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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 is a region on the HR 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 $1.4M_{\odot}$ (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. MS 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. Fortunately for late-stage AGB stars, "typical stellar radii [are] of several hundred solar radii. In combination with... masses well below 8 $M_{\odot}$, the resulting surface gravities are typically 4–5 orders of magnitude below that of a Sun-like star" (Höfner & Olofsson 2018). The low surface gravity means that material is much more easily ejected from late-stage AGB stars than for Sun-like stars, or other 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. In this process, the dust carries surrounding gases with it away from the star—"small grains are adequetely coupled to the gas in the sense that they efficiently communicate the momentum they absorb from the radiation field to the gas, and that momentum is effectively diffused throughout the gas" (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 stellar winds:

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

where L_*, R_*, and M_* are given in solar units. This model assumes that mass loss is proportional to luminosity (radiation pressure), and inversely proportional to surface gravity. 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 $10^{-6}\ \mathrm{M_\odot\,yr^{-1}}$.

Many other mass loss equations, such as the following one given by Schröder & Cuntz (2005) as an improvement for estimating mass loss in giants with low gravity, are merely variations of Reimers' equation:

$$\dot{M} = \eta\,\frac{L_* R_*}{M_*}\left(\frac{T_{eff}}{4000\,K}\right)^{3.5}\left(1 + \frac{g_\odot}{4300 g_*}\right),$$

where L_*, R_*, and M_* are defined as before, g_* and $g_\odot$ are the stellar and solar surface gravity respectively, and $\eta = 8(\pm1) \times 10^{-14}\ \mathrm{M_\odot\,yr^{-1}}$.

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

[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.

of material in a spherically symmetric shell[3] is moving away from the star, then we have the relation

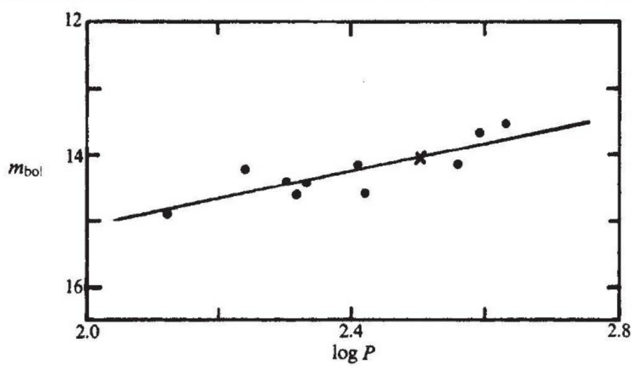
$$\dot{M} = 4\pi r^2 \rho v.$$

Because pulsation causes more material to be present in the stellar atmosphere, density (and opacity) increases, 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.

Mira variables are known to have a period-luminosity relation; using period and luminosity data from Mira variables in the Large Magellanic Cloud (LMC) as seen below,



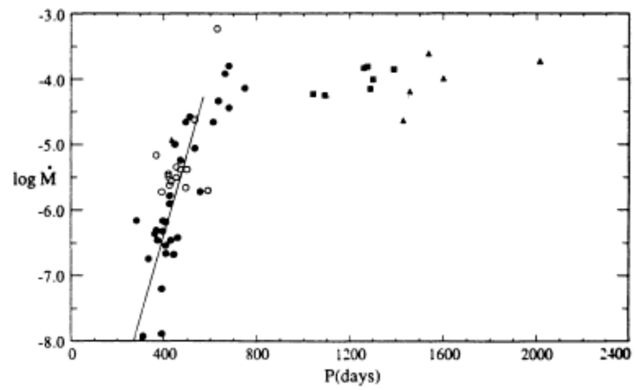
Glass & Evans (1981) give a period-luminosity relation for Mira variables:

$$m_{bol} = 19.25 - 2.09 \log P.$$

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 the following between pulsation period and mass loss for Miras:



Vassiliadis & Wood (1993) give the relation

$$\log \dot{M}\ [\mathrm{M_\odot\,yr^{-1}}] = -11.4 + 0.0123\,P\ [\mathrm{days}]$$

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

$$\log \dot{M}\ [\mathrm{M_\odot\,yr^{-1}}] = -11.4 + 0.0125\left(P\ [\mathrm{days}] - 100\left(\frac{M_*}{M_\odot} - 2.5\right)\right)$$

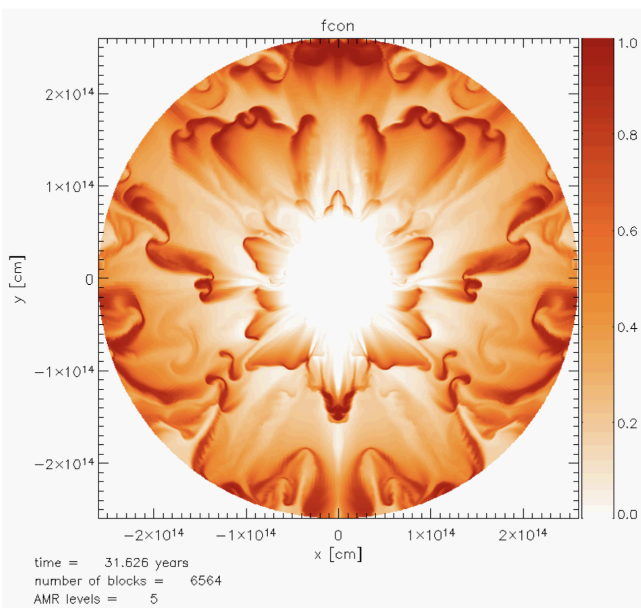
for stars with $M \geq 2.5M\odot$. From these equations, it can be seen that there is an exponential increase in the mass loss rate towards the end of an AGB star's life. This increase by a factor of ~ 100 from before (we approximated the mass loss rate to be $10^{-6}\ \mathrm{M_\odot\,yr^{-1}}$) puts the rate of mass loss at $10^{-4}\ \mathrm{M_\odot\,yr^{-1}}$, which happens to be approximately the mass loss rate due to superwinds (Iben & Renzini 1983).

