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LUMINOSITIES AND MASSES FOR THREE CENTRAL STARS OF PLANETARY NEBULAE IN THE MAGELLANIC CLOUDS FROM ULTRAVIOLET SPECTROSCOPY WITH THE *IUE*

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ABSTRACT

Values of $M \sim 1\ M_\odot$, $L \sim 4.5 \times 10^4\ L_\odot$, and $T \sim 1 \times 10^5$ K are determined for central stars of planetary nebulae of known distances. The results follow from *IUE* observations of the continuous spectra of the central stars of three nebulae in the Magellanic Clouds. If the derived value for M approximately equals the C-O core mass in the red giant stage, the mass of the progenitor star is $\sim 4.0\ M_\odot$, and thus $\sim 3\ M_\odot$ were lost, presumably in winds. The stars are still on horizontal tracks and probably have not yet attained maximum temperature; core-envelope separation occurred $\sim$ 2100–4500 years ago. With estimated $m_v \sim 19.5$, they are undetectable in the visible, where they cannot be resolved from the nebulae. With $M_{\rm bol} \sim -6.8$, the stars are remnants of C stars near the theoretical upper luminosity threshold; thus the lack of observed C stars at this bolometric magnitude is probably an observational problem, not a theoretical one. The observed L each are well above the Eddington luminosity for a 0.6 $M_\odot$ star, thus there can be little doubt that the three stars are notably more massive than the value 0.6 $M_\odot$ which, it has been suggested, characterizes the vast majority of planetary nebula central stars and most DA white dwarfs. This discrepancy may arise from selection effects that favor observation of the most luminous nebulae in the Magellanic Clouds, from errors in the distance determinations for galactic planetaries, or from compositional differences in the progenitor stars between the Galaxy and the Clouds. We show that the LMC and SMC are not more than 10% farther away than the distances given by Crampton and by Crampton and Greasley respectively.

Subject headings: mass-luminosity relation — nebulae: planetary — stars: carbon

I. INTRODUCTION

The central stars of planetary nebulae (PN) are currently the subject of much theoretical interest. After a red giant ejects a PN, the stellar core follows a track at nearly constant luminosity in the H-R diagram (Paczynski 1971), evolving toward higher effective temperatures until, finally, nuclear energy sources are exhausted or quenched and the star descends a white dwarf cooling track. The luminosity of the core during normal evolution on the horizontal track is a direct indicator of its mass, and the latter is related by theory to the mass of the progenitor star (Paczynski 1971; Iben 1981; Renzini and Voli 1981).

The masses of the central stars of PN and of white dwarfs into which they evolve are somewhat controversial. From a discussion of available data on objects in the Galaxy, it is reported that the majority of DA white dwarfs have masses in a narrow range ($\pm 0.1\ M_\odot$) around 0.6 $M_\odot$ (Koester, Schulz, and Weidemann 1979) and that the same is true of PN nuclei (Weidemann 1977; Schönberner and Weidemann 1981; Schönberner 1981; Mendez *et al.* 1981). However, Shipman and Sass (1980) find a mean mass for white dwarfs of 0.75 $M_\odot$ and a 1 σ mass range for white dwarfs that extends from 0.5 $M_\odot$ to 1.0 $M_\odot$. Stellar evolution calculations provide no strong rationale for a narrow range in core mass among the PN progenitors, and observational data on PN nuclei luminosities are affected by the considerable uncertainty in the distances of most objects.

[1]Guest Observer, *International Ultraviolet Explorer*.

