IX. THE FUTURE OF PLANETARY NEBULAE RESEARCH

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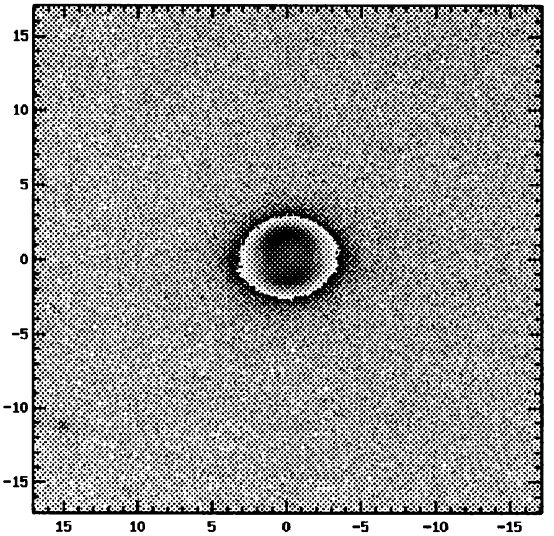

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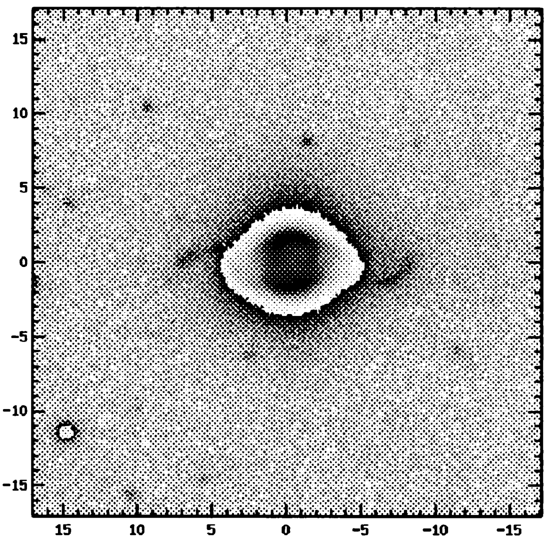

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COMMENTS ON PN EVOLUTION

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1. Introduction

The improved distances given earlier in the symposium by Harris (parallaxes) and Terzian (expansion distances) are used to discuss the evolution of PN and their central stars. A critical note is given concerning the use of model nebulae to derive abundances and central star parameters.

The purpose of this discussion is to evaluate the effect of the new and improved distance determination discussed earlier in the symposium, on the knowledge of post-AGB evolution. In particular:

1) what is known of central star properties,
2) how observations fit in with models of evolution,
3) how nebular abundances are related to evolution.

After listening to the summary of Dopita (these proceedings) one may ask the following. Is it really necessary to study the galactic PN when one can study the PN in the Magellanic Clouds, for which the distance is quite well known. Dopita has given central star temperatures, luminosities and nebular abundances for a host of PN in the Magellanic Clouds, and has discussed the evolution on the basis of these properites. Should one not rely on these results and not put so much effort into obtaining good distances for galactic PN?

I think that the answer is that the galactic PN continue to form the basis for our knowledge of evolution. The results for the Magellanic Cloud planetary nebulae rests to a large extent on the modelling of the nebular spectra. Because the number of ionization stages is limited, the resultant temperatures and consequently the luminosities may be unreliable. The models are not nearly as sensitive to the central star properties as they are to the abundances. Dopita claims an accuracy for the abundances of about 15% which is somewhat better than the value of 30% often given in the literature for galactic PN abundances. But even this may be too

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optimistic. Consider the best observed case: NGC 7027, which has been the subject of 4 detailed investigations in the past 6 years. High resolution, low noise, spectra are available covering the wavelength range from 1100 Å to the near infrared, and sometimes extending into the far infrared. In Table I I have listed the abundances of some of the more important elements as determined by different authors. All use model nebulae with similar input parameters. The spectral line intensities used are the same or similar, except that Beintema et al. (1996) also include the far infrared ISO measurements. The carbon abundance is in all cases determined from the collisionally excited lines (not from the recombination lines). The differences are seen to be large: the extremes vary from a factor of 2 or 3 for N, O and Ne to a factor 5 for carbon and magnesium. The ratio of nitrogen to oxygen seems to be reasonably well-determined (within 50%), but a factor of 2 uncertainty remains for the carbon to oxygen ratio. I don't know which, if any, of these abundance determinations is correct. But if such differences already exist for such a very well studied object, one should be very careful about drawing conclusions for nebulae which are less well observed. Furthermore, there must be something wrong with the assumptions going into present day abundance analyses, which should be carefully investigated.Finally, the central star parameters found by modelling the spectrum may not be very accurate.

