On the role of reduced wind mass-loss rate in enabling exoplanets to shape planetary nebulae

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Abstract

We use the stellar evolution code MESA-binary and follow the evolution of three exoplanets and two brown dwarfs (BDs) to determine their potential role in the future evolution of their parent star on the red giant branch (RGB) and on the asymptotic giant branch (AGB). We limit this study to exoplanets and BDs with orbits that have semi-major axis of 1 AU ≲ a ≲ 20 AU, a high eccentricity, e0 ≳ 0.25, and having a parent star of mass M∗,0 ≥ 1M⊙. We find that the star HIP 75458 will engulf its planet HIP 75458 b during its RGB phase. The planet will remove the envelope and terminate the RGB evolution, leaving a bare helium core of mass 0.34M⊙ that will evolve to form a helium white dwarf. Only in one system out of five, the planet beta Pic c will enter the envelope of its parent star during the AGB phase. For that to occur, we have to reduce the wind mass-loss rate by a factor of about four from its commonly used value. This strengthens an early conclusion, which was based on exoplanets with circular orbits, that states that to have a non-negligible fraction of AGB stars that engulf planets we should consider lower wind mass-loss rates of isolated AGB stars (before they are spun-up by a companion). Such an engulfed planet might lead to the shaping of the AGB mass-loss geometry to form an elliptical planetary nebula.

Keywords: stars: AGB and post-AGB; binaries: close; stars: mass-loss; planetary systems; planetary nebulae: general

1. INTRODUCTION

Hundreds of observational and theoretical studies in recent years have converged on the understanding that binary interaction shapes the majority, and possibly all, planetary nebulae (PNe) (e.g., limiting to a sample from the last five years, Jones et al. 2016; Chiotellis et al. 2016; Akras et al. 2016; García-Rojas et al. 2016; Jones 2016; Hillwig et al. 2016a; Bond et al. 2016; Chen et al. 2016; Madappatt et al. 2016; Ali et al. 2016; Hillwig et al. 2016b; Jones & Boffin 2017b; Barker et al. 2018; Bond, & Ciardullo 2018; Bujarrabal et al. 2018; Chen et al. 2018; Danehkar et al. 2018; Frank et al. 2018; García-Segura et al. 2018; Hillwig 2018; MacLeod et al. 2018; Miszalski et al. 2018; Sahai 2018; Wesson et al. 2018; Aller et al. 2019; Desmurs et al. 2019; Jones 2019; Kim et al. 2019; Kővári et al. 2019; Miszalski et al. 2019; Orosz et al. 2019; Akras et al. 2020; Bermúdez-Bustamante et al. 2020; Jones 2020). Substantially smaller number of studies deal with the possibility that planets and brown dwarfs (BDs) might also shape PNe (e.g., De Marco & Soker 2011; Kervella et al. 2016; Boyle 2018; Sabach, & Soker 2018a; Sabach & Soker 2018b; Schaffenroth et al. 2019, as some examples from the last decade).

A stellar companion can strongly deform the envelope of the asymptotic giant branch (AGB) progenitor of the PN, by spinning-up the envelope and by the direct effects of its gravity, mainly during a common envelope (CEE) phase and during the termination of the CEE. One of the extreme outcomes at the termination of the CEE might be two opposite ‘funnels’ along the symmetry axis of the bloated AGB envelope, which can collimate bipolar outflows (e.g., Soker 1992a; Reichardt et al. 2019; García-Segura et al. 2020; Zou et al. 2020). A stellar companion can also deform the envelope by accreting mass and launching jets during the CEE (e.g., Chamandy et al. 2018; López-Cámara et al. 2019; Schreier et al. 2019; Shiber et al. 2019; Lopez-Camara et al. 2020). All these processes shape the descendent nebula to possess large-scale highly non-spherical morphologies. Planet companions, on the other hand, are not expected to have these large effects. It is not clear yet whether planets can launch jets. Even if they do...
(e.g., Soker 2020), the outcome might be two opposite small clumps along the symmetry axis (*ansae*; FLIERS).

