DEPARTURE FROM AXISYMMETRY IN PLANETARY NEBULAE

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ABSTRACT

Many planetary nebulae (PNs) exhibit symmetries that range from unremarkable spherical and elliptical shapes to quite exotic bipolar and point-symmetric shapes. However, there are many that exhibit distinctly nonaxisymmetric structure in either (1) the shape of the nebula, or (2) the off-centered position of the illuminating star. By examining a large number of well-resolved images of PNs, we estimate that ~30%-50% of all PNs exhibit distinctly nonaxisymmetric structure. In this paper, we discuss how such departures from axisymmetry can arise from the binary nature of the progenitors of the PNs. The scenarios include (1) relatively close binaries with eccentric orbits, and (2) longer orbital period systems with either circular or eccentric orbits. In the first mechanism, the departure from axisymmetry is caused by the variation of mass loss and/or mass transfer with the changing distance between the companions in their eccentric orbit. In the second mechanism, the departure from axisymmetry is the result of the time-varying vector direction of the mass-losing star, or that of a possible pair of jets from the companion, as the stars move around their orbit. In order to assess the fraction of PNs whose nonaxisymmetric morphologies are expected to arise in binary systems, we have carried out a detailed population synthesis study. In this study, a large number of primordial binaries are evolved through the lifetimes of both stars, including wind mass loss. We then assess whether the primary or the secondary (or both) produces a PN. The expected deviations from axisymmetry are then classified for each binary and the results tabulated. We find that ~25% of elliptical and ~30%-50% of bipolar PNs are expected to acquire non-axisymmetric structure from binary interactions.

Subject headings: binaries: general — ISM: general — planetary nebulae: general — stars: AGB and post-AGB — stars: mass loss

1. INTRODUCTION

Intermediate-mass stars form planetary nebulae (PNs) in their transition from asymptotic giant branch (AGB) stars to white dwarfs. Although single AGB stars are expected to rotate very slowly, and indeed the extended circumstellar envelopes of most AGB stars appear spherically symmetric (e.g., Sahai & Bieging 1993), most PNs have a large-scale axisymmetric rather than a spherical structure (for recent papers on the subject see Kastner, Soker, & Rappaport 2000). The nonspherical PNs can be divided into two main classes, elliptical PNs and bipolar PNs. Bipolar (also called "bilobal" and "butterfly") PNs are defined as axially symmetric PNs having two lobes with an "equatorial" waist between them. The elliptical PNs have a large-scale elliptically shaped shell with no, or only small, lobes or waists. These two main classes can be further subclassed according to other morphological features (e.g., Manchado et al. 2000). A few examples of these subclasses are:

1. Inner regions that are axisymmetric, e.g., elliptical, with the outer regions (mainly the halos) being spherical. (By “axisymmetric” we mean that there exists at least one axis in three dimensions about which the nebula is rotationally symmetric.)

2. More than one axisymmetric substructure, where the symmetry axes of the different substructures have different directions, although all symmetry axes basically still pass through the central star. These are termed “point-symmetric PNs” (for a recent review see Manchado et al. 2000) or “quadrupolar PNs” (Manchado, Stanghellini, & Guerrero 1996). The common view is that these PNs are formed by precessing jets (e.g., Livio 2000). The jets may be blown by the AGB star or post-AGB progenitor, or from an accreting stellar companion (Soker & Rappaport 2000, hereafter SR00).

3. Substructures that have no symmetry axes, or either the symmetry axes of different substructures lack a common intersection point or the illuminating star is displaced from the intersection point. These last kind of PNs, among other types, are defined by us as having a “departure” from axisymmetry. This “departure” refers only to large-scale structures, and not to small blobs, filaments, bubbles etc.

All classes of PNs may possess departure from axisymmetry. Circular PNs possess departure if their central star is not at the center of the nebula and/or they contain a spiral structure (Soker 1994; Mastrodemos & Morris 1999). Examples of circular PNs with off-center illuminating stars are difficult to find, since there are not many circular PNs, and those that are born spherical may be distorted quite easily by the ISM and/or instabilities and lose their circular appearance. Therefore, the best example of a circular nebula with an off-center illuminating star is not a PN, but rather a PN progenitor—the thin shell around the carbon star TT Cygni (Olofsson et al. 2000). The presence of a spiral structure also applies to elliptical and bipolar PNs. In most cases, the spiral structure is expected to be smeared shortly after the ionization by the central star. Hence, the spiral structure may reveal itself only in the proto-PN phase. Since spiral structures are best detected during their forma-
tion, they can be seen in massive binaries where one of the stars is a Wolf-Rayet star, e.g., WR 98A (Monnier, Tuthill, & Danchi 1999). We know of no good examples of PNs or proto-PNs with spiral structure. Bipolar or elliptical PNs would also be said to possess departure from axisymmetry if their illuminating star does not lie on a symmetry axis, or if there is a large-scale asymmetry between their two “sides”; the latter terminology can refer to either two opposing sides of the symmetry axis and/or the two sides of the equatorial plane. Some examples of this type of departure from axisymmetry can be seen in Hubble Space Telescope (HST) images: the PN MyCn 18 (the Hourglass Nebula), a bipolar PN that has an off-center illuminating star; NGC 7027, a bipolar PN with unequal “sides”; NGC 3132, an elliptical PN with an off-center illuminating star; and NGC 7662, an elliptical PN with unequal “sides.” It should be noted that point-symmetric PNs also depart from pure axisymmetry, but they are not defined by us as having departure if they can be built by pure rotations of the different symmetry axes of the different substructures. Only if displacements of one or more of the symmetry axes relative to the central star is detected, and/or large-scale asymmetry exists, would we define a point-symmetric PN as having a departure from axisymmetry.

The axisymmetric structures of PNs have resulted in a long-standing debate as to whether a binary companion, either stellar or substellar, is necessary for the formation of these PNs. In the present paper we consider another possible role that binary stellar companions can play: the formation of PNs with departure from axisymmetry.

Four main processes can result in large-scale deviations from axisymmetry.

1. Interaction with the ISM.—In this case, the most prominent features are on the outskirts of the nebula (e.g., Tweedy & Kwitter 1994, 1996; Rauch et al. 2000), with smaller or no deviations from axisymmetry in the inner regions of the nebula. In large PNs, the ISM may penetrate the outer regions of the nebula, and influence the inner structure as well as the outer regions (Dgani & Soker 1998).

2. Local mass-loss events.—If one or a few long-lived cool spots exist on the surface of the AGB star during the mass-loss process itself, they can lead to enhanced mass-loss rates in one to a few particular directions. This process seems to be important in massive stars (e.g., as suggested for the ~30 $M_\odot$ star HD 179821 by Jura & Werner 1999), but it is not clear if this process can operate efficiently in AGB stars, where strong convection may not allow such spots to live long enough.

