PLANETARY NEBULAE IN THE MAGELLANIC CLOUDS

M. A. DOPITA
Mt. Stromlo and Siding Spring Observatories
The Australian National University.

ABSTRACT. We present a simple two-wind model for the evolution of the Magellanic Cloud planetary nebulae (PN) which reproduces the observed density / radius / ionised mass relationships, and serves to define the geometrical relationship between the ionised nebula and the star. From self-consistent photoionisation modelling of 78 Magellanic Cloud PN, we have constructed the H-R Diagram for the central stars, and have derived both the chemical abundances and the nebular parameters. We find that the central stars have masses generally between 0.55 and 0.7 $M_\odot$. Type I PN have more massive precursors, and show clear evidence for the Third dredge-up episode and for the dredge-up of ON processed material. The expansion velocity of the nebula is closely correlated with the position of the central star on the H-R Diagram, proving that the nebula undergoes continuous acceleration. Excluding Type I PN, the mean abundances derived for the LMC and the SMC agree with those derived from H II regions and evolved, radiative SNR.

I. Introduction

The study of the evolution of planetary nebulae (PN) in the Magellanic Clouds (MC) allows many of the quantitative uncertainties relating to the distance scale and the reddening to be overcome. This population has been the subject of a systematic and detailed study by us and our group in recent years, and data on the diameters, fluxes, expansion velocities and kinematics have all been accumulated (Dopita *et al.* 1985,1987,1988; Dopita, Ford and Webster 1985 ; Meatheringham *et al.* 1988 ; Meatheringham, Dopita, Morgan 1988 ; Wood, Bessell and Dopita, 1986; Wood *et al.* 1987). This has led to a general understanding of the outlines of the evolutionary sequence (Dopita and Meatheringham 1990a), a necessary prerequisite to detailed modelling of individual PN. In this paper, I will briefly summarise this evolutionary model, and go on to show how the acquisition of high quality spectrophotometry in some hundred PN has permitted rapid progress to be made in the detailed modelling of MC PN and their central stars.

2. An Evolutionary Model

The dynamical evidence (Dopita *et al.* 1987) leads us to the adoption of a two-wind model to describe the outlines of the evolutionary sequence for PN. In this model, the PN shell is ejected at a velocity of about 10 km s^{-1} in a relatively short period of time during the AGB phase of evolution. The PN precursors are the OH/IR stars. Once the envelope has been largely lost and the central star becomes hot enough, radiation pressure drives a fast stellar wind. In this case, the ionised gas will be trapped between the compressed AGB wind and the hot pad of shocked stellar wind. In the particular case that the total energy content can be represented by a simple power law in time, $E(t) = E_o t^{\alpha}$, and if the radial density distribution in the undisturbed AGB wind is given by a power law in radius, $\rho(r) = \rho_o r^{\beta}$, then, from dimensional considerations, the radius of the outer shock, R , and the velocity of expansion, V_{exp} , are given by;

$$R = A.\,(E_o / \rho_o)^{1/(5+\beta)}.\, t^{(2+\alpha)/(5+\beta)}; \qquad V_{exp} = B.\,(E_o / \rho_o)^{1/(5+\beta)}.\, t^{(\alpha-\beta-3)/(5+\beta)} ,$$

A and B being dimensionless constants. If we assume that the nebula is evolving into a AGB wind that has been blown at a steady mass-loss rate and velocity(β = -2),then the

R. Haynes and D. Milne (eds.), The Magellanic Clouds, 299–306.

observational material on the Magellanic Cloud PN limits α to lie in the bounds $1 < \alpha < 2$. This result is in accord with radiative-driven wind theory since the PNn evolutionary models of Wood and Faulkner (1986) predict α to lie in the theoretical range $1 < \alpha < 1.7$. In the limiting cases, $\alpha = 1$ and $\alpha = 2$, we have, for $\beta = 2$:

$$\alpha = 1.0; \quad V_{exp} = const.; \quad R = const.\ t$$
$$\alpha = 2.0; \quad V_{exp} = const.\ R^{1/4}; \quad R = const.\ t^{4/3}.$$

The velocity of expansion therefore depends only very weakly on radius during the optically thick evolution, a result supported by observations (Sabbabin and Hamzaoglu 1982; Phillips 1984). The weakness of this dependence makes it a poor test of theoretical evolutionary scenarios, despite its fairly extensive use in the literature (e.g.Sabbadin *et al.* 1984; Okorokov *et al.* 1985).

