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Planetary Nebulae: Origin and Evolution

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Abstract: There has been a great deal of progress in our understanding of planetary nebulae and their central stars during the past decade and a half. Most of this has come about through progress in observational techniques covering almost the entire electromagnetic spectrum. Theories of planetary nebula evolution have been put to better and better tests as more and more discriminating data have become available.

This review describes some of the progress made in observations and their interpretation, particularly in the context of the evolution of the nebulae and the central stars. It includes a discussion on the improved determinations of magnitudes and temperatures of the central stars, and of progress in the measurement of distances, and a reassessment of the observed mass-distribution of the central stars. The last topic has been at the centre of a lively debate for almost a decade now and has been responsible for a large number of studies of central star evolution, some this review briefly touchs upon.

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1. Stellar Magnitudes and Zanstra Temperatures

Since the determination of the central star temperatures by the Zanstra method requires an accurate measurement of the magnitude of these stars, we begin with a discussion of the recent developments in the magnitude measurements. Magnitude measurements of central stars are observationally difficult because of the presence of the bright nebular background in which the stars are embedded. Further, since many of these stars are very hot and faint in the visible it is often difficult to see them. In fact 20–25% of planetary nebulae had unseen central stars until a few years ago, the notable example being NGC 7027, the brightest PN in the sky. Using new techniques, it has now been possible to unmask many of these nuclei and estimate their brightness. Apart from finite aperture filter photometry which has been in vogue for a long time (see Kaler 1989 and references therein) and which works quite well for relatively bright stars ($V \leq 16\overset{\mathrm{m}}{.}0$) embedded in extended nebulae, two of the more recent techniques designed particularly to detect the faint nuclei are (i) the imaging technique and (ii) the cross-over technique. The imaging technique has been used by Reay *et al.* (1984), Walton *et al.* (1986), Gathier and Pottasch (1988), and more recently by Jacoby and Kaler (1989) and Heap and Hintzen (1990) to obtain accurate magnitudes of a fair number of faint central stars. Two-dimensional CCD images of the nebulae and the central stars are obtained in Hβ and in continua free from emission lines. The Hβ map is used with the help of models and other spectroscopic information to produce a nebular continuum map at the appropriate wavelength which is then subtracted from the observed continuum map to yield a magnitude measurement of the star. It has been possible with the help of this method to see and estimate magnitudes of the central stars of NGC 7027, 2440, 2452, etc., none of which were earlier accessible to measurement. Even with this technique central stars of some of the well known nebulae are still unseen, e.g., NGC 6302, 6537. While there is general agreement among the various estimates on most of the objects ($\Delta V \leq 0\overset{\mathrm{m}}{.}4$) there are some outstanding discrepancies also (see Table 1), the reasons of which are not entirely clear.

The 'cross-over' technique is a highly innovative one in which no measurement of the star is involved. It is especially tailored to estimate magnitudes and temperatures on the 'fading' part of the evolutionary tracks where the nebulae are optically thick to radiation beyond the Lyman continuum and where the fast-evolving more massive central stars are presumed to be located. The idea is a simple one in principle. The nebular emissions in He$^+\lambda$4686 and Hβ in the optically thick case are directly proportional to the stellar fluxes shortward of 228Å and 912Å respectively. The ratio I(λ4686)/I(Hβ) thus defines a colour which when combined with an assumed spectral energy distribution (usually a blackbody) yields an estimate of the stellar temperatures, $T_{\rm cross}$. During the course of evolution of the star-nebula system, the nebula may become optically thin in the Lyc while still remaining thick in the He$^+$ ionizing radiation. The Zanstra temperature $T_{\rm Z}$(He$^+$) obtained by using I(λ4686) and the V magnitude is then the true colour temperature of the star while the hydrogen Zanstra temperature $T_{\rm Z}$(H I) obtained by using I(Hβ) is a lower limit. However, as the central star starts fading eventually optical thickness in the Lyc is restored and the two Zanstra temperatures should become equal. The V magnitude of the central star is not known *a priori* but a reasonable initial guess of it may be made and the Zanstra temperatures calculated. They will be unequal to each other and to $T_{\rm cross}$ obtained earlier. The V magnitude could then be iterated upon to find the true value where the equality of the temperatures occurs. The result is a simultaneous determination of V as well as $T_{\rm Z}$(H I) and $T_{\rm Z}$(He$^+$). Kaler and Jacoby (1989) used this technique to estimate the 'cross-over' temperatures and magnitudes of 62 planetary nebulae whose optical thickness to radiation beyond Lyc was independently established from spectroscopic considerations. For nearly 50% of these nebulae other methods of measurement had yielded values of V and $T_{\rm Z}$(H I) and $T_{\rm Z}$(He$^+$) which are found to be in good agreement with $V_{\rm cross}$ and $T_{\rm cross}$.

