The Role of Planets in Shaping Planetary Nebulae

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ABSTRACT. In 1997 Soker laid out a framework for understanding the formation and shaping of planetary nebulae (PN). Starting from the assumption that nonspherical PN cannot be formed by single stars, he linked PN morphologies to the binary mechanisms that may have formed them, basing these connections almost entirely on observational arguments. In light of the last decade of discovery in the field of PN, we revise this framework, which, although simplistic, can still serve as a benchmark against which to test theories of PN origin and shaping. Within the framework, we revisit the role of planets in shaping PN. Soker invoked a planetary role in shaping PN because there are not enough close binaries to shape the large fraction of nonspherical PN. In this article we adopt a model whereby only ~20% of all 1–8 \( M_\odot \) stars make a PN. This reduces the need for planetary shaping. Through a propagation of percentages argument, and starting from the assumption that planets can only shape mildly elliptical PN, we conclude that ~20% of all PN were shaped via planetary and other substellar interactions, but we add that this corresponds to only ~5% of all 1–8 \( M_\odot \) stars. This may be in line with findings of planets around main-sequence stars. PN shaping by planets is made plausible by the recent discovery of planets that have survived interactions with red giant branch (RGB) stars. Finally, we conclude that of the ~80% of 1–8 \( M_\odot \) stars that do not make a PN, about one-quarter do not even ascend the AGB due to interactions with stellar and substellar companions, while three-quarters ascend the AGB but do not make a PN. Once these stars leave the AGB they evolve normally and can be confused with post-RGB, extreme horizontal branch stars. We propose tests to identify them.

1. INTRODUCTION

Soker (1997) established an observationally based framework whereby planetary nebulae (PN) with different morphologies were mapped to the shaping mechanism that could produce them. These mechanisms ranged from single stars to a multitude of binary interactions with stellar and substellar (brown dwarf and planetary) companions.

Many discoveries, both observational and theoretical, have been made in the last 10 years that have thickened the debate of what shapes PN. Key to the debate have been the theoretical works of Soker (2006b) and Nordhaus et al. (2007) (but see previous work by Soker & Zoabi 2002), who described the difficulty with which single asymptotic giant branch (AGB) stars can sustain rotation and global magnetic fields for long enough to affect the geometry of the mass loss and the shape of the subsequent PN. In the case of single stars, rotation and global magnetic fields have been the leading mechanisms suggested for the shaping of nonspherical PN (e.g., García-Segura et al. 2005). Lacking a full understanding of how single AGB stars can produce winds that greatly diverge from a spherical distribution, several authors started looking more favorably to binary origin explanations (for a review, see De Marco 2009), where the companion is either an AGB wind shaping agent (i.e., via gravity) or it induces primary envelope rotation and magnetic fields.

Irrespective of what camp of the debate each researcher favors, the scheme of Soker (1997) has been used as a basis against which to test various hypotheses (e.g., García-Segura et al. 1999; Parker et al. 2006a; Lü et al. 2009). Therefore, in light of the last decade of observational and theoretical results, there is scope for a revision of that framework. In particular, the role of planets in shaping PN was already discussed in the late 1990s, but could not be observationally quantified at that time. Today, we know more on the statistics of planetary systems, and, although many questions still remain, this is enough to update our estimate of the role of planets in shaping PN.

Finally, new planetary discoveries are changing our understanding of stars. New questions are being asked as to the influence planets have on stellar evolution and, conversely, how stars affect planet evolution and survival (see, for instance, Schuh et al. 2011). The role of planets in PN shaping is topical in this context.

In § 2 we explain the PN shaping framework laid out by Soker (1997). In § 3 we discuss new results in the field of PN (§ 3.1) and planets (§ 3.2), which allow us to reassess the work of Soker (1997) in § 4. In § 5 we present some arguments regarding the detection of naked central stars, and in § 6 we conclude.

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2. THE PN SHAPING FRAMEWORK IN 1997

Soker (1997) presented a classification of 458 PN, based on the morphological systems of Schwarz et al. (1993) and Corradi & Schwarz (1995), with the aim of distinguishing between the role of stellar and substellar companions. Soker (1997) further classified elliptical PN into those with large and small departures from sphericity. He divided PN morphologies into four categories and flanked each category with the physical process most likely to give rise to that shape using a series of observational arguments.

1. Spherical PN are formed by progenitors that did not have a companion or did not interact with their companion. Some departure from sphericity (though no axisymmetry) may be expected if the companion separation is large, but still interacting in some way with the primary and the PN is formed over a span of time comparable with the orbital period.

2. Bipolar PN are formed by a close stellar companion that avoided a common-envelope phase or that entered the common envelope only late in the evolution. The stellar companion accretes a substantial fraction of the AGB wind and blows two opposite jets that shape the nebula into a bipolar structure. Point-symmetric structures are also possible due to precession of the accretion disk around the companion.

3. Elliptical PN with large departure from sphericity are formed by stellar companions in a common envelope. The companion in the envelope does not blow strong jets (or blows no jets at all), but the interaction with the envelope ensures high equatorial mass loss that leads to an expanding ring structure.

