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The Formation of Planetary Nebulae: Mass Loss Mechanisms of Late-Stage AGB Stars

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1. INTRODUCTION

The asymptotic giant branch (AGB) is a region on the Hertzsprung-Russell diagram populated by low- to intermediate-mass stars late in their lives. Stars in this region range from $0.6 - 10\ M_\odot$. However, knowing that stars in this mass range eventually become white dwarfs, and that white dwarfs have a maximum (stable) mass of $1.4 M_\odot$ (Chandrasekhar limit), it is apparent that these stars must have lost the majority of their mass—up to several solar masses—at some point in their evolution Willson & Bowen (1984). A natural question to ask would be how such stars shed their mass.

Mass loss is of critical importance in the discussion of the formation of planetary nebulae. Main sequence stars lose most of their mass as they evolve, and the majority of that mass loss takes place on the AGB track. This lost mass is partially composed of gases which are eventually responsible for the planetary nebulae that we see—a planetary nebula (abbreviated PN or plural PNe) is an interstellar cloud composed of ionized gases ejected from a low- to intermediate-mass star near the end of its stellar lifetime. However, not all gases appear as PNe—the vibrant colours associated with PNe are caused by ionizing ultraviolet radiation from the central star (CSPN). For the glow to be visible, the CSPN must have a temperature of at least $30,000$ K, and the density in the cloud should be be upwards of 100 particles per cm^3 (Prialnik 2000).

This paper aims to explore the transition of AGB stars as they shed mass to form planetary nebulae, as well as the mechanisms that drive the transition. Despite the fact that the physics behind some of these mechanisms is not well understood quantitatively (Blöcker 2001), an attempt will be made to present theories on the formation of PNe.

2. STELLAR WINDS

Stellar winds are outflows of gas which cause the ejection of material in the stellar atmosphere into what is called a *circumstellar envelope (CSE)*. In order for these gases to be ejected from the star such that they are no longer gravitationally bound to the (core of the) star, they must be accelerated past the escape velocity of the star. For late-stage AGB stars, which typically have radii several hundred times that of the sun, but are not significantly larger in mass (Höfner & Olofsson 2018). Given the relation $g \propto \frac{M}{R^2}$, the lower surface gravity of AGB stars means that material is much more easily ejected relative to stars earlier in their evolutionary lifetimes. The dynamics of stellar winds are complex and varied—there are coronal winds, sound-driven winds, dust-driven winds, magnetic rotating winds, Alfvén wave driven winds, line driven winds, etc. (Lamers & Cassinelli 1997)

For cooler stars with temperatures in the range of $\sim 3000\,K$, stellar winds are primarily of the dust-driven variation. Radiation pressure from the star imparts its momentum onto grains of dust which are able to condense in the upper atmospheres of these stars due to the lower temperatures. When dust condenses, the opacity to radiation is increased, and thus, the radiation pressure, directed radially outwards, is able to eject this dust away from the star. Through *momentum coupling*, the dust is able to to transfer its momentum to the surrounding gases, and, in a sense, "carry" the gases away from the star (Gilman 1972). These dust-driven winds have terminal velocities in the range of $10 - 30\ \mathrm{km\,s^{-1}}$ (Lamers & Cassinelli 1997). Because these dust grains can absorb radiation over a broad range of wavelengths, this mechanism of mass loss is also called *continuum driven* winds.

Unfortunately, as reliable (theoretical) models are not available, many turn to the following empirical formula by Reimers (1975) for estimating mass loss due to dust-driven stellar winds:

$$\dot{M} = -4 \times 10^{-13}\,\eta \left(\frac{L_* R_*}{M_*}\right)\ \mathrm{M_\odot\,yr^{-1}},\ \eta \sim 1 \qquad (1)$$

where $\dot{M}$ is the rate of mass loss, and L_*, R_*, and M_* are stellar luminosity, radius, and mass, respectively, given in solar units. The fitting parameter η is determined empirically. Knowing the approximate stellar parameters of late-stage AGB stars allows us to estimate the amount of mass lost. AGB stars are typically several thousand times as luminous as the Sun, several hundred times larger in radius, and have a mass of several solar masses. This roughly gives us a mass loss rate on the order of 10^{-6} $\mathrm{M}_\odot\,\mathrm{yr}^{-1}$.