The stellar wind provides the pressure which confines the ionised material to a thin shell. Since the pressure of the stellar wind is in equilibrium with the gas pressure in the H II region and the extent of the HII region is determined by the ionising flux from the central star, S_*, we derive the following relationship between the thickness of the ionised shell, ΔR, of density, n, and radius, R:

$$R = const.(\Delta R/R) / (1 - \Delta R/R)^4; \quad n = const.\ S_*^{1/2} R^{-3/2}.(\Delta R/R)^{-1/2}.$$

Gathier *et al.* (1983), and, more recently, Pottasch and Acker (1989) and Dopita and Meatheringham (1990a) have pointed out that the strong relationship between nebular mass and nebular radius is strong evidence in support of the idea that the majority of these PN are optically thick. For optically thick PN, the above equations permit us to derive a reduced mass : radius relationship, where the reduced mass is the nebular mass corrected to unit luminosity of the central star. This is shown in Figure 1.

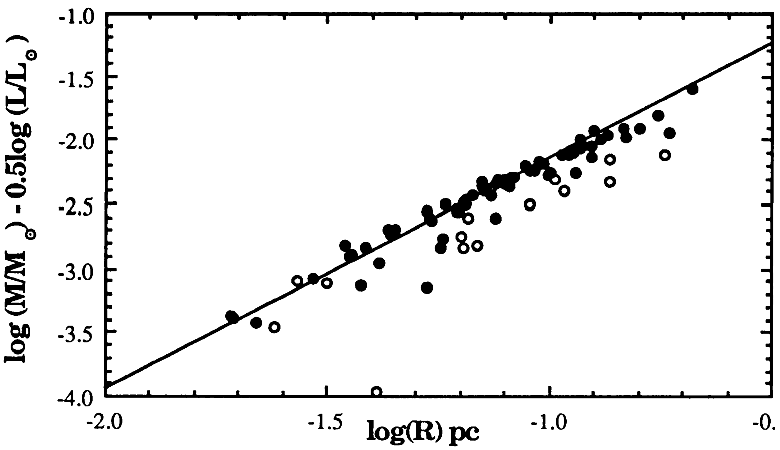

Figure 1: The reduced mass : radius relationship for those Magellanic Cloud PN for which we have detailed models. The open and filled circles represent optically thin and thick PN, respectively. The line represents the theoretical sequence, normalised at logR = -1.0.

This gives a good description for the optically thick sequence. However, for optically thin objects there is no clear transition from an optically thick to optically thin sequence, optically thin nebulae being found at all radii and temperatures. Thus the intrinsic scatter in the wind parameters during the AGB phase of evolution must be quite large.

3. Photoionisation Models

We use the spectrophotometric results presented by Dopita and Meatheringham (1990a,b). This database has the advantage of a good wavelength coverage (~3400-8000Å), a good sensitivity and dynamic range (>300), and a spectral resolution of ~5Å, which is more than adequate to resolve important diagnostic lines. The objects observed are almost all drawn from the Sanduleak, MacConnell and Philip (1978) list, which is a fairly uniform magnitude limited sample. They were chosen to cover the full range of excitation classes and densities, and the sample includes some objects with peculiar spectral signatures such as unusually low [OIII] / Hβ ratios, or very strong [NII] lines. However, fainter objects such as the Jacoby PN studied by Henry, Liebert and Boroson (1989), are not well represented.

