SECTION IV

ORIGIN OF PLANETARY NEBULAE

RED GIANTS AS PRECURSORS OF PLANETARY NEBULAE

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ABSTRACT

Several physical processes taking place during the red (super)giant phase of intermediate-mass stars have direct observational consequences for the subsequent nebular stage. These processes include: the regular wind and the envelope ejection, the thermal pulses during the AGB phase, the dredge-up processes, and the dust formation in expanding circumstellar envelopes. In this paper it is briefly discussed how such processes affect the mass range of PN nuclei and their evolution, and the PN lifetime, composition and dust content. The last section is devoted to a cursory discussion of PNe which can be generated by binary stars.

1. INTRODUCTION

The nebular phase represents just a chapter in the life of those stars which ultimately become white dwarfs, and therefore the understanding of most properties of PNe and their central stars is necessarily rooted to the study of the previous evolutionary history of these objects. On the other hand, the derivation of physical parameters from the observation of PNe (e.g. chemical abundances) involves a totally different sort of input physics with respect to that currently in use in the case of stars, thus allowing both useful consistency checks and the derivation of quantities which are not accessible to the study of normal stars (e.g. the helium abundance of red giants cannot be directly derived).

Evolutionally speaking, only a few thousand years separate the nebular stage from the red (super)giant phase, when stars are ascending the Asymptotic Giant Branch (AGB), intermittently burning either hydrogen or helium in two separate shells, and in the meanwhile shedding their envelope, thus preparing the condition for the later glowing of the nebula.

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AGB stars are then of particular relevance for PN sudies, to the extent that practically all processes taking place in them have direct *observable* consequences for the PN stage. In this review I will try to elucidate the most important among these causal links between particular processes taking place during the AGB phase, and phenomena which may not become apparent before the nebular stage has been reached. In particular, these processes include: i) the mass loss processes known as red-giant wind and superwind, ii) the superwind quenching at particular phases of the thermal pulse cycles, iii) the dredge-up and envelope burning processes which establish the final nebular composition, and iv) grain formation in the AGB ejecta. Some of these topics have been discussed in other recent reviews (Renzini 1979, 1980a, b, Iben and Renzini 1982a), and they will be only summarized here.

2. THE MASS LOSS PROCESSES AND THEIR CONSEQUENCES

PNe are clearly the manifestation of some mass loss process which operated earlier in the history of their exciting stars. As pointed out by Shklowski (1956), the expansion velocity of PNe indicates that the nebular material has been ejected while the star was a red giant, and subsequent observational and theoretical studies have conclusively confirmed Shkowski's argument. In particular, an impressive body of observational evidences now shows that red giants and supergiants are indeed losing mass, with the appropriate expansion velocities ($\sim 10 \div 20$ km/s) and, in some cases, with the appropriate rate for the production of a PN. However, in a recent series of papers (Wood and Cahn 1977, Renzini and Voli 1981, Renzini 1981a, b, Iben and Renzini 1982a) arguments are given indicating that at least two distinct mass-loss regimes must operate in AGB stars: the regular wind and the so-called superwind.

2.1 Wind and Superwind in AGB Stars

Most red giants (including AGB stars) are losing mass at a rate which is conveniently expressed by the Reimers formula (cf. Reimers 1975). Stars whose mass loss rate (MLR) follows the Reimers expression are considered in the regular *wind* regime, and evolutionary studies show that AGB stars can reach MLR's of at most a few 10^{-6} $M_\odot$/yr in this regime (c.f. Iben and Renzini 1982a). This is largely insufficient to account for the existence of PNe. In fact, combining current estimates of the mass, radius and expansion velocity of PNe, one derives that the MLR during the process leading to the PN ejection should be at least several 10^{-5} $M_\odot$/yr, and possibly much higher. Therefore, the termination of the AGB phase must coincide with a dramatic increase of the MLR, indicating that another, more efficient, mass loss process has to supersede the regular *Reimers* wind. The concise term *superwind* seems appropriate for designating this efficient mass loss process (Renzini 1981a), whose physical nature, though not yet unambiguously identified, is probably connected with the dynamical pulsations of the envelope (e.g. Wood 1974, Tuchman et al. 1979, Tuchman, this volume). Indeed, MLR's ranging from a few 10^{-5} $M_{\odot}$/yr up to several 10^{-4} $M_{\odot}$/yr appear to be rather common among infrared and OH maser sources (cf. Knapp et al. 1982), and then such objects are most likely in the superwind regime.