Many other mass loss models, such as ones given by Schröder & Cuntz (2005) for low-gravity stars, or the one given by Equation 2, are merely variations of Reimers' equation with additional terms to better fit empirical observations. For example, Volk & Kwok (1988) give the following equation as an improvement for estimating mass loss in AGB stars:

$$\dot{M} = -1.8 \times 10^{-12}\, \frac{M_*(0)}{8M_\odot} \left(\frac{L_* R_*}{M_*} \right) \mathrm{M}_\odot\,\mathrm{yr}^{-1}, \quad (2)$$

where $\dot{M}$, L_*, R_*, and M_* are defined as before, $M_*(0)$ is the (initial) main sequence mass of the star, and $M_\odot$ is the mass of the Sun. It can be seen that this is Equation 1 with an additional term and a modified fitting parameter.

We can use Equation 2 to make an estimate for AGB mass loss as before, where the main sequence mass is on the upper limit ($\sim 8M_\odot$), and stellar mass, luminosity, and radius are on the orders of 10^0, 10^4, and 10^2 respectively (as before). Doing the calculation yields a mass loss rate on the order of 10^{-6} $\mathrm{M}_\odot\,\mathrm{yr}^{-1}$. This is similar to the result we computed previously using Equation 1, which perhaps, along with its simplicity and general applicability, explains—despite the purported improvements by various alternatives—the long-standing and widespread usage of the Reimers equation.

2.1. *Superwinds*

The simple conclusion that PNe are made of the diffuse material from the CSE of an AGB star is a natural one. However, Kwok (2000) identifies several problems: (i) the densities of PNe shells are higher than that of those in the CSE of AGB stars, (ii) the shell- and bubble-like structures of PNe are well-defined with sharp boundaries, rather than diffuse like the CSE of AGB stars, (iii) and the observed expansion velocities of PNe are higher than that of stellar winds in AGB stars.

This evidence points to a so-called *superwind*, which is a rapid ejection of material caused by a sharp increase in the rate of mass loss at the very end of an AGB star's lifetime. Kwok et al. (1978) propose that as this superwind is ejected from the star at extreme velocities (on the order of 10^3 $\mathrm{km\,s^{-1}}$), it crashes into the existing, previously ejected stellar material (which travels out at much lower speeds of $10-20$ $\mathrm{km\,s^{-1}}$). The compression of the slower winds by the fast wind causes the formation of the definite structure that is seen in PNe.[1]

After a superwind ejects the bulk of the circumstellar envelope from the star, the conditions for the formation of a planetary nebula are nearly met.[2] As the CSPN continues burning its fuel and contracting, it heats up. This continues on until it reaches a temperature of approximately $30,000$ K, at which point the photons that it emits are sufficiently energetic to ionize the surrounding gases. The electrons in the atoms of the gases are excited, and as they drop down to lower energy levels, they re-radiate in the visible spectrum, giving the characteristic glow of PNe. The cause of this superwind is not entirely clear, but a potential source of the exponential increase in mass loss is the pulsation of AGB stars.

3. PULSATION THEORY

PNe play an important role in the enrichment of the interstellar medium (ISM) and galaxies. During the later stages of an AGB star's lifetime (when it is classified as a thermally-pulsating AGB star, or TP-AGB star), thermal pulses caused by the unstable double-shell burning cause metals from the core to be mixed into the outer layers of the star in a processed called *dredge-up*. When a PN is formed, stellar winds carry these heavier elements—which are now closer to the surface of the star and thus are easier to expel—into the ISM (Iben & Renzini 1983).

As it turns out, apart from being responsible for ISM enrichment, pulsation also has consequences on the mass loss of the star. Pulsation causes fluctuations in stellar radius as the star tries to maintain equilibrium despite thermal instability. Consequently, shock waves are produced, which levitate material in the atmosphere. If we think of mass loss as the rate at which some amount of material in a spherically symmetric shell[3] is moving away from the star, then we have the relation

$$\dot{M} = 4\pi r^2 \rho v, \quad (3)$$

[1] This is perhaps analogous to the "snow-plow" phase of supernovae (e.g. Moriya (2014); McCray & Kafatos (1987)).

[2] This is when something called a *protoplanetary nebula* is formed.

[3] Spherical symmetry turns out to not be a good assumption. Further discussed in §4.

where $\dot{M}$ is mass loss rate, ρ is the density of material, and v is the velocity of outflow of material.

Because pulsation causes more material to be present in the stellar atmosphere, density and opacity to radiation increase, and this means that there is a greater potential for mass to be lost to radiation pressure (Liljegren et al. 2017).

3.1. *Mira Variables*

Of particular interest in this discussion are Mira variables, which are a particularly promising (in terms of candidacy for being the progenitors for PNe) class of stars at the top of the AGB track with pulsation periods on the order of a year. As Miras evolve, the period of their pulsation of period increases (Fadeyev 2017). This is significant for multiple reasons.