3. A wide binary companion.—In the case where the AGB star has a wide binary companion (Soker 1994), the departure from axisymmetry results simply from the fact that the mass loss from the AGB star occurs while it is moving in its orbit. Interesting effects due to the orbital motion occur for a wide range of orbital periods (Soker 1994; Mastrodemos & Morris 1999). Soker (1999) takes the condition on the orbital period to be $0.3\tau_L < P < 30\tau_L$, where $\tau_L$ is the formation time of the relevant part of the nebula. In § 2 we use a somewhat different condition. The formation time can be $\tau_L \sim$ several $\times 10^4$ yr for a PN halo, $\tau_L \sim$ several $\times 10^5$ yr for the dense inner shell, and $\tau_L \approx$ several $\times 100$ yr for possible jets. Another requirement is that the velocity of the mass-losing star around the center of mass $v_L$ not be too small. This typically requires a companion of mass $M_2 \gtrsim 0.3 M_\odot$, depending on the orbital separation. We note that in the wide-orbit cases considered in this work, the orbital separation may be too large to allow the companion to directly influence the mass-loss process. Hence, the companion has no role in most of these cases in the formation of the axisymmetrical structure itself (besides helping to produce a spiral structure). According to the binary model, a tertiary and closer stellar or substellar object is required to spin up the AGB progenitor to form any axisymmetric structure that is observed.

4. A close binary companion in an eccentric orbit.—This occurs when the companion is close enough to influence the mass-loss process from the AGB star and/or from the system as a whole, and the eccentricity is substantial (Soker, Rappaport, & Harpaz 1998, hereafter SRH98). If the companion is close enough to significantly influence the mass-loss process, then a bipolar or elliptical PN is formed. In these cases, the companion may (1) tidally spin-up the AGB star (Soker 1997), (2) stop the AGB wind if it strongly influences the wind’s acceleration zone (Harpaz, Rappaport, & Soker 1997), (3) accrete and blow a collimated fast wind (CFW; Morris 1987; SR00), or (4) gravitationally influence the AGB wind (Mastrodemos & Morris 1999). If, as we assume here (see also SRH98), any of these mechanisms influences the mass-loss rate in a way that depends on the orbital separation, then the mass-loss rate and/or geometry will change periodically around the orbital, and the nebula will have a departure from axisymmetry. For example, if the mass loss is completely stopped at periastron, then the nebula will have a center-of-mass velocity, relative to the binary system, in the direction of motion of the AGB star during apastron passages (SRH98).

In a recent paper, Soker (1999) analyzes the structure of PNs that were surveyed by Ciardullo et al. (1999) for the presence of resolved visual wide-binary companions of their central stars. Ciardullo et al. (1999) used the HST and found ten PNs for which they argue in favor of a probable physical association of the resolved stellar companion with the central star, while for nine others the association was less likely. Soker (1999) analyzes these 19 PNs, and the rest for which no companions were found, and demonstrates that the departure, or lack thereof, from axisymmetry of the PNs is consistent in most cases with Ciardullo et al.’s claim for an association, or nonassociation, of the resolved stars in the PNs. Another relevant system is the carbon star TT Cygni and its thin spherical shell (Olofsson et al. 2000). The shell has a radius of $2.7 \times 10^{17}$ cm, it expands at a velocity of ~12.6 km s$^{-1}$, and its center is displaced by ~1.3 $\times 10^{16}$ cm from the central star, TT Cygni. Olofsson et al. (2000) claim that this implies a relative velocity of ~0.6 km s$^{-1}$ between the shell and the central star. We would attribute this offset directly to the orbital motion itself. As noted by Olofsson et al. (2000), a binary companion at an orbital separation of ~$10^4$ AU with a mass of ~1 $M_\odot$ will cause TT Cygni to have this velocity around the center of mass. The binary system would then have completed ~$1/4$ to ~$1/3$ of an orbital revolution since the shell ejection, ~$7 \times 10^3$ yr ago.

A fifth process due to a very wide binary companion can form a local signature, but does not influence the overall structure of the PN. Such a companion, if it has a strong wind, may blow a small bubble inside the nebula (Soker 1996). The bubble can be used to distinguish between stars
located within the nebula and foreground or background stars. Such a bubble, formed by a very wide companion, might be the "vertical bridge" observed by Corradi et al. (1999) near a star located in Wray 17-1. We do not consider these systems in the present work.

In the present paper we estimate the fraction of PNs that are likely to acquire nonaxisymmetrical structures from binary companions, specifically via processes 3 and 4 listed above. In § 2 we describe the criteria used for each process, and in § 3 we present the results of our population synthesis and compare them with observations. Our main results are summarized in § 4.

2. CRITERIA FOR BINARY INTERACTION

2.1. Wide Companions

By wide systems we mean to those with companions to the AGB star that may influence the morphology via the orbital motion of the mass-losing progenitor around the center of mass, but that are not sufficiently close either to accrete and blow a strong collimated fast wind (CFW) or to directly influence the mass-loss process from the primary star. The range of orbital period (or separation) in these systems depends on the mass of the companion, its nature (e.g., a white dwarf [WD] or a main-sequence star), and the wind speed, all of which influence the accretion rate and the possible formation of a CFW by the companion. In addition, as discussed below, the allowed range of orbital periods depends on which part of the nebula will exhibit the departure from axisymmetry. In most cases, but not all, the orbital periods of these systems will be in the range of \(10^3 - 3 \times 10^4\) yr. Simple estimates suggest that the departure from axisymmetry, e.g., the dislocation of the central star from the center of the nebula, will be of the order of \(\beta \equiv v_1/v_w\), where \(v_w\) is the expansion velocity of the nebula and \(v_1\) is the velocity of the mass-losing star around the center of mass (Soker 1994). Often, but not always, the expansion velocity, \(v_w\), corresponds approximately to the wind speed of the AGB star progenitor. The value of \(v_1\) can be expressed as a function of the orbital separation and the constituent masses as

\[ v_1 = 3\left(\frac{a}{100 \text{ AU}}\right)^{-1/2} \frac{M_2}{M_\odot} \left(\frac{M}{M_\odot}\right)^{-1/2} \text{ km s}^{-1}, \]  

while the orbital period is given by

\[ P_{\text{orb}} = 1000\left(\frac{a}{100 \text{ AU}}\right)^{3/2} \left(\frac{M}{2 M_\odot}\right)^{-1/2} \text{ yr}, \]  

where \(M = M_1 + M_2\), \(M_1\) is the mass of the AGB star, \(M_2\) is the mass of the companion, and \(a\) is the orbital separation. When the eccentricity is not zero, \(a\) is taken to be the semimajor axis, and the velocity given by equation (1) is some average velocity.