TABLE 1. Abundances in NGC 7027

ELEMENT	Beintema (1996)	Kwitter (1996)	Keyes (1994)	Middlemass (1990)
Carbon	7.41 (−4)	32.4 (−4)	6.5 (−4)	11.2 (−4)
Nitrogen	1.32 (−4)	3.11 (−4)	1.4 (−4)	1.86 (−4)
Oxygen	4.47 (−4)	7.59 (−4)	3.1 (−4)	4.90 (−4)
Neon	0.62 (−4)	1.82 (−4)	1.0 (−4)	1.20 (−4)
Magnesium	6.6 (−6)		38 (−6)	21.4 (−6)
N/O	0.30	0.41	0.45	0.38
C/O	1.66	4.27	2.10	2.29

2. Abundance variations within a nebula

It seems rather strange that, to a first approximation, all PN with 4 exceptions, have very similar H, He abundances, and that these abundances do not vary through the nebula. After all, about 15 to 20% of the PN have Wolf–Rayet spectra, indicating that the star has an extended envelope which is essentially without any measurable hydrogen. If mass is continu-

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ally ejected from these objects, as is very likely since many of them are very young, this hydrogen–poor material should cause at least the inner parts of these PN to be hydrogen–poor.

Measurements of the spectrum close to the central star in PN such as NGC 40, BD+303639 and others, fail to show regions of hydrogen–poor material near the central star. One of the more extreme cases is the PN known as He 3–1333 or CPD -56^o8032. It is a small nebula with a diameter of 1.3 arcsecs, and a linear radius of 1.4×10^{16} cm if placed at the distance of 1.5 Kpc. The central star is now losing mass at a rate $M = 4 \times 10^{-6}$ $M_\odot$ yr^{-1} with a velocity of 225 km s^{-1} (Crowther et al., 1996). Since the total ionized mass in the nebula is about $5\times$ 10^{-4} $M\odot$, this mass would have been deposited by the hydrogen–poor wind in the past 100 years. Yet the nebulae appears to have normal solar abundances (Rao, 1987). Furthermore, the spectrum does not seem to have changed in an important way, since the object was discovered more than 25 years ago.

It is interesting to investigate this further. Not only young objects can be considered, but older ones such as NGC 246 (age about 10^4 years) should be measured at different positions in the nebula. This latter PN has a helium rich PG 1159 central star, which very probably is descended from a Wolf–Rayet star. One might therefore expect to see evidence for the emission of hydrogen–poor material at some earlier stage. It would be worthwhile looking for abundance gradients in nebulae.

3. Central star properties

In order to obtain properties of the central stars, and especially those properties related to the evolution, such as the stellar luminosity, it is necessary to know the distance to the PN. For this reason I will restrict myself here to those PN whose distance is know from either parallax measurements (see Table 2 of Harris, these proceedings) or expansion measurements (see Table 1 of Terzian, these proceedings). In both cases, the distances are independent of any (assumed) property of the nebula or its central star.

3.1. DISTANCES FROM PARALLAX MEASUREMENTS

In Table II the nebulae whose distance is known from parallax measurements are listed. The distance in column 2 is that of Harris (these proceedings). The effective temperature, in column 3, is an average value of that found by two methods: a rough atmospheric analysis of the central star spectrum, and the Zanstra method. The first method is discussed by Napiwotzki and Schönberner (1995) and the references cited therein, and the second method, and the combination of the two, is discussed by Pottasch (1996). The two methods give consistent results and it is likely that

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the temperature is correct to about 15%. The stellar radius is determined from the visual magnitude V_o, corrected for extinction. Use is made of the model atmospheres of Mendez et al., (1989) in deriving the radius, but a very similar result would have been obtained assuming the stars radiate as blackbodies (see discussion of Pottasch, 1996).

Once the stellar radius is known, the surface gravity can be computed if the stellar mass is known. In order to give a rough idea of what the gravity is, the mass of all of these central stars was assumed to be 0.6 $M_\odot$, which should be a reasonable first approximation. The resulting gravities are shown in the 5th column of Table II. For comparison, surface gravity can be determined from an analysis of the spectrum. The analyses reported in the literature (Werner et al.,1995; Bergeron et al., 1994; Napiwotzki and Schönberner, 1995; see Pottasch, 1996 for a more complete reference list) are somewhat uncertain, and the values quoted in Table II may have an uncertainty of a factor of 3. Within this uncertainty, the spectroscopic values of gravity are in agreement with the values deduced from the distance, and the temperature and brightness of the central star. This indicates that we are on the right track.

