THE ASTROPHYSICAL JOURNAL, 315:L107–L112, 1987

NEW EVOLUTIONARY RELATIONSHIPS FOR MAGELLANIC CLOUD PLANETARY NEBULAE

MICHAEL A. DOPITA, STEPHEN J. MEATHERINGHAM, AND PETER R. WOOD
Mount Stromlo and Siding Spring Observatories, Australian National University

B. LOUISE WEBSTER
School of Physics, University of New South Wales

DAVID H. MORGAN
Royal Observatory, Edinburgh

AND

HOLLAND C. FORD
Space Telescope Science Institute[1]

Received 1986 November 3; accepted 1987 January 16

ABSTRACT

Two new evolutionary correlations have been discovered to apply to the population of planetary nebulae (PN) in the Magellanic Clouds. First, the age of the nebular shell is found to follow a relationship $\tau = 890 [(M_{\rm neb}/M_0)(V_{\rm exp}/{\rm km\ s^{-1}})]^{0.6}$ yr, which is shown to be consistent with a model in which the total energy of the ionized and swept-up gas drives the expansion down the density gradient in the precursor AGB wind. Second, a tight correlation is found between the expansion velocity and a combination of the excitation class and the Hβ flux. This appears to be determined by the mass of the planetary nebula nuclear star. These correlations provide strong observational support for the idea that the PN shells are ejected at low velocity during the asymptotic giant branch phase of evolution, and that they are continually accelerated during their nebular lifetimes.

Subject headings: galaxies: Magellanic Clouds — nebulae: planetary — stars: evolution — stars: white dwarfs

I. INTRODUCTION

Although there exists a substantial body of literature on the planetary nebula stage of stellar evolution, as yet there is no clear understanding of the relationship between the expanding nebular shell and the planetary nebula nuclear star (PNn) as it evolves from an asymptotic giant branch (AGB) star to a hot, dense white dwarf. The major reason for this is that dynamical studies have, in the past, been exclusively concerned with the study of the Galactic PNs, with all of the concomitant problems of uncertain distance scale, population type, and reddening. For example, no clear consensus has emerged on what is the evolutionary trend of expansion velocity. Robinson, Reay, and Atherton (1982) have suggested that the high- and low-mass PNs have different expansion velocity/radius relationships. Phillips (1984) finds a monotonic relationship, with a small subset of large-diameter, slowly expanding nebulae. Some authors have suggested that a maximum in expansion velocity is reached at a radius of about 0.2 pc, with a slow decline to larger sizes (Smith 1969; Bohuski and Smith 1974; Sabbadin, Bianchini, and Hamzaoglu 1984). The recent series of papers by Sabbadin and his collaborators has provided a great detail of knowledge on the evolution of the nebular properties with age (Sabbadin and Hamzaoglu 1982; Sabbadin *et al.* 1984; Sabbadin 1986*a*, *b*).

The sample of planetary nebulae in the Magellanic Clouds offers notable advantages in evolutionary studies by furnishing us with a luminosity-limited sample at a known distance and with low line-of-sight reddening. In this *Letter* we describe the discovery of a new evolutionary relationship for planetary nebulae using the results of our (almost) complete survey of the kinematics, internal dynamics, and Hβ photometry of this population (Dopita *et al.* 1985, 1987; Meatheringham *et al.* 1987*a*, *b*).

II. THE OBSERVATIONAL DATA BASE

The majority of the objects we have observed come from the list of Sanduleak, McConnell, and Philip (1978), which includes many objects previously known as planetary nebulae (Henize and Westerlund 1963). This list was supplemented by a few objects from the Jacoby (1980) list, many of which are exceedingly faint and difficult to observe, and from the Morgan and Good (1985) list. One or two (unpublished) identifications by these same workers were also observed. The excitation classifications were made on the basis of UK Schmidt objective prism material by Morgan (1984) and are good to about one class.

The observations of the internal expansion velocities were made using the Cassegrain échelle spectrograph on the ANU 1 m and 2.3 m telescopes at Siding Spring and the RGO spectrograph on the Anglo-Australian 3.9 m telescope also at Siding Spring. The observational techniques and reduction procedures are fully described elsewhere (Dopita *et al.* 1985).