In Table 1 data obtained on a selected set of planetary nebula central stars using the above methods have been displayed. Notice the discrepant cases where measurements by Gathier and Pottasch (1988) are at variance with the measurements by other authors. Fainter V magnitudes lead to higher Zanstra temperatures and fainter absolute magnitudes for a given distance so that on the HR diagram these stars are displaced towards the tracks of more massive central stars. Thus for NGC 2440 Gathier and Pottasch infer a central star mass close to $1 M_\odot$ while Heap and Hintzen conclude that it is $0.64 M_\odot$. The 'cross-over' method has further been used by Kaler and Jacoby (1990) on a set of Magellanic Cloud planetaries where no direct measurement on the central stars is possible with existing facilities. For the first time temperatures and magnitudes of these central stars have thus been estimated.

The discrepancy between the Zanstra temperatures, where in many cases $T_{\rm Z}$(H I) is found to be significantly lower than $T_{\rm Z}$(He$^+$), has often been interpreted as evidence for incomplete absorption by hydrogen of Lyc photons while optical thickness in He$^+$ ionizing radiation remains valid. A careful consideration of this discrepancy however, shows that this may not be true since it is in the lower temperature ranges ($4.0 < \log T_{\rm Z}(\rm H\,I) < 5.0$) that the discrepancy is more apparent. Gathier and Pottasch (1988) argue effectively for the case of excess UV radiation beyond 228Å as the real cause of the discrepancy for these moderately hot stars; in other words, there is a departure from the blackbody law. From their data as well as the data of Kaler and Jacoby (1989) it is apparent that the discrepancy is reduced beyond $\log T_{\rm Z}(\rm H\,I) = 5.2$. Since the

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Table 1 – Magnitudes and Zanstra temperatures of a few selected central stars

PN Name	V	$V_{\rm cross}$	$\log T_{\rm Z}$(H I)	$\log T_{\rm Z}$(He$^+$)	$\log T_{\rm cross}$	Ref
NGC 2440	18.8±0.5		5.51	5.53		(1)
	17.6±0.15		5.30	5.28		(2)
		17.7			5.34	(3)
NGC 5189	14.83±0.09		4.86	5.04		(4)
		17.84			5.26	(3)
NGC 6445	18.97±0.10		5.26	5.33		(4)
	19.04		5.25	5.26		(5)
		19.13			5.26	(3)
NGC 6565	20.2±0.34		5.42	5.25		(4)
	18.5		5.16	5.08		(5)
		17.76			5.03	(3)
NGC 6772	18.90±0.06		5.05	5.10		(4)
	18.6		5.02	5.10		(5)
		19.54			5.18	(3)
NGC 6781	16.91±0.09		4.92	5.04		(4)
	16.89		4.93	5.0		(5)
		17.63			5.05	(3)
NGC 7027	17.0±0.2		5.45	5.33		(6)
	16.18±0.2		5.35	5.29		(2)
	16.32±0.35					(7)

References: (1) Atherton, Reay and Pottasch (1986); (2) Heap and Hintzen (1990); (3) Kaler and Jacoby (1989); (4) Gathier and Pottasch (1988); (5) Jacoby and Kaler (1989); (6) Walton *et al.* (1988); (7) Jacoby (1988).