The values of surface gravity are those expected from white dwarf stars, or stars very close to the white dwarf stage. In fact, their spectra show them to be white dwarfs. The spectral types are given in the last column of Table II: DA, only hydrogen lines; DAO, hydrogen and helium lines; DOZ, helium and carbon lines (the PG 1159 stars). The fact that all PN with measured parallax have white dwarf central stars is an interesting selection effect. At least part of the explanation is that the earlier stages occur more quickly, so that a large fraction of the nearby central stars have already reached the white dwarf stage.

The luminosity of the central star (in units of solar luminosity) is given in column 6 of Table II. The values vary from less than 10 to about 300. These values are expected for stars which have stopped nuclear burning and are on the cooling tracks, i.e. white dwarfs.

3.2. DISTANCES FROM EXPANSION MEASUREMENTS

Before continuing the above discussion, the results from a similar analysis using the expansion distances will be given. In Table III, all the nebulae given in Terzian's Table 1 are listed, with the exception of NGC 2392, which is not given because no expansion was detected in the VLA measurements. The distances, given in the 2nd column of Table III, are roughly the average of the values listed by Terzian, with twice the weight given to the radio expansion measurements. For NGC 246 a slightly smaller distance is given, because this is indicated by the spectral type of the companion to the

TABLE 2. Central star properties (parallax distances)

NEBULA	DIST. (pc)	$T_{\rm eff}$	V_O	log g	Spectrosc. log g	$L/L_\odot$	Spectral Type
S 216	130pc	10^5	12.37	7.32	7.3	71	DAO
PW 1	433	9×10^4	15.10	7.32	7.5	28	DAO
NGC 6853	380	1.2×10^5	13.77	7.03	6.9	290	sdO/DAO
A21	541	1.2×10^5	15.71	7.50	7.4	100	DOZ
NGC 6720	704	1.2×10^5	15.50	7.19	7.0	200	DA
A31	211:	10^5	15.29	8.07:		13	
A24	322:	10^5	17.15	8.45:		5	
NGC 7293	213	1.1×10^5	13.43	7.36	7.0	95	DAO
A74	752	6.5×10^4	16.68	7.32	7.2	13	DAO

central star (see Pottasch 1996 and references therein). Furthermore for BD $+30^o3639$, the smaller of the two distances listed by Terzian is used. For NGC 6302, the distance given may be somewhat too large, because at this distance its radio emission, if it were placed at the galactic bulge, would somewhat exceed (by about 50%) the brightest of the known galactic bulge PN.

The effective temperatures are listed in the 3rd column of Table III. The references are given in Pottasch (1996) except for NGC 7027 (Beintema et al., 1996), NGC 6210 and NGC 3242 (McCarthy et al., 1990), NGC 6302 (Pottasch et al., 1996) and NGC 6572 (Mendez et al., 1993). The values of effective temperature are in general reasonably well known and the values found in the literature in the past 15 years do not differ from what is given here by more than 10 to 20%.

The visual magnitude of the star, corrected for extinction, is given in column 4. With the exception of the central stars of NGC 7027 and 6302, these are all bright stars with mainly foreground extinction which is possible to determine by comparing the radio continuum with the Hβ emission, and assuming a standard extinction low. For NGC 6302 the central star is not seen; it is presumably hidden behind the dust line running across the center of the nebula. For NGC 7027 the extinction is mostly local to the nebula, and because the dust has an irregular distribution, the extinction is difficult to determine. Two possible values of V_o are therefore listed. The first comes from the HST measurements of Wolff et al., (1995), who find an extinction to the star considerably higher than that found to the nebula in general. This would mean that the extinction is very local to the central star. The second value of V_o comes from the work of Robberto et al., (1993), who determine the extinction from the Balmer decrement across the nebula.

The extinction to the star is then the sum of the foregound extinction plus one half of the nebular extinction close to the center of the nebula.

The stellar gravity listed in column 5, is then determined in exactly the same way as described above. It may be compared to spectroscopic determinations in only 4 cases. In one case, NGC 246, the agreement is reasonable, although there is a rather large discrepancy among the different spectroscopic determinations, each of which in turn represents an attempt to model a different part of the spectrum ($log\ g = 5.7$ comes from the optical absorption lines, while $log\ g = 6.5$ comes from the X-ray spectrum). The other 3 values of $log\ g$ come from analysis of the hydrogen and helium absorption line spectra in the optical region (Mendez et al., 1992; McCarthy et al., 1990). They are seen to be consistently an order of magnitude lower than the values we have determined. The differences do not depend on a model atmosphere, because the same model was used in both cases. The differences only depend on the distancē used: the spectroscopic gravities are consistent with only much larger distances (a factor 3 to 4) than found by the expansion method.

