THE EVOLUTION OF PLANETARY NEBULAE, THEIR PRECURSORS AND THEIR PROGENY — A COMMENTARY

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1. The Legend

There appears to exist in the minds of most of the participants of this conference a highly stylized picture of how the majority of all stars evolve after reaching the asymptotic giant branch. This is a fascinating development as, just three decades ago, no one understood what an asymptotic giant branch (AGB) star is or does, either theoretically or observationally, and, just two decades ago, no one understood the nature of the transition from AGB to planetary nebula, other than that it happened. And, yet, today, the evolution from AGB to planetary nebula and to white dwarf is described by a very beguiling picture whose outlines have become substantially fixed.

The standard picture is: (1) The AGB star alternately burns hydrogen and helium in shells above an electron-degenerate core. Helium burning always begins as a thermonuclear runaway, and elements processed by partial helium burning during the flash make their way to the surface after each flash in a dredge-up episode. (2) As the AGB star brightens, the rate of mass-loss from its surface accelerates, and eventually there is a complete detachment of a contracting stellar remnant from an expanding ejected shell. The mechanism of mass loss involves first inflation of the stellar envelope by shocks driven by pulsations and then radiation pressure on grains formed in the outer part of the envelope. (3) The remnant continues to contract as it burns hydrogen or helium in a shell. Whether helium or hydrogen burns depends on where in a flash cycle of the AGB precursor final detachment of the expanding shell and contracting remnant occurs. (4) The fraction of nebular mass in molecular form relative to the fraction in ionized form depends on, among other things, the surface temperature of the remnant and the amount of mass in the nebula which is self shielding. When the surface temperature of the remnant becomes high enough, photons from the remnant cause a portion of the nebula to fluoresce in the optical. (5) A fast wind from the remnant forms a hot bubble which helps shape the nebula. If the remnant has a companion, this companion will also contribute to shaping. Bipolarity is common and the symmetry axis could coincide with the spin angular momentum or magnetic moment axis of the remnant, if single, or with the orbital angular momentum vector, if in a binary. (6) Eventually, nuclear burning dies out and the remnant cools as a white dwarf. The nebula disperses. (7) Depending on where in its flash cycle the AGB precursor leaves the AGB, the remnant white dwarf may experience a final helium shell flash to become a "born-again" AGB star, or a final hydrogen shell flash to become a "self-induced nova". In the born-again case, the central star burns helium and essentially retraces its steps as a hydrogen burner on a similar time scale; when the nebula fluoresces a

R. Weinberger and A. Acker (eds.), Planetary Nebulae, 587–596.

https://doi.org/10.1017/S0074180900172614 Published online by Cambridge University Press

second time, it is substantially larger then it was the first time. During the final nuclear-burning phase, further mass is lost from the surface of the remnant, possibly exposing highly processed matter. (8) The fact that there are different evolutionary channels leading to the white dwarf state, even for single stars, may be responsible for some of the differences among white dwarfs with regard to surface composition. The fact that some are formed in close binaries can be responsible for additional differences.

In the following, articles referenced by author, but not by year, appear in this volume; they are not cited in the list of references at the end.

2. Thermally Pulsing Asymptotic Giant Branch Interiors

An AGB star possesses an electron-degenerate core composed of carbon and oxygen (if the mass of its progenitor is $\sim$ 1-8 $M_{\odot}$) or of oxygen, neon, and magnesium (if the mass of its progenitor is $\sim$ 8-10 $M_{\odot}$). In both instances, the core has the dimensions of a hot white dwarf $\sim 10^9$ cm and the hydrogen-rich envelope has the dimensions of a giant of radius a few times 10^{13} cm. During the early AGB (E-AGB) phase, hydrogen does not burn as the core grows in mass until it nearly reaches the hydrogen-rich envelope, whereupon hydrogen is reignited. In the case of a CO core, hydrogen and helium then burn alternately in shells situated between the core and a convective envelope. Hydrogen burning is quiescent and lasts approximately 90% of the thermally pulsing AGB (TP-AGB) lifetime.