Kaler-Jacoby sample is a preselected optically thick sample, it implies that departures from the blackbody law are not significant for the very hot stars. It is possible that a combination of both optical thinness in Lyc and departure from the blackbody law beyond 228Å produces the Zanstra discrepancy although in some of the cases, including the outstanding one of NGC 2392, there is independent evidence that the nebulae are optically thick in Lyc. The property of 'optical thinness in Lyc' is a rather elusive one and since the classical Shklovsky method of measuring distances utilised it as one of its principal tenets it has often been implicitly assumed based on just a consideration of the sizes. It has also become evident that due to structure and the clumped distribution of matter, a nebula may be optically thick in some directions while it is thin in other directions.

2. Distances

By far the most difficult observational parameter to determine for the nebulae is the distance. Significant progress has been achieved in the last ten years or so in measuring distances to nebulae through independent methods (see Lutz 1989). However, the total number of nebulae for which independent distance estimates are available is still small and for discussions of large samples of nebulae it is still common to use statistical distance scales. The statistical scales suffer from large inaccuracies because they are based on one or the other assumed property of the nebulae which is then applied to all without careful discrimination. A popular statistical distance scale incorporating properties of both optically thick and optically thin planetary nebulae is due to Daub (1982). He had a list of fourteen calibrators and used radio fluxes and angular radii to develop a nebular mass-radius relation that showed a steady increase in mass to $R = 0.12$ pc followed by a flat portion characterised by a nebular mass of $0.14 M_\odot$. The nebular mass that Daub calculated for his calibration is the so-called root mean square mass and is related to the true mass $M_{\rm i}$ of the nebula through the volume filling factor ε : $M_{\rm rms} = M_{\rm i} \varepsilon^{-1/2}$. Maciel and Pottasch (1980) developed an independent distance scale along similar lines and noted that their data showed a steady increase of the nebular mass with the radius to about 0.4 pc. Daub's list of calibrators has been superseded in the last few years through improved measurements and enlarged samples. Putting together the data on about 37 planetary nebulae with independent distance measurements, Mallik and Peimbert (1988) took a fresh look at this calibration and also evaluated filling factors of the nebulae in the sample. The results are displayed in Figures 1 and 2. The two immediately obvious results are: (i) the filling factor ε decreases with increasing radius of the nebula, and (ii) the ionized mass $M_{\rm i}$ keeps increasing with size. The authors do not recover the Daub calibration, nor support his conclusion about the transition from the optically thick to the optically thin phase at $R = 0.12$ pc. The average root mean square mass for nebulae larger than $R = 0.12$ pc in this sample is $0.67\ M_\odot$ which is considerably larger than Daub's value of $0.14 M_\odot$. Based on these results Mallik and Peimbert have proposed a new distance scale appropriate for optically thick planetary nebulae and which should be applicable between $R = 0.02$ pc and $R = 0.30$ pc. This distance scale is given by $d = 0.0171 F({\rm H}\beta)^{-1/2}$ where the distance d is in parsecs and $F({\rm H}\beta)$ is the observed Hβ flux corrected for

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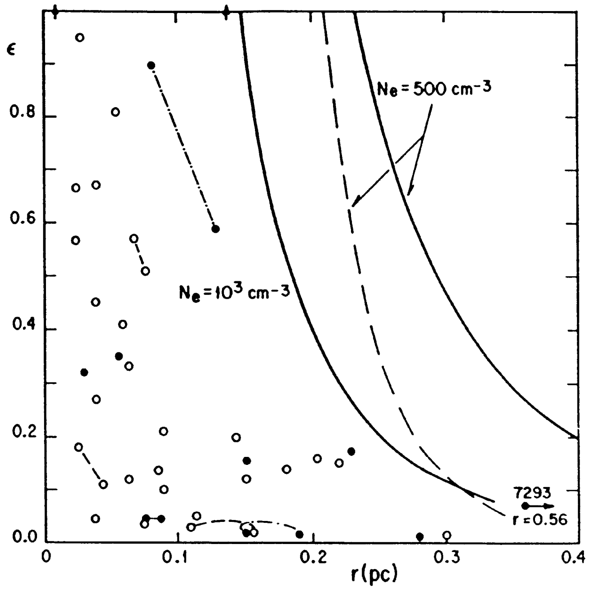