4. Elliptical PN with small departure from sphericity are formed by a substellar companion (a brown dwarf or a planet) that spins-up the envelope of the AGB progenitor. Weak jets may be present.

The preceding framework was based primarily on a series of key observational results and in part on a handful of theoretical studies, which we summarize next:

1. The theoretical argument was then, and is still now, that the axisymmetric structure (including point-symmetric) requires the presence of a stellar or substellar companion (Soker 2001b, 2004, 2006b). The rarer point-symmetric PN cannot be explained by a model based on shaping by the fast wind during the PN phase and seem to require precessing accretion disks. Theoretical models showed that binary interactions have the ability to produce the observed PN morphologies (e.g., Morris 1987).

2. From population synthesis studies, the fraction of PN that were derived from binary interaction was far lower than the needed 90% (that is, the entire PN population minus 10% spherical PN). For instance, Han et al. (1995) derived that only $38 \pm 4\%$ of all PN derive from binary interactions (common envelopes, mergers, and wider binary interactions).

3. We knew observationally that $\sim 10\%$ of all PN are round. We also knew that $\sim 15\%$ of PN are bipolar, while the remaining $\sim 75\%$ are elliptical (mildly, extremely, and with or without additional structures). The detailed classification does change from author to author (e.g., Corradi & Schwarz 1995), so we refrain here from describing additional subdivisions.

4. At the time, it appeared that the PN observed around post–common-envelope central stars were not bipolar, but rather elliptical (Soker 1997).

5. Bipolar PN have relatively higher expansion velocities, more in line with the escape velocities of main-sequence, rather than AGB, stars (Corradi & Schwarz 1995). Elliptical PN, on the other hand, have expansion velocities that can be explained by winds from AGB stars.

6. The spherical halos of many PN are much fainter than the elliptical inner region. In the binary model this is accounted for by a binary interaction that occurs at a late stage in the superwind phase, the period of enhanced mass loss that is observed to take place toward the end of the AGB (Delfosse et al. 1997). The interaction both increases the mass-loss rate and causes the departure from axisymmetry; even a planet can play a role in this process (Soker 2000).

7. Planet statistics were poor in that year.

Later, Soker (2001a), realizing the possible importance of wider stellar companions, added a fifth class of wide (but not very wide) companions that accrete mass and blow jets. The shaping is only by the jets. A moderately elliptical PN is formed, with pronounced signature of jets (although not as strong as in the preceding scenario 2). Finally, De Marco & Moe (2005) and Soker & Subag (2005) introduced the concept that not all $1–8 M_\odot$ stars actually make a PN. Single stars can make a spherical PN of a subluminous nature that is harder to detect; Soker & Subag (2005) termed this class “hidden PN.”

In Table 1 we summarize the conclusions of Soker (1997; col. [3]), Soker (2001a, 2001b; col. [4]) and Soker & Subag (2005; col. [5]), based on the preceding results, as well as the conclusions of the present work, which will be justified in the following sections. Once the spherical PN are accounted for by mechanisms involving no interaction and bipolar PN are accounted for by close companions outside the common envelope ($\sim 10\%$ and $\sim 15\%$, respectively), the remaining $\sim 75\%$ of all PN needs to be accounted for by other interactions. Soker (1997) expected that the only other PN shaping interaction would be a common-envelope interaction, and these interactions are not frequent enough to account for $75\%$ of all PN. This led Soker (1997) to conclude that there are not enough stellar companions to produce the large fraction of nonspherical PN. Even including much wider binaries in the class of interacting binaries (Soker 2001a), there was still a need for a relatively large number of planetary companions to help shape PN.

3. IN THE LIGHT OF NEW RESULTS

Since the mid-2000s, several results of both a theoretical and observational nature allowed us to refine the conclusions of
Soker (1997, 2001a, 2001b) and Soker & Subag (2005). Here, we divide the new results into two classes. Those pertaining PN and those that regard the presence and frequency of planets around main-sequence and evolved stars.

3.1. Highlights of Relevant PN Research in the Last Decade

The fact that shaping axisymmetric PN with single stars may be difficult was discussed before (e.g., Morris 1987; Soker & Livio 1989; Soker 1997, 2006a; Nordhaus et al. 2007; but see also De Marco 2009). Recently (Soker 2006b; Nordhaus et al. 2007), it has become even more implausible. Global magnetic fields in AGB stars tend to feed back negatively onto the star’s spin, slow it down, and shut down the magnetic field itself in less than ~100 yr, i.e., shorter than it is needed to shape the superwind ≥1000 yr. Magnetic fields in the successful shaping models of, e.g., Garcia-Segura et al. (2005) are imposed and constant. The suggestion of Blackman et al. (2001) that tapping part of the convection energy to sustain the magnetic-field forming dynamo is a viable mechanism to sustain AGB fields was questioned by Soker & Zoabi (2002), as well as, later on, by the authors themselves (Nordhaus et al. 2007).