Helium burning begins as a thermonuclear runaway and both carbon and s-process elements are produced, as detailed by Lattanzio. During the helium flash, the surface luminosity first dips, as hydrogen burning is extinguished, and then increases, as the energy produced by helium burning leaks out of the production region (see Wood). During this phase, carbon and s-process elements are dredged to the surface. Then the luminosity drops as helium continues to burn quiescently for about 10% of the time between flashes. Helium stops burning and another phase of quiescent hydrogen burning ensues. The excursions in luminosity during a complete cycle can be substantial.

In the case of an ONeMg core, carbon-burning and helium-burning shells alternate (Nomoto 1984, 1987), but *no one* has yet followed the ignition and extinction of hydrogen burning in a *complete* model. Yet, unless they are "Blöcker-Schönberner" (1990) stars, the most luminous LPV's in the Magellanic clouds have ONeMg cores. They are surely experiencing helium shell flashes and dredge-up (Wood, Bessell, and Fox 1983), and, because of their superabundances of lithium (Smith and Lambert 1989, 1990), they must also experience phases of quiescent hydrogen burning, interrupted by helium shell flashes.

3. Pulsation, Dust, and Mass Loss

The mechanism for mass loss from AGB stars and whether or not a "superwind" terminates the AGB phase in all cases have been debated for years. It is definitely clear from the statistics in the Magellanic clouds that thermally pulsing AGB stars with small core masses (0.5-0.6 $M_{\odot}$) exist for of the order of 5-20 $\cdot 10^5$ yr, whereas those with large core masses ($\gtrsim 0.8$-$0.9\ M_\odot$) exist only for of the order of 10^5 yr or less. From this, one can infer average mass-loss rates of $\dot{M} \sim 10^{-7} - 10^{-6}\ M_\odot$ yr^{-1} for stars of small core mass and $\sim 10^{-5} - 10^{-4}\ M_\odot$ yr^{-1} for those of large core mass. Thus, there has long been evidence that mass-loss rates increase with luminosity.

A promising theoretical approach has been adopted by Bowen (1988) and Bowen and Willson (1991). The models show that, beyond a certain radius, shocks inflate the envelope beyond that of a corresponding hydrostatic model, producing an extended region of much higher density than in a hydrostatic model. Radiation pressure on grains formed in the envelope accelerates the dust grains and collisions between grains and ambient atoms and molecules accelerate the gas. The nearly periodic oscillatory motion near the photosphere gradually develops into an outflowing wind. Applying the results of the hydrodynamic calculations to construct synthetic AGB model evolutionary sequences, Bowen and Willson (1991) show that the mass loss rate of the evolving AGB star accelerates exponentially, growing indeed into a "superwind" (Renzini 1981).

4. Superwinds and Pre-Planetary Nebulae

Both large OH/IR sources and carbon-rich systems such as IRC+10216 could rightfully be called proto-planetary nebulae or pre-planetary nebulae (PPNe) in the sense of being precursors of what has traditionally been called a PN, namely a very hot central star and an ionized nebular shell. However, the term has come to mean different things to different people. I think it is probably wise to follow Sun Kwok's lead in insisting that the name be reserved for systems in which pulsation driven mass loss has ceased once and for all and in the spectrum of which two components can clearly be identified as coming from, respectively, a central star and a circumstellar shell (or shells) no longer connected by high density matter to the central star. The consensus definition appears to include all systems for which the central star has a surface temperature between 5,000K and 30,000K. By demanding that there be no large amplitude light variations, one insures that the mass of the remnant hydrogen-rich envelope of the central star is small enough that pulsation can no longer drive mass loss at superwind rates, and physical detachment of central star and expanding shell has taken place.

5. Classical Planetary Nebulae and Their Central Stars

5.1. The Interacting Winds Model

The zero-order standard model of a classical PN is characterized by a set of spherically symmetric layers surrounding a hot, compact central star. The central star emits ionizing radiation (surface temperature between 30,000K and 300,000K) and emits a fast ($\sim$ 3000 km s^{-1}) particulate wind with a momentum flux comparable with or larger than that of the circumstellar shell (Perinotto). The fast wind interacts with the matter in the shell (or shells) previously ejected in the superwind(s), causing this matter to be swept up into a new shell compressed between the in-

https://doi.org/10.1017/S0074180900172614 Published online by Cambridge University Press

ner, more rapidly moving, wind and the outer, less rapidly moving, wind (Kwok, Purton, and FitzGerald 1978; Kwok 1982; Kahn 1983, 1989; Dyson).

