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Invited Review Paper

Planetary Nebulae: A Modern View

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ABSTRACT. Our current understanding of the origin and evolution of planetary nebulae is reviewed. We now recognize that a planetary nebula represents a dynamical system in which evolution is tightly coupled to the evolution of the central star. Not only is the ionization structure of the nebula controlled by the radiative output from the central star, the dynamics and morphology of the nebula are heavily influenced by the mechanical energy output from the central star. Since the time scale of evolution of the central star is strongly dependent on its mass, the extent of the radiative and mechanical interactions between the star and the nebula not only vary with time, but also vary with stellar mass. The physical properties of planetary nebulae are discussed in this context.

1. INTRODUCTION

Planetary nebulae (PNe) were discovered over 200 years ago and have been extensively studied since spectroscopic observations became possible in the 1850s. Their strong emission-line spectra make them easily distinguishable from other celestial objects. The optical spectra of PNe, consisting mainly of recombination lines of hydrogen and helium and collisionally excited lines of light elements, are produced in a gaseous shell ionized by a hot central star. For many years, PNe have served with great success as a laboratory for atomic physics, and many interesting physical processes (e.g., forbidden lines and two-photon emission) were discovered through the study of PNe (cf. Aller 1984; Pottasch 1984; Osterbrock 1989). The long history of this classical subject may suggest that this is a well-understood phenomenon, but in fact we have only recently begun to discern the nature of PNe.

Theoretical understanding of the origin of PNe began with the work of Shklovskii (1956a, b), who suggested that PNe are progenitors of white dwarfs and descendants of red giants. This view was supported by Abell and Goldreich (1966), who used the expansion velocities of PNe and the escape velocities of red giants to argue that PNe are the suddenly ejected atmospheres of red giants. In the late 1960s, it was commonly believed that the central stars of PNe evolve from red giants through the horizontal branch, increase in luminosity as their temperature increases, and then cool down to white dwarfs. The nebula represented the red-giant atmosphere ejected through a combination of dynamical and pulsational instabilities (cf. IAU Symp. 34, Osterbrock and O'Dell 1968).

This picture of PN evolution has changed greatly in the last 20 years as a result of progress in stellar-evolution models and observations extending beyond the visible part of the electromagnetic spectrum. We now know that PNe emit in every part of the spectrum from radio to X ray. Extensive observational data have been compiled on the velocities, fluxes, angular sizes, etc., for over 1000 PNe in the Galaxy (cf. Acker et al. 1992). Physical properties of the nebulae (e.g., mass and density) and the central stars (e.g., temperature and luminosity) can be derived from these primary data. This review is not intended to give a comprehensive discussion on all the techniques used to study PNe, but instead to highlight the change and progress in our understanding of the origin and evolution of PNe as the result of modern observations. For the more classical areas of PN research that are not covered here, the reader is referred to the recent reviews by Pottasch (1992) and Peimbert (1992).

2. ON THE EXISTENCE OF PLANETARY NEBULAE

PNe are discovered primarily by examination of survey plates, and 1143 objects are spectroscopically classified as PNe in the *Strasbourg-ESO Catalogue of Galactic Planetary Nebulae* (Acker et al. 1992). The total population of PNe in the Galaxy is expected to be at least ten times higher. This seems to suggest that PNe are a common phenomenon, and the question of why PNe should exist at all has rarely been raised. However, the answer to the existence question of PNe is not as simple as it seems.

The existence of PNe requires two components: a circumstellar nebula of certain mass and density, and a hot central star to ionize it. Since the nebula is expanding, their typical sizes ($\sim$0.2 pc) and expansion velocities ($\sim$25 km s^{-1}) together imply a dynamical lifetime of only $\sim 10^4$ yr. If the nebula was ejected when the star was a red giant, then the central star must evolve from $\sim$3000 to $\sim$30,000 K within this short time. In the classical model, there is no *a priori* reason that the time scale of the evolution of the central star is in any way related to the dynamical time scale of the nebula. For example, if the central star evolves

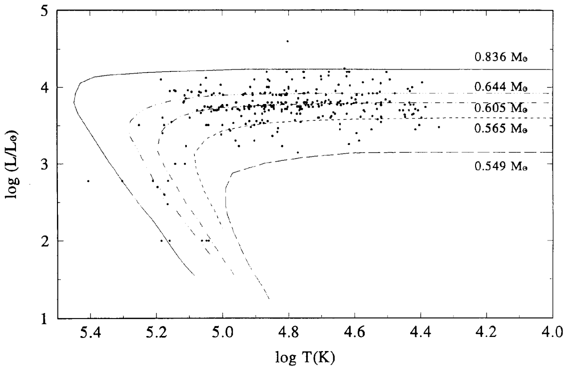

FIG. 1—The PN evolutionary tracks of Schönberner (1983) for 0.549, 0.565, and $0.644M_\odot$, and of Blöcker and Schönberner (1990) for 0.605 and $0.836M_\odot$. Also plotted are 303 PNe using the luminosities derived by Zhang and Kwok (1993, see Sec. 7).

too slowly, the nebula would have totally dispersed before the central star is hot enough to ionize it. If the central star evolves too quickly, then the nebula would be illuminated only briefly before the star finishes nuclear burning and becomes a white dwarf.

The first attempt to give a quantitative answer to this question was made by Paczyński (1970, 1971). Paczyński assumed that the central stars of PNe are undergoing hydrogen shell burning in a layer outside an electron degenerate carbon-oxygen core, and based this assumption on PNe being descendants of asymptotic-giant-branch (AGB) stars. Using a static stellar-structure model, it can be shown that the luminosity of the star is only dependent on the core mass (M_c):

$$L/L_\odot = 59250(M_c/M_\odot - 0.52), \qquad (1)$$

and the effective temperature of the star is only a function of the amount of hydrogen in the envelope around the core (ΔM_e). Over the short lifetimes of PNe, the mass of the core only changes very little, which implies that the central stars of PNe evolve with constant luminosity until hydrogen is exhausted. This was in contradiction with the observational data at the time (Seaton 1966; O'Dell 1968), which suggested that the luminosities of central stars increase with temperature (along the Harman–Seaton sequence; Harman and Seaton 1964) before turning down to the cooling track. The Paczyński models were improved by Schönberner (1979, 1981), Iben (1984), and Wood and Faulkner (1986), where the effects of thermal pulses are included. Examples of the Schönberner PN central-star evolutionary tracks are plotted in Fig. 1.