A simple example is a case in which a star in orbit ejects a shell of matter impulsively, i.e., in a time that is much shorter than the orbital period. Later, the dust in the shell can reflect the light of the central star; or still later in the evolution, that same star will reveal its hot core and ionize the shell. Simple geometry gives the offset of the central star as

\[ f = \beta \phi^{-1}[1 - \cos \phi]^2 + (\phi - \sin \phi)^2]^{1/2}, \]  

where \(f\) is the distance from the star to the center of the shell in units of the shell's radius, \(R_{sh} = v_w \tau_s\), where \(\tau_s\) is the age of the shell, and \(\phi\) is the angle that the binary has gone through (in radians) since the ejection event. The function describing \(f\) has some interesting properties. It peaks at a time corresponding to \(\sim 4\) rad when the maximum fractional offset is \(\sim 1.26\beta\), and asymptotically approaches \(\beta\). However, it does not reach a value of \(0.5\beta\) until the orbit has progressed through \(\sim 1\) rad. Therefore, if a 5% effect is required for a case with \(\beta = 0.1\), the system should go through at least \(\sim 1/5\) of an orbit.

The mass loss during the AGB phase is not impulsive, but rather a more continuous wind mass-loss process. However, during the final stages of the AGB (as well as in thermal pulses) there are expected to be strong variations in the mass-loss rate. In such cases, equation (3) may be relevant in describing the "departure" from axisymmetry of the corresponding portions of the resulting PN. For this to hold, the typical timescales for these variations in the mass-loss rate should not be much longer than the orbital period. If the variation timescale is longer, then a spiral structure will be formed (Soker 1994; Mastrodemos & Morris 1999). If not too many spiral turns have developed, we then also expect to find nonaxisymmetric structure in the PN. However, in this case such structure may exist only until the central ionizing source has fully turned on, and the subsequent heating effects tend to smooth out the ringlike structure.

In the present paper we assume that any departure of more than \(\sim 5\%\) can be detected, whether it is a displacement of the central star due to an impulsive mass-loss episode, or nonaxisymmetric density structure that leads to a spiral pattern. We therefore simply require that for the detection of a departure from axisymmetry the velocity ratio should be

\[ \beta \equiv \frac{v_1}{v_w} > 0.05. \]  

Substituting typical values, this condition reads

\[ \beta = 0.05\left(\frac{a}{800 \text{ AU}}\right)^{-1/2} \left(\frac{v_w}{15 \text{ km s}^{-1}}\right)^{-1} \times \left(\frac{M_1 + M_2}{2 M_\odot}\right)^{-1/2} \left(\frac{M_2}{1 M_\odot}\right) > 0.05. \]  

Note that we have used a characteristic orbital speed rather than the velocity periastron or apastron, since we cannot tell at what position the mass-loss episodes will take place.

Our second condition is that the orbital period not be too long or too short. As noted from equation (3), for \(\beta = 0.1\) a departure of 5% requires \(\sim 1/5\) of an orbit to be completed. We require, therefore, that the binary system completes at least \(1/5\) of an orbit since the relevant mass-loss episode occurred, so that the mass-losing star has sufficient time to depart from the center of the shell. This gives an upper limit on the orbital period. The lower limit on the orbital period is based on numerical results (Mastrodemos & Morris 1999; our unpublished results), and it has to do with the spiral structure that is produced by the orbital motion when the mass-loss rate is continuous rather than impulsive (Soker 1994). If the orbital period is too short, the tight spiral structure will be smeared very quickly as the nebula is ionized. Moreover, we have found from our unpublished numerical simulations that there is a gasdynamical smearing of the rings in only \(\sim 6-8\) turns. We therefore require that there be no more than \(\sim 6\) spiral loops during the
appropriate formation time. The number of spiral loops is
\[ N_{\text{s}} = \frac{\tau_f}{P_{\text{orb}}} \]
and is limited by the above arguments to be in the range of
\[ \frac{1}{6} < \frac{\tau_f}{P_{\text{orb}}} < 6, \quad (6) \]
where \( \tau_f \) is the formation time of the particular PN component under consideration. As mentioned in the previous section, the formation time can be \( \tau_f \sim \text{several} \times 10^4 \) yr for a PN halo, \( \tau_f \sim \text{several} \times 10^5 \) yr for the dense inner shell, and \( \tau_f \approx \text{several} \times 100 \) yr for possible jets. This latter case, which is referred to in the next section as class C, is relevant to cases in which the progenitor blows jets (or CFW) during its post-AGB phase. Note that in this case the fast flow is blown by the progenitor, unlike cases in which the CFW is blown by the accreting companion, as discussed in the next subsection. Specific limits on \( \tau_f \) are set in § 3, where we carry out the population synthesis study.

2.2. Closer Companions in Eccentric Orbits

By closer systems we mean those in which companion stars either accrete from the wind of the mass-losing star and blow their own winds (the CFW), and/or directly influence the mass-loss process from the mass-losing star. The maximum orbital separation at which the mass and angular momentum accretion rates are high enough to blow a CFW strongly depends on the speed of the AGB star wind (Soker 2001b). In most, but not all, cases the orbital periods of these systems will be in the range of 30–1000 yr (Soker 2001b; we do not consider systems that are sufficiently close that they circularize). SRH98 demonstrate how a close companion in an eccentric orbit can cause the central star to be displaced from the center of the nebula. They postulate that the mass-loss rate from the AGB star varies systematically with orbital phase; hence, the center-of-mass velocity of the nebula will be different from that of the center of mass of the binary system. SRH98 consider several effects, including a tidal enhancement of the stellar wind near periastron and a cessation of the stellar wind when the Roche lobe of the AGB star encroaches on its extended atmosphere near periastron passage. Tidal effects require the companion to come close to the AGB star at periastron passages. SRH98 find that the condition for this is
\[ 0.4 R_c < R_q \lesssim R_L, \]
where \( R_c \) is the critical potential lobe of the AGB star at periastron, and \( R_q \) is the AGB stellar radius. We find that these close systems have strong tidal interactions and hence reach circularization, i.e., \( e = 0 \). These will not cause any departure from axisymmetry by our criteria. The condition used by SRH98 for the cessation of the AGB wind to be significant is that at periastron passage
\[ R_{\text{wz}} \gtrsim R_L, \quad (7) \]
where \( R_{\text{wz}} \) is the radius of the “wind formation zone,” i.e., the region from which the AGB wind is accelerated. Harpaz et al. (1997) consider a wind’s acceleration zone to extend to \( R_{\text{wz}} = 10 R_c \). We here use a more “conservative” approach, and take \( R_{\text{wz}} = 5 R_c \). Another condition to be fulfilled is that the eccentricity be \( e \gtrsim 0.2 \), and that the companion mass be above some minimum value, which we take to be 0.5 \( M_{\odot} \). The SRH98 results may pertain to binary systems with semimajor axes in the range of \( a \approx 7–80 \) AU, which correspond to orbital periods in the range of \( P \approx 15–500 \) yr. SRH98 propose that this mechanism can apply to the bipolar PN MyCn 18 (the Hourglass Nebula), where the central star is displaced from the center of the nebula (Sahai et al. 1999).