Figure 1 – Filling factor versus radius diagram for PN with scale independent distances. Filled circles denote Type I PN, open circles the rest. Those circles joined by broken lines denote the same object with two different distance estimates. The areas to the right of the solid lines correspond to optically thick PN with N_e(FL) smaller than 10^3 and 500 cm^{-3} respectively, while the area to the right of the broken line corresponds to optically thin PN with N_e(FL) smaller than 500 cm^{-3}.

extinction in erg cm^{-2} s^{-1}. This new distance scale is similar to that of Cudworth (1974) for the optically thick nebulae but extends much beyond Cudworth's transition value of $R = 0.07$ pc. Using this scale I find a local planetary nebula space density of 19 ± 4 kpc^{-3}, a scale-height of distribution of 153 pc and a birthrate of 1.5×10^{-3} kpc^{-3} yr^{-1}. This birthrate is within a factor of two of the recently determined white dwarf birthrate due to Downes (1986) and Fleming *et al.* (1986).

3. Mass Distribution of the Central Stars

The first detailed study on the mass distribution of the central stars was taken up by Schonberner (1981) and Schonberner and Weidemann (1983) and remains controversial to this day. They worked on a local sample of planetary nebulae which had accurately determined magnitudes and temperatures. A statistical distance scale equal to 1.3 times the Cahn and Kaler value was used in conjunction with a common velocity of expansion of 20 km s^{-1} to produce sizes and kinematic ages. Schonberner's evolutionary models of post-AGB Population I stars were used and it was assumed that a one-to-one correspondence existed between the theoretical evolutionary ages and nebular kinematic ages. This led these authors to set the zero-point of time on the evolutionary tracks at $\log T_e = 3.7$. The resulting mass distribution was highly peaked with only about 25% of the central stars having masses in excess of 0.64 $M_\odot$ and none above 0.8 $M_\odot$. There was a sharp cut off on the lower side, for no central star was seen below a mass of 0.55 $M_\odot$. The central peak at 0.58 $M_\odot$ agreed with the peak in the DA white dwarf mass distribution (Koester *et al.* 1979). It has become increasingly apparent that the Schonberner plot is more a result of selection effects on the sample than an actual representation of the true central star mass distribution. The high sensitivity of the evolutionary time-scale to the central star mass ($t_{ev} \approx m_c^{-9.6}$) coupled with the observational difficulties in measuring faint magnitudes makes it hard to find massive central stars in a common sample. Similarly, the evolutionary timescales for stars below 0.55 $M_\odot$ are so long that theoretically they do not become hot enough to ionize the ejected shell before its dispersal through expansion. This along with the fact that the Shklovsky method overestimates distances to optically thick nebulae appears to have produced the sharp low-mass cut off in the Schonberner distribution. Heap and Augensen (1987) produced a broader mass distribution using very similar methods but utilising the IUE data to find UV magnitudes of the stars and the Daub (1982) scale to obtain the distances. This has been criticised by Weidemann (1988) on the ground that Daub's distances are too short.