The evolution time of the central star is simply given by

$$\Delta t = \frac{\Delta M_e}{\dot{M}_c}, \qquad (2)$$

where $\dot{M}_c$ is the nuclear burning rate. For a core mass (M_c) of $0.6M_\odot$, $\dot{M}_c$ is $\sim 10^{-7}\,M_\odot\,\mathrm{yr}^{-1}$. If ΔM_e is $\sim 10^{-3}\,M_\odot$, then Δt is $\sim 10^4$ yr. However, Δt is a very strong function of the core mass (Renzini 1982). According to the approximate formula given by Tylenda (1989),

$$\log \Delta t \sim 7.3 - 5.9(M_c/M_\odot), \quad M_c > 0.7M_\odot, \qquad (3)$$

a star of $1.0M_\odot$ will have a nuclear burning lifetime of only 25 yr! The fading time of PNe from $T = 30{,}000$ to the point where the stellar luminosity has dropped by a factor of 10 from the horizontal track is also highly dependent on core mass ($\propto M_c^{-9.6}$, Iben and Renzini 1983).

The results of Paczyński have profound implications. A low-mass star will evolve too slowly to become a PN (termed a "lazy PN" by Renzini), and a high mass ($>1M_\odot$) star will be luminous too briefly to be detected. Consequently, only stars with core masses in a very narrow mass range ($\sim 0.6M_\odot$) will be seen as PNe. The actual transition time (and therefore the existence of PNe) is critically dependent on the mass of the hydrogen envelope at the end of the AGB. If the AGB is ended by a sudden ejection, there will always be an undetermined amount of mass left around the core. This will result in a long delay in the evolution to high temperature and no PN will form. However, if the hydrogen envelope is depleted by a steady stellar wind, the wind will continue until the stellar temperature has changed significantly, therefore ensuring the minimum amount of transition time between AGB and PN phases (Kwok 1982).

3. THE NEBULAR MASS PROBLEM

The nebular mass of a PN can be estimated by its density (which can be determined by forbidden-line ratios) and the physical size of the nebula. It has been traditionally assumed to be $\sim 0.2M_\odot$ after the work of Shklovskii (1956a,b). However, size determinations require a knowledge of distances, which are very poorly known for galactic nebulae (see Sec. 4). Using a sample of PNe with individual distance estimates, Pottasch (1980) found that PNe have masses spreading over several orders of magnitude and suggested that such a large mass range is the result of PNe being ionization bounded. An empirical relationship known as the mass-radius relationship,

$$M_i \propto R_i^\beta, \qquad (4)$$

has been found, with proposed values for β from 1 (Maciel and Pottasch 1980) to 5/3 (Daub 1982).

Comparison of nebular masses is best done in a stellar system where all PNe can be assumed to be at the same distance. Figure 2 shows the masses and radii of PNe in the SMC, LMC, and the Galactic Center (Wood et al. 1986, 1987; Dopita et al. 1988). The nebular mass can be seen to increase monotonically with radius from a value of $0.01M_\odot$ and asymptotically approach a value of $0.27M_\odot$, which can be interpreted as the total mass of the nebular when it is completely ionized. Another explanation for the mass-radius relationship is that the nebular mass in fact increases with age as the result of the interacting winds process (Kwok 1982). The fact that not all PNe that lie on the rising part of the mass-radius relationship are optically thick is emphasized by Méndez et al. (1992).

It is clear that the ionized nebular mass is not a static constant value, but evolves with time as a result of photoionization and dynamics of the nebular expansion. It is also

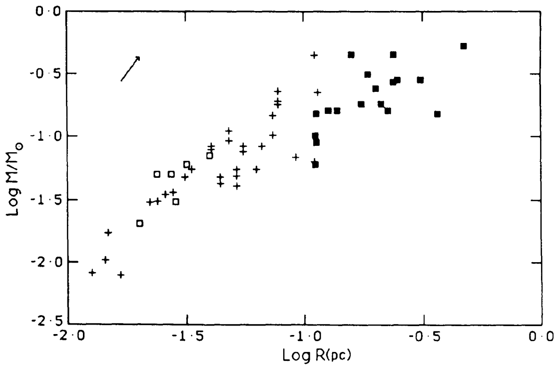

FIG. 2—The mass of ionized gas in PNe as a function of nebular radius. The open and filled squares are Magellanic Clouds PNe and the crosses are Galactic center PNe. The arrow shows the effect of a 20% increase in assumed distance (from Wood et al. 1987, copyright 1987, American Astronomical Society, reproduced with permission).

certain that both processes contribute to the increase of nebular mass with time and the assumption that most PNe are ionization bounded are probably too simplistic.

4. THE DISTANCE PROBLEM

As in other areas of astronomy, distance determination for PNe is a major problem. The traditional way to derive distances is through the Shklovskii method which assumes that all PNe have the same masses (Cahn and Kaler 1971). In this case, the distance can be shown to be related to the nebular flux (e.g., free-free continuum flux S_ν or Hβ flux) and angular size (θ) in this way:

$$S_\nu \propto \theta^{-3} D^{-5}. \tag{5}$$

Therefore, distances can be determined by the measurements of flux and angular size, and the derived distances are referred to as statistical distances. Many different distance scales have been published employing the Shklovskii method (Cahn and Kaler 1971; Milne and Aller 1975; Acker 1978).

Such distance scales are suspect as we now know that the ionized masses of PNe are not constant. However, the Shklovskii method can be generalized assuming there is a mass-radius relationship. Using Eq. (4), it is easy to show that

$$S_\nu \propto \theta^{2\beta-3} D^{2\beta-5}. \tag{6}$$

For example, if one assumes that Lyman continuum photon output is a constant, β is 3/2, and $S_\nu \propto D^{-2}$ (Milne 1982). Statistical distance scales have been created using certain PNe as calibrators to derive the value of β (Maciel and Pottasch 1980; Daub 1982; Cahn et al. 1992). However, if $\beta = 5/2$, the dependence on distances disappears altogether. This suggests that the errors in the distances will increase rapidly as β approaches 5/2.