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

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

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 "highly dynamical and turbulent dust formation [zones]" and flow instabilities (e.g. Rayleigh-Taylor) in stellar atmospheres lead not to symmetric, but to inhomogeneous and asymmetric dust production as seen in the figure below:



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 substantial fraction of the mass lost by the asymptotic giant branch (AGB) primary, but the systems avoid the common envelope phase for a large fraction of the interaction time." 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[5] (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. Pulsation period increases as a star ages, causing mass loss to increase exponentially to rates on the order of 10^{-4} $M_\odot$ yr^{-1}. This culminates in a final "superwind", which is ultimately responsible for the formation of PNe. The candidacy of Mira variables as the progenitors for PNe is discussed in the context of these mass loss mechanisms, and theories explaining the wide range of shapes of PNe are considered.

[5] 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.

REFERENCES

Bedijn, P. J. 1986, in Light on Dark Matter, ed. F. P. Israel (Dordrecht: Springer Netherlands), 119–126

Bisnovatyi-Kogan, G. S. 2011, Stellar Physics (Springer-Verlag Berlin Heidelberg), doi: 10.1007/978-3-642-14734-0

Blöcker, T. 2001, Astrophysics and Space Science, 275, 1, doi: 10.1023/A:1002777931450

Bobrowsky, M., Sahu, K. C., Parthasarathy, M., & García-Lario, P. 1998, Nature, 392, 469, doi: 10.1038/33092

Cohen, M., Anderson, C. M., Cowley, A., et al. 1975, ApJ, 196, 179, doi: 10.1086/153403

De Marco, O. 2014, in Asymmetrical Planetary Nebulae VI Conference, 122

Fadeyev, Y. A. 2017, Astronomy Letters, 43, 602–613, doi: 10.1134/s1063773717080059

Gilman, R. C. 1972, ApJ, 178, 423, doi: 10.1086/151800

Glass, I. S., & Evans, T. L. 1981, Nature, 291, 303, doi: 10.1038/291303a0

Habing, H. J. 1990, in From Miras to Planetary Nebulae: Which Path for Stellar Evolution?, ed. M. O. Mennessier & A. Omont, 16

Höfner, S., & Olofsson, H. 2018, A&A Rv, 26, 1, doi: 10.1007/s00159-017-0106-5

Iben, I., J., & Renzini, A. 1983, ARA&A, 21, 271, doi: 10.1146/annurev.aa.21.090183.001415

Kwok, S. 2000, The Origin and Evolution of Planetary Nebulae (Cambridge University Press), doi: 10.1017/CBO9780511529504

Kwok, S., Purton, C. R., & Fitzgerald, P. M. 1978, ApJL, 219, L125, doi: 10.1086/182621

Lamers, H. J. G. L. M., & Cassinelli, J. P. 1997, Introduction to Stellar Winds (Cambridge University Press), doi: 10.1023/A:1001827020719

Liljegren, S., Höfner, S., Eriksson, K., & Nowotny, W. 2017, Astronomy Astrophysics, 606, A6, doi: 10.1051/0004-6361/201731137

McCray, R., & Kafatos, M. 1987, ApJ, 317, 190, doi: 10.1086/165267

McDonald, I., & Zijlstra, A. A. 2016, The Astrophysical Journal, 823, L38, doi: 10.3847/2041-8205/823/2/l38

Moriya, T. J. 2014, On the 'snow-plow' phase of supernovae interacting with dense circumstellar media. https://arxiv.org/abs/1402.2519

Pottasch, S. 1984, Planetary Nebulae (Cambridge University Press), doi: 10.1007/978-94-010-0320-9_40

Prialnik, D. 2000, An Introduction to the Theory of Stellar Structure and Evolution (Cambridge University Press)

Ragland, S., Traub, W. A., Berger, J.-P., et al. 2006, The Astrophysical Journal, 652, 650, doi: 10.1086/507453

Reimers, D. 1975, Memoires of the Societe Royale des Sciences de Liege, 8, 369

Schröder, K.-P., & Cuntz, M. 2005, The Astrophysical Journal, 630, L73–L76, doi: 10.1086/491579

Soker, N. 1997, ApJS, 112, 487, doi: 10.1086/313040

Soker, N. 1998, The Astrophysical Journal, 496, 833, doi: 10.1086/305407

Vassiliadis, E., & Wood, P. R. 1993, ApJ, 413, 641, doi: 10.1086/173033

Willson, L. A., & Bowen, G. H. 1984, Nature, 312, 429, doi: 10.1038/312429a0

Woitke, P. 2006, A&A, 452, 537, doi: 10.1051/0004-6361:20054202