For exploratory purposes, both the wind and the superwind processes are currently parametrized in evolutionary calculations (e.g. Fusi Pecci and Renzini 1976, Wood and Cahn 1977, Iben and Truran 1978, Renzini and Voli 1981), through a numerical coefficient η placed in front of the Reimers formula, and a parameter b entering into the expression for the envelope mass -M_{PN}- at the onset of the superwind regime:

$$M_{PN}(M_H) = b \cdot f(M_H) \qquad (1)$$

where M_H is the mass inside the location of the hydrogen-burning shell (the so-called core mass), and $f(M_H)$ is an appropriate function (see for more details: Renzini and Voli 1981, Iben and Renzini 1982a).

M_{PN} is clearly also the mass ejected by the superwind process. Since luminosities and radii of AGB stars are rather sensitive to M_H, M_{PN} is expected to be rather sensitive to M_H, and then, ultimately, to the stellar initial Mass M_i. This expectation is reflected in the adopted parametrization, where (for b = 1) M_{PN} ranges from 0.02 $M_{\odot}$ for $M_H = 0.50$ to 1.3 $M_{\odot}$ for $M_H = 1.4$. The fact that the amount of superwind material around the central stars of PNe can considerably vary depending on M_i may have important consequences for the PN lifetimes, a point which will be discussed in Section 2.5. Moreover, in this frame the central stars of PNe are then expected to be surrounded by an inner and denser shell (the remnant superwind), and by an outer more tenuous shell (the remnant regular wind) which may extend for several pc. This picture is in qualitative agreement with the observation of nebulae with extended halos (Millikan 1974), as pointed out by Fusi Pecci and Renzini (1976).

2.2 Masses of PN Nuclei and the Mass Range of PN Producers

Coupling evolutionary calculations and parametrized mass loss algoritms, Iben and Renzini (1982a) give the following expression relating the stellar final mass M_f to the initial mass M_i:

$$M_f = \sim 0.53\eta^{-0.082} + 0.15\eta^{-0.35}(M_i - 1). \qquad (2)$$

This expression is most accurate for $1/3 < \eta < 2$, and is fairly insensitive to b for $1/2 < b < 1$. Note that the final mass M_f (i.e. the mass of the white dwarf remnant) is also practically identical to the mass of the central star during the PN phase.

Of great interest is also the critical initial mass M_W below which the hydrogen-rich envelope is actually ejected *before* the core mass can reach the Chandrasekhar limit ($\sim 1.4\ M_\odot$), and above which this limit is attained, carbon is ignited in the electron-degenerate core, thus leading to a supernova explosion. Therefore, stars in the mass range $0.85 \lesssim M_i \lesssim M_W$ are those which eventually produce white dwarfs, and then are likely to experience a PN stage. Following the parametrization sketched above, Iben and Renzini (1982a) give:

$$M_W = \sim 1.0 + 9.33\eta^{0.35} - 3.53\eta^{0.27} + 0.8(b - 1.0), \qquad (3)$$

which implies a range for M_W from ~ 4.7 to ~ 8, for η increasing from 1/3 to 2 (with b = 1).

The mass range of potential PN producers is therefore rather extended, and, correspondingly, great quantitative differences are to be expected in the behaviour of PNe and their nuclei, depending on the initial mass of the parent stars.

According to Eq. (2), PN nuclei should have masses ranging from slightly more than $0.50\ M_\odot$ (for $M_i = 0.85$) up to $1.4\ M_\odot$ (for $M_i = M_W$). The recognition that actual PN nuclei have masses in this range represents a crucial test for the current theory of stellar evolution and the adopted parametrization of the mass loss processes. This point will be discussed in Section 2.4.