In order to determine the PN nebular abundances, and the position of the central star on the HR diagram we require to know only the absolute Hβ flux, the nebular density, and to have accurate spectrophotometry over as wide a wavelength as possible. This is possible because, with the aid of a photoionisation code, the ionisation temperature can be determined from the nebular excitation, the luminosity of the central star can be determined from the absolute Hβ flux, and the chemical abundances can be determined from the electron temperature of the nebula and from its detailed emission line spectrum. We have used the generalised modelling code MAPPINGS (Binette, Dopita and Tuohy, 1985) to compute the emission line spectra of isobaric nebulae in photoionisation equilibrium with central stars having a Black-Body photon distribution. The nebular gas is assumed to have a filling factor of unity in the emitting volume, but to have a shell structure with an inner radius defined by the interface between the swept-up material lost from the star during the AGB and the hot, shocked, stellar wind of the PNn. The outer boundary is set either by the Strömgren sphere of the planetary nebular nucleus (PNn) in the case of optically thick models, or by truncation of the model at a finite optical depth at the Lyman Limit, in the case of optically thin nebulae. The local nebular density is given in Meatheringham and Dopita(1990), derived either from the observed [SII] 6717/6731Å line ratio, or from the [OII] 3727/3729Å line ratio (Dopita *et al.* 1988; Barlow 1987, and Monk, Barlow and Clegg 1988). The model gives these densities which are the emission weighted means of the particular ionisation zones within which they are produced.

3.1 DETERMINATION OF STELLAR PARAMETERS

The "observed plane" of the H-R Diagram for the Magellanic Cloud PN is the Excitation Class - Hβ Flux plane, since Excitation Class is closely related to T_{eff}, and Hβ Flux is closely related to L_*. The challenge for the modeller is to discover the transformation.

The detailed definition of excitation class, E, differs somewhat from author to author (c.f. Aller 1956; Feast 1968; Webster 1975; and Morgan 1984). We will use here the classification given by Dopita and Meatheringham (1990a), which, since it was defined in terms of two line-ratios, is a continuous variable:

$$E = 0.45 \{ F(5007) / F(H\beta) \} \qquad 0.0 < E < 5.0$$
$$E = 5.54 \{ 0.78 + F(4686) / F(H\beta) \} \qquad 5.0 \leq E < 10.0.$$

Our modelling allows us to derive an excitation temperature, related fundamentally to these two line-ratios, but involving other diagnostic line ratios. Since our models are self-consistent, abundance effects are largely eliminated. Our method of deriving effective temperature is closely related to the so-called energy balance method developed by Preite-Martinez and Pottasch (1983) from an original idea of Stoy (1933). This relies on the principle of thermal balance in the nebula. Hotter stars produce a greater heating effect per photoionisation, and therefore a higher equilibrium temperature. However, the equilibrium temperature also depends on nebular chemical abundances. In general, a temperature derived by a global model which allows for abundance variations should be more accurate. From our models, we find that the correlation between E.C. and log (T_{eff}) is linear:

$$log\ [\ T_{eff}\ ] = 4.524 + 0.0906.E\ .$$

Given the effective temperature, the luminosity of the central star is determined by the absolute Hβ flux. For the case of optically thick objects, our models show that reddening - corrected Hβ flux can be represented as a function of luminosity and excitation class:

$$log\ [\ L* / L_{\odot}\ ] = \ log\ [\ L_{H\beta}\ ]\ -31.256 + 0.1897E\ \ -0.03763E^2 + 0.001833E^3\ .$$

Even in the case of optically thin objects it is still possible to make a reasonably accurate estimate of the luminosity thanks to spectrophotometric diagnostics.