It seems that the main effect of a planet in shaping the mass-loss toward a non-spherical PN is by spinning-up the envelope, to the degree that the mass-loss becomes axisymmetrical. Soker (1998b) discussed the way by which a planet can enhance mass-loss and can lead to a non-spherical outflow from giant stars, like AGB stars, or red giant branch (RGB) stars. It goes as follows. A planet-spun-up AGB envelope might sustain a dynamo (e.g., Nordhaus & Blackman 2006), that in turn leads to non-spherical mass-loss by the effect of magnetic fields (e.g., Leal-Ferreira et al. 2013; Vlemmings 2018), including possibly the influence on dust formation and distribution (e.g., Soker 2000, 2001a; Khouri et al. 2020). Another effect of massive planets that are deep inside the envelope of giant stars, after the dynamical in-spiral phase, is the excitation of waves that become large on the surface and might influence the rate and morphology of dust formation and therefore of the outflow (e.g., Soker 1993). On a more general ground, dust formation seems to be an important process in the last phases of the CEE, both for sub-stellar and stellar companions (e.g., Soker 1992b, 1998b; Glanz, & Perets 2018; Iaconi et al. 2019, 2020).

Stars on the upper RGB and AGB can acquire a large amount of angular momentum by engulfing planets (e.g., Soker 1996; Siess & Livio 1999a; Massarotti 2008; Carlberg et al. 2009; Villaver & Livio 2009; Mustill & Villaver 2012; Nordhaus et al. 2010; Nordhaus & Spiegel 2013; García-Segura et al. 2014; Staff et al. 2016; Aguilera-Gómez et al. 2016; Veras 2016; Sabach, & Soker 2018a; Sabach & Soker 2018b). The probability for this process to take place on the upper AGB sensitively depends on the mass-loss rate from the star. We note that most known exoplanets will be engulfed before their parent star reaches the upper RGB, because most known exoplanets have close orbits (detection biased). These systems are not relevant to us as the planet will not shape the outflow just before the termination the RGB or AGB. Exoplanets (and BDs) that shape post-RGB nebulae or PNe should have semi-major axis of \( a_0 \gtrsim 0.5 \) AU.

In earlier studies our group considered the possibility that AGB stars that did not (yet) interact with any companion that substantially spun-up the envelope, have much lower wind mass-loss rates than what traditional formulae give (Sabach, & Soker 2018a; Sabach & Soker 2018b). We termed these angular momentum (\( \dot{J} \)) isolated stars *isolated stars*.

Sabach, & Soker (2018a) study the fate of four observed exoplanetary systems that have low eccentricity. To follow the evolution of the star they use the single mode of the evolutionary code MESA (section 2). To examine whether tidal forces will cause the planet to spiral-in to the envelope of the star during the AGB phase, they use a simple prescription for the tidal force. Sabach, & Soker (2018a) found that when low-mass stars evolve with the traditional wind mass-loss rate they are not likely to swallow their planets in these four systems. With a lower mass-loss rate, down to about 15% of the traditional one, the stars reach much larger radii on their AGB and much larger luminosities. The larger radii substantially increase the likelihood for the AGB star to swallow the planet. This, by the studies we cited above, might lead to the formation of elliptical PNe. The higher luminosity might account for bright PNe in old stellar population (see relevant discussion in Sabach, & Soker 2018a; Sabach & Soker 2018b).

Sabach, & Soker (2018a) justified the much lower wind mass-loss rate by their assumption that the stellar samples from which the mass-loss rate formulae were derived were contaminated by AGB stars that suffer binary interaction, and binary interaction increases the mass-loss rate. About half of main sequence stars in the mass range 1 – 2\( M_\odot \) have a stellar binary companion (e.g., Moe & Di Stefano 2017). Many of these binary systems are close enough for the companion to increase the mass-loss rate of the primary star. The point that Sabach, & Soker (2018a) make is that for many other stars a close exoplanet (or a close BD) enhances the mass-loss rate. Overall, both stellar and sub-stellar companions enhance the mass-loss rate from many AGB stars.