2.3 The Superwind Quenching

The onset of the superwind regime marks the beginning of a fast decrease in the envelope mass M_e of AGB stars. Stellar structure calculations indicate that, decreasing the stellar mass, the average location on the HR diagram of an AGB star will at first move to the right, towards larger and larger radii [cf. Eq. (1) in Becker and Iben 1979] ,and, increasing the radius, the superwind instability will most likely be enhanced. This tendency to larger radii (lower effective temperatures) is reversed when M_e falls below a critical value, M_{eD}, marking the departure of the star from the Hayashi line. The value of M_{eD} is very small, and should be in the range from ~ 0.001 to $\sim 0.01\ M_\odot$, depending on the actual value of M_H, as indicated by Paczynski (1971) models. Since the star is now contracting, the superwind instability may become less violent, and suddendly gets quenched leaving a residual envelope mass M_{eR} ($\lesssim M_{eD}$). The theoretical determination of M_{eR} presents severe difficulties. Nonetheless, this quantity plays a crucial role in the subsequent evolution of the star, in particular for what concerns the nebular phase.

It is important to realize that M_{eR} can fluctuate considerably from one star to another, even among stars with virtually identical initial mass. This follows from i) the fact that $M_{eR} \ll M_{PN}$, ii) the hydrodynamical nature of the superwind process, and iii) the possibly episodic character of the superwind, which might consist in a number of discrete ejection events, as indicated by the hydrodynamical models of Wood (1974) and Tuchman et al. (1979). For example, let us take an assembly of stars for which $M_{PN} = 0.2$ (a popular value) and $M_{eD} = 0.001\ M_{\odot}$. If each ejectiontion event removes typically $\sim 10^{-3}\ M_{\odot}$ (as suggested by Tuchman et al.) then some 200 events are required to expel the whole envelope. But clearly nobody can pretend that all such stars will suffer exactly 200 events, instead of, say, 199 or 201! Therefore, M_{eR} will fluctuate from one star to the next by at least a factor of 2, and in some special cases M_{eR} could be considerably smaller than M_{eD}.

Another important aspect of the problem concerns the precise *phase* ϕ during the thermal pulse cycle at which the superwind ceases, where $\phi = 0$ when this happens in coincidence with one helium-shell flash, and $\phi = 1$ when it happens while the star is almost suffering one of such flashes, but not quite. In general, $\phi = \Delta t/\Delta t_{ip}$, where Δt is the time elapsed since the last pulse, and Δt_{ip} is the interpulse period.

It would be rather interesting to establish if there is any preferred value of ϕ, i.e. if envelope ejection and/or superwind quenching take more often place at some particular phase, for instance in coincidence with one flash. However, since speculations on this point can easily go too far, I will assume in the following that the ϕ-spectrum is just flat, but one should keep in mind that this may not be the case.

It is also worth noting that there is no reason why M_{eR} and/or ϕ should not depend (*on average*) on the final mass M_f, and then on M_i. In conclusion, the post-AGB evolution is essentially determined by three parameters, M_f, M_{eR}, and ϕ, the latter two being possibly only marginally correlated with the first one. The effects on the post-AGB evolution of varying each of these quantities is discussed in the coming section.

2.4 The Evolution of PN Nuclei

Naively enough, the transition from the AGB to the region of PN nuclei (which follows the superwind quenching) is often regarded as practically instantaneous. Conversely, as convincingly shown by Härm and Schwarzschild (1975), this transition time can be awfully long if certain conditions are not fulfilled. The transition time t_{tr} is defined as the time interval between the superwind quenching and the instant when the effective temperature of the remnant star reaches 30,000 K, i.e. when the central star becomes hot enough to excite the previously ejected envelope.

Iben and Renzini (1982a) give the following expression for t_{tr}:

$$t_{tr} = \sim 1.6\ 10^6 yr\ (M_{eR} - M_{eN})/(M_H - 0.44) \qquad (4)$$

where M_{eN} is the envelope mass when the star reaches T_{eff} = 30,000 K, and from the models of Paczynski (1971) one can derive:

$$M_{eN} = \sim 1.8\ 10^{-5} M_H^{-8.23}\ . \qquad (5)$$

For illustrative purposes, let us consider the case $M_H = 0.6$, for which $M_{eN} = \sim 1.2\ 10^{-3}\ M_\odot$. Then Eq. (4) gives t_{tr} = 3000, 8000, and 18,000 yr, respectively for M_{eR} = 1.5, 2.0 and 3.0 $10^{-3}\ M_\odot$. The *age* of a PN (time since the quenching of the superwind) is roughly given by $t_{PN} \simeq R_{PN}/v_{exp}$, where R_{PN} is the observed nebular radius and v_{exp} is the nebular expansion velocity. Observed PNe have ages between ∿1000 and ∿30,000 yr, the majority clustering around 5000 yr. Clearly, for each observed PN, one must have $t_{tr} < t_{PN}$, and, because of the arguments presented in section 2.3, any fluctuation and/or trend in M_{eR} will necessarily translate into sizable fluctuations/trends of t_{tr}. The PN stage can even be completely bypassed if t_{tr} is too long (for instance, longer than 30,000 yr), since in this case the ejected envelope would disperse before the central star becomes hot enough to excite the nebula (Renzini 1981a). One can then conclude that i) the initial PN radius ($= t_{tr} \cdot v_{exp}$) depends on the residual envelope mass M_{eR}, and ii) quite possibly, there may exist stars which eject their envelope but do not experience an *observable* PN stage.

Another timescale is of capital importance for the understanding of PNe and their nuclei. This is the *fading time* t_f, defined by Iben and Renzini (1982a) as the time taken by the star to fade by a factor of ten in luminosity, after the star has reached the critical temperature of 30,000 K. From the models of Paczynski (1971), Iben and Renzini emphasize that t_f is dramatically sensitive to M_H, the mass of the post-AGB remnants, with $t_f \propto \sim M_H^{-9.6}$! Indeed, a 1.2 $M_\odot$ model takes only 45 yr to fade, while a 0.6 $M_\odot$ model takes ∿15,000 yr (Iben 1982). From these facts Renzini (1979, 1981a) concluded that initially more massive stars, which according to Eq. (2) should residuate more massive remnants, can only produce PNe with *bolometrically* faint nuclei (say, Log $L/L_\odot < \sim 2$), while low-mass precursors ($\sim M_\odot$) which residuate low-mass remnants ($\sim 0.55\ M_\odot$) can only produce PNe with bright nuclei (Log $L/L_\odot \simeq 3$), since their fading time is longer than 30,000 yr. Obviously, there will be some intermediate initial mass for which t_f is comparable to the nebular lifetime, and for these objects the central stars are expected to experience a sizable decrease in luminosity during the nebular phase. Schönberner and Weidemann (1981) and Schönberner (1981) have questioned these conclusions, and rather argue that irrespective of M_i practically all stars with $M_i < M_W$ leave remnants with $M_f \simeq 0.6$. This result follows from the particular sample of PNe that they have considered, which is selected according to the availability of the V magnitude of the central stars. Since there are quite many PNe with visually undetected central stars (a classical prototype being NGC 7027), their mere existence implies that these stars must have masses considerably above the values preferred by Schönberner and Weidemann. Therefore, their analysis neither invalidates the arguments of Renzini (1979, 1981a), nor implies that all stars with $M_i < M_W$ generate post-AGB stars with essentially the same mass, a claim which, in any case, would be hard to justify in terms of stellar evolution theory and mass loss during the AGB phase. More recently, Kaler (1982) has analyzed a large sample of PNe finding consistency with Renzini's predictions.

We are now left with the discussion of the role played by ϕ. Iben and Renzini (1982a) mention that, particularly in low-mass post-AGB stars, the actual value of ϕ can considerably affect the fading time t_f, an aspect which deserves further numerical experiments. But aside from this, for each set of values (M_H, M_{eR}), the quantity ϕ is expected to control: i) the possibility for the star to suffer a final helium-shell flash after the superwind quenching, and ii) in the case that this happens, the time t_{FF} elapsing from the beginning of the nebular phase ($T_{eff} = 30{,}000$ K) to the outbreak of the final flash. As extensively discussed by Iben et al. (1982), when a final flash takes place in the region of PN nuclei the star describes an extended loop in the HR diagram which partly overlaps the previously traced path. Iben et al. argue that some PN nuclei can actually be percurring one of such post-flash loops, rather than being fading for the first time. Indeed, the duration of the loop is of the order of 1/5 Δt_{ip}, and then can be comparable to the nebular lifetime for post-AGB stars in an appropriate mass range. Iben et al. suggest that the PNe A30 and A78 are likely candidates for having central stars in the post-flash phase.

