Why Galaxies Care About AGB Stars:
A Continuing Challenge through Cosmic Time
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The missing mass conundrum of post-common-envelope planetary nebulae

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Abstract. Most planetary nebulae (PNe) show beautiful, axisymmetric morphologies despite their progenitor stars being essentially spherical. Angular momentum provided by a close binary companion is widely invoked as the main agent that would help eject an axisymmetric nebula, after a brief phase of engulfment of the secondary within the envelope of the Asymptotic Giant Branch (AGB) star, known as a common envelope (CE). The evolution on the AGB would thus be interrupted abruptly, its (still quite) massive envelope fully ejected to form the PN, which should be more massive than a PN coming from the same star were it single. We test this hypothesis by deriving the ionised+molecular masses of a pilot sample of post-CE PNe and comparing them to a regular PNe sample. We find the mass of post-CE PNe to be actually lower, on average, than their regular counterparts, raising some doubts on our understanding of these intriguing objects.

Keywords. (ISM:) planetary nebulae: general, (stars:) binaries: close, ISM: jets and outflows

1. Introduction

Most planetary nebulae (PNe) show beautiful, aspherical morphologies with high degrees of symmetry, despite their progenitor stars being essentially spherical. The mechanism behind their shaping, however, is still poorly understood (e.g. Balick & Frank 2002). Angular momentum provided by a close binary companion has been widely invoked as the main shaping agent that would eject an axisymmetric nebula (Jones & Boffin 2017).

The mechanism in close binary systems is thought to be as follows: a star undergoing the Asymptotic Giant Branch (AGB) stage engulfs a companion via Roche-lobe overflow as it expands during the AGB phase. The system then undergoes a very brief (∼1 year) common-envelope (CE) stage, where the evolution of the AGB star is abruptly interrupted. Spiraling-in of the secondary and drag forces would then lead to the ejection and shaping of this CE into a bipolar PN whose equator would be coincident with the orbital plane of the binary star, as happens to occur in every single case analysed so far (Hillwig *et al.* 2016).

On theoretical grounds, however, the physics of the CE "friction" and ejection processes remain very elusive. Simulations show most of the gas to be ejected along the equatorial plane, but are unable to gravitationally unbind the whole envelope of the AGB (e.g. Huarte-Espinosa *et al.* 2012, García-Segura, Ricker & Taam 2018). An exception would imply tapping energy from atomic recombination in the envelope (e.g. Ohlmann *et al.* 2016), but then the achieved expansion velocities would likely be too large.

This draws a somewhat uncomfortable big picture: we simply do not understand the physics lying behind the death of a significant fraction of stars in the Universe.

Single star vs. CE evolution: the total nebular mass. It can be argued that CE evolution implies significant differences in the mass-loss history of the primary star.

Let us consider a single AGB star on its way to produce a PN. Most of its envelope's mass is slowly lost along the AGB evolution, and gets too diluted in the Interstellar Medium (ISM) to be detected. In contrast, the mass lost by the star during the superwind phase (last ∼500-3000 years), which amounts to ∼0.1-0.6 $M_\odot$ for a 1.5 $M_\odot$ star (see review by Höfner & Olofsson 2018), will form the nebula visible during the PN stage.

On the other hand, let us consider the same AGB star, but now as part of a binary system close enough to engulf its companion and undergo a CE stage. AGB engulfment will thus occur during the last few (∼1-20) million years of the AGB stage (e.g. Fig. 1 in MacLeod, Guillochon & Ramirez-Ruiz 2012), effectively interrupting the evolution of the star. All the mass the star did not lose into the ISM during these last million years will be present in the CE, and therefore will *also* be part of the PN as it is suddenly ejected.

In other words, despite the large uncertainties in the mass-loss history along the AGB, *PNe arising from CE events should, on average, be more massive than their single star counterparts.*

This additional mass should be detectable, as it will be close to the central stars during the lifetime of the PN, as opposed to the single star case, where it will be long gone, diluted into the ISM. Testing this hypothesis would lead to a better understanding of the ejection process. Nevertheless, complete mass determinations of post-CE PNe are virtually nonexistent. Here we present the results of a pilot survey of this kind.