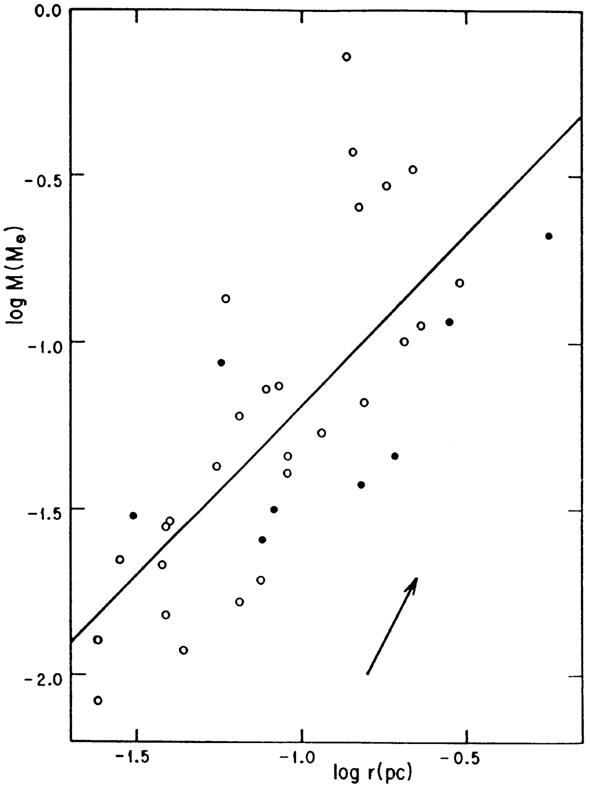

Figure 2 – Mass versus radius diagram for PN with scale independent distances. Filled circles Type I PN, open circles the rest. The straight line is the least squares fitting to the data given by $\log M(\epsilon) = (-0.16 \pm 0.17) + (1.02 \pm 0.15) \log r$; with a correlation coefficient of 0.77. The arrow indicates the change in mass if an object is 1.4 times farther away than assumed.

With a reanalysis of the same data but with distances changed to 1.3 times the Cahn and Kaler value, Weidemann was able to convert the Heap-Augensen distribution to one identical with Schonberner's. The exercise highlights the pitfalls in using erroneous statistical distances and calls into question this procedure to obtain the central star mass distribution. Nevertheless this procedure continues to be used as in the recent study by Kaler *et al.* (1990) of the central stars in large planetary nebulae (R > 0.15 pc on the Cahn-Kaler scale). The results are, of course, quite different, with a wider spread in masses and show that about 40% of the nebulae have central stars more massive than or equal to 0.7 $M_\odot$, of which 17% are heavier than 0.8 $M_\odot$. While the distances may be questioned, the authors point out that for this sample a change in this parameter will move the points

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Table 2 – Initial masses from studies of mass distribution

Authors	Range of Central Star Masses	Range of Initial Masses $\eta = 1/3$	$\eta = 1$	Empirical
Schonberner	0.55–0.8	0.86–2.0	1.1–2.8	2.3–5.3
Heap and Augensen	0.55–1.0	0.86–2.9	1.1–4.0	2.3–6.5
Gathier and Pottasch	0.54–0.9	0.82–2.5	1.1–3.5	2.1–6.0
Kaler, Shaw and Kwitter	0.55–(> 0.9)	0.86–(> 2.5)	1.1–3.5	2.3–6.0

diagonally on the HR diagram in near parallels to the fading part of the evolutionary tracks which suggests that the masses may not be drastically affected. In this context it is refreshing to note that the recent work by Dopita and Meatheringham (1990) on a sample of Magellanic Cloud planetaries where the uncertainties in the distances are minimised, also shows a mass distribution of the central stars wider than Schonberner's. The Clouds seem to be having central stars on the average more massive than found in the local Galactic sample and this may be due to differences in the stellar populations.

Pottasch and co-workers (Pottasch 1983, 1989; Gathier and Pottasch 1989) have adopted a different approach, where they use individually determined distances to place the central stars on the HR diagram. Claiming a greater accuracy thus, they find a spread in masses with $m_c \approx 0.8 M_\odot$ quite common in the sample. The true central star mass distribution cannot be determined since incompleteness is a serious problem in such studies. Hopefully, as the number of nebulae with individually determined distances increases this approach may lead to accurate mass distributions.