In the present paper we consider another process that may cause departure from axisymmetry in relatively close eccentric binary systems. This is the formation of a collimated fast wind (CFW) by the companion (Morris 1987; SR00). The companion is assumed to accrete from the AGB wind, to form an accretion disk, and to blow a CFW. The interaction between the CFW, if strong enough (for exact condition see SR00), and the AGB wind will form a bipolar PN (Morris 1987). If the companion has an eccentric orbit, then the mass accretion rate, and hence the CFW’s strength by our assumption, will change around its orbit. If the CFW is strong enough and the periodic changes in its intensity are large enough, this may lead to a departure from axisymmetry, because both the orbital velocity of the star blowing the CFW and the interaction pattern between the CFW and the slow AGB wind will change with orbital phase. The changes in accretion rate and orbital velocity were mentioned briefly by Miranda et al. (2001b, their § 3.5) as a possible effect in the PN Hu 2-1, and was also discussed in a theoretical context by Soker (2001b). Obviously, detailed hydrodynamic simulations are required to understand these effects more quantitatively.

We assume that this CFW mechanism for producing departure from axisymmetry is important whenever the following conditions are met. First, the accretion rate at periastron, \( \dot{M}_2 \), is such that
\[ \dot{M}_2 \gtrsim |\dot{M}_1|, \quad (8) \]
where \( \dot{M}_1 \) is the mass-loss rate from the AGB star, and \( \dot{M}_2 \sim 0.01–0.1 \). Second, the mass accretion rate at apastron should be lower than at periastron by a factor of \( \gtrsim 2 \). The last condition implies that \( e \gtrsim 0.2 \).

If circularization of the binary occurs, the processes discussed in this subsection will not be important. In our population synthesis study (see § 4), we check for circularization as in SR00. We note, however, that there are close binary systems with \( a \approx 1 \) AU that do have eccentric orbits (Van Winckel 1999; Van Winckel, Waelkens, & Waters 1995; Fekel et al. 2001), even though our simple formula would indicate that circularization should have occurred. In our formulation, we may therefore miss some interesting cases.

3. POPULATION SYNTHESIS

In our population synthesis and evolution study, we utilize Monte Carlo techniques, and follow the evolution of some \( 5 \times 10^4 \) primordial binaries. For each primordial binary, the mass of the primary is chosen from an initial mass function (IMF), the mass of the secondary is picked according to an assumed distribution of mass ratios for primordial binaries, the orbital period is chosen from a distribution covering all plausible periods, and the orbital eccentricity, \( e \), is chosen from a uniform distribution (the details of all these prescriptions and procedures are given in SR00). Once the parameters of the primordial binary have been selected, the two stars are evolved simultaneously using relatively simple prescriptions (SR00). We explicitly follow the wind mass loss of both stars, at every step in the evolution. For this purpose we have developed a wind mass loss prescription that depends on the mass and evolutionary state of the star, and that is designed to reproduce reasonably well the observed initial-final mass relation for...
single stars evolving to white dwarfs (see SR00 for details). We also take into account the evolution of the binary system under the influence of stellar wind mass losses.

At each step in the evolution, we compute the fraction of the stellar wind of one star that will be captured via the Bondi-Hoyle accretion process by its companion. In addition to the mass-capture rate, we also estimate whether sufficient angular momentum will be accreted to allow for the formation of an accretion disk before the accreted matter falls on the companion, and we check whether the total rate of accretion exceeds a certain critical value to form a CFW (see SR00; note that an exponent of 1/2 is missing in the second parenthesis of SR00's eq. [2] for the condition on accreted angular momentum). Finally, we test whether tidal forces will circularize the binary before the onset of the superwind (the final intensive wind [FIW] at the end of the AGB phase).

Unlike the study of SR00, we are also very much interested in wider binary systems, where there is little or no interaction between the AGB star wind and the companion. We therefore also keep track of these systems and their properties during the evolution.

We have added to the population synthesis code new segments to specifically examine the fraction of systems with the specified binary parameters that are outlined in the previous section and enumerated in Tables 1–3.

3.1. Results

In Tables 1–3 we summarize the number of PNs that are expected to exhibit departure from axisymmetry via the influence of wide binary companions and/or close eccentric binary systems, under the prescribed constraints. The meanings of the different symbols in Tables 1–3 are as follows: \( v_{\text{min}} \) is the minimum allowed orbital velocity of the mass-losing star around the center of mass, \( v_f \) (utilized in the constraint given by eq. [4]); \( \tau_f \) is the formation time of the relevant component in the PN, and is used in the constraint on the orbital period as given by equation (6); \( e_{\text{min}} \) is the minimum allowed orbital eccentricity; and \( \mu \) is the minimum ratio of the Bondi-Hoyle accretion rate to the mass loss rate of the AGB star that is used in the constraint given by equation (8). The classes are as indicated in the tables, where A–E are wide binary cases, and G–K are close eccentric binary systems. For class K, which is the SRH98 mechanism, the conditions are: (1) according to equation (7), where the radius of the wind's acceleration region is set to \( R_{\text{w},a} = 5R_p \), where \( R_p \) is the AGB stellar radius, and we set \( R_p = 0.38(1 - e) \) at periastron; (2) the companion mass is greater than 0.5 \( M_\odot \); and (3) \( e > 0.2 \).

The results are expressed in Tables 1–3 as a percentage of the total number of binary systems we start with, which is about equal to the total number of systems that form PNs (see SR00 for more details regarding the efficiency of forming PNs in binary systems). Each tabulated value indicates how many systems belong both to the class along the row and the class along the column. For example, 3.1% ± 0.1% of all binary systems have the properties of class A, while 4.0% ± 0.1% have both the properties of class A and class B (Table 3). The indicated uncertainties are statistical, taken as the square root of the number of systems in each group divided by the total number of systems. Table 1 is for systems in which the initially more massive star forms the PN, while Table 2 is for systems in which the initially less massive star is the progenitor of the

| Parameter                      | A     | B     | C     | D     | E     | G     | H     | I     | J     | K     |
|--------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| \( v_{\text{min}} \) (km s\(^{-1}\)) | 0.75  | 0.75  | 5     | 2.25  | 2.25  | ...   | ...   | ...   | ...   | ...   |
| \( \tau_f \) (yr)             | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   | ...   |
| \( e_{\text{min}} \)          | 5 \times 10^3 | 5 \times 10^3 | 500 | 5 \times 10^4 | 5 \times 10^4 | ...   | ...   | ...   | ...   | ...   |
| \( \mu \)                     | ...   | ...   | ...   | ...   | ...   | 0.2   | 0.2   | 0.4   | 0.4   | 0.2   |

