Why Galaxies Care About AGB Stars:
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AGB stars in binaries and the common envelope interaction

Orsola De Marco[1,2]

[1]Department of Physics and Astronomy, Macquarie University,
Sydney, NSW 2109, Australia
email: `orsola.demarco@mq.edu.au`

[2]Research Centre in Astronomy, Astrophysics and Astrophotonics,
Macquarie University, Sydney, NSW 2109, Australia

Abstract. One may argue that, today, proceedings articles are not useful. Results belong in refereed papers and even reviews are best in publications that are long enough to do justice to the topic reviewed. In this short review, reflecting a presentation that was given at the IAU343 symposium, *Why Galaxies Care about AGB Stars*, I have therefore endeavoured to include some practical snippets that, while remaining true to the presentation, also provide a quick look up reference. After a reminder of how few AGB stars actually interact with a companion, and a pictorial summary of the types of interactions that can happen, I list the rapidly growing body of 3D common envelope simulations. Next, I highlight shortfalls and successes of simulations, and then spend some time comparing the two simulations of planetary nebulae from common envelope interactions to date. Finally, I summarise a handful of results pertaining to common envelope interactions between giants and planets.

Keywords. stars: AGB and post-AGB, binaries (including multiple): close, planetary nebulae: general, methods: numerical

1. Introduction

The common envelope (CE) interaction takes place when an expanding star fills its Roche lobe and starts to transfer mass to its companion. For certain configurations, such as a giant transferring mass to a less massive, more compact companion, the mass transfer can be unstable and result in a fast, dynamical-timescale inspiral of the companion through the envelope of the primary (Paczynski 1976, Ivanova *et al.* 2013). The companion and the core of the giant orbit one another within the envelope of the primary and orbital energy and angular momentum are transferred from the orbit to the CE gas via gravitational drag. The inspiral results in a smaller orbital separation and an ejected envelope or in a merger of the companion with the primary's core, where most of the envelope remains bound to the merged core and will settle into a new equilibrium configuration within a thermal timescale.

This interaction can explain the existence of compact binaries where one or both of the components were larger in the past than the present-day orbit. A large number of single and binary star classes may be post-CE objects, such as cataclysmic variables, X-ray binaries, the progenitors of (some) type Ia supernovae, double degenerates including neutron stars and black holes, as well as a number of mergers caught in the act, loosely catalogued under the name of intermediate luminosity red transients (Kasliwal 2012)†.

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† This transient class may in fact include quite a heterogeneous group of stars, but several at least have been identified as CE mergers. For more information see De Marco & Izzard (2017).

When a CE interaction takes place during the asymptotic giant branch (AGB) phase of a star, a planetary nebula (PN) may be ejected. We know that at least one in five PN are ejected common envelopes (Miszalski *et al.* 2009). In all cases tested, the axis of symmetry of the nebula coincides with the orbital axis, very likely, in this case, implying causality (Hillwig *et al.* 2016). A nebula may even be ejected in the case of a common envelope on the RGB as is likely the case PN ESO 330-9 (Hillwig *et al.* 2017).

Understanding the CE interaction necessitates hydrodynamic simulations in 3 dimensions. Among the many parameters that we would like to know about, a most essential quantity is the final orbital separation of the emerging binary as a function of stellar and system parameters. On it rests the prediction of the delay times (e.g., Toonen & Nelemans 2013) between binary formation and explosion as type Ia supernova or other types of mergers, including those that emit detectable gravitational waves. The comparison of predicted and observed delay times can inform as to the nature of the stars that underwent the outburst, and hence the past history of the systems, including identifying the progenitors of supernovae Ia. Another consequence of how fast double degenerates merge are the yields of iron (for double white dwarf mergers that give rise to supernovae Ia) and r-process elements manufactured by neutron star-neutron star mergers (Pian *et al.* 2017).