Specifically for low mass companions, down to planets, Sabach & Soker (2018b) suggest that giant stars that acquire no angular momentum from a companion along their late evolution (beyond the main sequence), i.e., \( J_{\text{isolated}} \) stars, have much lower mass-loss rates than what traditional formulae give. AGB stars with lower mass-loss rates reach much higher luminosities in the post-AGB track, when they ionise the PN. Sabach & Soker (2018b) further argue that it might be that the bright PNe in old stellar populations result from the combination of lower mass-loss rates that they explored, and of higher AGB luminosities that some new stellar models give (e.g., Miller Bertolami 2016; Gesicki et al. 2018; Méndez 2017; Reindl et al. 2017).

We here adopt the approach of Sabach, & Soker (2018a) and Sabach & Soker (2018b) in considering a much lower wind mass-loss rate (section 2). We differ from them by studying the fate of observed exoplanets and BDs with high eccentricities, for which we must use the binary mode of MESA to follow the evolution of the
planetary systems (section 2). Our study is another in a series of papers that study the fate of confirmed exoplanets as their parent stars turn to RGB or AGB stars (e.g., Nordhaus & Spiegel 2013; Sabach, & Soker 2018a). We describe the results of our simulations in section 3, and we summarise our main results in section 4.

2. NUMERICAL METHOD

2.1. The MESA-binary code

To follow the fate of the five observed systems, three exoplanets and two BDs, that we study here, we conduct stellar evolution simulations using the Modules for Experiments in Stellar Astrophysics (MESA; Paxton et al. 2011, 2013, 2015, 2018, 2019), version 10398 in its binary mode. In each system we follow the evolution of the parent star, either to the time the star engulfs its planet (or BD; in what follows in many cases we refer by planets also to BDs) and the system enters a CEE phase, or to its post-AGB phase if no engulfment takes place.

We study planets with high-eccentricity orbits and so we have to pay attention to tidal forces that act to circularise and synchronise the orbit (the later effect results in a decrease in the semi-major axis). We set the tidal effects in MESA-binary (the parameters do_tidal_circ and do_tidal_sync), taking the circularization type ‘Hut_conv’ which is the default of MESA-binary for convective envelope (Hurley et al. 2002). This is relevant to our study as the planets we follow experience strong tidal interaction only during the RGB and AGB phases of their parent stars, when the envelope is fully convective. We turn off the effects of magnetic breaking (the parameter do_jdot_mb) as we expect weak magnetic activity during the RGB and AGB phases before the planet enters the envelope. We take all other parameters to have their default values in MESA-binary.

2.2. Mass-loss scheme

As we mentioned above, we adopt our earlier approach (Sabach, & Soker 2018a; Sabach & Soker 2018b, where there are more details and discussions of the low wind mass-loss rate), and give here only the essential information. For the empirical mass-loss formula for winds on the RGB we take (Reimers 1975)

\[ \dot{M}_{\text{RGB}} = 4 \times 10^{-13} \eta L M^{-1} R, \]

where the giant’s mass, \( M \), luminosity \( L \), and radius \( R \), are in solar units, and \( \eta \) is the wind mass-loss rate efficiency parameter. The mass-loss rate on the upper AGB should be larger than the Reimer formula (e.g., Vassiliadis & Wood 1993). Therefore, we use the MESA formula from Bloecker (1995)

\[ M_{\text{AGB}} = 4.83 \times 10^{-9} M^{-2.1} L^{2.7} \dot{M}_{\text{RGB}}. \]  

We follow Sabach, & Soker 2018a and take the same value of \( \eta \) for the mass-loss rate expressions on the RGB and on the AGB.

The commonly used value is \( \eta = 0.5 \) (e.g., McDonald & Zijlstra 2015). With the assumption that Jsolated stars (those that acquired no angular momentum from a companion) experience a much lower wind mass-loss rate than non-Jsolated stars, we also take lower values of \( \eta \). Miglio et al. (2012), for example, find for the old metal-rich cluster NGC 6791, that this parameter might be as low as \( \eta = 0.1 \), i.e., much lower than typically taken. We follow Sabach, & Soker (2018a) and study the range \( 0.05 \leq \eta \leq 0.5 \).