A surprising feature of these studies is the discovery of low-mass central stars clustered below the 0.546 $M_\odot$ theoretical track. There is a severe discrepancy here between the observed nebular ages and the theoretical evolutionary ages with the latter larger by almost two orders of magnitude. A related problem is the low luminosity of these stars, with a few having a log $L/L_\odot$ between 2.5 and 3.0. Since current theory predicts formation of planetary nebulae at the thermally pulsing AGB stage, the minimum luminosity expected of a central star is greater than log $L/L_\odot = 3$. Gathier and Pottasch present arguments supporting their distances and also list other observational evidences to assert that low luminosity central stars do exist. If this were the case, theory has to find ways to accommodate these stars in the general scheme of evolution. By having a shorter transition time on the evolutionary tracks from the AGB to the hot central stars (log $T_e > 4$), or by having prolonged mass-loss during this transition, it may be possible to explain the existence of these objects as planetary nebulae.

The masses of central stars may be related to the initial masses of the progenitors with the help of the initial-final mass relation. This relation can be obtained from theory as a function of the assumed mass-loss rate as in Iben and Renzini (1983). Alternatively, an empirical relation may also be derived from cluster white dwarf data as has been done by Weidemann and Koester (1983). A comparison of these initial-final mass relations shows that the theoretical one based on Reimer's mass-loss rate runs much steeper than the empirical one. The range of initial masses of the progenitors implied by these relations is given in Table 2. While the theoretical relation predicts that the minimum initial mass may be as low as the Galactic turn-off at 0.95 $M_\odot$ for a T_G = 12 Gyr, the empirical relation suggests a drastically different range. One major problem with the theoretical relation is the low value of the maximum progenitor mass which ranges between 2.0 and 4.0 solar masses. The theory of chemical enrichment of the envelopes of AGB stars predicts hardly any enrichment for such low initial masses which is at variance with the abundance studies of the nebular envelopes. Also some clusters with white dwarfs have larger turn-off masses. A more drastic mass-loss rate law should alleviate some of these problems. Various other arguments seem to be supporting a flat initial-final mass relation.

4. Chemical Enrichment

A careful study of the abundance patterns in planetary nebulae provides an independent test of the predictions of the stellar evolution theory particularly during the preceding stages of AGB evolution. Nitrogen and helium enhancements in Peimbert Type I and Type II planetary nebulae are well established while the abundance of carbon shows large variations. Further the nitrogen and helium enhancements are generally correlated in accordance with current theory (Iben and Renzini 1983). Two recent studies by Kaler *et al.* (1990) and Kaler and Jacoby (1990) on samples in the Galaxy and the Magellanic Clouds, respectively, have correlated core masses with N/O and He/H ratios. It appears that at the lower end ($m_c < 0.65\ M_\odot$), N/O is roughly constant but at around 0.7 $M_\odot$ the N/O ratio rises steeply, reaching values greater than 2 in both the samples. Beyond 0.9 $M_\odot$ the data are too sparse and definite statements are difficult to make. In the Galactic sample there is evidence of oxygen depletion in Type I planetaries with (N + O)/H remaining fairly constant. While the steep rise in N/O may be evidence of the hot bottom burning during the third dredge-up as envisaged in Renzini and Voli (1981), the correspondence between the core masses in the models and as determined observationally remains rather poor. Moreover, the very large helium enhancements often seen as in NGC 6302 are not predicted by any models. The conclusion seems inescapable that there are flaws in the theory of dredge-up and unless the vast body of data has systematic underestimates of the central star masses, observations indicate the onset of dredge-ups at lower core masses.

5. Conclusion

Many of the doubts raised here may be dispelled as better data become available. In particular, when the Hubble Space Telescope starts making systematic observations of planetary nebulae in the Local Group galaxies, we would be able to get around the most nagging problem in PN research—the problem of distances, and establish stricter correlations against which theories of evolution of these stars can be tested rigorously.

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