During the lifetime of a PN, the central-star temperature changes by a large factor and the number of ionizing photons emitted changes by several orders of magnitude. This will have significant effects on the ionization structure and therefore the value of β. An alternative approach to estimate the value of β is to employ a theoretical central-star evolution model and calculate the change in the optical thickness of the nebula with time (Kwok 1985; Marten and Schönberner 1991). Figure 3 shows the evolutionary tracks for stars of 0.60 and 0.64$M_\odot$ in the S_ν-θ plane using the evolutionary model of Schönberner (1983). During the ionization-bounded phase (the rising portion of the curves), the tracks of different distances practically coincide. This implies that a nearby, young PN will look almost the same as a distant evolved nebula and therefore no distance information can be extracted. Until we have a better handle on the mass-radius relationship, statistical distance scales cannot be regarded as reliable.

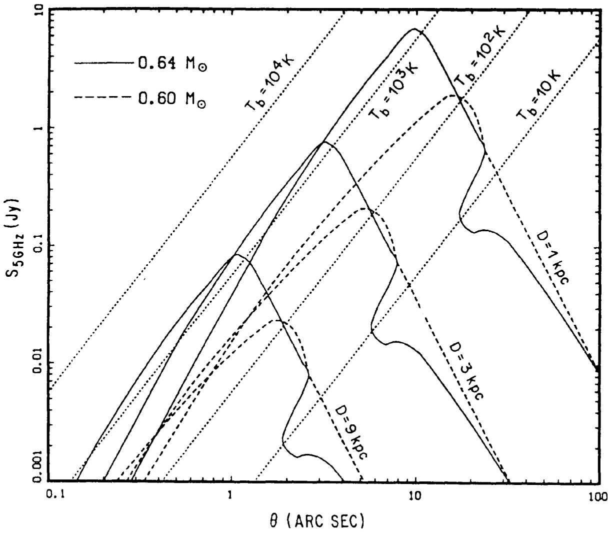

FIG. 3—The evolution of the 5 GHz flux as a function of angular radius for PNe central-star masses of 0.64 (solid line) and 0.60$M_\odot$ (dashed lines) at distances of 1, 3, and 9 kpc. Complete ionization of the nebula occurs just after the flux peak. Lines of constant T_b are plotted as dotted lines. This diagram illustrates the potential difficulty in distinguishing nearby young PNe from distant evolved PNe during the ionization-bounded phase (from Kwok 1985).

The problem of statistical distances is also illustrated in the study of Galactic bulge PNe. While these PNe can be assumed to be at the same distance, the statistical distances derived for Galactic bulge PNe show a large variation of distances, ranging from 4 to >30 kpc (Stasińska et al. 1991; Pottasch and Zijlstra 1992).

The failure of the statistical methods of distance determination has led to an emphasis on individual distance determinations (Gathier 1984, 1987). The methods that have been employed included, e.g., the reddening-distance method (Lutz 1973; Kaler and Lutz 1985), and the H I 21 cm absorption method (Gathier et al. 1986a,b). The observational H-R diagrams derived from these distance estimates still show significant deviations from the theoretical evolutionary tracks (Pottasch 1989) and are not necessarily more reliable than statistical distances (Zhang 1993).

A promising method of individual distance determination is the stellar-atmosphere models of Méndez et al.

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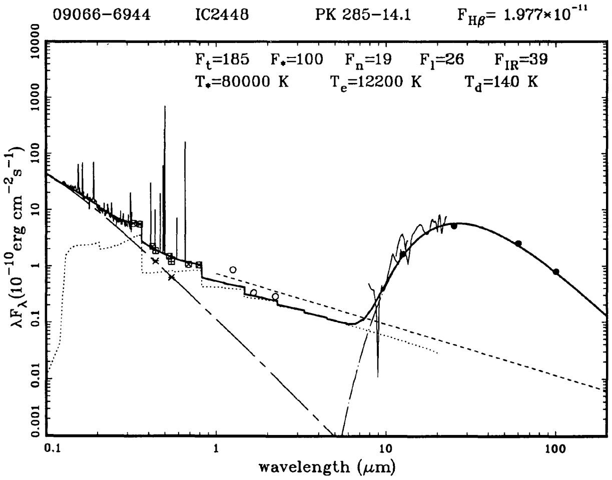

FIG. 4—The spectral energy distribution of the young PN IC 2448. The dotted line shows the model nebular (*b-f* and *f-f*) continuum, the dashed line is the *f-f* continuum extrapolated from radio measurements, and the dot-dashed line is the central star. The total model curve is shown as a solid line. The various symbols are ground-based and *IRAS* observations (from Zhang and Kwok 1991, copyright 1991, Springer International).

(1988). They are able to obtain the distances using the central-star temperatures and gravities derived from the analysis of absorption-line profiles. However, since this method is restricted to bright central stars, only 23 nebular distances have been determined by this method (Méndez et al. 1992).

Individual distances for 145 Galactic PNe were derived by Zhang (1993) based on central-star properties derived from distance-independent parameters. These distances were found to be in good agreement with the spectroscopic distances of Méndez et al. (1992).

For PN central stars that have visual companions, spectroscopic distances can be obtained for the companion. This method should yield excellent distances for PNe that have visually resolved binary nuclei (Pottasch 1984).

The observations of PNe in the Magellanic Clouds also allow the possibility of using these objects as calibrators for galactic PNe (Kingsburgh and Barlow 1992). For optically thin PNe, a nebular mass of $0.217 M_\odot$ is used to derive statistical distances. For optically thick PNe, Kingsburgh and Barlow (1992) assume a constant Hβ flux.

The most direct method to determine individual PNe distances is by expansion parallaxes. High-resolution and dynamic range VLA maps over a time span of several years have yielded distances of NGC 7027 and BD+30°3639 (Masson 1989a,b; Hajian, Terzian, and Bignell 1993). However, even this method is not without pitfalls as both the expansion velocity inferred from line profiles and image sizes are affected by the dynamical and ionization evolution of the nebulae (see Sec. 11).

Distance determinations for PNe remain a confusing issue. Quite often very discrepant distances are found for the same object (cf. Terzian 1993). Because of this uncertainty, the total PNe population in the Galaxy is also uncertain by a factor of 2–3.

