total mass loss from metal-poor stars, so stars of lower initial mass will undergo supernovae. The rarity of supernovae

with well-characterised progenitors mean there are few observations to constrain this.

4. Observations

(1) *Magneto-acoustic mass loss:* Outflows from red giant branch stars are seen in their chromospherically active optical lines (Dupree, Hartmann & Avrett 1984). These observations are indeed modelled with increasing mass-loss rates and decreasing wind velocities as stars evolve, from $\sim 10^{-14}$ $M_\odot$ yr^{-1} and hundreds of km s^{-1} for the Sun, to $\sim 10^{-9}$ to 10^{-8} $M_\odot$ yr^{-1} and tens to 100 km s^{-1} near the horizontal branch (Dupree, Smith & Strader 2009), to $\sim 10^{-7}$ $M_\odot$ yr^{-1} and $\sim$10 km s^{-1} near the RGB tip (McDonald & van Loon 2007), with the caveat that these observations do not probe the wind's terminal phase. To first order, these winds are relatively well modelled by a Reimers-like formalism, with a constant of proportionality of $\eta \approx 2 \times 10^{-13}$ $M_\odot$ yr^{-1} (McDonald & Zijlstra 2015), but there are indications that $\dot{M}$ may increase more precipitously with luminosity (Dupree, Smith & Strader 2009; Heyl et al. 2015) and/or have a stronger mass dependence (Miglio et al. 2012). Most stars seem to survive this phase, with the likely exception of the lowest-mass, most-metal-poor stars, and a small percentage of helium-rich stars in globular clusters (McDonald & Zijlstra 2015).

(2) *Pulsation-driven mass loss:* Pulsation amplitudes grow as the star evolves and lower harmonics are excited. These pulsations drive powerful shocks through the outer atmosphere, observable as optical emission lines. These shocks may disrupt the ability of the chromosphere to heat plasma near the stellar surface: photometric variability becomes obvious, and shock signatures appear in the stellar spectra, at approximately the same time as circumstellar gas becomes visible in the radio and dust formation is seen in the infrared (McDonald & van Loon 2007). Both phenomena occur within the (bolometric) magnitude below the RGB tip at solar metallicity.

A clear onset of dust production is seen when stars reach $P \approx 60$ days, with infrared (e.g. $K - [22]$) colours stabilising until $P \approx 300$ days, when another increase is seen: the strong correlation with pulsation period and constancy of infrared colour suggests a pulsation-driven wind occurs in this regime (McDonald & Zijlstra 2016). Bulk motions recorded in the photosphere are relatively low, $\sim$10 km s^{-1}, and well below the escape velocity of the star (Hinkle & Barnbaum 1996). Typical expansion velocities and mass-loss rates seen at $60 \lesssim P \lesssim 300$ days are $\lesssim$10 km s^{-1} and $\sim 10^{-8}$ to $\sim 10^{-7}$ $M_\odot$ yr^{-1} (McDonald et al. 2016, & in prep.). It is important to sample gas mass-loss rates here, as infrared colours may be influenced by dust which is falling back onto the star, or otherwise not committed to leaving the system.

(3) *Radiation-driven mass loss:* Above $P = 300$ days, a good correlation exists between $\dot{M}$ and L, and v_∞ and L, implying that radiation driving of winds is important (Danilovich et al. 2015). These relations may saturate in the 'superwind' regime, where the wind becomes optically thick at $\sim 10^{-4}$ $M_\odot$ yr^{-1} (Vassiliadis & Wood 1993). Stars in this regime are typically pulsating with large amplitudes in the fundamental mode. However, a pulsation amplitude–period–luminosity relationship also exists (Kjeldsen & Bedding 2011; Wood 2015). Massive stars follow a similar trend, but the not the warmer supergiants which lack pulsations (e.g. α Ori versus VY CMa; Harper, Brown & Lim 2001; Richards et al. 2014). Hence, we expect a wind in these regimes to be driven both by pulsation and radiation pressure, with the relative energy input changing with radius (Willson 2000).

RGB versus AGB stars: It is very rare for RGB stars to reach $P > 60$ days or achieve large amplitude pulsations (Wood 2015), hence exceptionally few single RGB stars are expected to form dust. Conversely, the lowest-mass AGB stars (common in the oldest populations) will reach $P > 60$ days below the RGB tip. The lowest-mass metal-rich AGB stars reach these criterion from $\sim$700 $L_\odot$ (McDonald et al. 2011a; McDonald, Zijlstra & Boyer 2012), and the luminosity function of dusty sources does not change across the RGB tip (McDonald & Zijlstra 2016), suggesting that the transition from magneto-acoustic to pulsation-/dust-driven winds only occurs on the AGB.

Metallicity dependences: The metallicity dependence of these processes requires further work. RGB mass loss is only significant in low-mass stars, and is seen to be largely metallicity independent (McDonald & Zijlstra 2015). The onset of dust production at the lowest stellar masses is observed to increase to above the RGB tip by [Fe/H] ~ –1.2 dex (Boyer et al. 2009). However, the infrared colours (dust opacities) seen in metal-poor globular cluster stars are identical (at a given period) to those of nearby stars, despite the globular cluster stars having fewer condensible metals (McDonald et al., in prep.). Preliminary observations of nearby dwarf galaxies show substantial carbon- and oxygen-rich dust production down to at least [Fe/H] ~ –1.3 dex in more luminous sources (Boyer et al. 2015, & in prep.). The translation of these dust column opacities to mass-loss rates remains controversial, as it depends on assuming properties about dust opacity per unit mass and terminal wind velocities (McDonald et al. 2011b). Gas mass-loss rates of metal-poor stars exist in the Magellanic Clouds (Groenewegen et al. 2016; Matsuura et al. 2016), but not at low enough metallicity to elucidate the metallicity dependences of mass-loss rates for higher-mass AGB stars. Further observations are encouraged in this regime.

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