Number as percentage of all PNs

| Class | A     | B     | C     | D     | E     | G     | H     | I     | J     | K     |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| A     | 4.5   | 3.3   | 0     | 0.01  | 0.01  | 0.23  | 0.04  | 0.23  | 0.04  | 0.08  |
| B     | 11.9  | 0     | 0.01  | 1.9   | 1.9   | 0.38  | 1.9   | 0.38  | 1.3   |       |
| C     | 1.3   | 0     | 0     | 0.64  | 0.43  | 0.28  | 0.27  | 0.64  |       |       |
| D     | 0.01  | 0     | 0     | 0     | 0     | 0     | 0     | 0     | 0     |       |
| E     | 1.9   | 0.84  | 0.21  | 0.81  | 0.21  | 0.50  |       |       |       |       |
| G     | 4.6   | 1.4   | 4.8   | 1.1   | 1.4   |       |       |       |       | 4.9   |
| H     |       | 1.4   | 1.1   | 1.4   |       |       |       |       |       |       |
| I     |       | 4.8   | 1.1   | 3.6   |       |       |       |       |       |       |
| J     |       | 1.1   | 1.1   |       |       |       |       |       |       |       |
| K     |       |       | 5.2   |       |       |       |       |       |       |       |

Note.—Numbers are expressed as a percentage of all planetary nebulae. This table is for the case in which the progenitor of the PN is the initially more massive star, and the companion is a main-sequence star. The different classes have the following meanings: A through E are for wide binaries (in most cases \( P_{\text{orb}} \gtrsim 1000 \) yr), which should exhibit departures from axisymmetry due to the fact that the wind-emitting AGB star is undergoing accelerated orbital motion. A and D have departures from axisymmetry only in the PN halos (A allows for small departures, D only larger departures). B and E have departures from axisymmetry in their main shells (B allows for small departures, E only larger departures). C allows for departures from axisymmetry due to jets (or collimated fast wind), blown by the progenitor during its post-AGB phase. G through K are for closer and eccentric orbits (in most cases \( 30 \lesssim P_{\text{orb}} \lesssim 1000 \) yr, and \( e \gtrsim 0.2 \)). G through J exhibit departures from axisymmetry due to a collimated fast wind in an eccentric binary that is modulated with the orbital frequency. K results from periodic interruptions or enhancements of the AGB star wind by an encroaching companion in an eccentric orbit.
### TABLE 2
**SECONDARY PROGENITORS**

| Parameter | A  | B  | C  | D  | E  | F  | G  | H  | I  | J  | K  |
|-----------|----|----|----|----|----|----|----|----|----|----|----|
| $v_{\text{min}}$ (km s$^{-1}$) | 0.75 | 0.75 | 5  | 2.25 | 2.25 | ... | ... | ... | ... | ... | ... |
| $\tau_f$ (yr)       | $5 \times 10^4$ | $5 \times 10^3$ | 500 | $5 \times 10^4$ | $5 \times 10^3$ | ... | ... | ... | ... | ... | ... |
| $e_{\text{min}}$ | ... | ... | ... | ... | ... | 0.2 | 0.2 | 0.4 | 0.4 | 0.2 |
| $\mu$ | ... | ... | ... | ... | ... | 0.01 | 0.1 | 0.01 | 0.1 |

Number as percentage of all PNs

| Class | A  | B  | C  | D  | E  | F  | G  | H  | I  | J  | K  |
|-------|----|----|----|----|----|----|----|----|----|----|----|
| A     | 0.64 | 0.64 | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0.01 |
| B     | 5.1 | 0  | 0  | 0.02 | 0.14 | 0  | 0.14 | 0  | 0.32 |
| C     | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| D     | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| E     | 0.02 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| G     | 0.55 | 0  | 0.40 | 0  | 0.55 |
| H     | 0  | 0  | 0  | 0  | 0  |
| I     | 0.40 | 0  | 0.40 | 0  | 0  | 0  |
| J     | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| K     | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | 1.1 |

**Note.**—Numbers are expressed as a percentage of all planetary nebulae. This table is for cases in which the initially less massive star is the progenitor of the PN, and the companion is a white dwarf. The different classes have the following meanings: A through E are for wide binaries (in most cases $P_{\text{orb}} \geq 1000$ yr), which should exhibit departures from axisymmetry due to the fact that the wind-emitting AGB star is undergoing accelerated orbital motion. A and D have departures from axisymmetry only in the PN halos (A allows for small departures, D only larger departures). B and E have departures from axisymmetry in their main shells (B allows for small departures, E only larger departures). C allows for departures from axisymmetry due to jets (or collimated fast wind), blown by the progenitor during its post-AGB phase. G through K are for closer and eccentric orbits (in most cases $30 \leq P_{\text{orb}} \leq 1000$ yr, and $e \geq 0.2$). G through J exhibit departures from axisymmetry due to a collimated fast wind in an eccentric binary that is modulated with the orbital frequency. K results from periodic interruptions or enhancements of the AGB star wind by an encroaching companion in an eccentric orbit.

### TABLE 3
**TOTAL**

| Parameter | A  | B  | C  | D  | E  | F  | G  | H  | I  | J  | K  |
|-----------|----|----|----|----|----|----|----|----|----|----|----|
| $v_{\text{min}}$ (km s$^{-1}$) | 0.75 | 0.75 | 5  | 2.25 | 2.25 | ... | ... | ... | ... | ... | ... |
| $\tau_f$ (yr)       | $5 \times 10^4$ | $5 \times 10^3$ | 500 | $5 \times 10^4$ | $5 \times 10^3$ | ... | ... | ... | ... | ... | ... |
| $e_{\text{min}}$ | ... | ... | ... | ... | ... | 0.2 | 0.2 | 0.4 | 0.4 | 0.2 |
| $\mu$ | ... | ... | ... | ... | ... | 0.01 | 0.1 | 0.01 | 0.1 |

Number as percentage of all PNs

| Class | A  | B  | C  | D  | E  | F  | G  | H  | I  | J  | K  |
|-------|----|----|----|----|----|----|----|----|----|----|----|
| A     | 5.1 | 4.0 | 0  | 0.01 | 0.01 | 0.23 | 0.04 | 0.23 | 0.04 | 0.10 |
| B     | 16.9 | 0  | 0.01 | 1.9 | 2.0 | 0.38 | 2.0 | 0.38 | 1.6 |
| C     | 1.3 | 0  | 0  | 0.64 | 0.43 | 0.28 | 0.27 | 0.64 |
| D     | 0.01 | 0.01 | 0  | 0  | 0  | 0  | 0  | 0  |
| E     | 1.9 | 0.84 | 0.21 | 0.81 | 0.21 | 0.50 |
| G     | 7.1 | 1.4 | 5.2 | 1.1 | 5.5 |
| H     | 1.4 | 1.1 | 1.1 | 1.4 |
| I     | 5.2 | 1.1 | 4.0 |
| J     | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| K     | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | 6.2 |

