Formation of Planetary Nebulae

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1 Introduction

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A planetary nebula (abbreviated PN or plural PNe) is an interstellar cloud composed of ionized gas ejected from a low- to intermediate-mass star near the end of its stellar lifetime. Although this progenitor star begins its life with several solar masses, it ends its life as a white dwarf, which is at most 1.4 solar masses. A natural question to ask would be how that asymptotic-giant-branch star sheds its mass. This paper aims to to explore the transition of AGB stars as they form a 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 [17], an attempt will be made to present theories on the causes of formation of 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 30,000K, and the density in the cloud should be be upwards of 100 particles per cm^{-3}.

2 Mass Loss

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 $M_\odot$. source? 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 the more massive AGB stars must have lost multiple solar masses at some point in their evolution.

Mass loss plays a pivotal role in the formation of PNe, as it explains why a massive AGB star of, for example, $8M_\odot$ forms a PN and becomes a white dwarf rather than becoming a neutron star.

3 Pulsation Theory

PNe play an important role in the enrichment of the interstellar medium (ISM) and galaxies. During the later stages of and AGB star's lifetime (when it is classified as a thermally-pulsating AGB star, or TP-AGB star), a thermal pulse caused by the unstable double-shell burning causes 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. [14]

As it turns out, this pulsation also has other consequences on the mass loss of the star. Pulsation causes fluctuations in stellar radius and consequently, produces shock waves which levitate material in the atmosphere. If we (naively) think of mass loss as the rate at which some amount of material in a spherically symmetric shell [1] is moving away from the star, then we have the relation

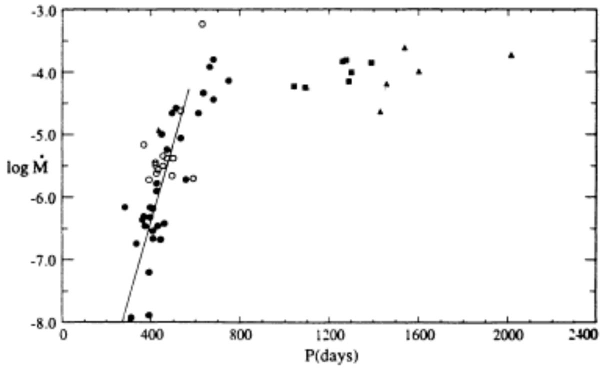
$$\dot{M} = 4\pi r^2 \rho v.$$

Because pulsation causes more material to be present in the stellar atmosphere, density increases, and as we have already seen before, radiationand that means more mass is loss.

McDonald and Zijlstra found that when a star begins pulsating with a period of 60 days, mass loss is triggered, and "a second rapid mass-loss-rate enhancement is suggested when the star transitions to the fundamental pulsation mode,

[1] Symmetry turns out to be, for the most part, an incorrect assumption.

at a period of 300 days."[8] This sharp increase in mass loss rate at $P \sim 300$ days is supported by empirical data from Vassiliadis and Wood [21], who found the following relation between pulsation period and mass loss for Miras:



The researchers give the relation

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

for stars with $M \leq 2.5 M\odot$, and help how to write this without it being really ugly?

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

for stars with $M \geq 2.5 M\odot$.

4 Stellar Winds

For cooler stars, this material is mainly composed of dust grains which have condensed in the outer atmospheres. "The grains can absorb radiation over a broad range of wavelengths, so the outflows of the cool stars are said to be 'continuum driven' winds." [10] what wind speeds??? 10km/s. source?

Unfortunately, as reliable (theoretical) models are not available, many turn to Reimers' formula [16] for mass loss by stellar winds:

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

where L_*, R_*, and M_* are given in solar units.

Many other mass loss equations, such as the one given by Schröeder and Cuntz [18] as an improvement—although it is "not applicable to molecule-driven, dust-driven, and pulsational winds"—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 $\eta = 8(\pm 1) \times 10^{-14}\ \mathrm{M}_\odot\,\mathrm{yr}^{-1}$.