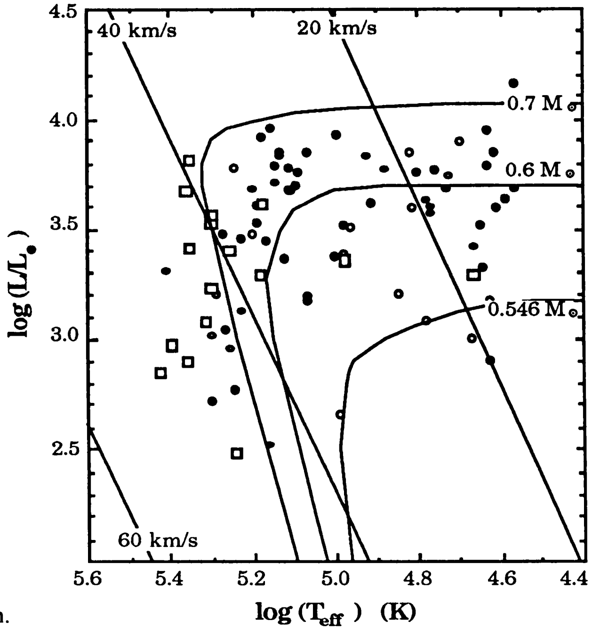

Figure 2: The derived H-R Diagram for the LMC and the SMC PN.
Filled circles represent optically thick PN, open circles optically thin PN, and the open squares, the Type I PN.
The empirically fitted lines of constant velocity of expansion are shown, and, for three different core masses, theoretical evolutionary tracks are given.

The effective temperatures and luminosities of the central stars, as derived from the modelling, are given in Figure 2. Distance modulii to the LMC and SMC of 18.5 and 18.8, respectively, have been assumed. This more than quadruples the sample of Magellanic Cloud PNn which have been placed on the H-R Diagram, previous studies being those of Aller *et al.*(1987), and Monk *et al.* (1988). The bright optically thick objects are found in a range of core masses between 0.56-0.70 $M_{\odot}$, with a mean of about 0.62 $M_{\odot}$. This is consistent with the results of Barlow (1989), or Dopita and Meatheringham (1990a). However, it is very evident that the mean mass is higher, and the range of core masses wider, than those derived by Schönberner (1981) for a group of nearby, evolved PNn. Note that the Type I PN are found preferentially at high T_{eff}, lower luminosities and, in general, at larger values of the core mass ($M_c \geq 0.7M_{\odot}$). This is consistent with the commonly held assumption that the Type I PN represent the more massive progenitor stars. The optically thin PN occupy a broader region of the diagram, of somewhat lower mean mass, from 0.546 - 0.65$M_{\odot}$, implying that the efficiency of mass loss during the AGB is a very strongly decreasing function of the core mass and luminosity.

The effective temperature, luminosity, and the velocity of expansion of the nebula are well correlated through

$$(V_{exp} / \mathrm{km.s^{-1}}) = -128\pm4 + 38\pm2 \, [\, \log(T_{eff}) - 0.25\pm0.05 \log (L / L_{\odot}) \,] \, .$$

The lines of constant velocity of expansion are also shown on Fig 2. It is clear that this relationship is fundamental to the understanding of the dynamical evolution of PN. There is little or no correlation of the dynamical age with the effective temperature. This can arise in an accelerated nebula if the velocity of expansion is correlated with the nebular radius, which is true, but with a very large scatter, for our sample. This once again demonstrates that nebular shells undergo acceleration during the evolution of the PNn towards higher temperatures.

3.2 NEBULAR ABUNDANCES

The mean abundances for Magellanic Cloud PN, derived without consideration of the Type I planetaries, which are known to be He-and N- enriched, is given in Table 1. We also compare these abundances with some previously published estimates for PN, HII regions and evolved SNR (Aller *et al.* 1987; Dufour, Shields and Talbot (DST) 1982; Monk, Barlow and Clegg (MBC) 1988; Russell and Dopita (RD) 1990). It is a striking result that all the abundances agree, within the errors, with those derived by Russell and Dopita (1990) for HII regions and SNR in the Magellanic Clouds. This estimate was based on spectrophotometry of a similar standard, and upon analysis using MAPPINGS. Our results for nitrogen are quite different from the results of Aller *et al.* (1987); and Monk, Barlow and Clegg (1988), and the size of this discrepancy is not fully understood.

TABLE 1: Mean chemical abundances in the Magellanic Clouds.