Finally, the common envelope must by necessity interrupt the natural evolution of the giant star along the giant branch. In the case of AGB stars this will prevent a natural termination of the AGB, eliminating or limiting the number of helium shell flashes that characterise the upper AGB. This will mitigate the third dredge-up and the ejection of carbon-rich (as opposed to oxygen-rich) gas into the ISM, as well as the abundance of s-process elements. While this may not have a significant effect on yields in general, because of the scarcity of AGB stars interrupted by a CE interaction, it may mean that post-AGB stars (and their PN) deriving from a CE interaction are not sampling the range of elemental abundances that are more normally ejected into the ISM. Calculating yields using these PN would then by necessity provide a biased value. If these PN were in any way more conspicuous (brighter) and used in preference for yields measurement then, clearly our measured yields would be biased (see discussion in De Marco *et al.* 2009).

In Section 2 we discuss the number of available binaries in a given AGB star population that can undergo a strong interaction. In Section 3 we catalogue the type of interactions that are possible and the type of knowledge that we would like to acquire about these interactions. In Section 4 we talk about hydrodynamic simulation models of the CE interaction. Finally in Sections 5 and 6 we talk about planetary nebulae from CE interactions and planets in common envelopes with giants, respectively. We do not conclude.

2. How many AGB stars are in close binary systems?

Not every peculiarity of AGB and post-AGB stars can be explained by a binary interaction. Yet binary interaction do cause peculiarities in typical stars, sometimes making them more noticeable: more variable, brighter... something that can cause them to draw attention onto themselves, making them selectively more observed and seemingly more common.

According to the recent studies of Raghavan *et al.* (2010), approximately half of all solar-mass stars are in binaries with a period distribution peaked at ∼300 years (see cartoon depiction in Fig. 1). Most of these binaries are anyway so wide that they will not interact with their companion, possibly leaving only a quarter of all the main sequence binaries able to interact at all.

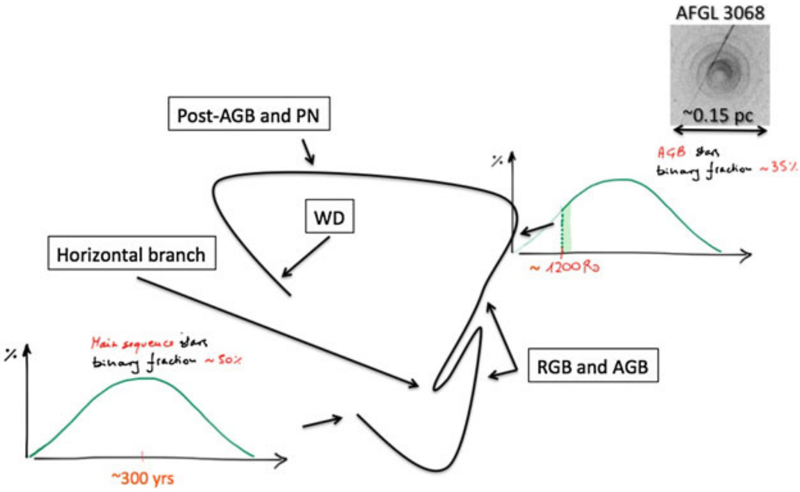

Figure 1. A schematic of the HR diagram, overlaid with a cartoon of the period distribution of sun-mass stars, which are in binaries approximately half the time. On the top right of the diagram we show a cartoon of the approximate period distribution expected of AGB binaries, where short period binaries, i.e., those with a separation smaller than approximately a couple of times the radius of the star, have already entered an interaction, leaving only approximately 35 % of the AGB stars in binaries. However, a much smaller fraction than that are close enough to interact strongly. The image of AFGL 3068 is from Mauron & Huggins (2006).

The closest of these binaries, those with initial orbital separation smaller than a couple of times the maximum RGB radius of the primary will interact during the RGB. For strong interactions like the CE interaction, the binary, if it survives, may never become an AGB star. Its envelope may be too feeble, or in any case the presence of a close companion may prevent expansion. This leaves only the binaries with initial separation between a couple of RGB maximum radii and a couple of AGB maximum radii to interact during the AGB (this is depicted as the pale green stripe in Fig. 1). *Hence, only a few percent of the AGB stars can interact strongly with a companion (Madappatt et al. 2016).* Therefore, of all AGB stars one can expect a small percentage to have a “lurking” companion, ready to interact either when tides decrease the orbital separation, or when the star expands further.