5. THE MISSING-FLUX PROBLEM

If PNe go through a transition from ionization bounded to density bounded during their lifetime, the leakage of ultraviolet photons during the latter phase could represent a significant fraction of the energy output. Specifically, stellar luminosities calculated under the ionization-bounded assumption (e.g., Zijlstra and Pottasch 1989) can be severely underestimated (Schönberner and Tylenda 1990). The *IRAS* sky survey has detected infrared emission from ~1000 PNe, suggesting that PNe emit a large fraction of flux in the infrared. Both factors contribute to the uncertainties in the estimate of the total flux emitted by the central star. Since the luminosity of central stars depends on accurate measurements of the total flux and distance, the uncertainties in these two quantities give rise to large errors in the observational distribution of PNe on the H-R diagram.

Figure 4 shows the energy distribution of a typical young PN. In the radio, the spectra of PNe are dominated by free-free continuum emission. From $\lambda = 1$ mm to 10 μm, dust emission is the major contributor. The continuum between 1 and 10 μm is due to bound-free emission of the nebular shell. The visible and near-UV continua are a combination of the photospheric spectrum of the central star, two-photon, and bound-free emissions from the nebula. Superimposed on the visible and infrared continua are numerous recombination and collisionally excited lines. The near-ultraviolet continuum is primarily due to the central star. X-ray emission from PNe can be attributed to photospheric or coronal emission from the central star (Chu, Kwitter, and Kaler 1993), and thermal emission from the shocked central-star wind (Leahy et al. 1993, see Sec. 10). For young PNe, the central-star, gas, and dust components each contribute approximately 1/3 of the total emitted flux (Zhang and Kwok 1991). Only by including the emitted fluxes from all three components can the accurate total flux, and therefore luminosity, be derived.

6. CENTRAL-STAR TEMPERATURES

Because of the strength of the nebular emission and the high stellar temperature, the temperature of the central star can rarely be measured directly. The conventional method (known as the Zanstra method) is to derive the central-star temperature from a comparison of the nebular recombination flux with the stellar continuum magnitude. This method has been applied to more than 300 nebulae (Kaler 1983; Pottasch 1984; Shaw and Kaler 1989; Gleizes, Acker, and Stenholm 1989; Gathier and Pottasch 1989). Since the Zanstra method assumes that the nebula is optically thick, and PNe change from optically thick to optically thin in hydrogen and helium at different times, this can lead to different estimates of the central-star temperature by using hydrogen or helium lines. The fact that stellar atmospheres are not well approximated by blackbodies can also contribute to errors in the Zanstra temperatures (Henry and Shipman 1986). However, it can be argued that since PNe central stars have a large variety of spectral types and abundances, the blackbody assumption is probably no worse than any specific set of atmosphere models (Kaler 1983).

The energy-balance method, which compares the nebular forbidden and recombination lines, was first introduced by Stoy (1933), and extensively applied to PNe by Kaler (1976) and Preite-Martinez and Pottasch (1983). Using the results of the PNe spectroscopic survey of Acker et al. (1989), Preite-Martinez et al. (1989) and Preite-Martinez et al. (1991) were able to determine the central-star temperature for about 500 nebulae. Although the energy-balance method avoids the assumption of optically thick H I (or He II) as required by the Zanstra method, it can underestimate the total emitted line fluxes by failing to include UV or infrared lines, in particular the collisionally excited H I lines (Clegg 1993). For central stars that are bright enough to allow acquiring high-resolution absorption-line profiles, Méndez et al. (1988) were able to derive both the effective temperature and the gravity ($\log g$) by analyzing the line profiles in terms of model atmospheres. These recent results give much more accurate determinations of the central-star temperatures when compared to earlier efforts.

7. MASS OF THE PN CENTRAL STARS

Since the central stars of PNe represent the cores of their AGB progenitors, their masses are given by the core mass-luminosity relationship [Eq. (1); Paczyński 1971; Wood and Zarro 1981; Iben and Renzini 1983; Boothroyd and Sackmann 1988]. Our knowledge of the distribution of central-star masses is therefore directly linked to our ability to determine luminosities, i.e., from distances and total fluxes, both of which suffer from large uncertainties (see Secs. 4 and 5). The unsatisfactory state of this conventional approach has led to recent efforts that rely on distance-independent parameters. The central-star masses for nearly 100 galactic bulge PNe have been determined by Tylenda et al. (1991) using optical fluxes. Observational positions for ~200 PNe were compared to theoretical models in a plot of the nebular line ratio $I(\text{He II})/I(\text{H}\beta)$ vs. a ratio of the nebular Hβ flux to the flux from the central star (Szczerba 1990). Core masses for 303 galactic PNe were determined by Zhang and Kwok (1993) using radio surface brightnesses and central-star temperatures (Fig. 5).

It has long been established that the masses of white dwarfs have a very narrow range and sharply peak around $0.6 M_\odot$ (Weidemann 1990). Observations of PNe in the Magellanic Clouds are confined to the interval of 0.56–$0.64 M_\odot$ (Barlow 1989), although some high-mass PNe have been identified located on the descending parts of the evolutionary tracks (Kaler and Jacoby 1990). While the existence of high-mass PNe is not excluded, they are observationally selected against because of their short lifetime and the initial mass function (Shaw 1989). Since PNe with higher stellar masses evolve to higher temperatures, it is possible to estimate the lower limit to the central-star masses from their temperatures (Tylenda 1989). Among the PNe with highest stellar masses are NGC 7027, NGC 2440, and NGC 6302. Since the rate of change of the stellar temperature is higher for high-mass stars, masses of several massive central stars have been determined using the fading of the ultraviolet fluxes over the lifetime of the *IUE* satellite (Heap 1993).

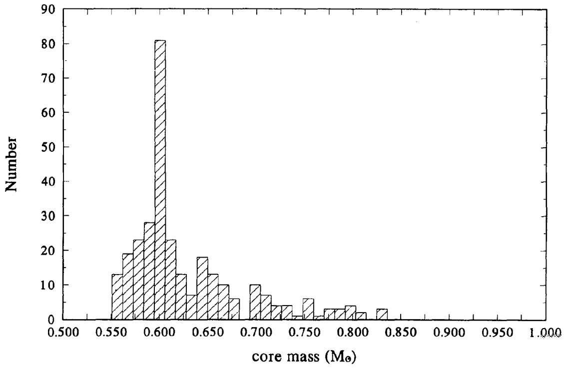

FIG. 5—Distribution of the core masses of 303 PNe (values from Zhang and Kwok 1993).