**Note.**—Numbers are expressed as a percentage of all planetary nebulae. This table is for the total of all PN progenitors under study. The different classes have the following meanings: A through E are for wide binaries (in most cases $P_{\text{orb}} \geq 1000$ yr), which should exhibit departures from axisymmetry due to the fact that the wind-emitting AGB star is undergoing accelerated orbital motion. A and D have departures from axisymmetry only in the PN halos (A allows for small departures, D only larger departures). B and E have departures from axisymmetry in their main shells (B allows for small departures, E only larger departures). C allows for departures from axisymmetry due to jets (or collimated fast wind), blown by the progenitor during its post-AGB phase. G through K are for closer and eccentric orbits (in most cases $30 \leq P_{\text{orb}} \leq 1000$ yr, and $e \geq 0.2$). G through J exhibit departures from axisymmetry due to a collimated fast wind in an eccentric binary that is modulated with the orbital frequency. K results from periodic interruptions or enhancements of the AGB star wind by an encroaching companion in an eccentric orbit.
PN. Table 3 is the sum of Table 1 and Table 2. We note that the uncertainties involved in the criteria for detecting departure from axisymmetry are larger than the statistical uncertainties that result from the finite sample of systems studied in the Monte Carlo population synthesis. Hence, the number in the table are given to the accuracy of 2 significant digits.

We note that the different classes have the following observational consequences. Class A: PNIs with departure from axisymmetry in the halo, allowing for very small degrees of departure ($v_\theta = 15$ km s$^{-1}$ and $\beta > 0.05$ in eq. [4]). Class D: PNs with a large degree of departure from axisymmetry in the halo ($\beta > 0.15$). Class B: departure from axisymmetry of the main PN shell, allowing for very small degrees of departure. Class E: PNs with a large degree of departure from axisymmetry in the main shell. Class C: departure from axisymmetry is expected from a CFW (or jets), if they are formed by the progenitor during its post-AGB phase. The same mechanism can operate for a CFW blown by the companion, although here effects due to the interaction of the CFW with the AGB star wind make predictions more complicated. Here we assume the typical velocity of the jets to be $v_j = 100$ km s$^{-1}$, and take $\beta > 0.05$. Classes A–E refer to the influence of a wide companion, whether in an eccentric or circular orbit. Classes G–K are closer systems, where a strong interaction with the companion star, including possible accretion, is important. Many of the systems in classes G–K will form bipolar PNs (SR00). In cases in which the polar outflows are very fast, the departure from axisymmetry may be noticed only in the slower equatorial flow. Such a case might be the Egg Nebula (CRL 2688), with its two highly symmetric “searchlight” beams (Sahai et al. 1998a, 1998b). In this object, the equatorial disk, as revealed by the NICMOS camera, shows a clear departure from axisymmetry (Sahai et al. 1998a, 1998b).

The main findings from the population synthesis are as follows:

1. $\sim 5\%$ of halos should show departure from axisymmetry. Of all PNs that have a halo, $\sim 5\%$ are expected to show signs of departure from axisymmetry because of a wide binary companion (class A). Only an extremely small fraction ($\sim 0.01\%$) will have a large departure (class D). Approximately $\frac{1}{3}$ of class A systems, or $4\%$ of all PNs, will show a departure in their main shell as well (classes B and A). We note also that in $\sim 1/20$ of PNs that possess a non-axisymmetric halo ($0.23\%$ of all PNs), the companion may have influenced the structure because of its eccentric orbit as well (classes A and I). These are systems with large eccentricity, so that the companion gets close to the mass-losing star at periastron passage. The main problem with PNs belonging only to class A, i.e., only the halo showing a departure from axisymmetry, is how to distinguish between departure caused by a wide binary companion and that caused by interaction with the ISM, since the large tenuous halos are expected to be significantly influenced by the ISM.

2. $\sim 25\%$ of elliptical PNs should exhibit departure from axisymmetry. Only $\sim 1.2\%$ of all PNs with a halo (and not many PNs have an observable halo) should have departure only in their halo. This number is estimated from class A systems ($5.1\%$) minus systems belonging to class A and any other class, e.g., classes $A + B$, have $4.0\%$ of all PNs with a halo. Only $\sim 1.3\%$ may have departure from their jets, if they exist (class C alone). Therefore, the majority of PNs that have a significant departure from axisymmetry because of a wide companion come from class B, and they amount to $\sim 17\%$. Most of these will be elliptical or spherical PNs. If we add several more percent of elliptical PNs that result from the influence of eccentric companions at large distances (mainly from class G), and remember that $\sim 90\%$ of all PNs are elliptical or spherical PNs, we conclude that $\sim 25\%$ of all elliptical PNs have an observable departure from axisymmetric because of a companion.

3. We underestimate PNs with departure from axisymmetry because of strong tidal interactions. In our simulation we check for tidal circularization (see SR00 for details). The eccentricity of systems for which the circularization time is shorter than the evolutionary time is set to $e = 0$; hence, they cannot cause departure from axisymmetry. However, it is well known that there are binary systems with post-AGB stars, which have orbital periods ranging from less than a year up to a few years, and substantial eccentricities $0.1 \leq e \leq 0.4$ (e.g., Van Winckel 1999; Waelkens et al. 1996). Such close binary systems, with orbital separations of a few AU, will cause departure from axisymmetry via the SRH98 mechanism (see § 2.2), in which the companion directly influences the mass-loss process (as in class K), as well as by accreting from the mass-losing star (as in classes G–J discussed above). Therefore, as noted already in § 2.2, we may miss some bipolar PNs that do have departure from axisymmetry because of a companion in an eccentric orbit where the Roche lobe remains well outside the AGB envelope.

4. We underestimate PNs with departure from axisymmetry because of Roche-lobe overflow. We do not simulate systems that go through Roche-lobe overflow or a common envelope. However, systems that go through a common envelope may still possess substantial departure from axisymmetry. This is evident from the bipolar PN NGC 2346, which exhibits considerable departure from axisymmetry in its equatorial plane (e.g., see Corradi & Schwarz 1995), and has a binary central star that went through a common envelope (Bond & Livio 1990).