More massive stars have a much higher binary fraction with the most massive stars being in binaries most of the time (e.g., Sana *et al.* 2012). Additionally, the period distribution of more massive stars may have a peak at much shorter period (in virtue of more complex, possibly bimodal distributions; Duchêne & Kraus 2013), increasing the fraction of those stars that interact. This means that, even if the initial mass function dictates that the fraction of massive stars is very small, on balance, the mean mass of interacting AGB binaries may be slightly larger than for single stars.

3. Close binary star interactions on the AGB

A schematic of the strong binary interactions that can take place when an AGB star does have a companion sufficiently close is presented in Fig. 2. We do not include interactions where the companion only accretes wind from the primary star. The figure caption explains the parameters that we would like to know for each type of interaction. Importantly, each interaction can lead to the next one. Tides alter the orbit of a binary such that, particularly in the case of giant-compact star binaries, the two stars may come into close proximity, at which time the giant star can overflow its Roche lobe.

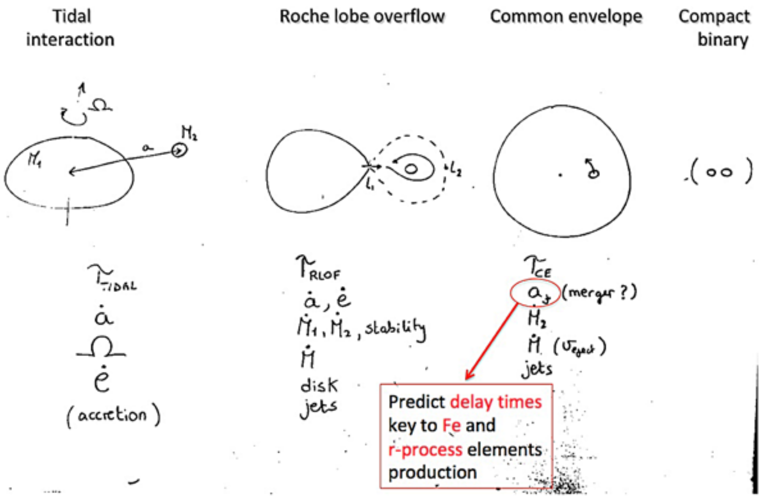

Figure 2. A schematic of the types of close binary interactions that can take place on the AGB and the parameters that they affect. During a tidal interaction (timescale $\tau_{\rm tidal}$) the orbital elements (separation a and eccentricity e) may change as well as the stellar rotation, Ω, and there could be accretion from the wind of the AGB star. During Roche lobe overflow, orbital elements as well as stellar masses, M_1 and M_2, can change, disks and jets may form and the timescale, $\tau_{\rm RLOF}$, and stability of the interaction are all unknown. During the CE interaction, which occurs over a much faster timescale ($\tau_{\rm CE}$) we worry about the final separation of the system, a_f, or if the system merges. We also want to know whether the secondary accretes, how much mass the system loses ($\dot{M}$), the ejection speed, $v_{\rm eject}$, and whether jets are launched.

Mass transfer between a convective giant and a companion is often unstable. If mass is lost (usually via the L2 and L3 Lagrangian points) then the change in angular momentum leads to a shortening of the orbital separation and an increase in mass transfer rate. This is the hallmark of instability, soon leading to the next phase, a CE interaction. The timescales for the tidal, Roche lobe overflow and CE phases are very variable and there is no way that a single simulation of the entire interaction, from the tidal phase to the formation of the compact binary, can be carried out. Attempts at quantifying the Roche lobe overflow phase have been partly successful (MacLeod *et al.* 2018a,b, Reichardt *et al.* 2018) in demonstrating that the behaviour of the RLOF phase leading into the CE phase, are approximately as expected analytically. Yet resolution does play a role in the length of the unstable RLOF phase and the geometry and dynamics of the ejection. Tides in particular are so sensitive to small changes in the envelope shape and on how the energy is dissipated by the convective eddies in the envelope, that we cannot hope to model it in 3D at present. The best modelling tools for this phase are still analytical following prescriptions such as that of Zahn (1966).