Empirically, Mira variables are known to have a positive period-luminosity relation (Robertson & Feast 1981; Glass & Evans 1981) as seen in Figure 1.

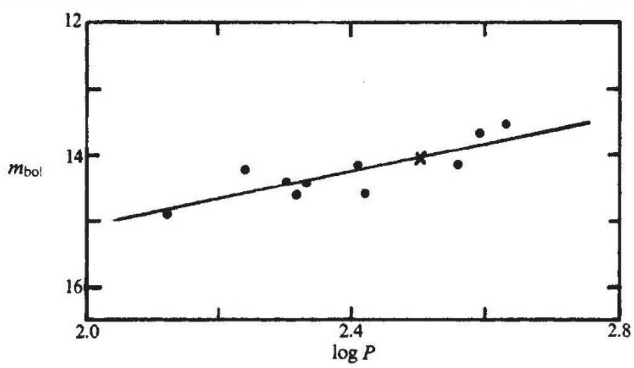

Figure 1. Period (logarithmic) in days plotted on the x-axis against apparent bolometric magnitude on the y-axis for Mira variables in the LMC (Glass & Evans 1981).

This period-luminosity relation implies that Miras near the end of their lifetimes have higher luminosities.[4] This increased luminosity, being linked to increased radiation pressure, implies that mass loss by stellar winds is greater (see §2).

Moreover, when a star begins pulsating with a period of 60 days, mass loss due to pulsation is initiated. After some time, as the pulsation period increases to ~ 300 days, the star transitions to the fundamental pulsation mode, and mass loss increases by a factor of ~ 100 (McDonald & Zijlstra 2016; Bedijn 1986). This sharp increase in mass loss rate at $P \sim 300$ days is supported by empirical data from Vassiliadis & Wood (1993), who observed that relation the between pulsation period and mass loss for Miras (and for OH/IR stars[5]) is exponential, as seen in Figure 2.

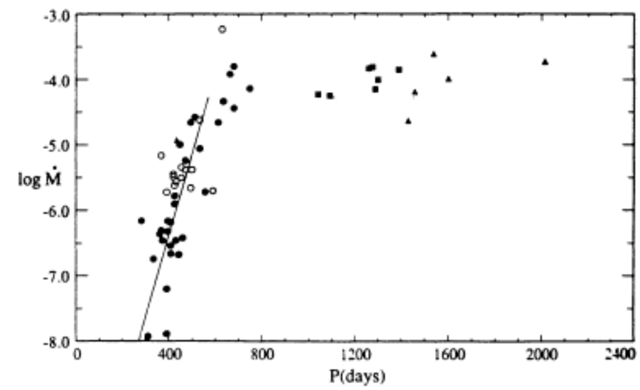

Figure 2. Pulsation period plotted against mass loss rate in $M_{\odot}\, yr^{-1}$ for Mira variables (circles) and for OH/IR stars in the Galaxy (triangles) and the LMC (squares) (Vassiliadis & Wood 1993).

For period P measured in days, and mass loss rate $\dot{M}$ measured in solar masses per year, Vassiliadis & Wood (1993) give the relation

$$\log \dot{M} = -11.4 + 0.0123\, P \tag{4}$$

for stars with $M \leq 2.5 M\odot$, and

$$\log \dot{M} = -11.4 + 0.0125 \left(P - 100 \left(\frac{M_*}{M_\odot} - 2.5 \right) \right) \tag{5}$$

for stars with $M \geq 2.5 M\odot$. From these equations, it can be seen that there is an exponential increase in the mass loss rate towards the end of an AGB star's life.

We can apply these quantitative relationships to make some estimates. Let us consider Omicron Ceti, also called Mira (the namesake/prototype for the Mira class of stars), with stellar parameters $P = 332$ days, $M_* = 1.18 M_\odot$ (Wyatt & Cahn 1983), $L_* \simeq 9000 L_\odot$, and $R \simeq 370 R_\odot$ (Woodruff, H. C. et al. 2004). Using Equation 1, a simplistic formula which disregards pulsation, we obtain a mass loss rate of $1.12 \times 10^{-6}\ \mathrm{M_\odot\, yr^{-1}}$, which is far lower than observed mass loss rates for similar stars. Taking into account pulsation-induced mass loss,

[4] Luminosity is written such that more negative numbers indicate greater luminosity.