Several theoretical papers have studied the effects of a binary companion on a mass-losing AGB star. These papers show that the relation between the binary interaction type and resulting PN morphology may not be as straightforward as envisaged by the simple scheme of Soker (1997): the seminal work of Mastrodeo-mos & Morris (1999) studied the effects of a companion accreting from an AGB star wind and forming a stable accretion disk and jets, and Reyes-Ruiz & López (1999) and Nordhaus & Blackman (2006) studied the formation of accretion disks and jets around the primary’s core by disrupted companion. Further, Blackman et al. (2001) concluded that more massive companions may blow powerful jets that can inflate bipolar lobes. Equatorial flows can be formed by companions in common-envelope interactions (Sandquist et al. 1998) and in wider orbits (Edgar et al. 2008), but it is not clear whether bipolar morphologies can arise from these systems (Soker 1997). Finally, the PN morphology may change after it is initially established at the hand of the fast post-AGB wind (Huarte Espinosa et al. 2010), although it is not known exactly which types of structures are susceptible to this change and which are not.

Population synthesis simulations that predict the fraction of PN shaped by binary interactions (e.g., Han et al. 1995) start from the assumption that all stars in the main-sequence mass range 1–8 M_☉ will form a PN. Using a different population synthesis technique, Moe & De Marco (2006) predicted the number of PN (with radius <0.9 pc) present today in the Galaxy, if all of the 1–8 M_☉ stars actually make a PN (46,000 ± 13,000 objects). This number was recently updated by Moe & De Marco (2011, in preparation) to 61,000 ± 17,000 objects. They compared this prediction with the actual number of observed PN (with radius <0.9 pc—this radius limit is key to avoid much larger uncertainties that would derive from PN detection) of 8000 ± 2000, derived from extragalactic PN counts (Jacoby 1980), or 13,000 ± 2000, derived from a local sample count (Frew 2008). The predicted number is discrepant with the observationally based estimate of the Galactic PN population at the 3σ level. This calculation supports the earlier suggestion of Soker & Subag (2005) that not all stars in the 1–8 M_☉ range

### Table 1

| Evolutionary channel | By-product | Percentage | 1997 | 2001 | 2005 | This work |
|----------------------|------------|------------|------|------|------|-----------|
| 1  No interaction    | Spherical PN | ~10 | ~10 | ~10 | ~5' (19') |
| 2  Close stellar companion outside envelope | Bipolar PN | ~11 | ~15 | ~15 | ~3' (13') |
| 3  Stellar companion in a common envelope | Extremely elliptical PN | ~23 | ~25 | ~25 | ~7' (28') |
| 4  Substellar companion in a common envelope | Mildly elliptical PN | ~56 | ~35 | ~15 | ~5' (20') |
| 5  Wide stellar companion | Elliptical PN with jets | ... | ... | ~15 | ~5' (20') |
| 6  No interaction | Naked central stars (post-AGB) | ... | ... | ~20 | ~60' |
| 7  Strong interaction on the RGB | EHB stars (post-RGB) | ... | ... | ... | ~14' |

Note: Subdivision of the evolutionary channels taken by all 1–8 M_☉ stars and the evolution of our understanding of the percentages over the past decade. The percentage are from Soker (1997, 2001a, 2001b), Soker & Subag (2005), and the present paper. EHB stars are formed form RGB stars that have lost most of their envelope due to a strong binary interaction with a stellar companion and will never ascend the AGB.

* All these percentages should be considered “a few percent.” However, their relative accuracy may be much better than their absolute one. They add up to 25 instead of 26 because of rounding errors.

1 All numbers in brackets are fractions of the PN population and add up to 100. The distribution of percentages within brackets reflects the distribution of morphological types.

2 We maintain these two channels separate for historical reasons, although we know that these two evolutionary channels do not always result in the corresponding morphologies. They could be combined into one channel called “strong binary interactions.”

3 It is conceivable that also substellar companions may blow jets if they are destroyed in a common-envelope interaction and form a disk around the primary’s core (§ 3.1 and Nordhaus & Blackman 2006).

4 These uncertainties are of the order of ±5%.
actually make a PN. If so, the PN population does not need to mirror the main-sequence population, but it derives from only a subset of it. In Table 1 we reserved a row for “naked central stars.” We exchange the term “hidden PN” used by Soker & Subag (2005) with “naked central star of PN,” to reflect the observational consequence that these will not be classified as PN at all. Still, we do predict that very deep observation may reveal very intrinsically faint PN that are expected to be spherical. While Soker & Subag (2005) listed the spherical PN together, whether observed or hidden, in Table 1 we classified them into two groups: spherical PN and naked central stars.

Zijlstra (2001), De Marco (2009), and Miszalski et al. (2009b) cataloged the morphologies of PN associated with post–common-envelope binaries, concluding that there is a preferential association between these binaries and bipolar PN (although not all post–common-envelope central stars do have a bipolar PN). This releases the constraint of Soker (1997) to associate bipolar PN with binary systems that avoided a common-envelope interaction. In recent years the issue of what conditions dictate that a binary avoids a common-envelope interaction has been hotly debated (e.g., Beer et al. 2007; Cariberg et al. 2009; Bear & Soker 2010; Nordhaus et al. 2010), including when a binary enters a common envelope at a late stage (Corradi et al. 2011). Therefore, at this point we consider all close binary interactions (common envelope and not) in the same group.