4. Simulations: the state of play

Starting with the pioneering paper of Taam *et al.* (1978), which calculated a model of a CE interaction between a 16 $M_\odot$ giant and a neutron star companion in 1D, several papers followed in the same series, calculating a variety of CE models for a range of different stars and with a range of different techniques in 2 and 3D. These early works gave rise to what was for a long time the industry standard for CE simulations, namely the SPH effort of Rasio & Livio (1996) and the Eulerian code calculation of Sandquist *et al.* (1998, 2000). A period of time followed before a new generation of models were carried out, namely by Ricker & Taam (2008, 2012) using Flash (Fryxell *et al.* 2000), a

Table 1. A list of all publications known to the author that include 3D hydrodynamic simulations of the common envelope interaction.

Country/Group	**Code**[1]	**Publications**
USA	SPH Nested grid	Terman *et al.* 1994[2], Terman *et al.* 1995 Terman & Taam 1996 Sandquist *et al.* 1998, 2000
USA	SPH	Rasio & Livio 1996
USA	FLASH-AMR	Ricker & Taam 2008, 2012
Australia	Enzo unigrid and AMR, SNSPH, PHANTOM SPH	Passy *et al.* 2012, Kuruwita *et al.* 2016, Staff *et al.* 2016a,c, Iaconi *et al.* 2017, 2018, Galaviz *et al.* 2017, Reichardt *et al.* 2018
Canada	Starsmasher SPH	Nandez *et al.* 2014, 2015; Nandez & Ivanova 2016 Ivanova & Nandez 2016
Germany	AREPO moving mesh	Ohlmann *et al.* 2016a,b, 2017
USA	AstroBEAR AMR	Chamandy *et al.* 2018
USA	Athena++[3] nested grid	MacLeod *et al.* 2018b,a[4]

Notes:

[1] Lagrangian codes implemented with smooth particle hydrodynamics (SPH) techniques and Eulerian codes implemented with a variety of mesh refinement techniques such as adaptive mesh refinement (AMR).

[2] This is paper 3 in a series of 10 papers which tackled simulations of the CE interaction in 1, 2 and 3D. The first paper in the series, by Taam *et al.* (1978), was in 1D.

[3] This is a descendent of the Athena code (Stone *et al.* 2008).

[4] Currently aimed at studying the phase just prior to the in-spiral.

grid code exploiting the adaptive mesh refinement (AMR) techniques, and Passy *et al.* (2012) using the Enzo grid code with no AMR (O'Shea *et al.* (2004), but see also Passy & Bryan (2014)), as well as the smooth particle hydrodynamics (SPH) code SNSPH (Fryer *et al.* 2006). Fortunately, many more efforts followed in quick succession, which are summarised in Table 1.

The main challenge facing simulations is the long run times that often extend into months and the fear that the results are dependent on a resolution that cannot be increased nor properly studied (Iaconi *et al.* 2018). As a consequence of long run times, only a very limited parameter space has been simulated, concentrating on low mass and relatively compact RGB stars (see Iaconi *et al.* (2017) for a list of simulations). Typically, the binary simulation is started with the companion so close to the primary that the primary is already overflowing its Roche lobe. This allows a faster computational time, because the dynamical in-spiral is triggered immediately, but likely leads to differences in the simulations' outcome. Most importantly, MacLeod *et al.* (2018a,b) and Reichardt *et al.* (2018) have recently discussed the effects of calculating the phase of unstable Roche lobe overflow preceding the CE inspiral and how this phase leads to very distinctive ejecta properties and may play a role in the light properties of systems observed (see also discussions in Pejcha *et al.* (2016b,a) and Galaviz *et al.* (2017)).

A persistent issue connected with simulations of the CE interaction is that, unless recombination energy is allowed to contribute†, the common envelope is lifted but not fully unbound. Simulations typically unbind 10% of the entire envelope early in the inspiral, while the remainder is lifted out of the orbital volume, contributing to orbital stabilisation, but if not unbound would fall back onto the binary (see Iaconi *et al.* (2017) for a list of simulations). Even allowing the entire recombination energy budget to do

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† For information on the debate of how much energy should be allowed to to contribute rather than being radiated away see (Ivanova 2018; Grichener *et al.* 2018, and references therein)

work, only the envelope of low mass systems becomes unbound ($M \lesssim 2$ M$_\odot$; Nandez & Ivanova 2016), leaving open the question of what other physical mechanism may unbind the envelope in the more massive stars. Solutions or partial solutions have been put forth, such as the action of jets during the dynamical inspiral that can unbind a few times more envelope than if they are not present (Shiber & Soker 2018, and Shiber *et al.* in preparation).