One observational finding is directly relevant to our study that aims at the shaping of elliptical PNe. This finding is the observation that many elliptical PNe have an outer faint and spherical halos (e.g. Corradi et al. 2003). Since single AGB (Jsolated) stars spin extremely slowly on the upper AGB (e.g., Soker 2006), we expect these stars to blow a spherically faint halo. Interacting with a low mass companion on the upper AGB causes these stars to have a non-spherical mass-loss and at a higher mass-loss rate, forming the brighter elliptical inner shell (e.g., Soker 2000). These PNe might suggest a late interaction with a very low mass companion, e.g., a BD or a planet.

3. EVOLUTION OF FIVE OBSERVED EXOPLANETS AND DROWN DWARFS

3.1. The five systems

Our aim is to explore which of the five observed exoplanets and BDs that we list in table 1 might enter the envelope of their parent star when the later is on its upper AGB, and for what wind mass-loss rate efficiency parameter \( \eta \). We study these specific systems that we found by searching the Extrasolar Planets Encyclopaedia; (exoplanet.eu; Schneider et al. 2011; the system HD 72946 with a BD companion is from Maire et al. 2020) because they have the relevant range of all parameters, in particular a semi-major axis in the range of \( 1 \text{ AU} \leq a \leq 20 \text{ AU} \). There are many more exoplanets with a semi-major axis in this range, but the mass of the planet and/or the eccentricity are not known. The first five columns of the table list the name and input parameters from observations. We add a subscript ‘0’ to indicate the initial values of the stellar mass \( M_\star \), of the semi-major axis \( a \), and of the eccentricity \( e \), as these quantities change during the post-main sequence evolution. We do not change the planet mass \( M_p \) (by planet
we refer below also to the two WDs) during the evolution. The giant star will not evaporate the planet (e.g., Schreiber et al. 2019), and the planet will accrete almost no mass before it enters the envelope. The last six columns of table 1 indicate the outcome for six different values of the wind mass-loss rate parameter \( \eta \) (equations 1 and 2). We either indicate that the star does not engulf the planet, and so there is no CEE (‘No CEE’), or in cases where the planet does enter a CEE, we indicate the core mass, \( M_{\text{core}} \), and the envelope mass, \( M_{\text{env}} \) at the onset of the CEE.

### 3.2. Engulfment on the RGB

The planet HIP 75458 b enters the envelope of its parent star when the later is on the RGB for all values of \( \eta \) that we use here. In Fig. 1 we present the evolution of the stellar radius, periastron distance, and eccentricity of this system in the relevant post-main sequence phases. We see that tidal forces circularise the orbit before the onset of the CEE. Although the periastron distance increases, the semi-major axis decreases from before the onset of the CEE. We see that tidal forces circularise the orbit before the onset of the CEE. Although the periastron distance increases, the semi-major axis decreases from its initial value of \( a_0 = 273 R_\odot \) to about \( a \sim 140 R_\odot \), before it rapidly decreases as the planet dives into the RGB envelope. In Fig. 2 we zoom on a time period of about 10 yr when the planet enters the envelope of its parent star. We also present the evolution of stellar mass (purple line).

The planet HIP 75458 b removes the envelope of its parent star during the RGB phase and leaves a bare helium core of mass \( M_{\text{core}} = 0.4 M_\odot \), which then cools as a helium white dwarf. The planet might cause the nebula of the RGB star to have an elliptical shape. By definition this is not a PN. However, it is still a relevant system to our study. The influence of planets on the evolution of RGB stars and on their later evolution to the horizontal branch has been the subject of a number of theoretical and observational papers (e.g., Soker 1998a; Siess & Livio 1999b; Carlberg et al. 2009; Geier et al. 2009; Heber 2009; Charpinet et al. 2011; Bear & Soker 2012; Silvotti et al. 2014; Carlberg et al. 2016; Jimenez et al. 2020). Planets down to a mass of \( M_p \simeq M_J \) might remove the entire hydrogen-rich envelope of their parent RGB star if they enter the envelope on the upper RGB. Lower mass planets are likely to be evaporated before they reach close to the core (Soker 1998a); they release less gravitational energy and therefore cannot unbind the entire envelope.