The Hβ fluxes were measured using narrow-band interference filters in conjunction with the two-dimensional pho-

[1]Operated for NASA by AURA.

ton counting array (Stapinski, Rodgers, and Ellis 1981) on the ANU 1 m telescope, with supplementary determinations by speckle-mode Hβ imaging using the IPCS on the Anglo-Australian telescope (Meatheringham *et al.* 1987*b*).

Physical sizes for some PN have been measured by two techniques, speckle interferometry for the smallest and brightest objects (Wood, Bessell, and Dopita 1985), and by high time resolution imaging to remove the effects of translational seeing (Wood *et al.* 1987). The first technique gives angular diameters for those objects less than 0''.4 in diameter, whereas the second is good for objects larger than 0''.7 across. In a few cases, both measurements have been made, and the diameter is constrained between these two limits.

Given the Hβ flux and the angular diameter, the ionized mass of the PN can be derived. This mass is found to increase, roughly as the diameter, until a radius of about 0.1 pc is reached, and thereafter remain about constant in the range 0.15–0.5$M_\odot$, as the nebula becomes optically thin (Wood 1986).

III. EVOLUTIONARY CORRELATIONS

a) *Expansion Velocity/Excitation Class/Flux Correlation*

A recent study of expansion velocities of the SMC planetary nebulae has shown that a good correlation exists between the expansion velocity and the excitation class (Dopita *et al.* 1985). This correlation has also been found to apply to the LMC population (Dopita *et al.* 1987). However, it is apparent from the Hβ flux determinations (Meatheringham *et al.* 1987*b*), that a somewhat poorer correlation also exists between this quantity and the expansion velocity and/or excitation class. We were therefore encouraged to investigate the possibility that the expansion velocity, $V_{\rm exp}$, is determined by a combination both of the excitation class and Hβ flux. A relationship of the form

$$V_{\rm exp} = a + bE - c\left[14.0 + \log\left(F_{\rm H\beta}\right)\right] \tag{3.1}$$

was adopted, where E refers to the excitation class and a, b, and c are constant. The parameters a, b, and c were adjusted to minimize the RMS velocity difference between the expansion velocities given by equation (3.1) and those observed. The best-fit correlation for both the LMC and SMC planetaries gives an RMS velocity difference of 7.0 km s^{-1} between the observed and the fitted expansion velocities given by equation (3.1), where the distances to the LMC and SMC have been assumed to be 46 and 58 kpc, respectively. This correlation is shown in Figure 1 ($a = 35 \pm 6$; $b = 3.1 \pm 0.7$; $c = 14 \pm 5$). The correlations for the LMC and the SMC, taken separately, are not significantly different, but that of the SMC is appreciably tighter, despite the possibility that the SMC is extended along the line of sight. For both Clouds, a significantly better correlation is obtained when both the parameters are included. For example, with $b = 0$, the best fit for the SMC planetaries gives and RMS velocity difference of 9.0 km s^{-1} ($a = 64$; $b = 0$; $c = 31$). With $c = 0$, the best-fit RMS velocity difference is reduced to 7.8 km s^{-1} ($a = 10.5$; $b = 5$; $c = 0$). However, when both parameters are included, the RMS velocity difference drops to 5.9 km s^{-1} ($a = 35 \pm 7$; $b = 3.4 \pm 0.8$; $c = 17 \pm 5$). In Figure 2, we show this best-fit $V_{\rm exp}$ surface projected onto the $\log(F_{\rm H\beta})$: excitation class plane. In the event that the PN are optically thick, this plane represents a transformed Hertzsprung-Russell (H-R) diagram for the central stars, since excitation class is related to the Zanstra temperature and the Hβ flux counts the number of ionizing photons. Unfortunately, without a detailed nebular model, the relationship between the observed and true H-R diagrams remains uncertain.