Global magnetic fields may play a role in the envelope dynamics and ejection. Regos & Tout (1995) have discussed that a strong sheer would develop in the CE layers as they are being imparted angular momentum by the inspiralling companion. This sheer would feed an α-Ω dynamo and strengthen a strong, global magnetic field that may play a role in the envelope gas dynamics.

To corroborate or refute this prediction, Tocknell *et al.* (2014) used jets in PN as a way to probe the magnetic field at different stages during the CE interaction. An accretion disk can form around the companion either at the time of Roche lobe overflow or indeed later during the CE phase or shortly after. Some of the observed PN jets can be kinematically dated to have formed just before, while others just after the dynamical ejection. This is taken as an indication that a disk formed around the companion as it accreted mass, and that it was threaded by a magnetic field. If so then physical arguments can be used to connect the measured jet mass loss rates to the magnetic field strength. They deduced local fields of between 1 and 1000 G, depending on whether the jet is launched just before or just after the CE inspiral. In the former case the magnetic field is plausibly that characterising the surface of giants. In the latter case the derived field intensity is in line with predictions of the "wound" and intensified magnetic field by Regos & Tout (1995).

The only 3D magneto-hydrodynamic (MHD) simulation to attempt to study at least one aspect of magnetic fields is that of Ohlmann *et al.* (2016b), where their MHD calculation records field growth locally around the companion. We comment that this magnetic field is not the global magnetic field predicted by Regos & Tout (1995). The Ohlmann *et al.*, (2016b) field is a local field that grows as a result of the magnetorotational instability (Balbus & Hawley 1998) and not one that grows as a result of an α-Ω dynamo – the lack of properly resolved convection in CE simulations would make the *ab initio* simulation of such a field an impossibility. Finally, it has been suggested (Tricco & Price 2012) that the lack of divergence cleaning in the Pakmor & Springel (2013) MHD method utilised by Ohlmann *et al.* (2016b) may lead to *too strong* a field growth. Ultimately, these are very early days for MHD simulations of the CE interactions.

5. Planetary nebulae from common envelopes

When the AGB star suffers a CE interaction that leads to the ejection of the envelope, a PN may form. The CE ejecta will be ploughed up by the fast wind from the heating and luminous post-AGB primary and ionised by its ionising radiation. The shape of the PN will be influenced by the equatorially concentrated CE ejecta.

Two studies, García-Segura *et al.* (2018) and Frank *et al.* (2018), have carried out the experiment of ploughing the CE ejecta with a fast wind supposedly launched by the now hotter, post-AGB central star. While we refer the reader to the work of Reichardt *et al.* (2018) for a detailed comparison, we list here some of the salient similarities and differences between the two simulations (see Table 2).

A difference between the two studies' setups is that García-Segura *et al.* (2018) considered a very compact distribution of CE ejecta (~2 AU; Fig. 3), due to the short duration of the CE simulation of Ricker & Taam (2012; only 57 days of dynamical CE ejection). Ricker & Taam (2012), in addition, started the interaction when the primary was already overflowing its Roche lobe (Table 2), leading to an immediate inspiral and burst-like ejection of the common envelope. On the other hand, Frank *et al.* (2018) started

Table 2. A comparison of the initial setups and outcomes of the two existing simulations of post-common envelope planetary nebula.