2. Sample and Observations

Our pilot sample is composed of 10 post-CE PNe, which amount roughly to 1/6th of the total currently known. It covers a broad range of kinematical ages, central star effective temperatures and luminosities, orbital periods and morphologies. These objects are PM 1-23, Abell 41, Hen 2-428, ETHOS 1, NGC 6778, Abell 63, the Necklace, V458 Vul, Ou 5, and NGC 2346. They lacked any attempt at detecting their molecular content by means of radioastronomical observations, except for NGC 6778 (not detected by Huggins & Healy (1989)), and NGC 2346, already known to host a massive molecular envelope (e.g. Bachiller *et al.* 1989). We therefore carried out spectral observations of the sample (except NGC 2346), in search for ^{12}CO and ^{13}CO J=1-0 and J=2-1 emission, using EMIR on the IRAM 30 m radio telescope. The angular size of the objects of the sample is generally well suited to the telescope Half Power Beam Width at the observed frequencies.

We complemented the mm-range data with archival Hα images and optical spectra of the sample, from various telescopes and instruments, to derive their ionised masses.

3. Results

Molecular content. No object was detected in ^{12}CO or ^{13}CO down to an *rms* sensitivity limit in the range 6-25 mK at 230 GHz, except for NGC 6778. This PN shows a simple, broad ^{12}CO J=1-0 emission profile, as well as double-peaked emission profiles in ^{12}CO and ^{13}CO J=2-1, whose kinematics correspond to the broken, equatorial ring investigated by Guerrero & Miranda (2012). The peak intensity relations lead us to conclude that the ^{12}CO J=1-0 line is optically thin, and the excitation temperatures relatively low. Further analysis of these profiles and the excitation conditions in this nebula will be presented in Santander-García (in prep.).

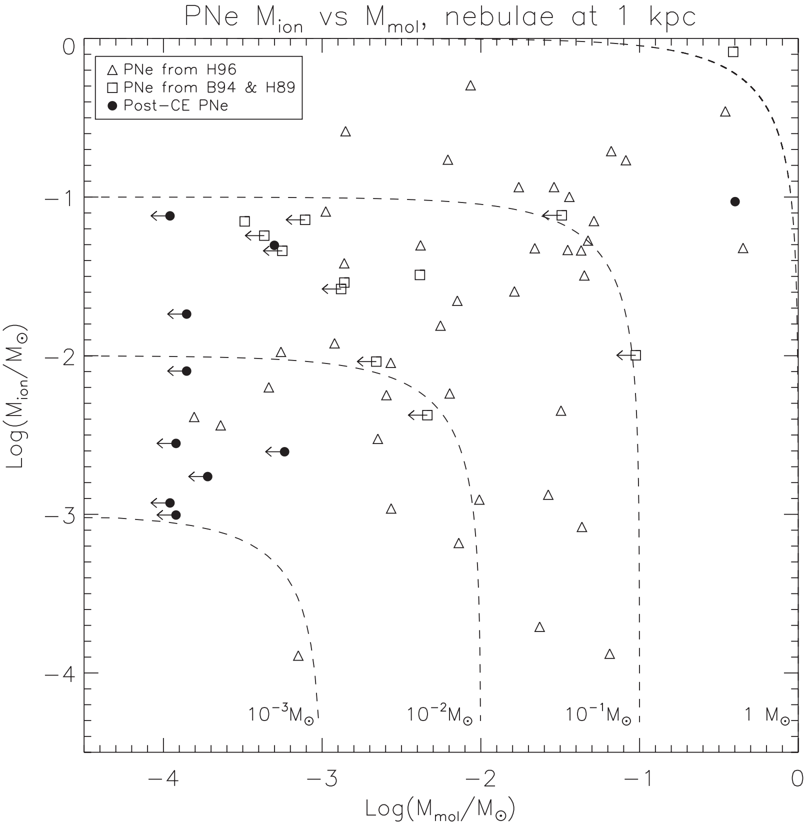

Figure 1. Logarithmic ionised mass vs. logarithmic molecular mass at 1 kpc of our post-CE PNe sample (filled circles), PNe from Huggins *et al.* (1996) (triangles), and a combined sample from Boffi *et al.* (1994) and Huggins *et al.* (1989) (squares). Dashed lines indicate equal total (ionised+molecular) mass; individual nebulae run along these lines as their gas content is progressively ionised.