The Macquarie/AAO/Strasbourg Hα (MASH; Parker et al. 2006a, 2006b; Miszalski et al. 2008) survey revised the fraction of spherical PN from ~10% to ~19%, where the fraction of spherical PN is higher for fainter/older PN. Decreasing the fraction of nonspherical PN to ~81%, this result slightly releases the pressure on the needed number of binary interactions. The MASH survey also slightly decreased the fraction of bipolar PN to 13%.³

Further, if very wide stellar companions shape mass loss by accreting AGB wind and blowing jets, the number of possible binary interactions that can create nonspherical PN is greatly increased. An example of such wide interactions is Mir A2, where despite the large orbital separation of ~40 times the AGB stellar radius (338–402 R⊙; Woodruff et al. 2004), the companion influences the wind morphology in the region between the two stars (Marengo et al. 2001; Karovska et al. 1997; 2005; Matthews & Karovska 2006; Karovska 2006).

Miszalski et al. (2009a) revised the fraction of PN binaries with periods shorter than ~15 days to 17 ± 5% (only slightly larger than the 10–15% determined by Bond (2000)). This fraction is a lower limit, due to the photometric precision of the survey used and the various survey biases (such as the angle between the orbital axis and the line of sight). However, accounting for such biases would not increase this fraction dramatically: Bond (2000) had assumed that the period distribution of the detected systems (P < 3 days) meant that longer periods could not be observed, and so a large fraction of binary PN may be hiding at periods slightly longer than 3 days. On the other hand, Miszalski et al. (2009a) determined observationally and De Marco et al. (2008) determined theoretically that the detection limit of this survey technique is ~2 weeks and that the paucity of central star binaries in the period range of 3 days to 2 weeks is real. We can therefore state that while the fraction of post–common-envelope binaries is only slightly larger than 17%, the fraction of central stars in binaries with periods longer than 2 weeks remains unknown and could be large.

We still do not know the fraction of PN that have binary central stars in the period range of 2 weeks to the maximum period that still allows for an interaction. Preliminary work by De Marco (2011; see also Passy et al. 2011, in preparation) indicates that this fraction may be larger than predicted by the current PN scenario, where almost all 1-to-8 M⊙ stars make a PN. If confirmed, this finding is in line with the conclusions of Soker & Subag (2005) and Moe & De Marco (2006).

3.2. Highlights of Relevant Exoplanet Research in the Last Decade

About a decade ago estimates of the percentage of planet-hosting solarlike stars stood at ~3%, although it was already suspected that the percentage might be much higher for stars with higher metallicities: ~25%–30% for stars with twice the solar metallicity (Fe/H > 0.3; e.g., Santos et al. 2004; Fischer & Valenti 2005). Lineaweaver & Grether (2003) extrapolated from the detected parameter space of planetary systems to below detection sensitivity and concluded that the real fraction of planet-hosting solarlike stars should be at least 9% for M_p sin i > 0.3 M_ J and P < 13 yr and at least 22% for M_p sin i > 0.1 M_ J and P < 60 yr. They also suggested that since this area of the planet mass-period plane is only a fraction of that occupied by our own solar system, these fractions may be even larger once the entire parameter space is sampled. This was the situation when Soker & Subag (2005) updated the PN formation channel statistics (see col. [5] of Table 1).

Today we have strong evidence that the planetary fraction increases with both metallicity and mass of the host star (Johnson et al. 2010), although our knowledge of the planet-hosting star fraction as a function of planet mass and orbital separation is grossly incomplete. A new finding in this respect is that of Bowler et al. (2010), who determined that ~26 ± 4% of stars having a main-sequence mass of 1.5 ≤ M_*/M⊙ ≤ 2.0 host massive planets at large separations (but still less than 3 AU). The new finding is not only of a larger fraction of planet-hosting stars, but
also puts the planets at larger orbital separations, where they can more easily be available to shape winds from AGB stars; if the planets are too close to their host, they interact with the star during the RGB phase and either prevent the star from reaching the AGB at all (and form a PN) or they just get destroyed before the star reaches the AGB (Nelemans & Tauris 1998; Villaver & Livio 2007, 2009). There is also an indication from the analysis of a handful of thick disk stars that the planetary fraction for low-metallicity old stars may be higher than for younger stars at similar metallicities (Sheehan et al. 2010).

Another relevant finding is that of brown dwarf and planetary mass companions around extreme horizontal branch (EHB) stars, also termed sdO and sdB subdwarfs. Although such findings regard stars that have gone through the RGB, not the AGB evolution, we can draw information of a general interest. EHB stars are on the horizontal branch (HB) and have small envelope mass, because their RGB progenitor lost most of its envelope (D’Cruz et al. 1996). Current consensus is that in most cases the mass loss was caused or enhanced by the interaction with a stellar-mass companion (Han et al. 2002).