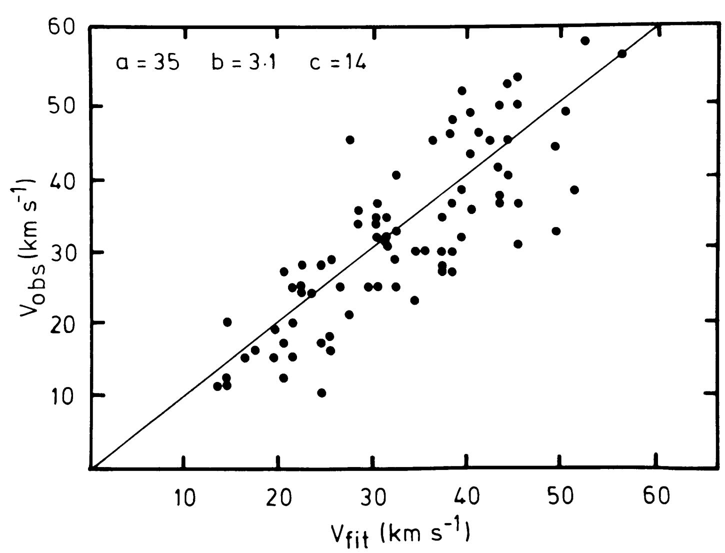

FIG. 1.—The correlation between the observed expansion velocity and the fitted expansion velocity given from the excitation class/Hβ flux combination of eq. (3.1) with $a = 35$, $b = 3.1$, and $c = 14$. All objects for which these quantities have been adequately determined in the Large and Small Magellanic Clouds are plotted, with the SMC points normalized to the distance of the LMC. There are no corrections for reddening.

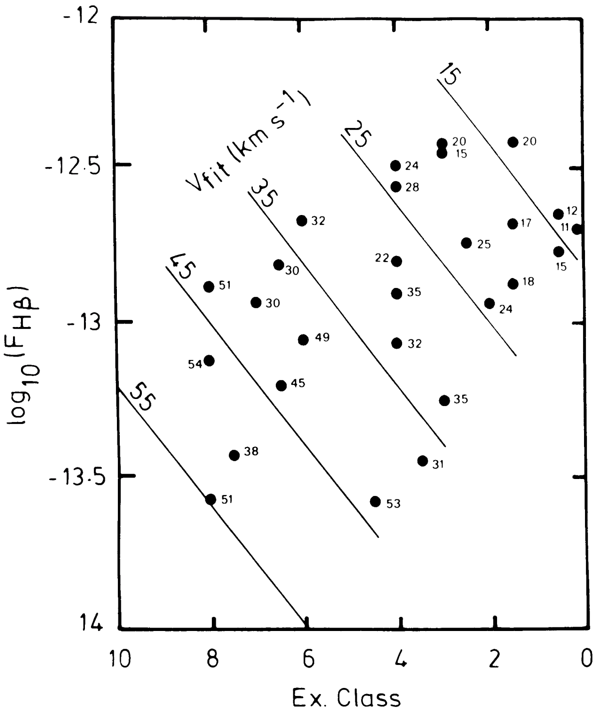

FIG. 2.—The Hertzsprung-Russell diagram for the planetary nebulae of the SMC transformed to the observable nebular parameters with lines of the least-squares expansion velocity fit and the measured expansion velocity for individual objects shown. The transformation is ill-defined, but this diagram demonstrates that the planetary nebulae are accelerated as the PNn fades, and that higher excitation class (high-temperature, more massive PNn) expand more rapidly.

b) *A Dynamical Age/Mass/Expansion Velocity Relationship*

A very direct evolutionary relationship is one that connects the dynamical age of the PN, $\tau_{\rm dyn} = R_{\rm neb}/V_{\rm exp}$, to observable parameters such as nebular mass and/or the expansion velocity. The nebular mass and dynamical age is known only for those nebulae for which angular diameters have been measured, a total of 19 objects of which four are in the SMC. A power-law relationship of the following form was adopted:

$$\log(\tau_{\rm dyn}/{\rm yr}) = a + b\log(M_{\rm neb}/M_0) + c\log\left[(V_{\rm exp} - d)/{\rm km\ s^{-1}}\right], \quad (3.2)$$

where a, b, c and d are constants chosen to minimize the RMS difference between the dynamical ages calculated from equation (3.2) and those observed. The best fit is shown in Figure 3, with the constants determined as ($a = 2.95 \pm 0.25$; $b = 0.60 \pm 0.08$; $c = 0.6 \pm 0.1$; $d = 0.0 \pm 5.0$). The RMS scatter is 0.175 dex. A correlation therefore exists between the *net momentum* and *dynamical age* of the ionized gas.

The objects in Figure 3 are well scattered along the correlation of Figure 1, so it is clear that the selection of objects for which angular diameters have been measured is in no way anomalous compared with the total population. There is, however, only a very poor correlation between the dynamical age and the expansion velocity. Thus the correlation of Figure 1 is independent of that of Figure 3, and the implication is that, for a given set of parameters characterizing the central star, the nebular mass may be quite widely variable.