Characteristic	García-Segura *et al.* (2018)	Frank *et al.* (2018)
Dimensionality	2D ($\theta = 0 - 90$ deg)	3D
RGB primary's mass	$M_1 = 1.05$ M$_\odot$	$M_1 = 0.88$ M$_\odot$
Companion's mass	$M_2 = 0.6$ M$_\odot$	$M_2 = 0.6$ M$_\odot$
Primary's radius	$R_1 = 32$ R$_\odot$	$R_1 = 90$ R$_\odot$
Initial separation	62 R$_\odot$	218 R$_\odot$
Primary's Roche lobe radius	$R_{RL,1} = 32$ R$_\odot$	$R_{RL,1} = 90$ R$_\odot$
Size of CE ejecta at end CE simulation	∼2 AU	∼100 AU
Total time of CE simulation	57 days	7000 days
CE simulation time after orbital stabilisation	15 days	2000 days
Total time PN simulation	10 000 years	7000 days
Size of PN at 7 000 days	100–200 au	100 au
Size of the PN at 10 000 years	2–4 pc	–

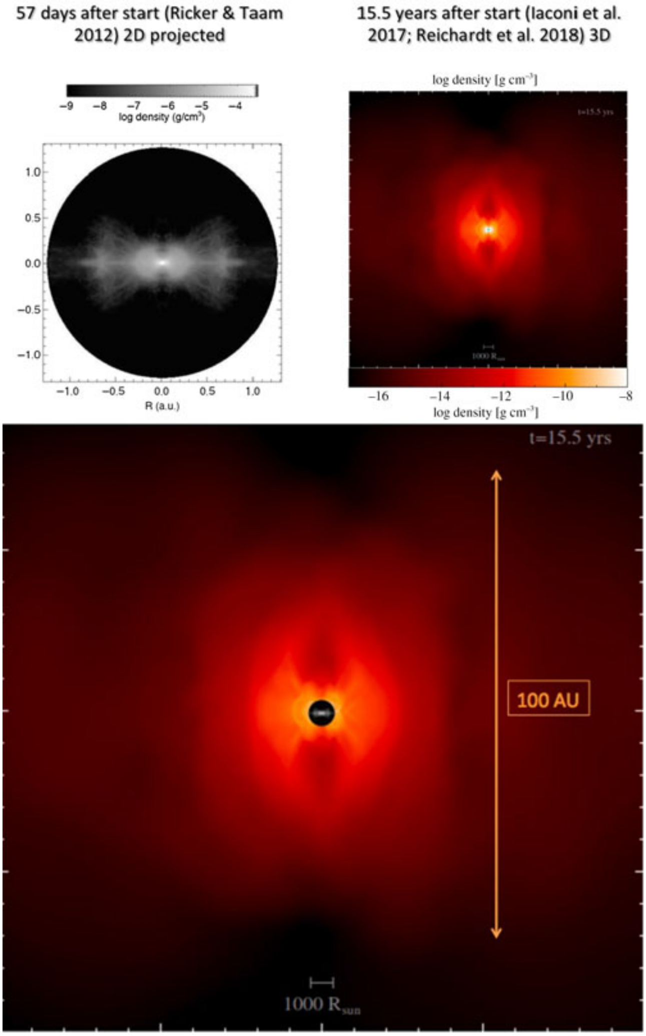

Figure 3. Top left: Figure 1 of García-Segura *et al.* (2018), showing the post-CE gas distribution at the end of the simulation of Ricker & Taam (2012), but projected into 2D and reflected about the horizontal axis. Top right: a slice in the plane perpendicular to the orbital plane at the end of the simulation of Reichardt *et al.* (2018). Lower panel, the top two panels are overlaid and scaled to one another. Both the PN simulated by the two studies extend to about 100 AU after approximately 10 000 days.

with CE ejecta that had more time to expand (15 years) and where the CE simulation was started at the start of Roche lobe overflow. The Roche lobe overflow phase has time to eject a disk from the L2 and L3 Lagrangian points for 7000 days, followed by the burst-like CE ejection, which ploughs into the disk. The evolution of the ejecta is then followed for a further 2000 days, allowing further expansion. This resulted in a very distinctive, overall larger (∼100 AU) density distribution (Fig. 3).

Another difference is that García-Segura *et al.* (2018) were able to evolve the PN to the age of 10 000 years thanks to the 2D configuration, while Frank *et al.* (2018) only calculated the initial 10 000 days because of the full 3D treatment.