Companions with likely brown dwarf or planetary masses have been discovered at 1 to a few AU from single (Silvotti et al. 2007) or close binary (Lee et al. 2009; Beuermann et al. 2011; Qian et al. 2009a, 2009b) EHB stars. For the latter group, the companions orbit close binaries that went through a common-envelope interaction when the RGB progenitor of the sdB star engulfed its stellar companion. It is not clear where these tertiary/lower-mass companions were located within the pre-common-envelope binary, but they may have survived despite the dynamical mayhem of the common-envelope interaction.1

Geier et al. (2009) discovered a companion with mass 8–23 $M_J$ (either a planet or a low-mass brown dwarf) with a period of only 2.391 days around HD149382. This is the first detection of a substellar object, with a lower possible mass reaching the planet domain, but see Jacobs et al. 2011, that went through a common-envelope evolution inside an RGB envelope. The survival of the planet implies that interactions between gas giants and stars alter stellar evolution; therefore, if a planet at a suitable distance is present around a growing AGB star, a common envelope with such a planet may be survived and lead to shaping of the ejecta. A second possible planet ($M \sin i = 1.25 M_J$) was recently discovered by Setiawan et al. (2010) at 0.116 AU from the metal-poor HB star HIP 13044.

4. UPDATING THE PN SHAPING FRAMEWORK

In light of the new discoveries (§ 3), we now reframe the results of Soker (1997) and subsequent updates by Soker (2001a, 2001b) and Soker & Subag (2005). The work discussed in § 3.1 releases the tight constraint that brought Soker (1997) to conclude that a large number of PN should be shaped by planets. The increasing numbers of brown dwarf and planet discoveries around evolved stars also give support to the idea that planets play a role in shaping PN, provided that they are at a suitable distance from the star to interact during the AGB. Finally, the larger fraction of planets detected recently around main-sequence stars, compared with what was believed a decade ago, provides us with more flexibility when discussing the role of planets in shaping PN.

In what follows we quote percentage figures with an accuracy of 1%. This accuracy is unrealistically high. However, we do so for ease of following some of the arguments. At the end, we will discuss what should be considered reasonable errors on these percentage estimates.

We start by returning to the discussion of § 3.1: instead of considering the PN population as the inevitable child of the 1–8 $M_\odot$ star population, needing to reflect its binary fraction, we can think of the PN population as deriving from only a subset of the 1–8 $M_\odot$ stars. We adopt the subdivisions of PN morphological types envisaged by Soker (1997), with the changes brought in by the MASH morphological discoveries (§ 2; Table 2).

First of all, we determine the fraction of all 1–8 $M_\odot$ stars that result in a PN of any shape. Moe & De Marco (2011, in preparation) concluded that only 21 ± 8% of all 1–8 $M_\odot$ stars (13,000/61,000) make PN and 82 ± 8% make no PN, or do not go through the AGB at all (see § 3.1). This estimate rests on single stellar evolution, the initial mass function, the galactic star formation history, and observations. It is almost independent of the binary fraction and period distribution.

An independent way to determine the fraction of all 1–8 $M_\odot$ stars that result in a PN of any shape is to consider only the main-sequence binary fraction and period distribution. A summary of how these fractions are determined can be found in Table 3. Approximately 57% of F and G main-sequence stars are in binaries and ~30% have an orbital separation of ≤30 AU (Duquennoy & Mayor 1991) and will interact at some time during the primary star’s life. We have taken a maximum

1It is not excluded that these planets formed in the ejected common envelope (Perets 2010).

| Percentage of PN | Class | Reference |
|------------------|-------|-----------|
| 81% ............ | Nonround PN | Parker et al. 2006a |
| 19% ............ | Round PN | Parker et al. 2006a |
| 13% ............ | Bipolar PN | Parker et al. 2006a |
| 28% ............ | Extremely elliptical PN | Parker et al. 2006a; Soker 1997 * |
| 20% ............ | Mildly elliptical PN with no jets | Parker et al. 2006a; Soker 1997 * |
| 20% ............ | Mildly elliptical PN with jets | Parker et al. 2006a; Soker 1997 * |

* Sixty-eight percent elliptical (Parker et al. 2006a) = 28% + 20% + 20%. The subdivision into three classes follows Soker (1997). The jet/no-jet division is from Balick et al. (1998).
separation that is possibly too large for some types of interaction, but is smaller than the distance between Mira and its interacting companion (see § 3.1). We assume, once again, that an interaction is needed to produce nonspherical PN. We also account for the fact that 14% of all stellar systems suffer a strong interaction on the RGB (orbital separation ≤ 3 AU; Duquennoy & Mayor 1991) that induces so much mass loss that the system is prevented from ever evolving to the AGB. We then deduce that 30–14 = 16% of all stars suffer an AGB interaction with a stellar companion and go on to form a nonspherical PN. This means that ~16% of all stars go through an AGB interaction, ~14% go through an RGB interaction and never ascend the AGB, and the remaining ~70% suffer no interaction with a stellar companion and evolve into naked central stars or central stars with round PN, unless they have an interaction with a substellar companion. As did Soker (1997), we assume that mildly elliptical PN are shaped by interactions with substellar companions. Hence, ~16% of all stars go through an interaction with a substellar companion and result in nonround and non–mildly elliptical PN. This is equivalent to stating that ~16% of all stars result in 61% of all PN (the nonround and non–mildly elliptical ones; Table 3), and this means that 26% (16/61 × 100) of all 1–8 $M_\odot$ stars make a PN of any shape. This estimate, which has a probable error of ±5%, is based on approximate binary considerations and is consistent with that outlined previously (compare 26% with 21 ± 8%), obtained by Moe & De Marco (2011, in preparation) almost entirely from single stellar evolution arguments and PN counts.