We find here that the system HIP 75458 belongs to a class of systems where the planet terminates the evolution of the star on the RGB, or at least causes the star to lose most of its envelope and to become a blue horizontal branch star (Soker 1998a).

**Figure 1.** The RGB evolution of the stellar radius (blue-thick line), the periastron distance (red line), and eccentricity (black-dashed line; scale on the right axis with \( \eta = 0.07 \)) for the system HIP 75458 and for two values of the wind mass-loss rate efficiency parameter \( \eta \). The upper and lower panels start at times (from the zero age main sequence) of \( t = 3.45 \times 10^9 \) yr and \( t = 3.435 \times 10^9 \) yr, respectively.

### 3.3. Possible shaping of PNe

Not including HIP 75458 b that suffers RGB engulfment, we find that out of the other five exoplanets, only beta Pic c might enters a CEE during the AGB phase of its parent star (table 1). First we note that the other planet in beta Pic, the planet beta Pic b, has a semi-major axis of 9.68 AU and a mass of \( \sim 12.7 M_J \). With a semi-major axis that is about 3.5 larger than that of beta Pic c, and being only slightly more massive, we ignore the influence of beta Pic b on the evolution of beta Pic c that we study here. On the other hand, the close planet beta Pic b will induce non-spherical mass-loss geometry from the parent star if the planet enters the stellar envelope. Such a non-spherical mass-loss process will influence the orbit of the wider planet beta Pic b, as non-spherical mass-loss might do (e.g., Veras et al. 2013; Dosopoulou & Kalogera 2016).
We have to reduce the mass-loss rate by about a factor of four below the commonly used value ($\eta = 0.5$) for beta Pic c to enter a CEE. Sabach, & Soker (2018a) find that in most cases they require $0.05 \lesssim \eta \lesssim 0.15$ for planets to enter a CEE with their parent star when the later is on its AGB. Our result for beta Pic c is compatible with their finding.

We present the evolution of beta Pic c for three values of $\eta$ in Fig. 3. We notice that already on the RGB tidal interaction reduces somewhat the eccentricity. Then, during the AGB phase of the parent star when mass-loss rate is high, there are the competing effects of mass-loss that acts to increase the semi-major axis, and of tidal interaction that acts to decrease and to reduce orbital separation (as the spin of the AGB is much slower than the orbital motion of the planet). Before the planet enters the envelope the mass-loss geometry is spherical on average. Therefore, the way the code MESA-BINARY treats the effect of mass-loss on the semi-major axis is accurate for our case. For $\eta = 0.5$ and $\eta = 0.15$ mass-loss rate is high, and the effect of mass-loss in enlarging the orbital separation wins that of the tidal interaction. In the case of $\eta = 0.15$ the tidal force is strong enough to circularise the orbit. For $\eta = 0.12$ the AGB reaches a larger radius on the AGB and, because tidal interaction is very sensitive to the ratio of the stellar radius to semi-major axis, tidal interaction manages to bring the planet into the AGB envelope.

In Figure 4 we zoom on the final million years or so of the evolution of the two lower panels of Fig. 3. We see the helium-shell flashes effect in causing substantial envelope expansion. This increases the tidal interaction strength, that in turn slows down the increase in the semi-major axis, or even decreases it a little. The star
finally engulfs the planet (lower panel) during such an envelope expansion of a helium-shell flash.

Consider the possible role of the planet in shaping the descendant PN. The planet beta Pic c, of mass $M_p = 9.3 M_J$, enters the envelope when its mass is $M_{env} \approx 0.6 - 1 M_\odot$ for the values of $\eta$ that we use. Namely, the planet mass is $M_p \approx 0.01 M_{env}$. Such a planet might excite large-amplitude (tens of per cents) oscillatory modes on the surface of the AGB star when it is deep inside the envelope (equation 5.7 in Soker 1992a), and might substantially spin-up the envelope (equation 10 in Soker 2001b).

We consider the planetary system of beta Pic to be a future progenitor of an elliptical PN due to the expected entrance of the planet beta Pic c to a CEE during the AGB phase of its parent star.