IV. DISCUSSION

A planetary nebula shell is believed to be expanding into, and ionizing, the wind produced during the asymptotic giant branch phase of evolution. In the optically thick phase of evolution, the structure of the nebula around the planetary nebula nucleus (PNn) is composed of the following zones (in order, working in):

1. The undisturbed and un-ionized AGB wind [number density $n(r)$, temperature $T_{\rm I}$).
2. An isothermal shock.

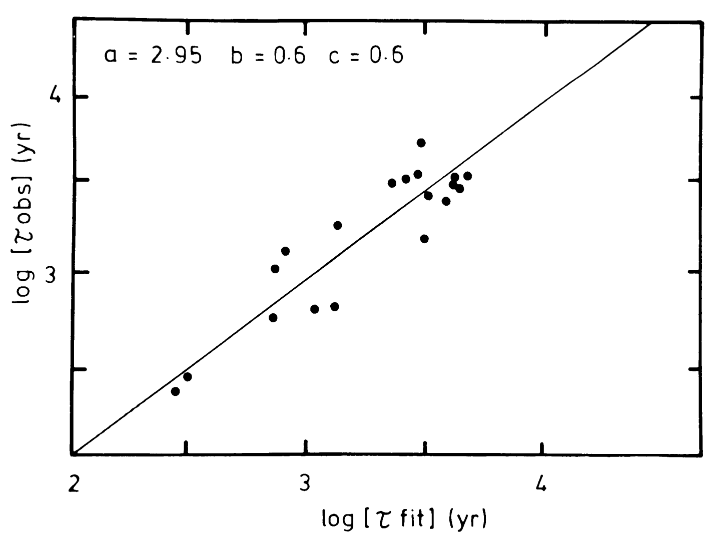

FIG. 3.—The correlation between the observed dynamical age and the least-squares fit dynamical age given by eq. (3.2) with $a = 2.95$, $b = 0.6$, and $c = 0.6$. All objects in the LMC and SMC for which diameters have been directly measured are shown. This shows that momentum varies at $t^{5/3}$.

3. A thin layer of shock-compressed isobaric un-ionized material (number density n_{I}, temperature T_{I}).
4. A weak D-type ionization front.
5. A shell of isobaric ionized gas, number density n_{II}, temperature T_{II}, which absorbs all the ionizing photons from the PNn.
6. A contact discontinuity between the ionized gas and shock-heated stellar wind gas.
7. A layer of shock-heated stellar wind gas.
8. A stellar wind shock.
9. A zone of undisturbed stellar wind gas about the PNn.

(See, for example, Dyson 1981; Kahn 1983; Kwok and Volk 1985; Volk and Kwok 1985). If the total energy content in the zones 3–7 inclusive of thermal energy, kinetic energy, and trapped radiation is assumed to be given by a power law

$$E(t) = E_0 t^{\alpha}, \tag{4.1}$$

and if the radial density distribution in the undisturbed AGB wind is given by

$$\rho(r) = \rho_0 r^{\beta}, \tag{4.2}$$

then, from dimensional considerations, the radius of the outer shock, R_{neb}, is

$$R_{\mathrm{neb}} = A(E_0/\rho_0)^{1/(5+\beta)} t^{(2+\alpha)/(5+\beta)}, \tag{4.3}$$

and the velocity of expansion, V_{exp}, is given by

$$V_{\mathrm{exp}} = B(E_0/\rho_0)^{1/(5+\beta)} t^{(\alpha-\beta-3)/(5+\beta)}, \tag{4.4}$$

where A and B are dimensionless constants.

For a steady AGB wind, $\beta = -2$, and the mass swept up is therefore proportional to R_{neb}. However, the observable is the ionized mass, which does not necessarily show this dependence. From the work of Sabbadin (1986*b*) and Wood (1986), it appears that we can take $M_{\mathrm{ion}} \approx CR^{\gamma}_{\mathrm{neb}}$, where $1 < \gamma < 3/2$. The observed momentum content of the ionized shell, is therefore:

$$M_{\mathrm{ion}} V_{\mathrm{exp}} \approx (A^{\gamma}BC)(E_0/\rho_0)^{(1+\gamma)/(5+\beta)} t^{(\alpha-\beta+2\gamma-3+\alpha\gamma)/(5+\beta)}. \tag{4.5}$$

However, our observed correlation between momentum and time is the $M_{\mathrm{ion}} V_{\mathrm{exp}} \approx Dt^{5/3}$. For this to be consistent with expression (4.5) with $\beta = -2$ and $1 < \gamma < 3/2$ requires that $6/5 < \alpha < 2$, i.e., that *the energy content of the nebula rapidly increases with time*.