The total luminosities can be computed from the radius and effective temperature and is given in column 7 of the table. The temperature uncertainty probably does not have a large effect on the luminosity. The principal uncertainty is the distance. The range of luminosity is from 500 to 10,000. The last column of the table gives the far infrared luminosity, found by combining the IRAS flux measurements and the distance. By comparing columns 7 and 8, it can be seen that the infrared luminosity varies between 10 and 50% of the total luminosity. For NGC 6302 the central star is not seen. The total luminosity in this case is the sum of all line and continuum radiation longward of $\lambda 912 \AA$. This assumes that all the shortward radiation is absorbed or re–absorbed by the nebula. For NGC 7027 it can be seen that the two assumptions concerning the extinction to the central star give strongly different predictions of the total luminosity, one being much less than the measured infrared luminosity. This must be wrong, so that it may be concluded that the other alternative is more nearly correct.

4. Comparison with evolutionary models

It is interesting to compare the central star properties described in Tables II and III with evolutionary models, predictions and expectations. Two properties in particular will be discussed: (1) the kinetic age of the nebula, as compared to the theoretical age; (2) the (over)abundances of certain common elements compared to theoretical expectations. In fact, this last point will be limited to investigating what the evidence is that nebulae of high helium and nitrogen abundances are associated with high mass stars.

TABLE 3. Central Star properties (expansion distances)

NEBULA	DIST.	T_{eff} K	V_O	log g	Spectrosc. log g	$L/L_\odot$	$L_{IR}/L_\odot$
NGC 246	500 pc	120,000	11.80	6.00	5.7-6.5	3.1×10^3	
NGC 3242	450	75,000	12.06	5.99	4.75	4.8×10^2	0.39×10^2
NGC 6210	1570	55,000	12.50	4.92	3.9	1.6×10^3	3.2×10^2
NGC 6302	1600	350,000				1.1×10^4	5.6×10^3
NGC 6572	1180	60,000	11.78	4.93		2.3×10^3	1.1×10^3
BD+30°3639	1500	35,000	9.19	3.45		7.9×10^3	3.2×10^3
NGC 7009	600	72,000	12.53	5.92	4.9	4.8×10^2	1.2×10^2
NGC 7027	790	160,000	12.43	5.97		1.0×10^4	4.1×10^3
			14.43	6.77		1.7×10^3	
NGC 7662	790	100,000	12.84	5.94		1.7×10^3	1.1×10^2

4.1. THE PN WITH PARALLAX DISTANCES

These nebulae are listed in Table IV. The central star masses and evolution times (given in columns 2 and 3) are found by using the theoretical HR diagrams from the article of Blocker (1995), together with the effective temperature and luminosity listed in Table II. Most of the masses found in this way are close to $0.6M_\odot$, except for A24 and A31 which are much higher. To reduce these values to $0.6M_\odot$ would mean that the distance would have to be increased by a factor of about 2.5, which would also reduce the calculated gravities so that they would be more in line with the values found for the other central stars. It would be interesting to study these stars spectroscopically. The evolution times have their zero point when the stellar temperature is 5000 K. This is not necessarily the time when the nebula is ejected, which is not precisely known. It is likely to have occurred at a slightly earlier time, just before the star began to move away from the AGB. In column 4 of Table IV the kinematic age is listed. This is found by dividing the radius of the nebula by the expansion velocity (preferably the [NII] expansion velocity, since this comes from the outer regions of the PN). It is expected that this should give the same age as that in the previous column for large nebulae because even if the expansion began before the surface temperature reached a value of 5000K, the temperature usually used as the value when the theoretical age begins, the difference is probably not large. In general, one cannot expect very good agreement, since the theoretical curves for different masses lie quite close to each other in this region of the HR diagram.In addition, errors in the effective temperature as well as the distance play a role. Still the agreement

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leaves something to be desired.

In the last 4 columns of Table IV the abundances for some of the nebulae are given, as summarized by Perinotto (1991). Not all nebulae have been measured. Those that have, all have a helium abundance somewhat higher than average, as well as a (very) high nitrogen to oxygen ratio. For this reason it might be suspected that they originate from high mass stars. This is not consistent with the masses given in the second column, except for A24. Definite conclusions cannot be drawn. At present it can only be stated that there is no definite evidence in this table for a relation between central star mass and helium and nitrogen overabundance.