3.4. Examining the role of eccentricity

To further reveal the dependence of the fate of the planet on the properties of its orbit we examine the role of eccentricity. We take the planet HD 38529 c with an observed eccentricity of $e_0 = 0.36$ and search for the initial eccentricity, $e_{n,0}$, that would allow the star to engulf the planet during the AGB phase. We make the calculations for one value of the wind mass-loss rate parameter $\eta = 0.12$, and find that, keeping all other observed parameters unchanged, an initial eccentricity of

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**Figure 3.** The evolution of the stellar radius (blue-thick line), semi-major axis (dash-dotted-purple line; $a_0 = 585 R_\odot$), the periastron distance (red line), and eccentricity (black-dashed line; scale on the right axis with $e_0 = 0.24$) for the system beta Pic c and for three values of the wind mass-loss rate efficiency parameter $\eta$. The graphs include the RGB (first peak in radius), horizontal branch, and AGB (second peak in radius) phases of the evolution, and in the upper two panels the early post-AGB phase as well. The upper panel starts at $t = 1.72 \times 10^9$ yr, and the two lower panels at $t = 1.71 \times 10^9$ yr. Note the different scales of the three panels.

**Figure 4.** Zooming on the final AGB evolution of the two lower panels of Fig. 3. The spikes in the blue line (stellar radius) are helium-shell flashes. The upper and lower panels start at $t = 1.84 \times 10^9$ yr. Note the different scales of the two panels.
Figure 5. The evolution with time of the stellar radius (thick-blue line), semi-major axis (dash-dotted-purple line; \( a_0 = 793 \, R_\odot \)), periastron distance (red line), and eccentricity (dashed-black line; scale on the right side) of the planet HD 38529 c, but with trial eccentricities, \( e_n,0 \), that are larger than the observed value of \( e_0 = 0.36 \). All panels start at \( t = 2.92 \times 10^9 \) yr. The graphs include the RGB, horizontal branch, and AGB phases of the evolution, and in the upper two panels the early post-AGB phase as well. For all the simulations the efficiency wind mass-loss rate parameter is \( \eta = 0.12 \). Note the different scales of the three panels.

\( e_n,0 \gtrsim 0.6 \) would have allowed a CEE to take place. We present the results in Table 2, where the meanings of the different variables are as in Table 1. In Fig. 5 we present the evolution of stellar radius, semi-major axis, periastron distance, and eccentricity, in the post-main sequence phases.

The result of this simple study is expected, namely, a higher eccentricity for a given semi-major axis, which gives a smaller periastron distance, increases the likelihood of engulfment. However, it is not a straightforward evolution, because as we see in Fig. 5 the eccentricity and semi-major axis of the orbit decrease already during the upper RGB phase of the parent star (see also Fig. 3 for the planet beta Pic c). The periastron distance \( a_p = (1 - e)a \), though, increases. As the initial eccentricity \( e_n,0 \) increases, the decrease in the semi-major axis and eccentricity on the RGB becomes more significant. The evolution with \( e_n,0 = 0.6 \) has a smaller semi-major axis than the other two cases when the system leaves the RGB. This smaller semi-major axis makes tidal interaction on the AGB stronger, and the system is more likely to enter a CEE.

In Fig. 6 we zoom on the last million years or so. As in the evolution of beta Pic c (Fig 4), engulfment occurs following a stellar expansion as a result of helium-shell flash, when the orbit is already circular.

4. SUMMARY
Table 2. Examining the eccentricity of the orbit of HD 38529 c that would bring it to form a CEE during the AGB phase of its parent star. The first four columns in the second row are the observed values where units are as in Table 1. The last three columns indicate the outcomes had the eccentricity of the orbit been larger, keeping all other observed properties unchanged. In all simulations the wind mass-loss rate parameter is \( \eta = 0.12 \). For \( e_n = 0.6 \) the planet enters a CEE, and we list the core and envelope masses (in \( M_\odot \)) at the onset of the CEE.