This result puts limits on the possible dependence of the expansion velocity on radius, recalling that this relationship is subject to considerable scatter (Sabbadin and Hamzaoglu 1984; Phillips 1984; Chu *et al.* 1984). Equations (4.3) and (4.4) imply, with $\beta = -2$ and $\alpha = 2$, that $V_{\mathrm{exp}} \propto R^{1/4}_{\mathrm{neb}}$. With $\alpha = 6/5$ we have $V_{\mathrm{exp}} \propto R^{1/16}_{\mathrm{neb}}$. This can be compared with the observational relationship found by Phillips (1984), $V_{\mathrm{exp}} \propto R^{0.22}_{\mathrm{neb}}$, suggesting that the $\gamma = 2$ solution is closer to the truth. In such an accelerating expansion, the contact discontinuity between the shocked stellar wind and the ionized nebular gas is Rayleigh-Taylor unstable, and radial mixing between these two phases is therefore expected.

Can the very steep increase in energy content with time be driven by a stellar wind from the central star? Certainly not on the Kahn (1983) or Kwok and Volk (1985) models, which have a thin photoionized nebular shell and which predict $\alpha = 1$ for a steady wind. Since pressure is energy content per unit volume, and since the photoionized gas at a temperature of $\sim 10^4$ K is in pressure balance with the shocked stellar wind, the ratio of the thermal energy content in these two zones is in the ratio of the volumes occupied by these zones. The fractional thickness of the ionized shell is typically of order 0.15 (Daub 1982; Phillips 1984) and the hot shocked stellar wind gas effectively fills the remainder of the volume (Kahn 1983); therefore, the ratio of shocked stellar wind/photoionized nebula thermal energy is typically 1.5 : 1. For a nebular shell of mass M_{neb}, the total energy content is given by

$$E(t) = M_{\mathrm{ion}} c^2_{\mathrm{II}}/3 + M_{\mathrm{neb}} V^2_{\mathrm{exp}}/2, \tag{4.6}$$

where c_{II} is the sound speed in the ionized gas. Since $M_{\mathrm{neb}} \geq M_{\mathrm{ion}}$ and $V_{\mathrm{exp}} \geq c_{\mathrm{II}}$, the kinetic energy term is dominant. Thus $E(t) \approx 0.5 M_{\mathrm{neb}} V^2_{\mathrm{exp}}$. For the case of a time-invariant stellar wind running into a cloud with a radial density gradient, Kwok and Volk (1985) derive the efficiency of conversion of wind energy into shell energy as $\varepsilon = 3(5+\beta)/(2\beta+7)(\beta+11)$. For $\beta = -2$, $\varepsilon = 1/3$. This is inconsistent with the ratio of 2/3 implied above; however, this difference may be the result of the breakdown of the thin-shell approximation used by Kwok and Volk, for the case where photoionization effects are negligible.

In effect, both the stellar wind parameters and the thickness of the photoionized layer are determined by the properties of the central star. If the stellar wind is radiation pressure driven, the energy input rate will vary as

$$\begin{aligned} \partial\varepsilon/\partial t &= 0.5 m V^2_{\infty} = \varphi(L_*/c) V_{\mathrm{esc}} \\ &= \varphi c^{-1} (GM_*)^{1/2} (4\pi\sigma)^{1/4} L^{3/4}_* T_{\mathrm{eff}}, \end{aligned} \tag{4.7}$$

where φ is a constant of order unity (with $V_{\infty} \approx 3V_{\mathrm{esc}}$; Abbott 1978), c is the speed of light, σ is Stefan's constant, and M_*, L_*, and T_{eff} are the mass, luminosity, and effective temperature of the PNn, respectively. From Wood and Faulkner (1986), the typical lifetime of a $0.7 M_{\odot}$ PNn at high luminosity is about 1000 yr. Taking $\log L_*/L_0 = 4.1$, $\log T_{\mathrm{eff}} = 4.9$, about 10^{45} ergs of mechanical energy can be deposited by the wind.