The Kahn model assumes that the fast wind flowing from the central star is converted into a shock heated gas bubble which is confined from below by the ram pressure of the wind as it escapes the star and from above by the back pressure from matter in the layer formed by the earlier superwind.

It is disappointing that there is as yet no satisfactory theory which, once parameters have been normalized to observational estimates, might allow one to predict the mass-loss rate of the central star as a function of mass and position in the H-R diagram. Such a theory would enable us to make progress in understanding the mystery presented by the surface composition of hydrogen-deficient central stars and white dwarfs.

5.2. Central Star Evolution

The first attempt to model the evolution of the central star is that of Paczyński (1971). This work has been extended by Schönberner (1979, 1981), whose classic tracks have been the standard reference for observers for over a decade. Wood and Faulkner (1986) have also provided a set of tracks in wide use.

A series of imaginative papers by Renzini (1979, 1981, 1982, 1983, 1989) provides a comprehensive framework for comparing theory with the observations, raising issues that are still being debated and acted upon. Heap emphasizes the fact that the rate at which a model central star of constant mass evolves to the blue during the high-luminosity plateau phase varies with about the 10^{th} power of the mass of the model (e.g., Iben and Renzini 1983), and that this fact can be used to estimate the masses of PNNi which are known to be in the plateau phase.

The growing wealth of information about PNNi in the Magellanic clouds (Dopita) is very gratifying to see. Combining their work (Kaler and Jacoby 1990, 1991) with that of Dopita and Meatheringham (1991a,b) and that of Aller et al. (1987), Kaler and Jacoby (1991) show that estimated masses of 80 studied PNNi lie in the range 0.56-1.22 $M_\odot$. The masses have been estimated on comparison with theoretical tracks of hydrogen-burning PNNi. The bulk of the brightest 33 central stars have estimated masses in the range 0.56-0.66 $M_\odot$, but there appears to be a secondary peak with masses $\sim$ 0.7-0.74 $M_\odot$. The masses of the other 47 stars appear, in the main, to follow a distribution similar to that defined by the bright sample, but roughly a dozen have masses extending from 0.74 $M_\odot$ to 1.22 $M_\odot$ in what appears to be a flat distribution. The absence, in the bright sample, of PNNi with large masses is consistent with the fact that the rate of evolution through the plateau phase increases rapidly with mass.

The clustering of PNN masses about 0.6 $M_\odot$ is due to the facts that (1) stars of initial mass $\lesssim 2$ $M_\odot$ all develop electron-degenerate helium cores which grow to $\sim$ 0.5 $M_\odot$ before a helium flash lifts degeneracy, and (2) $\sim$ 0.05 $M_\odot$ is added to the helium core during the quiescent core helium-burning (horizontal branch or red giant clump) phase. Thus, when they reach the TP-AGB phase, all stars initially less massive than $\sim$ 2 $M_\odot$ develop a CO core of approximately the same mass $\sim$ 0.55 $M_\odot$. The spread in final core mass about 0.6 $M_\odot$ may be interpreted to be a consequence of the fact that initially more massive stars (in the 1-2$M_\odot$ range) must lose more mass than lighter ones and therefore live longer and grow larger core masses before departing from the AGB as PNNi. The $\sim 0.05\ M_\odot$ mass difference between the common initial mass and the final mean mass can be used in conjunction with the theoretical fuel-consumption rate to derive a mean lifetime of $\sim 5 \cdot 10^5$ yr for TP-AGB stars originating from low mass main sequence progenitors. This estimate is quite consistent with the estimate of $\sim 3 \cdot 10^5$ yr given by Whitelock and Feast for Miras in the inner part of our Galaxy.