In Table 4 we finally adopt 26% as the fraction of 1–8 $M_\odot$ stars that are able to make a PN of any shape. Approximately 14% is the fraction of all stars that do not ascend the AGB because of a strong interaction on the RGB. The remaining ~60% is the fraction of all stars that do not make a PN because they suffer no interaction (for further discussion, see § 5). Finally, we split 16% into fractions reflecting the PN morphological types presumed to derive from binary interactions with stellar companions; i.e., 13% are bipolar (16 × 0.13/0.61 = 3.4), 28% are extremely elliptical (16 × 0.28/0.61 = 7.3), and 20% are mildly elliptical with jets (16 × 0.20/0.61 = 5.2). The remaining 10% of all 1–8 $M_\odot$ stars (26–16%) goes to form the two remaining PN classes: the 19% round PN (10 × 0.19/0.39 = 4.9) and the 20% mildly elliptical PN with no jets (10 × 0.20/0.39 = 5.1).

Recently, Moe & De Marco (2011, in preparation) carried out a more precise binary population synthesis model, completely independent of morphological subdivisions, and determined that 8% of all 1–8 $M_\odot$ stars suffer a strong interaction with a stellar companion on the AGB (common envelopes and interactions outside the envelope). This is in line with the approximate estimate based on binary considerations and morphological subtypes, where ~11% of all 1–8 $M_\odot$ stars suffer a strong AGB interaction (3.4 + 7.3%: Table 4 and col. [7] of rows 2 and 3 in Table 1).

In Table 1 (col. [7]) we list a revised subdivision of the evolutionary channels followed by intermediate mass stars and their link to PN morphology. During the last decade of simulations and observations we have learned that a one-to-one correspondence between morphologies and shaping channels is as improbable as the likelihood of finding two identical PN. This is why we stress (see also Table 1, note c) that these are only guidelines. The take-home messages are as follows:

1. Common-envelope and other interactions, where the companion is close to the AGB surface, likely result in strong collimation leading to bipolarity and extreme ellipticity.

### Table 3

| Percentage of 1–8 $M_\odot$ stars | Method of determination |
|----------------------------------|-------------------------|
| 57% Binaries                     | DM91 \(^a\)              |
| 43% Single stars                 | 100–57%                 |
| 30% Binaries with a < 30 AU—interaction on the RGB or AGB | DM91 \(^a\) |
| 70% Single stars and binaries with a > 30 AU—no interaction | 100–30% |
| 14% Binaries with a < 3 AU—interaction on the RGB | DM91 \(^a\) |
| 16% Binaries with 3 < a < 30 AU—interaction on the AGB | 30–14% |

\(^a\) Duquennoy & Mayor 1991.

### Table 4

| Percentage of 1–8 $M_\odot$ stars | Method of determination |
|----------------------------------|-------------------------|
| (14 + e)% \(\ldots\) Do not ascend the AGB and do not make a PN | DM91; Table 3 |
| 3% Make bipolar PN | 16% × 0.13/0.61 \(^d\) |
| 7% Make extremely elliptical PN | 16% × 0.28/0.61 \(^d\) |
| 5% Make mildly elliptical PN with jets | 16% × 0.20/0.61 \(^d\) |
| 5% Make spherical PN | (26–16%) × 0.19/0.39 \(^d\) |
| 5% Make mildly elliptical PN | (26–16%) × 0.20/0.39 \(^d\) |
| 26% Make PN of any shape | ∼(3 + 7 + 5 + 5 + 5)% |
| (60 – e)% Ascend the AGB but do not make a PN | (100 – 26 – 14%) |

\(^d\) These are the morphological percentages from Table 2.

\(\ldots\) This fraction is tied to the choice of the orbital separation limit (we have selected 3 AU; see Table 3) within which binaries and star-planet systems interact on the RGB. This limit is not well known. It also depends sensitively on the primary mass and the strength of the tides.

\(\ldots\) The symbol e denotes a small fraction of stars that have an interaction with a substellar companion on the RGB and, as a result, does not ascend the AGB. The same small fraction is taken out of the group of stars that do ascend the AGB.

\(\ldots\) Sixteen percent is the percentage of all stars that have a stellar companion and that suffer an interaction on the AGB, resulting in bipolar, extremely elliptical, and mildly elliptical with jets PN; 26% is the percentage of all stars that make a PN of any shape, so 26–16 is the percentage of all stars that make round and mildly elliptical PN; see Table 3.

\(\ldots\) These are the morphological percentages from Table 2.
2. Low-mass companions such as planets are likely only to promote small departures from a spherical shape.

3. Blowing jets may be promoted not only by an accreting stellar companion at some distance from the primary, but also by a disrupted lower-mass companion that forms a disk around the primary core (Nordhaus & Blackman 2006). If so, this would confuse the distinction between channels 4 and 5 in Table 1.