Provided that the ionization front is trapped in the swept-up matter, the pressure in the photoionized region and its extent are also determined by the properties of the central star. The pressure in the photoionized region is determined by the stellar wind, and the radial extent of photoionized region is fixed by this pressure and by the number of ionizing photons emitted by the central star. If the inner stellar wind shock occurs at $R = \theta R_{\rm neb}$ the pressure in the photoionized gas, which is in pressure equilibrium with the shocked stellar wind, is given by

$$P = \varphi(L_*/c)4\pi\theta^2 R_{\rm neb}^2 = \mu m_{\rm H} n_{\rm II} c_{\rm II}^2/3, \qquad (4.8)$$

where $\mu m_{\rm H}$ is the atomic weight, and $n_{\rm II}$ and $c_{\rm II}$ are the number density and sound speed, respectively, in the ionized gas. If the number of ionizing photons produced by the central star is S_*, then setting the number of ionizations equal to the number of recombinations in a photoionized shell of thickness ΔR we have, from equation (4.8)

$$\Delta R/R_{\rm neb} = \left[4\pi\left(c\mu m_{\rm H} c_{\rm II}^2\right)^2/(9\beta_{\rm eff})\right]\left(S_*/\varphi^2 L_*^2\right)\theta^4 R_{\rm neb}, \qquad (4.9)$$

where $\beta_{\rm eff}$ is the effective recombination coefficient of hydrogen. Since $T_{\rm eff}$ is high, and varies only slowly through the fading epoch of the central star, we can take $S_* = \text{const } L_*$. The quantity $\Delta R/R_{\rm neb}$ is observed to vary little with $R_{\rm neb}$ for Galactic PN, which implies that $L_* \propto 1/R_{\rm neb}$, approximately. Notice that $\Delta R/R_{\rm neb}$ is a sensitive function of θ. This emphasizes the intimate relation between the position of the stellar wind shock and the observed properties of the photoionized shell. In view of this, the inconsistency between the observed conversion efficiency of stellar wind to shell energy and the Kwok and Volk value may not be severe.

Thus far our discussion has centered on the more readily interpretable momentum/age correlation. What of the expansion velocity/excitation class/Hβ flux correlation? As we have already pointed out, there is no correlation between the dynamical age and the position of a nebula on this correlation. However, despite this, we still believe that the correlation represents an evolutionary relationship. The definition of the excitation class (Morgan 1984) ensures that it is closely related to the Zanstra temperature of the PNn. Furthermore, the Hβ flux should correlate well with the luminosity of the PNn, at least for the optically thick nebulae. The position of a PN on the expansion velocity/excitation class/Hβ flux correlation should therefore depend principally on the properties of the PNn. Since $T_{\rm eff}$ changes rapidly only in the relatively short-lived high-luminosity stage, and since the more massive stars achieve higher $T_{\rm eff}$, the excitation class should reflect the mass of the PNn. More massive PNn fade more rapidly; therefore the lower Hβ fluxes associated with the higher excitation nebulae in Figure 2 is also consistent with the identification of high-excitation nebulae with more massive PNn. The higher expansion velocities seen in this class of nebulae can therefore be interpreted as the consequence of the fact that these stars are more efficient at ionizing the surrounding AGB wind, and so delivering more energy to the nebula. The increase in velocity as Hβ luminosity decreases reflects the evolutionary trend toward higher expansion velocities in older nebulae.

If we accept that the expansion velocity is given by equation (4.4), then the fact that two nebulae at the similar stages of PNn evolution may have widely different dynamical ages implies on or both of two possibilities. Either the assumption of spherical symmetry has broken down, which is certainly the case in the bipolar nebulae, or else E_0/ρ_0 must differ strongly from one nebula to the next as a result of differing initial conditions in the ejected AGB star envelope. Such a variation would go a long way to explaining the considerable scatter in the $V_{\rm exp} : R_{\rm neb}$ relation. The physical explanation of this is probably that the PNn leave the AGB at different phases of the helium flash cycle. Objects which do this following the peak of the helium flash are evolving into a dense shell driven off at low velocity near the peak luminosity, and therefore the initial ionized mass will be low, the acceleration slow, and a given expansion velocity will be reached only at a relatively large radius and ionized mass. On the other hand, objects leaving the AGB between shell flashes will evolve into a low-density wind and rapidly accelerate to a high velocity. The low-velocity sequence discussed by Phillips (1984) and apparent in the work of Chu *et al.* (1984) may be the result of evolution from the AGB near the peak luminosity of the helium shell flash cycle.