5. $\sim 30–50\%$ of bipolar PNs should show departure from axisymmetry. The fraction of systems that belong to class G but do not have too long of an orbital period, i.e., do not belong to class B + G, is $\sim 5\%$. To these we add $\sim 1\%$ that belong to class K, but not to classes B or G. We find, therefore, that $\sim 6\%$ of all PNs have departure and have close companions. Most PNs that belong to classes G–K above will form bipolar PNs (but not all of them). Thus, not all the $\sim 6\%$ will form bipolar PNs, but somewhat less than that, $3%–5\%$. Now, since $\sim 10\%$ of all PNs are expected to be bipolar according to the binary model of SR00, and from observations this fraction could be somewhat larger (Manchado et al. 2000), we estimate that $\sim 30%–50\%$ of all bipolar PNs may show departure from axisymmetry. This number is a crude estimate, since as noted in points 3 and 4 above, many bipolar PNs are expected to be formed by systems not simulated here, e.g., those with Roche-lobe overflow (see SR00), and some of these may possess departure from axisymmetry. Considering these arguments, we can safely say that $\sim 30%–50\%$ of all bipolar PNs will show a departure from axisymmetry. Since the lobes of many PNs move at high velocities, the departure from axisymmetry will be easier to detect in the slow equatorial flow (e.g., the Egg Nebula mentioned above). The point-symmetric structure of many PNs, especially bipolar PNs, will make the detection of departure from axisymmetry more difficult.
The percentages of elliptical and bipolar PNs that are expected to possess departure from axisymmetry due to a binary companion, according to the population synthesis results, are summarized in Table 4 (rows labeled “Theory”).

3.2. Comparison with Observations

This subsection is not meant to present a rigorous statistical analysis; we do not use any complete samples of PN observations, and we do not conduct a thorough analysis of the different signatures of departures from axisymmetry. Our sole purpose here is to show that the estimates found from the population synthesis are compatible with available observations. The results are summarized in Table 4.

3.2.1. Elliptical PNs

In this subsection we evaluate the empirical evidence for departure from axisymmetry of elliptical PNs by direct inspection of three different available PN data sets. First, Soker (1997) used a data set of all PNs with resolved images that were available to him to examine morphologies in the context of binary models for the shaping of PNs. Soker (1997) estimated that out of 293 PNs that did not interact with a close stellar companion (his Tables 2 and 5), the structure of ~25 was influenced by a wide binary companion (PNs marked WB or ISM/WB in his tables; ISM/WB means that an interaction with the ISM may be an alternative explanation to the presence of a wide binary companion). From 113 PNs that presumably interacted with a stellar companion via a common-envelope evolution (his Table 4), Soker finds 10 ± 4 to show some signature of departure from axisymmetry due to an interaction with a companion. These findings mean that the structure of ~8–9% of elliptical PNs are likely to show signatures of departure from axisymmetry due to a wide companion, according to the “conservative” approach used by Soker (1997). This result is summarized in Table 4 (of the present paper; see row labeled “Soker 1997”). Soker did not consider small departures, and therefore avoided the problem of large clumps and filaments, but on the other hand he missed many PNs that do possess departure due to a binary companion. Therefore, Soker’s (1997) numbers should be compared with PNs expected to possess a large departure from axisymmetry, i.e., class D + E (1.9% in Table 3), and a fraction of class H, that which has an overlap with class A–D, but not with class E (0.2% in Table 3): in total, ~2.1% of all PNs, or ~2.5% of elliptical PNs. The fraction found by Soker (1997) is between those expected to possess large departure and the total number we expect to possess detectable departure. We consider this a satisfactory result.

Another search for departure from axisymmetry in a large sample of PNs was conducted by Soker (1999), who studied the sample of Ciardullo et al. (1999). Using the HST, Ciardullo et al. (1999) surveyed 113 PNs for the presence of resolved visual wide binary companions of their central stars. For 19 PNs they argue for probable or possible association of the resolved stellar companions with the central stars. Soker (1999) found that for 60% of the elliptical PNs among these 19 PNs, the departure likely resulted from a wide companion (the fraction is ~80% for the 10 PNs for which Ciardullo et al. argue for a probable association). Soker (1999) found that for the rest of the PNs in their sample, the fraction with observable departure from axisymmetry due to a wide companion is ~35%. Overall, the total fraction of elliptical PNs showing departure due to a wide companion in the list of PNs surveyed by Ciardullo et al. (1999) is estimated to be ~40% (see Table 4, row labeled “Soker 1999”). This is somewhat higher than the results of the population synthesis, which indicate only ~25%.

To study small departures from axisymmetry, we examined high-resolution HST images of PNs. We examined 71 images (same list as the one collected by Terzian & Hajian 2000), for which the different HST images can be found in the following papers: Balick (2000), Balick et al. (1998), Bobrowsky et al. (1998), Bond (2000), Ciardullo et al. (1997), Corradi et al. (2000), KwoK, Su, & Hrivnak (1998), Sahai et al. (2000a, 2000b), Sahai & Trauger (1998), Sahai et al. (1998a, 1998b), Su et al. (1998), and Terzian & Hajian (2000). A more accurate analysis, including a detailed list of the PNs, is postponed to a future project. We count only PNs for which the departure from axisymmetry can be clearly discerned in these images. Many of the images show large clumps and filaments that result from the stochastic nature of the mass-loss process, rather than from a companion. Examples are NGC 6210 and NGC 6326, which we still count here as having departure, although it is very likely that these are due to the stochastic nature of the mass-loss process, or other instabilities. Therefore, we here overestimate the number of PNs that acquire their departure from axisymmetry from a companion. Of these 71 images, 4 are difficult to classify based on the images alone, while 26 are bipolar PNs, and 41 are elliptical PNs. Out of the 41 elliptical PNs, many have large clumps and/or filaments in their inner regions, making it very difficult to decide whether a departure from an axisymmetric structure due to a companion exists. For 12 PNs we could not tell whether they do or do not possess departure from axisymmetry; 16 PNs do show a departure, while 13 do not exhibit a clear departure from axisymmetry. These results alone indicate that ~50% of elliptical PNs show some signature of departure from axisymmetry (see Table 4, row labeled “HST images”). Again, many are due to clumps and filaments that result from the stochastic nature of the mass-loss process.

The three different observational estimates of departure from axisymmetry in elliptical PNs (Soker 1997, 1999, and the study of the 71 HST images) are summarized in Table 4.
We argue that our estimate from the population synthesis, that \( \sim 25\% \) of all elliptical PNs should have a detectable departure from axisymmetry acquired from a companion, is compatible with observations, although it seems that the fraction of observed elliptical PNs with departure is somewhat higher than 25\% (see Table 4). This modest discrepancy can be accounted for by three effects. (1) Binary systems with longer or shorter periods, or with slower orbital motion than can satisfy our selection criteria, can still cause a noticeable departure from axisymmetry (see Soker 2001b for formation of CFW in somewhat wider binary systems). (2) Many PNs acquired their departure from axisymmetry from the stochastic nature of the mass-loss process. It is likely that the stochastic nature will be more prominent in the equatorial plane, making it even more difficult to distinguish between the mass-loss process and a wide companion. (3) The number of PNs that acquired their departure from axisymmetry via interaction with the ISM may be larger than what has been estimated. This latter mechanism has a small effect, since we avoided PNs showing departure only in their very outer regions (halos). We could not avoid including some PNs that acquired their departure via mechanism 2. However, many PNs show the same sense of departure in two or more regions. A stochastic process cannot explain these cases; hence, it will not account for all, or even most, of the cases with departure we consider here.