If, as in Soker (1997, 2001a) and Soker & Subag (2005), we assume that mildly elliptical PN with no jets were shaped mainly by a substellar companion, we predict that substellar companions have shaped \( \sim 20\% \) of all PN, which corresponds to \( \sim 5\% \) of all 1–8 \( M_{\odot} \) stars having suffered an interaction with a planetary companion on the AGB. However, if substellar companions can get disrupted, form a disk around the primary core, and blow jets, then these percentages could rise to as much as \( \sim 40\% \) and \( \sim 8\% \), respectively.

### 4.1. The Implied Fraction of Planets from the AGB Perspective

The fact that only \( \sim 30\% \) of main-sequence stars have substellar companions close enough to interact, combined with the fact that \( \sim 81\% \) of PN have nonspherical shapes that appear to need a companion, led Soker (1996) to state that “substellar objects (brown dwarfs or gas-giant planets) are commonly present within several AU around main-sequence stars. For a substellar object to have a high probability of being present within this orbital radius, on average several substellar objects must be present around most main-sequence stars of masses \( \leq 5 \, M_{\odot} \).”

We have derived here that \( \sim 5\% \) of all 1–8 \( M_{\odot} \) stars suffer a strong interaction with a substellar companion on the AGB. This estimate depends critically on (1) the assumption that mildly elliptical PN with no jets are mostly shaped by a substellar companion, (2) the frequency (\( \sim 20\% \)) of this specific PN morphology, and (3) the two independent arguments that predict that only 21\% or 26\% of 1–8 \( M_{\odot} \) stars make a PN at all (0.21 or 0.26 \( \times \) 0.20 \( \sim \) 0.05).

These substellar companions should occupy orbits between \( \sim 3 \) and \( \sim 30 \) AU around the main-sequence progenitors. Closer companions (whether stellar or substellar) suffer a strong interaction (likely a common-envelope interaction) on the RGB and are either destroyed or preclude the primary from ascending the AGB because of excessive mass loss (Soker et al. 1998; Bear & Soker 2010; Nordhaus et al. 2010). Companions farther out would not interact.

Using a population synthesis technique, one could use this estimate and work backward to determine the parent population of these star-planet systems. Even without such calculation, we can already draw a few conclusions. The median main-sequence progenitor mass of today’s PN population is 1.2 \( M_{\odot} \) and the median metallicity is approximately solar (Moe & De Marco 2006). Taking the maximum radii on the AGB, \( R_A \), and on the RGB, \( R_R \), from Iben & Tutukov (1985), Soker (1998) derived the following approximation for the ratio of the maximum AGB to maximum RGB radius as a function of mass:

\[
\log(A/R_R) = 3.7 \log^2(M/M_{\odot}) - 0.37 \log(M/M_{\odot}) + 0.16, \quad M \leq 2.25 \, M_{\odot},
\]

for stars which develop degenerate helium cores, and

\[
\log(A/R_R) = 2.2 - 1.8 \log(M/M_{\odot}), \quad M \geq 2.35 \, M_{\odot},
\]

for more massive stars, where \( M \) is the primary’s mass on the zero-age main sequence. From these relations we can state that for stars with spectral types earlier than A, the radius ratio is >2, while for stars with spectral types later than F-G, which correspond to the progenitors of central stars of PN, this ratio is <2. For the progenitors of PN, therefore, the planetary population has to be relatively far out. We have quoted limits of 3 and 30 AU, respectively. The lower limit depends critically on the adopted prescription of tidal capture and mass-loss (Soker 1996; Villaver & Livio 2007, 2009; Nordhaus et al. 2010).

Considering that the fraction of solarlike stars hosting relatively close-by planets may be of the order of 10–20\%, and considering that we predict that a low \( \sim 5\% \) of all solarlike stars have substellar companions farther out than \( \sim 3 \) AU, it is probable that the substellar companions farther out are the outermost companions in a system of multiple planets.

### 5. DO WE OBSERVE THE NAKED CENTRAL STARS?

In this subsection, we want to elaborate further on the suggestion that \( \sim 60\% \) of all 1–8 \( M_{\odot} \) stars that ascend the AGB do not make a visible PN. This is a surprisingly high number and implies a large population of post-AGB stars that, under the commonly assumed scenario, would have PN, but do not in the revised scenario. To be more precise, Moe & De Marco (2006, 2011, in preparation) predict that \( \sim 61,000 \) stars in the Galaxy are in the evolutionary phase appropriate to be surrounded by a PN of less than 0.9 pc in radius; i.e., these stars are in a post-AGB with \( T_{\text{eff}} \gtrsim 30,000 \) K, have left the AGB less than 25,000 yr ago, and have mass \( \sim 0.55 \, M_{\odot} \). This population is about six times larger than the Galactic PN population with radii smaller than 0.9 pc (11,000 PN; Frew 2008), from which we predict that 48,000 (61,000–13,000) stars in the Galaxy are...
“naked” central stars. It would be much harder to detect naked central stars, because of high reddening in the Galactic plane. However, we should consider that recent surveys have now detected $\sim$3000 PN (Frew & Parker 2010), which is $\lesssim$30% of the total (Jacoby 1980; Moe & De Marco 2006; Frew 2008). PN are particularly bright and have emission lines in the red part of the spectrum, which are less subject to reddening. The fraction of detectable naked central stars should be far smaller.