V. CONCLUSION

Two new evolutionary relationships have been found to apply to the Magellanic Cloud population of planetary nebulae. These, together with the previously known ionized mass : radius correlation put very strong observational restraints on the possible models to describe the PN evolution.

REFERENCES

Abbott, D. C. 1978, *Ap. J.*, **255**, 893.
Bohuski, T. J., and Smith, M. J. 1974, *Ap. J.*, **193**, 197.
Chu, Y.-H., Kwitter, K. B., Kaler, J. B., and Jacoby, G. H. 1984, *Pub. A.S.P.*, **96**, 598.
Daub, C. J. 1982, *Ap. J.*, **260**, 612.
Dopita, M. A., Ford, H. C., Lawrence, C. J., and Webster, B. L. 1985, *Ap. J.*, **296**, 390.
Dopita, M. A., Meatheringham, S. J., Webster, B. L., and Ford, H. C. 1987, in preparation.
Dyson, J. E. 1981, in *Investigating the Universe*, ed. F. D. Kahn (Dordrecht: Reidel), p. 125.
Henize, K. G., and Westerlund, B. E. 1963, *Ap. J.*, **137**, 747.
Jacoby, G. H. 1980, *Ap. J. Suppl.*, **42**, 1.
Kahn, F. D. 1983, in *IAU Symposium 103, Planetary Nebulae*, ed. D. R. Flower (Dordrecht: Reidel) p. 305.
Kwok, S., and Volk, K. 1985, *Ap. J.*, **299**, 191.
Meatheringham, S. J., Dopita, M. A., Ford, H. C., and Webster, B. L. 1987*a*, in preparation.
______. 1987*b*, in preparation.
Morgan, D. H. 1984, *M.N.R.A.S.*, **209**, 241.
Morgan, D. H., and Good, A. R. 1985, *M.N.R.A.S.*, **213**, 491.
Phillips, J. P. 1984, *Astr. Ap.*, **137**, 92.
Robinson, G. J., Reay, N. K., and Atherton, P. D. 1982, *M.N.R.A.S.*, **199**, 649.
Sabbadin, F. 1986*a*, *Astr. Ap.*, **160**, 31.
______. 1986*b*, *Astr. Ap.*, in press.
Sabbadin, F., Bianchini, A., and Hamzaoglu, E. 1984, *Astr. Ap.*, **136**, 200.
Sabbadin, F., Gratton, R. G., Bianchini, A., and Ortolani, S. 1984, *Astr. Ap.*, **136**, 181.
Sabbadin, F., and Hamzaoglu, E. 1982, *Astr. Ap.*, **110**, 105.
Sanduleak, N., McConnell, D. J., and Philip, A. G. D. 1978, *Pub. A.S.P.*, **90**, 621.

Smith, H. C. 1969, M.A. thesis, University of Virginia.
Stapinski, T. E., Rodgers, A. W., and Ellis, M. J. 1981, *Pub. A.S.P.*, **93**, 242.
Volk, K., and Kwok, S. 1985, *Astr. Ap.*, **153**, 79.
Wood, P. R. 1986, in workshop on The Late Stages of Stellar Evolution, in press.
Wood, P. R., Bessell, M. S. and Dopita, M. A. 1985, *Proc. Astr. Soc. Australia*, **6**, 54.
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, in preparation.

MICHAEL A. DOPITA, STEPHEN J. MEATHERINGHAM, and PETER R. WOOD: Mount Stromlo and Siding Spring Observatories, Australian National University, Private Bag, Woden P.O., ACT 2606, Australia

HOLLAND C. FORD: Space Telescope Science Institute, Homewood Campus, Baltimore, MD 21218

DAVID H. MORGAN: Royal Observatory Edinburgh, Blackford Hill, Edinburgh EH9 3HJ, United Kingdom

B. LOUISE WEBSTER: School of Physics, University of New South Wales, P.O. Box 1, Kensington, NSW 2033, Australia