Dopita makes the interesting statement that all of the PNNi in the Magellanic Clouds are helium burners, and this is consistent with Kawaler's (1988) statement that Galactic PNNi cannot be hydrogen burners. Kawaler's argument is based on a prediction that hydrogen burners should pulsate at a detectable amplitude, contrary to observations of galactic PNNi in the plateau phase. My feeling is that, on the basis of analyses thus far performed, it is not possible to tell whether the majority of cloud PNNi are either helium burners or hydrogen burners, but a definitive check is potentially possible using an analysis such as that performed for Galactic PNNi by Schönberner (1986), who concludes that most of the PNNi in his sample are hydrogen burners.

5.3. Nebular Mass, Chemistry, and Composition

Quantitative estimates of the amount of matter in ionized form are now being complemented by quantitative estimates of the amount of matter in molecular form (Huggins, Bieging 1988), giving total masses of detected matter which in many cases are substantially larger than the ~ 0.2-$0.3\ M_\odot$ of ionized matter that is often used in obtaining statistical parallaxes.

Huggins and Healy (1989) find that the ratio of molecular mass to ionized mass is very tightly anti-correlated with nebular radius R, and this is a nice demonstration of how the ionization front passes through superwind matter. A reasonable fit to the Huggins-Healy results over the range R = 0.002-0.6 pc is $M_i/M_m \sim 10\ (R/0.3\ \mathrm{pc})^{1.5}$. Complementary to this result is the existence of a correlation between the mass of the ionized nebular layer and nebular radius.

At this conference and elsewhere, Clegg (1989, 1991) has extensively reviewed the element abundance distributions in PNe, showing how departures from the solar system distribution and from the distribution in nearby HII regions provide clues to the nature of nucleosynthesis and mixing in the parent star during its nuclear-burning phases. Other recent reviews include those of Peimbert (1991), Barlow (1991), and Henry (1990). One of the most dramatic departures from the solar system distribution forms the basis for the "Type I PNe" classification of Peimbert (1978). In Galactic nitrogen-rich Type I PNe, the mean value of He/H is ~ 0.13 versus ~ 0.085 for both non-Type I nebulae and HII regions. The mean ratio of nitrogen to oxygen depends on the sample, but appears to be in the range 0.5-1 (Henry 1990). Large helium and nitrogen abundances could be evidence for the occurrence of the first and second dredge-up episodes in fairly massive intermediate-mass stars prior to the onset of thermal pulses (Kaler, Iben, and Becker 1978; Becker and Iben 1980). These dredge-up episodes mix into the hydrogen-rich envelope results of hydrogen burning in the interior prior to the TP-AGB phase.

Barlow gives an intriguing interpretation of the fact that emission from the nebula NGC 6302 has characteristics of both carbon-rich and oxygen-rich gas. Analysis of the optical spectrum shows that $(C+N+O)/H \gg$ solar, a clear signature of the third dredge-up, and that $C/O < 1$ and $N/O \gg 1$, a clear indication of envelope burning. He points out that, because the envelope is losing mass while dredge-up and burning are progressing, the abundances in the ejected matter will be continuously changing. One might expect in the final ejecta an outer O-rich region emitted before the third dredge-up has done much to alter the composition, an intermediate C-rich region composed of matter in which dredge-up increases the carbon abundance faster than it can be converted into nitrogen, and an innermost O-rich region made of matter in which envelope burning has converted C into N faster than C can be dredged up. After the system has evolved into a PNe with a hot PNN, instabilities produced by the fast wind as it strikes the neutral layers could cause some mixing between the different layers.

As usual, the Magellanic clouds provide additional insights and conundrums. The fact that the Galaxy, the LMC, and the SMC are an ordered sequence with regard to metallicity might be expected to lead to some systematic differences in the mean properties of various components in passing from one aggregate to another in the same order.