The time after the ejection of the common envelope when the fast wind starts, as well as the momentum of the fast wind are different for the two studies. These variables matter greatly to the PN that will form and we have not even scratched the surface of how to chose these parameters and how to interface the CE simulation with the PN simulation. We are therefore not going to compare these choices in this review and refer the reader to the two original publications (García-Segura *et al.* 2018; Frank *et al.* 2018).

Both studies observed a very pronounced hydrodynamic collimation thanks to the extremely thin and high density contrast funnel seen in Fig. 3, top left panel and equally present at the core of the top right panel figure. In addition, Frank *et al.* (2018) showed that 3D effects (asymmetry) could be observed if the fast wind momentum is low, though whether the asymmetries remain with further nebular evolution remains a question. Finally, we point out that there is a strong interplay between the disk ejected during the Roche lobe outflow and the mass which is ejected during the faster CE dynamical phase. These two ejections, which both precede the fast wind that later ploughs them, forming the PN, interact with one another generating different degrees of asymmetry and equatorial density concentrations. This interplay may contribute to the variety of PN shapes observed around post-CE binaries.

6. Planets in common envelopes

The interaction between planets and giants has been considered several times in different contexts and with different techniques (e.g., Soker 1998; Carlberg *et al.* 2009; Villaver & Livio 2009; Passy *et al.* 2012, to mention a few). simulated a CE interaction between 3 $M_\odot$ RGB and AGB giants and a 10 M_J companion. The results of those simulations were that the companion inspirals all the way to the core where, presumably, it would get destroyed. It was also determined that the length of the dynamical inspiral is slower than for more massive companions: ∼10 years for the RGB star and ∼100 years for the AGB case. Yet, it can be showed that during these times the planet is not fully ablated (Passy *et al.* 2012), which presumably would mean that it is tidally disrupted near the core, possibly even forming a disk (Nordhaus & Blackman 2006). The planet inspiral causes a modest expansion of the photosphere but substantial degree of spin-up, in line with certain observations (Carlberg *et al.* 2009).

It is also possible that the presence of the planet in the atmosphere of the giant may trigger secondary effects. In particular the expansion of the stellar envelope may cause a recombination front and some of the relatively high density, low temperature gas farther out may also host dust formation. This may be only of secondary importance because most of the gas would still remain at temperature higher than the condensation temperature. Another effect may have to do with pulsations. AGB stars such as Miras pulsate with periods of a couple of hundred days (Ireland *et al.* 2011), which is similar to the initial orbital period of the planet. Whether an interaction between the pulsations and the energy deposition by the companion during the inspiral is a possibility rests to be determined.

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Discussion

WHITELOCK: As you know symbiotic stars are binaries and some have jets, e.g. R Aqr. They are different from the binaries you are talking about but may be of interest. One of the nebulae you described as a PPN is actually a symbiotic Mira (if I remember correctly).

DE MARCO: The nebula in question, OH231.8+4.2 has a Mira at its centre, not a pAGB star as one might expect. We do not know of a nearby companion though. It is hard to explain. In Staff *et al.* 2016a we tried a CE-merger scenario that launched jets during a CE in-spiral before the merger. The numbers work out approximately, but who knows!

SAHAI: Boomerang is a good example, probably best example of a CE event, where you see *dust formation* (both in ejecta and the disk) formed around the central merged binary. But in this case the wind is not *dust-driven*. Dust has formed in the ejecta, presumably.

DE MARCO: Well, if so, dust in this case may have not contributed to the loss of the envelope. Dust formation on CE transient is observed. Yet it may form only at the equator and not be a way to drive a wind.

KOBAYASHI: You mentioned the impact of a jet on separation. But how much change do you expect on the delay-time of double-degenerate SNIa and NS merger?

DE MARCO: *If* jets really happen and *if* they leave the binary at a much wider orbital separation, then the delay time would become very long or even infinite! It is too early to tell whether the extent to which jets, if they happen, may affect the distribution of delay times.

RICKER: In your CE simulations with jets, have you considered jets at angles other than 90° to the orbital plane? Presumably these would change the shape of the outflow, and if the outflow shapes a later PN phase, the jet angle might contribute to the diversity of PN shapes.

DE MARCO: No, we have not...yet. But before doing so, we would have to justify why the accretion disk around the companion would have an angular momentum vector that is not aligned with the orbital one.