We can attempt to answer the question: "What stars become PNe?" in the context of stellar evolution. Stars with main-sequence mass $< 0.53 M_\odot$ will evolve directly to white dwarfs from the horizontal branch (Iben and Renzini 1983). Stars with core masses $\sim 0.55 M_\odot$ (corresponding to main-sequence mass of $\sim 1 M_\odot$ according to the initial-final mass relationship of Weidemann 1987) at the end of the AGB will evolve too slowly to have an observable PN shell. Stars with core masses of $> 1 M_\odot$ (and main-sequence mass of $> 6 M_\odot$) are unlikely to be seen as PNe because of observational selection effects.

8. THE MISSING-MASS PROBLEM

The detection of white dwarfs in open clusters suggests that the main-sequence mass of PNe progenitors can be as high as $8 M_\odot$ (Woolf 1974; Romanishin and Angel 1980; Reimers and Koester 1982). If all intermediate-mass stars (1–$8 M_\odot$) go through the PN stage and the current PN central-star and nebular masses are only 0.6 and $0.3 M_\odot$, respectively, where has the rest of the mass gone?

Infrared and millimeter-wave observations in the early 1970s found that AGB stars are losing mass at a high rate (10^{-6}–$10^{-4} M_\odot\,\text{yr}^{-1}$). If such mass loss continues for an extended fraction of the AGB lifetime, a significant fraction of the mass of the star can be lost, and circumstellar envelopes (CSEs) of substantial masses can be built up around the star. If the transition from AGB to PN stage is short, then such CSEs must have an effect on the formation of PNe (Kwok, Purton, and FitzGerald 1978; Kwok 1982). Furthermore, remnants of such envelopes should be detectable outside of the PN shell.

The strongest link between the CSEs of AGB stars and PNe is the dust component. The infrared color temperatures of AGB stars range from ~600 K for Mira variables showing the 9.7 μm silicate feature in emission, to ~200 K for OH/IR stars showing optically thick envelopes (silicate feature in self-absorption). While the dust color temperatures of most PNe are < 100 K, the color temperatures of the youngest PNe extend to as high as 200 K (Kwok 1990). This continuous sequence in infrared colors suggests that the infrared excesses observed in PNe are due to the remnants of the CSEs of their AGB progenitors. This monotonic decrease in color temperatures has different origins on the AGB and in PNe: the decrease in color temperature in AGB stars is due to an increasing rate of mass loss (and therefore increasing optical depths in the CSE) as stars ascend the AGB (Bedijn 1987; Volk and Kwok 1988), whereas the gradual decrease of the color temperature in PNe is the result of dispersal of the dust envelope.

The CO molecule was first detected in the young PN NGC 7027 by Mufson et al. (1975) and the number of detections has increased rapidly in recent CO surveys. Huggins and Healy (1989) found an empirical relationship between the ratio of the molecular to ionized mass and the nebular radius. This relationship can be interpreted to be due to the photodissociation of the remnant AGB molecular envelope as the central star evolves to higher temperatures. The amount of molecular gas is estimated to be $\sim 1.4 M_\odot$ in NGC 7027 (Jaminet et al. 1992) and smaller in other PNe.

The most compelling visual evidence for the remnant of AGB CSEs in PNe is the detection of halos in PNe. While such halos have been known since the 1930s (Duncan 1937), recent CCD observations can produce images of much higher dynamic ranges and have revealed the existence of halos in many PNe (Jewitt et al. 1986; Balick 1987; Chu et al. 1987; Balick et al. 1992). Two examples are shown in Fig. 6. The morphologies of the PN halos are remarkably uniform, supporting their AGB CSE origins. Spectroscopic observations of halos suggests that the halo masses are comparable to the PN shell masses (Middlemass et al. 1989, 1991).

Interestingly, the molecular hydrogen in NGC 6720 (the Ring Nebula) has been found to have the same spatial distribution as the ionized halo (Greenhouse et al. 1988; Kastner et al. 1993). Two possible explanations (in addition to several offered by Balick et al. 1992) are that the nebula of NGC 6720 is undergoing a period of H_2 dissociation (Greenhouse et al. 1988), or the ionized envelope is in the process of recombination as the result of the fading of the central star.

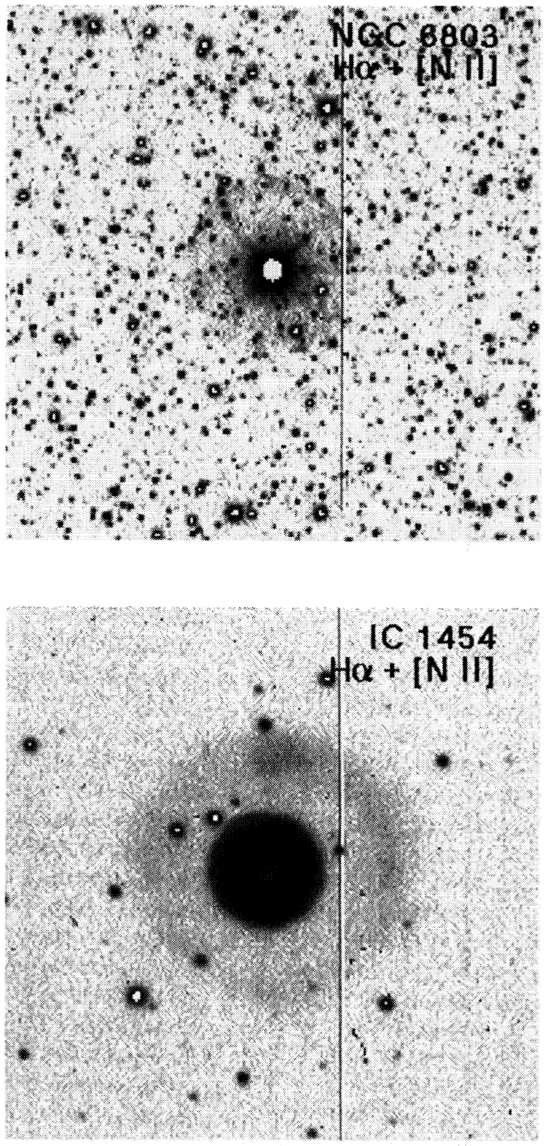

FIG. 6—Examples of optical halos in PNe: top: NGC 6803; bottom: IC 1454 (from Balick et al. 1992; copyright 1992, American Astronomical Society, reproduced with permission).