Clearly, PNe can have rejuvenated central stars only if t_{FF} is shorter than the nebular lifetime. The final flash time t_{FF} is a decreasing function of ϕ, and below a critical value t_{FF} is likely to be infinite, i.e. no final flash takes place, while for ϕ approaching unity t_{FF} tends to vanish. Obviously, this behaviour depends on the fact that for each value of M_H, the intershell mass has to reach a threshold value for a flash being initiated, and the smaller ϕ, the smaller the intershell mass, and so the longer the star must wait before suffering the final flash. Then, for ϕ below a critical value the final flash occurs when the nebula has already dispersed. The precise functional relationship $t_{FF}(M_H, M_{eR}, \phi)$ remains to be determined by further laborious stellar model calculations.

Finally, Renzini (1979, 1980b, 1982), Iben and Renzini (1982a), and Iben et al. (1982) argue that the final flash is likely to generate a hydrogen-deficient star, and, in particular, PN nuclei of the Wolf-Rayet variety, like in the case of A30 and A78.

2.5 Nebular Lifetimes and Nebular Radii

Owing to the extended mass range of PN progenitors it would be very surprizing if all PNe were to have the same lifetime. Indeed, Renzini (1981a) argues that PNe cease to be detectable after a time t_{max} since the envelope ejection, with

$$t_{max} \propto \sim M_{PN}^{0.4} \; SB_{min}^{-0.2} \qquad (6)$$

where M_{PN} is the mass of the remnant superwind and SB_{min} is the minimum surface brightness for a nebula being included in existing catalogues. Correspondingly, the nebular lifetime t_{PN} is given by $t_{max} - t_{tr}$, and t_{PN} can then be anywhere between zero (when $t_{tr} \geq t_{max}$) and $\sim t_{max}$. Note that t_{max} depends on M_{PN}, and then, in turn, on M_f and M_i. In the frame of the adopted parametrization of the superwind process, t_{max} is expected to increse by roughly a factor of 5, for M_i increasing from 0.85 $M_\odot$ up to M_w. Therefore, it should be quite dangerous to adopt a unique nebular lifetime for stars belonging to different stellar populations, e.g. young disk, old disk, halo.

A correlation is known to exist between the nebular radius and the luminosity of the central star, bigger PNe having, on average, fainter nuclei. This has been often interpreted as evidence that the locus in the HR diagram occupied by PN nuclei is an evolutionary sequence, with fainter PN nuclei being evolved versions of the brighter ones. While this effect is probably present, at least to some extent, it is worth realizing that three other effects can concur, perhaps dominantly, in producing the observed correlation. i) According to the discussion in the preceding paragraph, PNe produced by more massive precursors may grow bigger before disappearing, compared to those generated by less massive precursors, and according to Section 2.4 the former PN nuclei are expected to be fainter than the latter ones. ii) There should exist a trend in t_{tr} with $M_f(M_i)$, and if t_{tr} increases with M_f then the initial nebular radius ($= t_{tr}v_{exp}$) will also increase with M_f, and thus will correlate with the location of the nucleus on the HR diagram. iii) The larger M_{PN}, the larger the expected dust absorption during the early nebular stages, and then massive nebulae may not be detectable in the optical when still too compact. These considerations indicate that the interpretation of the nebular radius/luminosity correlation might not be so straightforward, after all.

3. THE COMPOSITION OF RED GIANT ENVELOPES AND PLANETARY NEBULAE

The nebular composition must reflect that of the stellar envelope at the onset of the superwind regime. In turn, this is the result of various mixing processes having contaminated the stellar envelope, at specific evolutionary stages, with materials having suffered various types of nuclear processing in the stellar interior. These mixing processes include: i) the three *canonical* dredge-up processes described in Iben and Truran (1978), Becker and Iben (1980), Renzini and Voli (1981), and Iben and Renzini (1982a); ii) the so-called Envelope-burning process (cf. Sugimoto 1971, Renzini and Voli 1981, and references therein); and iii) all those mixing processes which may be induced by rotationally-driven instabilities, and which theoretical astrophysicists find hard to model from first principles. Therefore, the study of the composition of PNe provides a very useful tool for checking current evolutionary models, and, in case , for getting new insight into the complicated question of the mixing processes of non-convective origin.

3.1 The Gas Composition

Renzini and Voli (1981) have published theoretical He/H, C/O and N/O values, as predicted by the canonical theory of stellar evolution (i.e. neglecting possible mixings of non-convective origin). These abundance ratios have been computed for various combinations of the parameters η, b and α (the ratio of the mixing length to the pressure scale height), and for quite many values of the initial mass. Not surprizingly, the abundance ratios are found to be very sensitive to M_i, since the various dredge-ups and the envelope burning process have very different efficiency in stars of different mass. Therefore, for the reasons discussed in Section 2.4, a correlation is expected between the nebular composition and the location of the central star on the HR diagram (Renzini 1979, 1981a).