Clegg emphasizes that *all* Magellanic cloud PNe which are not of type I have $C/O > 1$, whereas only about 60% of Galactic PNe have $C/O > 1$ (Zuckerman and Aller 1986). This would suggest that all AGB stars in the clouds experience third dredge-up episodes before departing the AGB. However, AGB carbon stars have not been identified in the oldest Magellanic cloud globular clusters (Frogel, Mould, and Blanco 1990). Could it be that, for AGB stars of very small mass and metallicity, the superwind is triggered almost at once by a large increase in the abundance of carbon due to dredge-up? Models show that dredge-up does not occur until the core mass exceeds a critical value and that one dredge-up episode in a low mass, low metallicity star is enough to establish carbon star characteristics. If carbon is increased, the formation rate of dust grains is also enhanced, leading perhaps to a sufficiently large mass-loss rate that departure from the AGB occurs long before another flash can take place. In this picture, the absence of AGB carbon stars in old clusters is simply due to the fact that the lifetime of such stars is extremely abbreviated by the sudden triggering of a superwind. Or, could it be that the central stars of the very lowest mass ($\lesssim 0.55\ M_\odot$) are "lazy" (Renzini 1981), evolving so slowly during the plateau phase that the ejected matter is dispersed over too large a volume before it can be ionized?

6. PNN Chemistry and the Born-Again Phenomenon

The superwind terminates once the mass of hydrogen-rich material left near the surface decreases below a critical value. What happens next depends on precisely where in the flash cycle this occurs (see Iben 1984, 1987, 1989). Of particular interest is the evolution of a model which departs from the AGB late during the quiescent hydrogen-burning phase with a mass of helium-rich matter which is close to the mass necessary for helium ignition during the AGB phase. In such a model, a final helium shell flash can take place after the star has departed the AGB. The model returns to the AGB as a "born-again" AGB star (Iben et al. 1983, Iben 1984). After the star departs from the AGB a second time and evolves to high temperatures, further mass loss via a fast wind may remove all of the remaining hydrogen, exposing first the He-N buffer layer and, thereafter, layers that have experienced partial helium burning.

An inspiration for the early quantitative work exploring the born-again scenario was the discovery that the central stars of Abell 30 (Hazard et al. 1980) and of Abell 78 (Jacoby and Ford 1983) appear to have ejected hydrogen-deficient matter rich in He and N long after the major portion of the nebula was formed. Another instance of the born-again phenomenon is V605 Aql, the central star of Abell 58, which underwent a nova-like explosion in 1919. The inner part of the nebula has developed some characterists of the Abell 30 and 78 systems. A clumpy nebulosity of dimensions $\sim 10^{16}$ cm hides the central star (Bond, Liebert, and Renzini) and an H-deficient knot with a speed of ~ 100 km s^{-1} and dimensions $\sim 2 \cdot 10^{16}$ cm has been detected (Pollacco et al.). Bond et al. point out that at maximum visual light, the spectrum of Nova Aql 1919 resembled that of an R CrB star, and this is indicative of hydrogen reignition during the post-AGB helium shell flash.

For the central star of A78, Werner and Koesterke (1992) estimate abundances by mass (He, C, N, O) $\sim$ (0.33, 0.5, 0.02, 0.15). For the central star of NGC 6751, Hamann and Koesterke estimate abundances by mass (He, C, N, O) $\sim$ (0.615, 0.27, 0.015, 0.10). These abundance mixes bear some resemblance to the mix predicted by the born-again scenario, except that the O/C abundance ratios, at $\sim 1/6 - 1/3$, are much larger than obtained in the theoretical calculations which use cross section for the $^{12}C(\alpha,\gamma)^{16}O$ reaction given by Fowler, Caughlan, and Zimmerman (1975). Thus, the estimated abundance ratios could be demonstrating that a much larger value for this cross section is in order. The ratio N/C can be used to estimate how much matter which has experienced partial helium burning is mixed with hydrogen-rich matter in the convective shell which is driven by hydrogen burning. For the PNN in A78, the ratio of the two forms of matter is ~ 15, and for the PNN in NGC 6751 it is ~ 10. For a 0.6 $M_\odot$ model, the mass of hydrogen-rich material remaining at the surface when the first phase of hydrogen-burning is completed is $\sim 10^{-4}$ $M_\odot$, giving 0.001-0.0015 $M_\odot$ for the mass of He, C, and O incorporated into the convective shell driven by hydrogen burning. This is only $\sim$ 5-10% of the mass of the original convective shell driven by helium burning, and this seems quite reasonable.