In order for gases to be ejected from 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" [7]. Thus, the low surface gravity makes something about it being easier to eject matter

Stellar winds causes the ejection of material into what is called a *circumstellar envelope (CSE)*. This material is no longer gravitationally bound to the core of the star. source? "In the case of hot early-type stars the winds are driven by the scattering of radiation by line opacity, so their outflows are called 'line driven' winds." [10] these winds can reach speeds of up to 2000km/s. source?

nobody really knows what causes superwinds

interacting stellar winds model

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. 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.

5 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 as being spherically symmetric around a star may help simplify and improve our understanding of the processes, but are known to be inaccurate. Woitke performed hydrodynamical simulations of dust-driven stellar winds, and concluded that "highly dynamical and turbulent dust formation [zones]" and flow (e.g. Rayleigh-Taylor) instabilitities [20] in stellar atmospheres lead not to symmetric, but to inhomogeneous and asymmetric dust production as seen in the figure below:

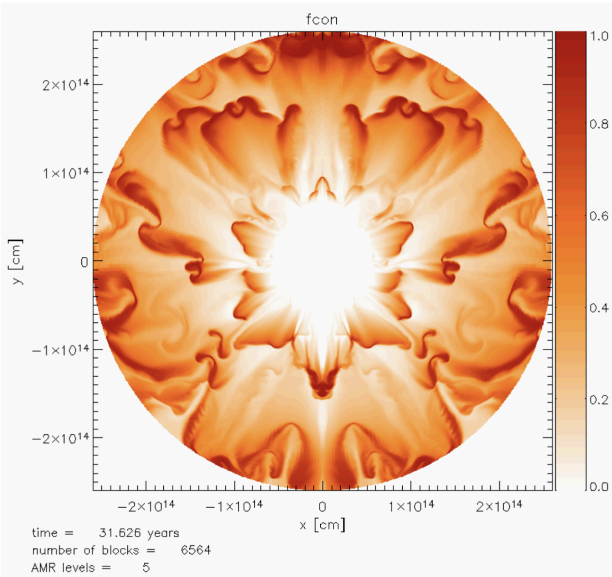


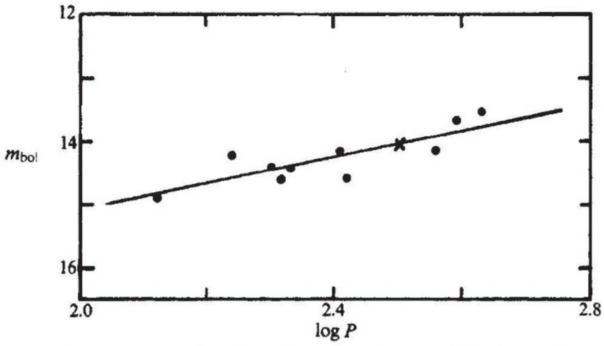
figure or not? something about binaries here maybe?

6 Mira Variables

Using data from Mira variables in the Large Magellanic Cloud (LMC), Glass and Evans give a period-luminosity relation for Mira variables:

$$M_{bol} = 0.76\,(\pm 0.11) - 2.09 \log P \text{ [5].}$$

This suggests that for Mira stars with higher periods (and thus are further along in their stellar evolution) have higher luminosities. Some LMC Miras are plotted in the figure below:



how this relates to reimers formula (which also assumes mass loss (which is really just gravitational energy carried away by stellar winds) is proportional to luminosity)

Ragland et. al. observed, using the IOTA telescope, that for well-resolved stars, "75% of AGB stars, 100% of oxygen-rich Mira stars show asymmetry" [15]. This is further evidence that Mira stars are the progenitors for PNe.

6.1 Readings

https://www.cfa.harvard.edu/research/oir/planetary-nebulae

https://en.wikipedia.org/wiki/Protoplanetary$_{n}ebula$

https://web.williams.edu/Astronomy/research/PN/nebula

https://www.spacetelescope.org/images/potw1530a/

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7 Conclusion???

quick summary of everythin here

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