The ^{12}CO J=1-0 profile of NGC 6778 allows us to derive a molecular mass of $5\times10^{-4}\,M_\odot$ (at 1 kpc) for this PNe by assuming a representative value of the ^{12}CO abundance of 3×10^{-4}. On the other hand, the sensitivities achieved in the rest of the observations allow us to derive conservative (3σ) upper limits for the molecular masses of the other objects in the sample.

Ionised content. The ionised mass of NGC 6778, NGC 2346, Abell 41, ETHOS 1, Hen 2-428 and PM 1-23 were derived from their Hβ fluxes and apparent sizes extracted from archival data. Assumptions about the electronic temperatures were made where necessary, in order to produce conservative estimates of the ionised masses of these nebulae (i.e., largest electron temeprature, T_e, wherever more than one was available). Ionised masses of the Necklace, Abell 63, Ou 5, and V458 Vul were obtained from Corradi *et al.* (2011), Corradi *et al.* (2015), Corradi *et al.* (2015), and Wesson *et al.* (2008), respectively.

Total mass comparison at 1 kpc. Masses found in this work scale with the distance to the nebulae squared. Distances to PNe, however, are still poorly known. Hence, in order to do a proper comparison with PNe not undergoing CE, we must first remove this large dependance by examining the mass every PNe would have at the same distance. Figure 1 shows the ionised and molecular masses of our sample of post-CE PNe at 1 kpc, together with the ionised and molecular masses of a large sample of 44 PNe selected by Huggins *et al.* (1996) in an attempt to approach a volume-limited sample, and another sample of 27 PNe in the Galactic disk, whose ionised/molecular masses were determined by Boffi & Stanghellini (1994) and Huggins & Healy (1989), respectively.

Strikingly, except for NGC 2346, the total masses of the post-CE sample seem similar, if not lower, than those of regular PNe. The median mass at 1 kpc of the combined comparison samples is 0.021 $M_\odot$, whereas for the post-CE sample it is $\leqslant$0.0081 $M_\odot$.

4. Conclusions

This preliminary work provides a first indication that, contrary to expectations, post-CE PNe seem to be slightly less massive, on average, than their single star counterparts. This discrepancy could however be removed if the molecular gas of these nebulae were too cold (or hot) to be detected, or the ionised gas too hot to emit Hα, but these possibilities seem rather unlikely. Some of the mass could also be in atomic, neutral form, which has not been investigated in this work, and will be part of a future study.

On the other hand, should these results be confirmed by further observations and careful analysis of the possible biases involved, they would present us with the following interesting (and so far speculative) implications. The problem of models unable to unbind such a large mass would be less severe. A fraction of the mass could fall back forming a circumbinary disk (as in Reichardt *et al.* 2018). If any of this material reaches the central stars, it could then be reprocessed perhaps offering an explanation for the correlation between large abundance discrepancy factors and post-CE central stars in PNe (Wesson *et al.* 2018). We can thus wonder whether the CE itself could be not a unique, only-once process, but an episodic, recurrent one. Grazing Envelope Evolution proposed by Soker (2015) and Shiber, Kashi, & Soker (2017) could help explain such a phenomenon.

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Discussion

De Marco: A CE interaction must eject the envelope or else the CE cannot be over. So low CE unbinding (ejection) cannot explain the observed low molecular mass. Could instead a scenario be envisaged that CE interactions only happen to AGB stars that already have a low envelope mass?

Santander-Garcia: That's a very interesting idea which could help explain the observations, provided a suitable physical mechanism can be found for the most massive ones to avoid CE interaction (or ejection). It would have some caveats though, since we would still need to explain the few massive cases such as NGC 2346.