7. Common-Envelope PNe and Binary Central Stars

As Livio has emphasized, at least half of all stars are born in binaries with short enough periods that the very presence of a secondary will have some *influence* on the shape of the nebula produced by the primary. Perhaps half of all binaries are in tight enough orbits that the formation of a shell of nebular material is a consequence of Roche-lobe overflow with the formation of a common envelope. Using an algorithm based on the orbital characteristics of main-sequence binaries and on theoretical considerations of the outcome of common-envelope evolution, Yungelson and Tutukov estimate the frequency of PNNi of various types. In their scenario, essentially *all* stars are initially in binaries (with separations up to 10^6 AU), and it is therefore not surprising that their model predicts that the majority of PNNi have a main sequence companion. A more startling prediction is that *most single* PNNi (20% of all PNNi in observable PNe) are actually a result of mergers which take place during a common envelope event, with the merged product eventually going on to become an AGB star.

The shapes of many PNe with bipolar symmetry (especially the "butterfly" types in Balick's classification of morphological types) may be a consequence of the drag forces that are set up as the ejected wind passes by the companion. The degree of density contrast between matter along the polar axis and matter in the equatorial plane is the major distinguishing feature of the observationally based classification scheme, and Bond and Livio (1990) argue that a moderate-to-high density contrast is a natural result of the dynamics of the common envelope process, as it is modelled in theoretical calculations. However, among the set of $\sim$ 13 PNe known to contain binary PNNi in tight enough orbits that they must have passed through a common envelope phase, only about half are clearly identified as of the butterfly or elliptical variety, corresponding, respectively, to high and moderate density contrasts. Thus, a common envelope phase may not be a guarantee that bipolarity will arise during the PNe phase.

Since fully 80% of all PNe exhibit bipolarity (Zuckerman and Aller 1986), it seems reasonable to suppose that many PNe in wide binaries (orbital separation $3 \cdot 10^{-5}$ pc $<$ A $<$ .01 pc) develop bipolarity even though they are not an ejected common envelope. If azimuthal symmetry is to be imposed on the PNe, the orbital period of the binary must be substantially less than the time scale over which the circumstellar shell has been ejected by the primary AGB star. For a mass-ejection rate of $\sim 10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$ and an ejected mass of 1 $M_\odot$, this means that $\mathrm{P_{orb}} \ll 10^5$ yr, or A $\ll 2 \cdot 10^3$ AU ~ 0.01 pc.

Common-envelope evolution will lead to a detectable PN only if the compact remnant of the star which fills its Roche lobe develops a surface temperature hotter than $\sim$ 30,000K before the ejected material becomes too dispersed. Systems which will develop evolutionary characteristics most similar to those achieved by single stars (here we include as "single" those stars which are in wide enough binaries that Roche-lobe overflow never occurs) are, of course, those in which the Roche-lobe filling star is an AGB star. If the mass-losing star is of the TP-AGB variety, Roche-lobe filling will in general occur during the large luminosity, large radius portion of a helium shell flash, and the result will be a PNN of the helium-burning variety. Depending on the degree of orbital shrinkage, which determines how much matter remains above the burning shell when mass loss ceases, and on the efficacy of the fast wind, the surface composition of the PNN and its white dwarf progeny could be either: H, He, and CNO elements; He and N; or some combination of C, O, and Ne. In the first instance, a self-induced nova event (Iben and MacDonald 1986) might be expected to occur.

In building up an understanding of close binary star evolution, it is extremely important to have reliable information about as many real PNe as possible which have close binary central stars. It is equally important to have reliable information about as many binaries as possible which are likely to evolve into PNe containing close binary central stars. Armed with this information, one may make a beginning at constructing a reasonable evolutionary scenario for systems of various types and estimating the efficiency of drag forces in reducing orbital separation during common envelope events.

UU Sge, the central star of Abell 63, is a fascinating example not only of close binary evolution, but of the evolution of our understanding of an observable system. Four different observational studies of the central star have been undertaken in recent years. The three most recent studies suggest sharply different characteristics for both components (see Walton, Walsh, and Pottash; Pollacco and Bell). Theoretical scenarios can be constructed to match each of the three sets of estimated characteristics (see Iben and Tutukov 1989 for one scenario), and a consideration of the expansion age of the nebula allows one to discriminate among the scenarios (Iben and Tutukov 1992).

Preparation of the manuscript has been supported by the NSF grant AST91-13662.

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