| HD 38529 c | Outcome: No CEE or \( M_{\text{core}}; M_{\text{env}} \) |
|------------|--------------------------------------------------|
| \( M_\star \) | \( M_p \) | \( a_0 \) | \( e_0 \) | \( e_n = 0.4 \) | \( e_n = 0.5 \) | \( e_n = 0.6 \) |
| 1.48       | 23.7    | 793   | 0.36   | No CEE   | No CEE   | 0.563;0.715     |

The main goal of this study is to better understand the engulfment of planets during the RGB and AGB phases of their parent stars, in particular in relation to the possibility that planets shape the outflow of some AGB progenitors of elliptical PNe. Planets (and BDs) can affect the mass-loss geometry of their parent AGB (or RGB) star to form an elliptical PN by spinning-up the envelope and/or by exciting waves in the envelope (section 1). The spinning-up process takes place mainly as the planet tidally interacts with the envelope and when it enters the envelope, while excitation of waves takes place mainly when the planet is deep inside the envelope. Both of these processes influence the mass-loss geometry mainly by affecting the formation of dust on the surface (section 1).

Our approach here followed earlier studies (e.g., Nordhaus & Spiegel 2013; Sabach, & Soker 2018a) in following the evolution of confirmed exoplanets (and BDs). We specifically focused on planets that have orbits with semi-major axis in the range of \( 1 \lesssim a_0 \lesssim 20 \) AU and high eccentricities. We examined five systems, from the Extrasolar Planets Encyclopaedia; (exoplanet.eu; Schneider et al. 2011) and from Maire et al. (2020) that fit our requirements. To study their evolution we used the stellar evolutionary code MESA-BINARY.

We also followed Sabach, & Soker (2018a) and assumed that low mass stars that do not acquire angular momentum from a companion (Isolated stars) have a much lower wind mass-loss rate during their RGB and AGB phases than the commonly used value (\( \eta = 0.5 \) in equation 1). We summarised the fate of the planets in Table 1.

We found that out of the five systems, one system, HIP 75458, enters a CEE during the RGB phase of the parent star for all values of \( \eta \) (Figs. 1 and 2). The planet removes the envelope and leaves a bare helium core that will evolve to form a helium white dwarf.

Only in one system the planet, beta Pic c, enters the envelope of its parent star during the AGB phase. For that to occur, we had to reduce the wind mass-loss rate by a factor of about 4 (\( \eta \lesssim 0.12 \); table 1). The four other systems do not enter a CEE phase even for the lowest value of \( \eta \).

Overall, our study of eccentric planetary systems strengthens the early conclusion of Sabach, & Soker (2018a) that was based on circular orbits and used a simple tidal interaction formula. The conclusion is that to have a non-negligible fraction of AGB stars that engulf planets we should consider a lower wind mass-loss rates of Isolated stars.

We also made a test on the influence of the eccentricity. Keeping all other parameters at their observed value, we examined for what eccentricity of its orbit the planet HD 38529 c would enter a CEE with its parent star during the AGB phase. The observed value of the eccentricity is \( e_0 = 0.36 \). We found that we need to increase the eccentricity to a value of \( e_n \gtrsim 0.6 \) for AGB engulfment to take place (table 2).

In the cases where we do have engulfment on the AGB, the evolution involves some decrease in eccentricity and in the semi-major axis on the upper RGB phase, although the periastron distance \( (1 - e)a \) increases (Figs. 3 and 5). The final AGB engulfment takes place after a large envelope expansion as a result of a helium-shell flash (Figs. 4 and 6).

The next step is to conduct a thorough statistical study. However, the number of relevant confirmed exoplanets with semi-major axis of \( 1 \lesssim a_0 \lesssim 20 \) AU around potential progenitors of PNe (stars with initial masses of \( M_\star \gtrsim 1 M_\odot \)) is too low to conduct a meaningful statistical study. The uncertainty in the wind mass-loss rate on the RGB, and in particular on the AGB, adds to the uncertainty of such a study. Nonetheless, we encourage future studies to follow the evolution of exoplanets as they are discovered, to better learn about their degree of significance in influencing the post-RGB evolution and/or in potentially shaping elliptical PNe.

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