9. DYNAMICAL ENERGY INPUT FROM THE CENTRAL STAR

While it is well known that the radiation from the central star is the energy source of the nebular emission, it has only recently been recognized that mechanical energy from the central star also provides significant energy input into the dynamics of the nebulae. One of the first scientific results that emerged from the *IUE* satellite was the discovery of high-speed stellar winds from central stars of PNe (Heap et al. 1978). P Cygni profiles from resonance lines such as N v, O v, C iv, Si iv, etc., have been detected. The observed terminal velocities of the winds range from 1000 to 4000 km s^{-1}, and the mass-loss rates have been estimated to be 10^{-9}–$10^{-7} M_\odot$ yr^{-1} by fitting the line profiles with ionization-structure models (Cerruti-Sola and Perinotto 1989). The wind velocities are found to increase with central-star temperatures. If the mass loss from the central star is driven by radiation pressure on resonance lines (Pauldrach et al. 1988), then the terminal velocities are expected to be proportional to the escape velocities (Abbott 1978), which increase as the central stars evolve to higher temperatures at constant luminosities. It is estimated that approximately half of the PN central stars surveyed show evidence of fast winds (Cerruti-Sola and Perinotto 1985), suggesting that this is a common property.

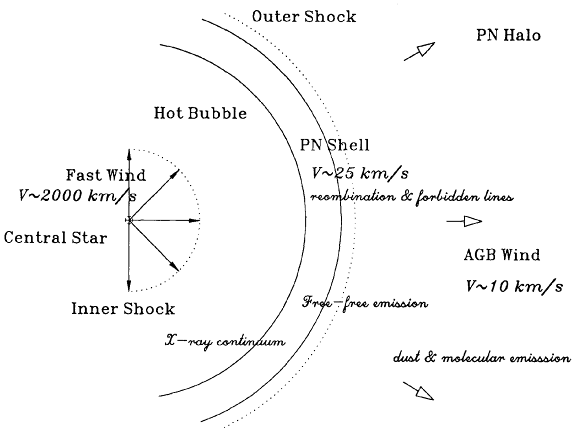

FIG. 7—A schematic diagram of the structure of a PN.

10. STRUCTURE OF THE PLANETARY-NEBULA SYSTEM

Figure 7 shows a schematic diagram of a PN system. In addition to the nebular shell that dominates the optical spectrum as a result of its high emission measure, there is also the halo (from the remnant AGB CSE) and a fast wind from the central star. If PNe indeed descend from AGB stars which have undergone large-scale mass loss, then the dynamical interaction between the central-star wind and the remnant AGB envelope is inevitable. Since the central-star wind is 100 times faster than the AGB wind, it can act as a "snow plow" and sweep up matter in the AGB wind into a high-density shell. The mass of the shell will increase as it expands. This picture is known as the interacting-stellar-winds model of PN formation (Kwok, Purton, and FitzGerald 1978).

The dynamics of interacting winds have been worked out by many authors (Giuliani 1981; Kwok 1982, 1983; Kahn 1983; Chevalier and Imamura 1983; Okorokov et al. 1985; Volk and Kwok 1985; Bedogni and d'Ercole 1986; Soker and Livio 1989; Frank, Balick, and Riley 1990; Kahn and Breitschwerdt 1990; Marten and Schönberner 1991; Frank 1993). In the simple one-dimensional adiabatic case, the interactions between the central-star wind and the shell, and between the shell and the AGB wind will create two shocks. The inner shock is situated near the central star and most of the volume interior of the shell is made up of shocked central-star wind (the "bubble") of temperatures in the millions of degrees. Thermal pressure from the bubble is responsible for driving the expansion of the shell. The outer shock is likely to be isothermal as the high density in the shell is efficient in cooling the gas. Using the observed central-star and AGB wind parameters, the model predicts with great success the observed properties (density, velocity, mass, etc.) of PNe.

11. MORPHOLOGY OF PLANETARY NEBULAE

The first detailed examination of PN morphology was carried out by Curtis (1918), who classified a sample of 78 PNe into the following groups: helical, annular, disk (uniform and centrally bright), amorphous, and stellar. Subsequent classification schemes often use similar descriptive forms: stellar, disk, irregular, ring, anomalous (Perek and Kohoutek 1967); elliptical, rings, bipolar, interlocking, peculiar, and doubtful (Greig 1971; Westerlund and Henize 1967); and round, elliptical, and butterfly (Balick 1987).

The origin of such diverse shapes has remained a mystery for a long time. Khromov and Kohoutek (1967) explain the morphology of PNe in terms of an open-ended cylinder projected onto the sky, and Curtis (1918), Masson (1989, 1990), and Aaquist (1990) employ a prolate ellipsoidal shell model. Recently, there has been strong interest in using the interacting stellar-winds model to explain the various morphologies of PNe (Balick 1987; Balick, Preston, and Icke 1987; Mellema et al. 1992; Icke 1991; Icke et al. 1992; Frank et al. 1993). By assuming a modest density variation as a function of latitude in the AGB CSE, Kahn and West (1985), Icke (1988), and Soker and Livio (1989) demonstrated that the interacting winds mechanism can produce a variety of morphologies commonly observed in PNe.

Recent high-resolution radio surveys of PNe have made possible the study of the morphology of a larger sample of PNe, particularly those which have been classified as "stellar" in the past due to inadequate angular resolution of optical imaging (Zijlstra, Pottasch, and Bignell 1989; Aaquist and Kwok 1990, 1991). The radio morphologies of PNe as revealed by these studies share many similarities with optical images. A common morphology is a double-peaked structure along the minor axis with extended emission along the major axis (often referred to as "bipolar"). The ends of the minor axis often have steep intensity gradients, suggesting that the nebulae are ionization bounded in the minor axis. The detection of such "bipolar" morphology in very high surface brightness (and therefore likely to be young) PNe suggests that PNe probably inherit their asymmetry from their AGB progenitors. Another uncertainty in the origin of PN asymmetry is the role of binary nuclei. Approximately 10% of the PN central stars searched for variability have been found to be in close binary systems (Bond 1989). It is suggested that the binary central stars could have major effects on the nebular morphology (Bond and Livio 1990).