Galaxy	Reference	He / H (by number)	Abundances: 12 + log[N(i) / N(H)] N	O	Ne	S	Ar
LMC	PN: this work.	0.106	7.23±0.20	8.30±0.06	7.52±0.13	6.67±0.15	6.00±0.25
	HII, SNR: RD	0.091	7.14±0.18	8.35±0.06	7.61±0.05	6.81±0.09	6.29±0.25
	PN: MBC	0.105	7.81±0.30	8.49±0.15	7.64±0.19		
	PN: Aller *et al*.		7.56±0.31	8.28±0.11	7.50±0.13		
	HII: DST	0.083	6.97±0.10	8.43±0.08	7.64±0.10	6.85±0.11	6.20±0.06
SMC	PN: this work.	0.100	6.74±0.24	8.08±0.08	7.23±0.15	6.43±0.20	5.60±0.25
	HII, SNR: RD	0.081	6.63±0.20	8.03±0.10	7.27±0.20	6.59±0.15	5.81±0.08
	PN: MBC	0.083	7.44±0.28	8.26±0.15	7.36±0.22		
	PN: Aller *et al*.		7.42±0.22	8.16±0.12	7.46±0.27		
	HII: DST	0.083	6.46±0.12	8.02±0.08	7.22±0.12	6.49±0.14	5.78±0.12

The difference between the Type I objects and the sample as a whole is clearly exemplified in figure 3, in which we plot the N/O ratio as a function of helium abundance.

Many points are found near the mean points for the LMC and the SMC found by Russell and Dopita (1990), and Type I objects stand out as having both high He/H ratios and high N/O ratios. Such a diagram has been extensively used by Kaler (1983; 1985) as a diagnostic of the importance of the various dredge-up processes occuring during the first Giant and AGB phase of evolution (Becker and Iben 1980; Renzini and Voli 1981). The first of these occurs during the first Giant Branch evolution when the convective envelope dips into the nuclear burning shell. This increases the N / O ratio, but produces little change in He. In the second, occuring in AGB stars with $M > 3M_{\odot}$, both N and He are dredged up. The third phase takes place during the thermal pulsing phase of the AGB, and this increases C / O and He / H at the expense of the N / O ratio. However, the so-called "hot bottom burning" can convert C to N, and so produce very large N / O ratios in the PN. Kaler concludes that the observational data do not support the hypothesis of "hot bottom burning" and dredge-up, since this gives too much N. However, if the third dredge-up phase occurs, some conversion of C to N must occur, although at about the maximum rate allowed by theory. It is apparent from figure 3 that some objects show appreciable He enhancements without any corresponding N / O enhancement; a signature of the third dredge-up phase without C/N conversion. Since the Type I objects have been shown to have more massive core masses, and hence more massive precursors, we can conclude that the C-to-N conversion is mass-dependent.

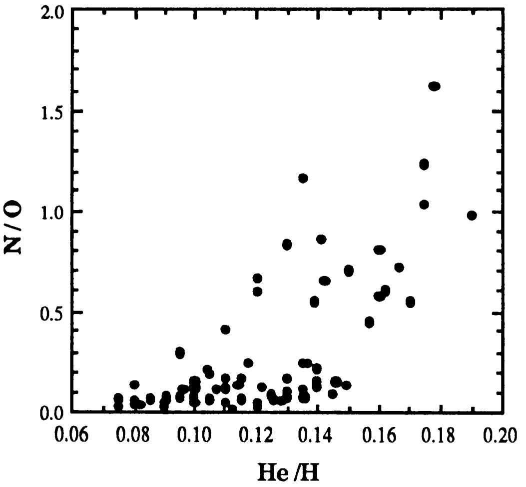

Figure 3: The correlation between the N/O ratio and the He/H ratio for MC PN. The Type I PN show evidence for the third dredge-up episode having occurred.

Finally, our data show evidence for a scatter in the initial abundances of PN, an effect certainly related to the mass of the precursor, and therefore to the chemical evolutionary history of the Magellanic Clouds. This is clearly demonstrated by Figure 4, in which we plot both the O/H ratio and the Ar/H ratio as a function of Ne/H ratio. The differences in the state of chemical evolution of the two clouds are evident, and it also apparent that the Type I objects are found to have the highest abundances in the Cloud in which they are located. The nucleogenic status of Ne is very simple; it is a pure α-process element. Since Ar is also a pure α-process element, a linear correlation between these abundances of these elements is to be expected. What is a surprise is the behaviour of O. For the LMC, the O abundance reaches a definite maximum, before decreasing with increasing Ne abundance, notably for the Type I nebulae. The effect is even more marked in the SMC. We therefore conclude that we have found observational evidence for dredge-up of ON-processed material in the Type I PN, which is more severe for PN with lower initial abundances. This is to be expected, since the number of seed nuclei is fewer, and the balance of the CNO nuclei in the H-burning layers will therefore shift from CN cycling equilibrium towards ON equilibrium.