One crucial entry in the theory is the so-called dredge-up law, giving as a function of M_H the amount of intershell material which, following each pulse, is captured by the convective envelope. Renzini and Voli used the Iben and Truran (1978) dredge-up law, which is very tentative for low values of M_H. Moreover, until recently a significant discrepancy was apparent between low-mass AGB models, where the third dredge-up was never active, and the existence of relatively faint carbon stars in the Magellanic Clouds, for which M_H should be as low as $\sim$0.6 $M_\odot$ (cf. Iben 1981a,b, Renzini 1981c). Since most PNe have relatively low-mass precursors ($\sim$1-2 $M_\odot$), and then low-mass nuclei [through Eq. (2)] , theory was in trouble in predicting the nebular composition of the most common objects.

However, Iben and Renzini (1982b,c) have eventually succeded in getting the third dredge-up in a low-mass model, thanks to appropriate opacities kindly provided by A.N. Cox and S. Hodson. In fact, following a thermal pulse, the opacity peak around 10^6 K due to incompletely ionized carbon ions triggers the appearance of a semiconvective region in the upper intershell. Moreover, this semiconvective region soon merges with the convective envelope, and intershell material (mostly helium and carbon) is efficiently convected to the surface. These findings are not only relevant for the nebular composition and carbon stars, but also for the nucleosynthesis of s-process elements in low-mass AGB stars (cf. Iben and Renzini 1982c).

Although the third dredge-up process is now known to operate also in low-mass stars, there remains to determine the third dredge-up law for low values of M_H (for, say, $0.50 \lesssim M_H \lesssim 0.80$), which should be obtained by future laborious calculations of evolutionary models. Therefore, until then the Renzini and Voli results for $M_i \lesssim 2.5$ should be used with caution.

Comparisons of Renzini and Voli theoretical abundances with observations have been presented by Peimbert (1981), Aller (1981) and Kaler (1982). By and large, these comparisons look promizing, in particular for the He/H and C/O ratios. Since much new data will certainly be presented at this meeting, I will not discuss these matters any further...

3.2 The Dust Component

The expanding environment of AGB stars, either in the regular wind or in the superwind regime, is certainly one of the ideal sites for the formation and growth of dust particles. The nature of the grains being formed clearly depends on the composition of the circumstellar envelope, and most crucially on the C/O ratio. If a star terminates its AGB phase while still oxygen rich ($C/O < 1$), then the daughter nebula should only contain oxygen-rich grains, e.g. silicates. When the star begins the superwind phase as a carbon star ($C/O > 1$), the daughter nebula should only contain carbon-rich grains, e.g. silicon carbyde, graphite, soot, etc. In some cases, the envelope may be ejected while the star is a S-type giant ($C/O \simeq 1$), and correspondingly the PN should be very poor in dust particles at all times. This dichotomy in the dust content of PNe is actually observed (e.g. Aitken and Roche 1982), and the theory of stellar evolution gives the initial mass ranges for the progenitors of carbon-rich and oxygen-rich nebulae (cf. Renzini and Voli 1981).

4. PLANETARY NEBULAE AND BINARY SYSTEMS

Before becoming white dwarfs (WD), stars have necessarirly to experience a high-temperature phase (T_{eff} > ∿30,000 K) during which they are powerful emitters of ionizing photons. This is true irrespectively of the particular process by which WD's are produced. In particular, a WD is formed in binary systems where a primary component less massive than ∿2.2 $M_\odot$ fills its Roche lobe while ascending the red giant branch. In this case a helium WD is formed, with a mass less than about 0.5 $M_\odot$. Similarly, a carbon/oxygen WD is formed when a primary star initially less massive than about 8 $M_\odot$ fills its Roche lobe while ascending the AGB.

According to Tutukov and Yungelson (1980), perhaps 2/3 of all binary stars suffer Roche-lobe contacts of the types mentioned above, and since binaries rival in number single stars, putting two and two together one is forced to conclude that binary-born WD's can be nearly as common as those produced by the wind/superwind processes in single stars. Moreover, since the secondary components can hardly accrete all the material shed by the primaries (cf. Greggio and Renzini 1982, and references therein), binary systems containing a primary evolving towards the WD stage are also expected to be surrounded by an expanding, rather massive and *non-spherically symmetric* shell.