Some PNe are found to have multiple shells. Among the 41 multiple-shell PNe studied by Chu et al. (1987), approximately 1/3 are classified as Type I where the shells are detached, and 2/3 as Type II where the shells are attached. Spectroscopic observations of the shells suggest in some cases that the outer shells are expanding faster than the inner shells (Chu 1989). The existence of multiple-shell PNe suggests that their AGB progenitors may have undergone several mass-loss episodes and the mass loss is not a monotonic function of time. In the AGB evolution model of Vassiliadis and Wood (1993), a "superwind" is triggered by radiation pressure on dust when the luminosity reaches a critical value. Since the luminosity of AGB stars fluctuates as the result of thermal pulse cycle, there may be several superwind phases during the AGB, creating multiple shells.

An alternative explanation is offered by Frank (1993) and Marten, Gesicki, and Szczerba (1993), who consider the complex kinematic and morphological PN structures observed (e.g., by Chu et al. 1991) to be the result of interactions of various discontinuities (both dynamic and radiative) under a three-wind (regular AGB, superwind, and fast wind) model. For example, the observed inner bright shell can be identified with the high-density, compressed nebular shell, whereas the faint outer shell is generated by the outer, low-density nebular matter expanding into the AGB wind. As a result, the multishell images of PNe cannot be simple-mindedly interpreted as a representation of the mass-loss history of the star.

12. HOW FAST ARE PLANETARY NEBULAE EXPANDING?

The traditional method to derive expansion velocities of PNe is to assume an expanding shell and measure the peak separations of the line of a particular ion (Wilson 1950; Weinberger 1989; Bianchi 1992). However, because of the ionization structure of PNe, different ions will yield quite different expansion velocities (Chu et al. 1984; Weinberger 1989). Furthermore, the line profiles measure the velocities of regions with the highest emission measure, and can be much smaller than the velocity as defined by the expansion of the Hβ image (Marten et al. 1993; Frank 1993). The use of the material velocity as the shock velocity can lead to erroneous dynamical ages. Given the uncertainties in both expansion velocities and distances, no credible conclusions can be drawn from the "velocity-radius relationships" as discussed, e.g., by Sabbadin et al. (1984).

Dynamical ages of PNe are commonly defined as the ratio of the physical radius to the expansion velocity. The discrepancy between the derived dynamical age and theoretical evolutionary ages of PNe have been noted by McCarthy et al. (1990) and by Kaler et al. (1990). Although McCarthy et al. (1990) have adopted the spectroscopic distances of Méndez et al. (1988), which are probably the most reliable, dynamical age to evolutionary age ratios of up to a factor of 30 were found. This again illustrates the potential problems of using a simple definition for the dynamical age which ignores the dynamical and ionization effects of PN evolution.

13. PLANETARY NEBULAE AS DYNAMICAL SYSTEMS

We now recognize that a PN is a dynamical system whose nebular evolution is closely coupled to the evolution of the central star. The existence of a planetary nebula depends on the nebular and central-star components evolving in step with each other. A complete description of the PN phenomenon therefore requires the following elements:

(1) Evolution model of the central star [$L_*(t)$ and $T_*(t)$]. Other than the question of whether central stars of PNe are predominately hydrogen or helium burning, one major uncertainty is the extent of mass loss in the post-AGB phase. Since the evolution time from the end of the AGB to the beginning of photoionization is critical for the existence of PNe, a better estimate on the mass-loss rate during the post-AGB phase is needed. Early evolutionary models either assume no mass loss (Paczyński 1971), or assume an *ad hoc* formula (Schönberner 1979, 1983; Kovetz and Harpaz 1981; Iben 1984; Wood and Faulkner 1986). A recent model by Blöcker and Schönberner (1990) uses more physical assumptions such as pulsation and radiation-driven wind models to estimate the mass-loss rates.

(2) Winds from central stars of PNe [$\dot{m}(t)$ and $v(t)$]. While mass loss during the post-AGB phase affects the transition time to PNe, mass loss during the PN phase has crucial effects on the dynamics of the nebula. Not only does the wind from the central star compress and accelerate the nebular shell, it also shapes the morphology of the nebula. On the observational side, the line profiles can be used to measure the terminal velocity and the mass-loss rate. Since the winds are likely to be driven by radiation pressure on resonance lines, theoretical estimates on $\dot{m}$ can also be made.

Dynamical evolution of PNe was modeled by Volk and Kwok (1985) assuming that the central-star wind velocity is three times the stellar escape velocity and a mass-loss formula based on a modified form of Reimers' formula. More realistic stellar-wind parameters from the stellar-wind models of Pauldrach et al. (1988) were employed by Marten and Schönberner (1991). These models have been successful in reproducing several observational facts such as the mass-radius relationship.

(3) Ionization structure. Since the central star is evolving rapidly, the amount of Lyman-continuum photons also changes significantly throughout the lifetime of the PNe. During the early stages of evolution, most of the central-star flux is absorbed by the dust component and reemitted as infrared radiation. As the central-star temperature increases, an increasing amount of the central-star flux goes into the gas component although the Ly α can be absorbed by the dust and contributes toward the heating of the dust. The nebula will change from ionization-bounded to density-bounded, although observationally this transition is difficult to determine. Schmidt-Voigt and Köppen (1987a,b) computed time-dependent ionization models together with dynamical evolution and compared the recombination-line strengths with observations. The effects of dust is included in the models of Volk (1992) and Marten, Szczerba, and Blöcker (1993).

As the ionization structure evolves with time, the atomic species available for cooling will also change. This can in turn lead to changes in the kinetic temperature of the gas, the sound speed, and the strengths of the shocks (Frank 1993).

A complete model of PNe must incorporate coupled, time-dependent solutions to the equations of stellar evolution, hydrodynamics, and line and continuum radiation transfer. Line profiles and images change greatly as the PNe evolve. It is important to remember that the observational properties of PNe (morphology, kinematics, etc.) reflect only the ionized parts of the nebula and proper interpretation of the observed data is only possible if one keeps in mind the evolving nature of PNe.