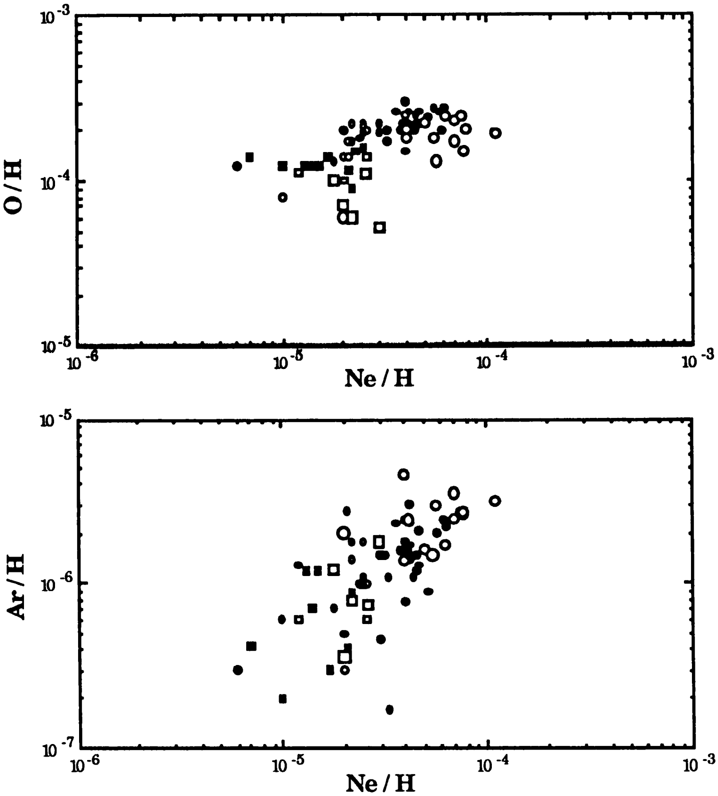

Figure 4: The correlation between the O/H and Ar/H abundance ratios with the Ne/H abundance ratio. Ne is chosen because it is a simple α-process element seen in more than one ionisation stage in PN. The symbols are as follows: for the LMC–filled circles, optically thick PN; small open circles, optically thin PN; large open circles, Type I PN, and for the SMC– filled squares, optically thick PN; small open squares, optically thin PN; large open squares, Type I PN. The curious behaviour of the O/N ratio against the Ne/H ratio is taken to be evidence for dredge-up of ON-processed material (see text).

4. Conclusions

We may conclude that the evolution of PN shells depends on the details of AGB mass-loss, and on the radiatively driven winds at later phases. This results in a close correlation of nebular mass with nebular radius. The observational evidence suggests that this process is moderated by both the core mass and the chemical abundances of the central star, such that expansion velocities depend on the position of the PN on the Hertzsprung- Russell (H-R) diagram. Self-consistent photoionisation modelling has yielded chemical abundances and allowed us to construct an H-R diagram. The majority of the central stars of optically thick nebulae have masses between 0.55 and 0.7 $M_{\odot}$. Optically thin objects are found scattered throughout the H-R diagram, but tend to have a somewhat smaller mean mass. The Type I PN, are found to have high core masses, and to lie on the descending branch of the evolutionary tracks. They show evidence for a third dredge-up episode resulting in correlated He and N abundance enhancements. We also find clear evidence, most notably in the Type I objects for dredge-up and the ejection of ON processed material into the PN envelopes.