In my opinion, this provides a quite attractive scenario for the production of asymmetric PNe (e.g. the so-called bipolar nebulae). In fact, these binary-born pre-WD's are rather commonly produced, there is gas around to be excited, and there is the source of ionizing photons.

Conversely, the idea that asymmetric PNe are produced by rotating red giants looks quite unattractive when considering that the surface layers of an AGB star rotate several hundred times slower than the initial main sequence rotational velocity. Moreover, significant angular-momentum losses are likely to occur before the envelope ejection, and ultimately the surface rotational velocity of single AGB stars may well be several orders of magnitude lower than ∿20 km/s, the typical expansion velocity of PNe. Clearly, it is not easy to see how such small velocity asymmetry could give rise to highly asymmetric nebulae. A search for binarity among the nuclei of asymmetric nebulae would then be very interesting in this context.

It is worth noting that binarism will also affect much of what said in the previous sections, including the question of the transition time, and the nebular composition. Although binarism introduces more complexities into already complex problems, the possibly common existence of binary-born PNe should always be kept in mind when comparing observations with the evolutionary theory of *single* stars.

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KWOK: You raised an important point about the transition time, which has to be kept at a reasonably small value. As the transition time is critically controlled by the residual hydrogen envelope mass and this residual mass may vary, depending on the ejection process, would it not be better if the AGB phase is terminated by a wind process alone and not by a sudden ejection? In this way, the residual mass will always be the minimum possible.

RENZINI: The superwind is not necessarily a sudden ejection of the envelope on a dynamical time-scale, although it may consist of a large number of ejection events, as suggested by the models of Wood and Tuchman.

OSTERBROCK: Can you comment on how the transformation from star to PN differs (or otherwise) for binaries and for single stars?

RENZINI: In single stars, the superwind is responsible for the PN ejection, a process which is probably highly spherically symmetric. In binaries, one has Roche lobe overflow from the primary, then matter is stored in an accretion disk, whose size is limited by its Eddington luminosity. So matter must be lost from the system, and I doubt that this will take place in a spherically symmetric way.

REAY: The inner and outer envelopes of A 30 are quite different in form, although both are expanding at a similar velocity. Can you comment as to why this should be so?

RENZINI: From the velocity you have determined for the hydrogen-free knots, one can deduce that some 1500 y ago the nucleus of A 30 was a Red Giant shedding hydrogen-free and carbon-rich material. Most likely, it was a R CrB star, and such stars are known to occasionally eject puffs of matter in a non-spherically symmetric fashion, a process which is responsible for the characteristic deep luminosity minima of these stars.

KALER: How do the high mass stars found in the Magellanic Clouds fit in with the large exponent on M_f? Could you place an error bar on your exponent?

RENZINI: There is indeed an inconsistency between the derived luminosity and the very short times (a few hundred years or less) that these stars (with $M_f \approx 1M_\odot$) should spend at such high luminosities. The expression for the fading time is derived from the old Paczynski tracks, and, although it is of crucial importance to compute further grids of post-AGB sequences, I think that the fading times are not going to change by large factors. It would also be desirable to set an error bar on the derived luminosities and masses.

BEGELMAN: In principle, one could have aspherical mass ejection if, instead of spherical pulsations driving the superwind, one has aspherical modes with zones of upwelling and downdrafts. Do you consider this to be plausible?

RENZINI: Perhaps. I have, however, the feeling that the envelope of AGB stars is spherically symmetric to a high degree.

WANNIER: Why is rotation a less attractive theory for producing asymmetric nebulae?

RENZINI: Because one would expect a lot of angular momentum loss during the whole previous history of the star, in particular, during the wind phase on the AGB, when some 50 per cent of the envelope mass is slowly ejected. Add even a small magnetic field and you derive a formidable torque breaking the whole convective envelope.

ROXBURGH: The solar wind is clearly dominated by the solar magnetic field. Surely, we should expect magnetic fields to be generated by dynamo action even in those slowly rotating but very large Giants. Such magnetic fields could drive and control the mass loss and produce asymmetries.

RENZINI: Maybe, but binaries produce much larger asymmetries.