14. THE MISSING LINK BETWEEN AGB AND PN

Our understanding of the origin of PN has been hampered by the observational gap between the end of the AGB and the beginning of the PN phase. While we expect these transition objects (commonly referred to as proto-planetary nebulae, or PPNe) to have spectral types of B-K, there is no easy way to distinguish them from ordinary stars in the visible part of the spectrum. However, if we assume the remnant of the AGB envelope to be present in these objects, then they should have color temperatures in between the most evolved AGB stars and the youngest PNe. The *IRAS* sky survey and the resulting *Point Source Catalogue* have made possible the search for PPNe using *IRAS* sources with color temperatures between 150 and 250 K as a starting point. As of 1993, over 30 candidates for PPNe have been discovered (cf. Kwok 1993). These are typically F and G supergiants with large infrared excesses. They typically show a "double-peaked" energy distribution corresponding to a reddened photosphere surrounded by a detached dust shell.

It is possible that there are many more post-AGB stars of lower masses (and have lower mass-loss rates on the AGB), some of which may never evolve to become PNe (Trams 1991).

A number of high-galactic-latitude supergiants have been suspected to be stars in the post-AGB phase of evolution (Bond 1992; Sasselov 1993). It was recognized by Bidelman (1951) that several A and F supergiants located at high galactic latitudes are unlikely to be Population I supergiants.

15. APPLICATION OF PNe TO EXTRAGALACTIC STUDIES

15.1 Planetary Nebulae as Extragalactic Distance Indicators

Because of the narrow mass distribution of the central stars of PNe, PNe have well-defined luminosity functions that can be calibrated by nearby galaxies. PNe are easily detectable by narrow-band ([O III] 5007 Å) imaging and can be observed in distant galaxies of all Hubble types. PNe are excellent standard candles because of the sharp cutoff at the high-luminosity end due to the rapid evolution of high-mass stars. There is also the absolute limit imposed by the Chandrasekhar limit. The application of PNe to the determination of the extragalactic distance scale has been reviewed by Jacoby et al. (1992) and will not be repeated here.

15.2 Planetary Nebulae as a Tracer of Galactic Dynamics

Since hundreds of PNe can be detected in a galaxy, covering both the nucleus and halo, PNe can be used as test particles to trace the dynamics of the galaxy. With current 4-m telescopes, velocities of PNe can be measured to at least 10 Mpc. The mass-to-light ratio as a function of galactic radius can be derived, probing the distribution of dark matter (Hui 1993).

15.3 Ultraviolet Excess in Elliptical Galaxies

One of the major problems in ultraviolet astronomy is the origin of the far-UV excess in elliptical galaxies and spiral bulges (Davidsen and Ferguson 1993). The most likely explanation to this mystery is contribution from post-AGB and post-early-AGB stars that fail to become PNe (Greggio and Renzini 1990). Since the formation of PNe relies on large-scale mass loss during the late AGB stages and a rapid evolution of the central star to ionize the ejecta (see Sec. 2), there can exist many low-metallicity or low-mass stars that evolve to high temperatures without being able to convert the UV fluxes to optical light as in PNe. These stars would be difficult to detect in the Galaxy because of interstellar extinction, but their collective UV light output can be significant in elliptical galaxies.

16. CONCLUSIONS

We now believe that PNe are descendants of AGB stars which are undergoing alternate hydrogen- and helium-shell burning (Iben and Renzini 1983). Mass loss from the surface gradually builds up an extended CSE and eventually exposes the carbon-oxygen electron-degenerate core. As the mass of the hydrogen envelope decreases, the star will move toward the blue side of the H-R diagram. Large-scale mass loss, which is probably caused by a combination of pulsation and radiation pressure on grains, can no longer operate and the envelope is slowly depleted by nuclear burning. Since the mass of the core is nearly constant, the star will evolve with constant luminosity during this phase of evolution. After a period of several thousand years (which is heavily dependent on core mass and is shorter for high-mass stars and longer for low-mass stars), the central star will become hot enough to ionize the dispersing CSE. Probably at the same time, a fast wind is initiated. This wind injects significant amounts of energy into the system and compresses and accelerates the remnant AGB envelope into a planetary-nebular shell. This wind also magnifies any asymmetry inherent in the AGB wind and creates the variety of morphologies that are observed in PNe.

PNe emit in almost every part of the electromagnetic spectrum. Their visual spectrum is dominated by recombination and forbidden lines emitted in the photoionized nebular shell. In the far infrared, dust continuum emission is particularly strong in young PNe. Molecular rotational transitions in the millimeter wavelengths can be observed from the remnant AGB envelope. At cm wavelengths, free-free continuum emission is easily detectable. The shocked central-star wind creates a high-temperature bubble which is expected to emit X-ray continuum emission.

A planetary nebula is a system in which the evolution of the central star is tightly coupled to the dynamical evolution of the nebula. The dynamical expansion of the nebula is determined by the strength and speed of the central-star wind, which in turn varies as the central star evolves. The evolution of the central star and its rapidly changing Lyman continuum output also controls the ionization structure of the nebula, which has profound effects on the observed properties of PNe. In this review, we have emphasized that correct derivations of physical parameters (such as expansion velocity, nebular mass, etc.) are only possible within the framework of a dynamical-ionization model.

The strong coupling between the star and nebula results in a narrow range of central-star masses centered around $0.6M_\odot$. Outside this range, the nebula cannot convert the majority of the stellar UV fluxes into visible photons, and the stars will remain undetected. This population of "failed PNe" could be responsible for the UV excess seen in elliptical galaxies.

Research on PNe has undergone a renaissance in recent years. Stellar-evolution theories, particularly for AGB stars, have greatly improved, leading to a better understanding of the progenitors of PNe. Multiwavelength observations of these AGB progenitors have led to the discovery of mass loss, which has significant implications on the formation of the nebula. PNe not only have served as a laboratory of atomic physics, but also as a testing ground of theories of supersonic dynamics. Identification of transition objects between the AGB and PN phases provide new constraints on the evolutionary models of PN. Progress in the understanding of the physics of the PN phenomenon has made possible the application of PNe in extragalactic studies with confidence. We can expect PNe to play an increasingly important role in the determination of the extragalactic distance scale as well as the mapping of dark matter in nearby galaxies.

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