[5] These are a "class of objects associated with late type giant stars that may be a later stage in the development towards the planetary nebula, either after the Mira phase or in place of it" (Pottasch 1984).

we apply Equation 4 to obtain 6.6×10^{-4} M$_\odot$ yr^{-1}, which is much closer to empirical values. Considering that we previously estimated mass loss in §2 to be on the order of 10^{-6} M$_\odot$ yr^{-1}, this also aligns with the expected increase by a factor of $\sim$ 100. This rate of mass loss conveniently happens to be in the approximate range of mass loss due to superwinds (Iben & Renzini 1983).

4. ASYMMETRY

The complexity of interactions between all of these physical processes means that much remains unclear. There is a lack of powerful, universal theoretical models that can be used to explain how PNe form. In particular, it is unclear what gives rise to the incredible variety of shapes of PNe. Assumptions of stellar winds (and thereby PNe) being spherically symmetric may help simplify and improve our understanding of the processes, but are known to be inaccurate. In fact, roughly 80 − 90% of PNe are not spherical (De Marco 2014; Soker 1997). Woitke (2006) performed hydrodynamical simulations of dust-driven stellar winds, and concluded that turbulent dust formation and flow instabilities (e.g. Rayleigh-Taylor) in stellar atmospheres lead not to symmetric, but to inhomogeneous and asymmetric dust production as seen in Figure 3.

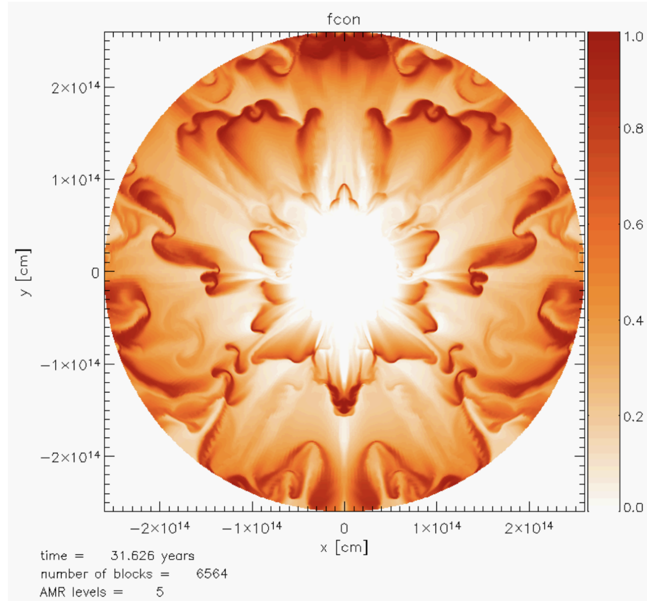

Figure 3. Snapshot of a 2D non-spherically model for dust condensation for $M_* = 1M_\odot$, $L_* = 10000L_\odot$, $T_* = 2500$ K. The solution becomes chaotic (Woitke 2006).

If we accept that Miras are the progenitors to PNe, then then this asymmetry may be explained by the asymmetry of Miras themselves. Ragland et al. (2006) observed, using the IOTA telescope, that for well-resolved stars, 75% of AGB stars, and 100% of oxygen-rich Mira stars show asymmetry" ($n = 16$).

One possible explanation for this observed asymmetry lies in binary star systems. The dynamic interactions between two stars of similar or different masses, as well as the physical and temporal nature of the interactions, can all play a role in the formation of PNe. For example, Soker (1998) postulates that bipolar nebulae (e.g. M2-9), which are characterized by twin lobes around the CSPN and account for 10−20% of PNe, are formed from binary stellar systems in which the secondary diverts a significant amount of the mass lost by the AGB primary, and the systems are only in a common envelope phase very briefly. Binary systems have also been found at the center of the Stingray Nebula, the youngest known PN (Bobrowsky et al. 1998), and at the center of the Red Rectangle, a rectangular protoplanetary nebula[6] (Cohen et al. 1975) However, the causes for asymmetry, and more generally, the astounding complexity and diversity of the morphology of PNe, remain far from absolute.

5. SUMMARY

This paper explores the mechanisms behind the mass loss that drives the transition of a low- to intermediate-mass star from the AGB track to the formation of a planetary nebula. Stellar winds and stellar pulsation are given as the primary drivers for mass loss, and quantitative relations are discussed. In particular, mass loss induced by stellar winds are proportional to luminosity, and inversely proportional to surface gravity. Pul-

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[6] A protoplanetary nebula (PPN), as noted earlier, is an object formed between the transition from AGB to PN. The radiation from the CSPN, which is at this point below the 30,000 K lower bound required to ionize the gases, is scattered/reflected by the gases, causing the PPN to be visible.

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