3.2.2. Bipolar PNs

Examining the 43 images of bipolar PNs given by Corradi & Schwarz (1995), we find that many show a clear departure from axisymmetry, mainly in the equatorial plane. Examples are 19W32, NGC 2899, NGC 650-1, Sh 1-89, and We 1-4. However, many require very careful examination. Such is the case with MyCn 18, whose lobes seem quite axisymmetric, but the central star is not in the center of the inner region as revealed by the HST (Sahai et al. 1999).

We turn to the 71 HST images mentioned in § 3.2.1, noting that even with these high-resolution observations we may still miss some PNs that do possess departure from axisymmetry, since departure has been revealed, or may reveal itself in other bands of the spectrum. For example, the Red Rectangle (BD \( \times 10^4 \)) contains a clear eccentric binary system, with \( P_{\text{orb}} = 318 \) days and \( e = 0.38 \) (Waters et al. 1998). The general structure of the Red Rectangle is highly axisymmetrical, up to a distance of \( \sim 1' \) from the central star (e.g., Van Winckel 2001). However, the 10 \( \mu \)m map presented by Waters et al. (1998; their Fig. 3) shows a clear departure from axisymmetry on scales of \( \sim 5'' \) from the central star. Their contour map shows that the equatorial matter is more extended on the west side. Another example is the Egg Nebula, which appears axisymmetric in the HST optical image, while only the NICMOS image shows a clear departure from axisymmetry (Sahai et al. 1998a, 1998b).

From the 26 bipolar PNs in the list of 71 HST images, 9 possess a clear departure from axisymmetry, 11 do not, and for 6 PNs it is difficult to tell because of the presence of numerous “blobs” and/or filaments. Based on these images alone, it turns out that \( \sim 35\%–60\% \) of all bipolar PNs possess departure from axisymmetry (Table 4). However, we still miss some (e.g., the Egg Nebula). On the other hand, many PNs acquire their departure from axisymmetry from large blobs and filaments, as noted above for elliptical PNs. An examination of 52 bipolar PNs Soker (1997; his Table 3) indicated departure from axisymmetry in five out of 52 PNs, i.e., \( \sim 10\% \). Of these, the departure in three (\( \sim 6\% \)) PNs was attributed to a companion, and for two PNs the departure was attributed to interaction with the ISM. We take the percentage found by Soker (1997) to be \( \sim 8\% \) (Table 4). As noted above, Soker did not consider small scale departure, and therefore avoided the problem of large clumps and filaments, but on the other hand he missed most of the PNs that do possess departure. The fraction found by Soker (1997) should be compared with the expected number of PNs that possess large departure, mainly class J, which has \( \sim 1\% \) (Table 3) of all PNs, or \( \sim 10\% \) of bipolar PNs.

Overall, it seems that our finding from population synthesis that 30\%–50\% of all bipolar PNs acquire their departure from a companion is compatible with available observations.

4. SUMMARY

We used a population synthesis code to estimate the number of PNs expected to possess detectable departure from axisymmetric structure as a result of a binary companion. For that, we considered mechanisms for causing departure from axisymmetry as proposed by us in earlier works: a wide companion with a long orbital period (Soker 1994), and/or a close companion in an eccentric orbit (SRH98). The departure can manifest itself as the illuminating star not being at the center of the nebula, one side being brighter or more extended than the other, the two sides having different magnitude Doppler shifts, or any combination of these. Point-symmetric structures, in which the nebula can be built from several axisymmetric structures all having the same center for their symmetry axis, are not considered by us as exhibiting departure from axisymmetry. We set different specific values in the criteria for causing significant departure from axisymmetry: orbital period, orbital velocity of the mass-losing AGB star around the center of mass, and formation time of the relevant nebular part in the case of wide binaries (§ 2.1, eqs. [4] and [6]), and the eccentricity and mass accretion rate for the close eccentric companions (§ 2.2). These values are indicated in Tables 1–3 for the different classes. A crude comparison with observations is summarized in Table 4. Our main findings are:

1. \( \sim 25\% \) of all elliptical or circular PNs are expected to possess detectable departure from axisymmetry (mainly classes A–E and some fraction of class G in Table 3). Of these \( \sim 25\% \), in \( \sim 19\% \) the initially more massive star is an AGB mass-losing star that has a main-sequence companion (Table 1), and in \( \sim 6\% \) the initially less massive star is the central star and the companion is a WD (Table 2).

2. \( \sim 30\%–50\% \) of all bipolar PNs are expected to possess detectable departure from axisymmetry (most of the systems in classes G–K; Table 3). In most of these systems, the AGB mass-losing star is the initially more massive star and the companion is a main-sequence star (Table 1). Only \( \sim 5\%–8\% \) out of these \( \sim 30\%–50\% \) have a WD companion (Table 2), while the rest, \( \sim 25\%–40\% \), have a main-sequence companion.

3. Since \( \sim 10\%–15\% \) of all PNs are bipolar, and the rest are elliptical or circular, we find from our results (first row of Table 4) that \( \sim 27\% \) of all PNs are expected to possess significant departure from axisymmetric structure.
4. We find satisfactory agreement in the fraction of PNs possessing departure from axisymmetry between the results of the population synthesis and the rough estimate we made from the observations (Table 4, last two rows). The largest uncertainties in the theoretical results are in the criteria for detectable departure from axisymmetry. The main difficulty in analyzing observations is to distinguish between a departure from axisymmetry caused by a companion and that caused by large-scale instabilities and stochastic mass-loss process. Considering these uncertainties, we find the agreement reflected in Table 4 to be satisfactory.

In light of our findings that a large fraction of PNs are expected to possess observable departure from axisymmetry, more attention should be paid to this effect when analyzing images and velocity maps of PNe. Some recent papers indeed do that. A departure from axisymmetry, in that the central star is not at the center of the nebula, is noted by Sahai (2000b) in the two PNe He 2-47 and M1-37.

Miranda et al. (2001b) and Miranda, Guerrero, & Torrelles (2001a, for IC 4846; see the summary by Miranda 2001) proposed that the difference between the systematic velocity of the precessing jets and the centroid velocity of the nebulae in these two PNe results from the orbital motion of the star that blows the jets. This is one of the manifestations of departure from axisymmetry in binary systems. Finally, we note that departure from axisymmetry can occur in other systems similar to PNs. Soker (2001a) argues that the departure of the nebula around η Carinae can be explained by the presence of the proposed binary companion, if it has an eccentric orbit.

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