Naked central stars would look like subdwarf O and B stars, most of which are post-RGB stars, and would be easily confused with them. In some cases they could be told apart from those sdOB stars that are in a post-RGB phase of evolution on the grounds of higher luminosity and larger surface gravity (although there is an overlap between post-RGB and post-AGB stars on the log $g - T_{\text{eff}}$ plane [Napiwotzki 1999 their Fig. 4]).

The fraction of naked central stars in the sdOB sample should be only a few percent of the total, because of their short lifetimes compared with the post-RGB phase. Any post-AGB object, independent of its mass, will fade below 100 $L_\odot$ in less than 100,000 yr (Vassiliadis & Wood 1994). All post-AGB objects with $M > 0.60$ $M_\odot$ will fade to $L = 100$ $L_\odot$ in only 10,000 yr. HB lifetimes are instead of the order of several tens of millions of years (Dorman et al. 1993).

We have an indication that the predicted number of post-AGB sdOB stars are there, but this must be corroborated by a more accurate count. O’Toole (2010, private communication—but see also Hirsch et al. 2008), determined that in about 120 sdO stars, there are several objects that could be in the post-AGB phase. This could constitute the few percent predicted. For the sdB stars, a few hundred of which have determined log $g$ and $T_{\text{eff}}$, several reside in the log $g - T_{\text{eff}}$ locus appropriate for post-AGB stars (Napiwotzki 1999; Hirsch et al. 2008). There should be fewer sdB post-AGB stars than sdO post-AGB stars, because their evolutionary times for the temperature $T_{\text{eff}} < 40,000$ K is quite a lot shorter than for $T_{\text{eff}} > 40,000$ K.

Looking at Fig. 2 of Napiwotzki (1999) or Fig. 3 of Hirsch et al. (2008) we see that there are a number of sdB and sdO stars that are not surrounded by a PN. Several objects are indeed found on the horizontal part of the post-AGB tracks, where a PN is expected. Others are seen on the descending part, but at high core mass such that one might expect that a PN would be present, considering the shorter evolutionary timescales. This sample is not homogeneous, and it is therefore difficult to determine whether the number of naked central stars on this plot is what is expected from the prediction by Moe & De Marco (2006, 2011, in preparation).

Deep imaging surveys may reveal a number of faint and spherical PN around naked central stars. The fact that the deep MASH survey approximately doubled the fraction of circular PN may already have borne out this prediction.

6. SUMMARY

The first assumption we adopt in this article, which is increasingly supported by observations and theoretical considerations, is that single stars are mostly unable to produce PN whose shapes diverge from spherical. Second, we bring to bear the population prediction that the fraction of stars in the initial mass range 1–8 $M_\odot$ that actually form PN is only $\sim$20% (see § 3.1).

As in the past, we make the simplistic assumption that mildly elliptical PN with no jets are formed exclusively by planetary interactions. This assumption is broadly justified by the following:

1. Simulations show that density contrasts drastically reduce for decreasing companion mass in common envelopes (Sandquist et al. 1998; De Marco et al. 2003) and outside the common envelope (Kim & Taam 2010); such interactions are therefore likely to lead to mildly elliptical shapes at best.

2. Known PN around close binaries are, by and large, bipolar or strongly elliptical and have often jets and substructures; if the stellar-mass companions are at larger orbital separations than those that interact in a common envelope, theoretical considerations suggest that accretion onto the companion promotes jets, which, once again, lead to more dramatic departures from spherical symmetry than a mild ellipticity.

Despite these justifications, the one-to-one correspondence between interactions with substellar companion and the generation of mildly elliptical PN should be considered only as a guideline to be confronted by observations and against which to continue testing future shaping theories.

With the preceding premise, we predict that the fraction of PN shaped by planets ($\sim$20%) corresponds to only $\sim$5% of all 1–8 $M_\odot$ stars having interacted with a planet on the AGB, indicating that a few percent of 1–8 $M_\odot$ stars should have Jupiter-class companions farther out than a few AU, a thing that seems increasingly plausible given new discoveries of planets around main-sequence stars (e.g., Johnson et al. 2010; Bowler et al. 2010; see § 3.2). Planets farther out may be the outer planets in planetary systems.

Finally, the implication that $\sim$60% of all stars in the initial mass range 1–8 $M_\odot$ do not go through a PN phase may be justified observationally. There are several hot subdwarf stars that occupy a location of the log $g - T_{\text{eff}}$ diagram appropriate for central stars of PN, but that do not exhibit a PN. In order to strengthen this claim, one would have to make a prediction of the fraction of all subdwarf O and B stars that are expected to be post-AGB in origin through a population synthesis. Also, one would have to homogeneously locate a sufficient number of these stars on the log $g - T_{\text{eff}}$ diagram to determine if the prediction is verified.

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