TABLE 4. Evolution Predictions (Parallax distances)

NEBULA	THEORY MASS	THEORY AGE	KINETIC AGE	He/H	$O/H \times 10^4$	N/O	C/O
S 216	0.6	9×10^4	30×10^4				
PW 1	0.6	20×10^4	4.3×10^4			1.5:	
NGC 6853	0.6	1×10^4	1.2×10^4	0.12	4.1	0.7	1.4
A 21	0.65	2×10^4	6.4×10^4	0.13:	3.4	0.65	
NGC 6720	0.6	1.5×10^4	0.5×10^4	0.12	6.4	0.3	1.2
A 31	0.9	40×10^4	2.9×10^4				
A 24	0.95	$>80\times10^4$	4.8×10^4			>2.7:	
NGC 7293	0.6	4×10^4	2.6×10^4	0.136	7.8	0.4	
A 74	0.55	80×10^4	24×10^4				
	$M_\odot$	YEARS	YEARS				

4.2. THE PN WITH EXPANSION DISTANCES

These nebulae are listed in Table V. The masses in 5 of the 9 cases are below 0.57 $M_\odot$; for 2 of these cases the luminosity is lower than the lowest tracks on the theoretical HR digrams. The predicted age for these 5 cases is much longer than the kinetic age, indicating that something is wrong. Either the distances are substantially too close, or the theoretical time scale for the development of the central star is substantially too long at low luminosities. The time scale is related to how quickly the envelope of the star is removed, so that in the theoretical calculation a stronger mass loss rate may drastically change the time scale.

For 3 of the 4 remaining stars the predicted mass is between $0.58M_\odot$ and $0.75M_\odot$. In these 3 cases the predicted age and the measured kinetic age are equal (within a factor of 2). For the last case, NGC 6302, the predicted mass is high, $0.9M_\odot$, and the predicted time is much shorter than the kinetic age.

If we look at the abundances, NGC 6302 is clearly different from the other nebulae with high He and N abundances. It also has the lowest C abundance, which could indicate that some of the carbon has been converted into nitrogen. But this is the only evidence for a relation between central star mass and helium and nitrogen abundances. All the other PN have a He/H ratio close to 0.10 (except for BD+30 3639 which apparently has a central star which is too cool to fully ionize helium) and a nitrogen to oxygen ratio within a factor 2 of 0.2. Even NGC 7027, which has a central star mass of $0.75M_{\odot}$, shows no significant increase in these elements compared to a star of $0.55M_{\odot}$.

Recall that the smaller of the two conflicting distances was used for BD+30 3639. Had the large distance been used, the luminosity would be increased by a fact 3, the central star mass to about $0.8M_{\odot}$, and the theoretical age lowered to about 200 years.

TABLE 5. Evolution Predictions (Expansion distances)

NEBULA	THEORY MASS	THEORY AGE	KINETIC AGE	He/H	$O/H \times 10^4$	N/O	C/O
NGC 246	0.58	5×10^3	8×10^3				
NGC 3242	<0.54	>200×10^3	1×10^3	0.09	4.4	0.2	0.6
NGC 6210	0.55	20×10^3	2.5×10^3	0.107	4.5	0.1	1.6
NGC 6302	0.9	0.1×10^3	2.5×10^3	0.18	5.0	1.6	0.2
NGC 6572	0.56	50×10^3	1.6×10^3	0.105	3.6	0.25	0.7
BD+30°3639	0.63	1×10^3	1.2×10^3	0.043	3.0	0.3	2.0
NGC 7009	<0.54	>200×10^3	1.9×10^3	0.11	5.0	0.4	0.44
NGC 7027	0.75	0.8×10^3	1.4×10^3	0.10	5.0	0.3	2.0
NGC 7662	0.56	50×10^3	2.3×10^3	0.10	3.6	0.2	1.7
	$M_{\odot}$	YEARS	YEARS				

5. Conclusions

In summary, only the following can be said. The new distances do not solve the existing problem that the predicted ages of the low luminosity PN are much longer than the kinematic ages, and that the high luminosity PN are predicted to evolve more quickly than they actually do. In fact, these results emphasize that these are real problems, and not a shortcoming in the observational data. Concerning a possible relation between nebular abundance and core mass: there is not very much evidence (one object) that the He and N abundance increase with increasing central star mass. Concerning the reality of the gravities derived from spectroscopic analyses: there is evidence that existing atmosphere models of high gravity central stars (on the cooling track) are good approximations, and that existing atmosphere models of lower temperature and gravities are not good approximations.

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