References

Aller, L.H. 1956 *Gaseous Nebulae* (New York:Wiley).
Aller, L.H., Keyes, C.D., Maran, S.P., Gull, T.R., Michalitsianos, A.G. and Stecher, T.P., 1987 *Ap. J.*, **320**, 159.
Barlow, M.J. 1987, *M. N. R. A. S.*, **227**, 161.
__________. 1989 in IAU Symp. 131 *"Planetary Nebulae"*, Ed. S. Torres-Peimbert (Kluwer:Dordrecht), p319.
Becker, S.A., and Iben, I. Jr. 1980, *Ap. J.*, **237**, 111.
Binette, L., Dopita, M.A., and Tuohy, I.R. 1985, *Ap. J.*, **297**, 476.
Dopita, M.A., Ford, H.C., Lawrence, C.J., and Webster, B.L. 1985, *Ap. J.*, **296**, 390.
Dopita, M.A., Ford, H.C., and Webster, B.L. 1985, *Ap. J.*, **297**, 593.
Dopita, M.A., and Meatheringham, S.J. 1990a *Ap. J.* (in press).
__________________________. 1990b (in prep).
Dopita, M.A., Meatheringham, S.J., Webster, B.L., and Ford, H.C. 1988, *Ap. J.*, **327**, 639.
Dopita, M.A., Meatheringham, S.J., Wood, P.R., Webster, B.L., Morgan, D.H., and Ford, H.C.,1987, *Ap. J.* **315**, L107.
Dufour, R.J., Shields, G.A., and Talbot, R.J. 1982 *Ap. J.*, **252**, 461.
Feast, M.W. 1968, *M. N. R. A. S.*, **140**, 345.
Gathier, R., Pottasch, S.R., Goss, W.M.,and van Gorkom, J.H. 1983, *Ast. Ap.*, **128**, 325.
Henry, R.B.C., Liebert, J., and Boroson, T.A., 1989, *Ap. J.*, **339**, 872.
Kaler, J.B. 1983, IAU Symp 103 *"Planetary Nebulae"* ed. D.R. Flower (Reidel: Dordrecht) p245.
________. 1985 *Ann. Rev. Ast. Ap.*, **23**, 89.
Meatheringham, S.J., and Dopita, M.A., 1990 *Ap. J. Suppl. Ser.*, (in press).
Meatheringham, S.J., Dopita, M.A., Ford, H.C., and Webster, B.L. 1988, *Ap. J.*, **327**, 651.
Meatheringham, S.J., Dopita, M.A., and Morgan, D.H., 1988 *Ap. J.*, **329**, 166.
Monk, D.J, Barlow, M.J., and Clegg, R.E.S. 1988 *M.N.R.A.S.*, **234**, 583.
Morgan, D.H. 1984, *M.N.R.A.S.*, **208**, 633.
Okorokov, V.A., Shustov, B.M., Tutukov, A.V., and Yorke, H.W., 1985, *Ast. Ap.*, **142**, 441.
Phillips, J.P., 1984, *Ast. Ap.*, **137**, 92.
Pottasch, S.R., and Acker, A., 1989, *Ast. Ap.*, **221**, 123.
Preite-Martinez, A., and Pottasch, S.R., 1983, in IAU Symp 103, *"Planetary Nebulae"*, ed. D.R. Flower, (Reidel:Dordrecht), p547.
Sabbadin, F., Gratton, R.G., Bianchini, A., and Ortolani, S., 1984, *Ast. Ap.*, **136**, 181.
Sabbabin, F. and Hamzaoglu, E., 1982, *Ast. Ap.*, **110**, 105.
Sanduleak, N., MacConnell, D.J., and Philip, A.G.D., 1978, *P. A. S. P.*, **90**, 621.
Schönberner, D., 1981, *Ast. Ap.*, **103**, 119.
Stoy, R.H., 1933, *M.N.R.A.S.*, **93**, 588.
Renzini, A. and Voli, M. 1981, *Ast. Ap.*, **94**, 175.
Russell, S.D. and Dopita, M.A., 1990 *Ap. J.* (in press, June).
Webster, B.L. 1975, *M. N. R. A. S.*, **173**, 437.
Wood, P.R., Bessell, M.S., and Dopita, M.A. 1986, *Ap. J.*, **311**, 632.
Wood, P.R., and Faulkner, D.J. 1986, *Ap. J.*, **307**, 659.
Wood, P.R., Meatheringham, S.J., Dopita, M.A., and Morgan, D.H 1987, *Ap. J.*, **320**, 178.

https://doi.org/10.1017/S0074180900200624 Published online by Cambridge University Press