TABLE 1

DERIVED PROPERTIES OF PLANETARY NEBULA CENTRAL STARS

Property	LMC P40	SMC N2	SMC N5	Dimensions
Extinction at Hβ, c	0.19	0.14	0.23	
Color excess, $E(B-V)$	0.13	0.097	0.16	
Nebular hydrogen emission, log F(Hβ)	−12.79	−12.67	−12.81	flux in ergs cm^{-2} s^{-1}
Nebular helium emission,[a] log F(λ1640)	−12.00	−11.84	−12.09	flux in ergs cm^{-2} s^{-1}
Stellar continuum emission,[a] log F(λ1640)	−14.40	−14.10	−14.22	flux in ergs cm^{-2} s^{-1} Å^{-1}
Stellar radius, R_*	0.70	0.67	0.67	$R_\odot$
Surface gravity, log g	4.84	4.74	4.84	acceleration in cm s^{-2}
Zanstra temperature, $T_{\rm eff}$	1.0	0.95	1.0	10^5 K
Luminosity, L_*	4.47	3.30	4.10	10^4 $L_\odot$
Absolute bolometric magnitude, $M_{\rm bol}$	−6.88	−6.55	−6.79	
Apparent visual magnitude, m_v	19.76	19.55	19.09	
Mass, M_*	1.2	0.90	1.1	$M_\odot$
Zanstra parameter, Q(228, 1640)	0.30	0.16	0.23	

[a]Flux at the Earth, with the effect of interstellar reddening removed.

Each of the Magellanic Clouds offers a substantial sample of PN at essentially the same distance from the Sun. The distances of the Clouds are relatively well determined and therefore the absolute luminosities as well as the relative luminosities of their PN and associated central stars can be measured. In Maran *et al.* 1982, hereafter Paper I) we reported UV spectroscopy of three high-excitation PN in the Clouds (LMC P40, SMC N2, and SMC N5) and discussed their composition and properties derived from ionization models fitted to the measured UV and visible wavelength lines. We found that locally synthesized C had been dredged up in the progenitor stars of the PN; with abundance ratio $N(\mathrm{C})/N(\mathrm{O}) \sim 2$ in each of the PN, these objects were C stars. Here, we discuss parameters of the central stars of P40, N2, and N5 determined from their UV continua, as measured with the *International Ultraviolet Explorer* (*IUE*), and from the emission-line data described in Paper I.

The analysis of UV continua requires careful attention to interstellar extinction. Account must be taken of substantial differences in the mean extinction laws for the Galaxy, the LMC, and the SMC that have been reported by independent groups of *IUE* observers, cited below. (Extinction in the Clouds typically is much larger than foreground galactic extinction.) However, the Zanstra temperature can be determined independently of extinction from the ratio of line and continuum fluxes at the same wavelength, λ1640.

II. OBSERVATIONS

The UV spectra were obtained in 1981 May 23 and 26 as described in Paper I, where the year is wrongly given as 1980. An analysis of the emission lines is reported there. Continua were detected with the *IUE* short-wavelength spectrograph in the spectra of all three sources and with the long-wavelength spectrograph in the spectrum of P40.

Our longest exposure, a 320 minute observation of P40 (Fig. 1, Plate L1) yielded the best continuum data, and, therefore, the discussion in § III is based on the P40 results. Weaker continua measured in the spectra of N2 and N5 yield similar results by identical analytical procedures (Table 1), but the data are poorer and new spectra with longer exposure times would be helpful. The N2 and N5 emission line data are, however, excellent and indicate that the ionizing sources are comparable in radius and temperature to the P40 central star, which lends confidence to the present results.

The interstellar extinction is derived from the ratio of the λλ1640, 4686 He II lines (Paper I). A new reduction of the *IUE* line data gives improved λ1640 line fluxes for two PN as follows: P40, 4.5×10^{-13} ergs cm^{-2} s^{-1}; N5, 2.1×10^{-13} ergs cm^{-2} s^{-1}. The revised logarithmic extinctions at Hβ are then $c = 0.19$ and $c = 0.23$ respectively. For N2, $c = 0.14$ as in Paper I. The observed UV continua were corrected for reddening in the LMC and the SMC using the respective extinction laws of Nandy *et al.* (1981) and Rocca-Volmerange *et al.* (1981). The independent determinations by Koornneef and Code (1981) for the LMC and by Hutchings (1982) for the SMC are in reasonable agreement with the adopted extinction laws.

III. ANALYSIS OF ULTRAVIOLET SPECTRA

We discuss briefly the determination of stellar parameters.

Stellar continuum.—The observed continua are composites of stellar and nebular contributions, as the PN are not resolved spatially. The stellar component

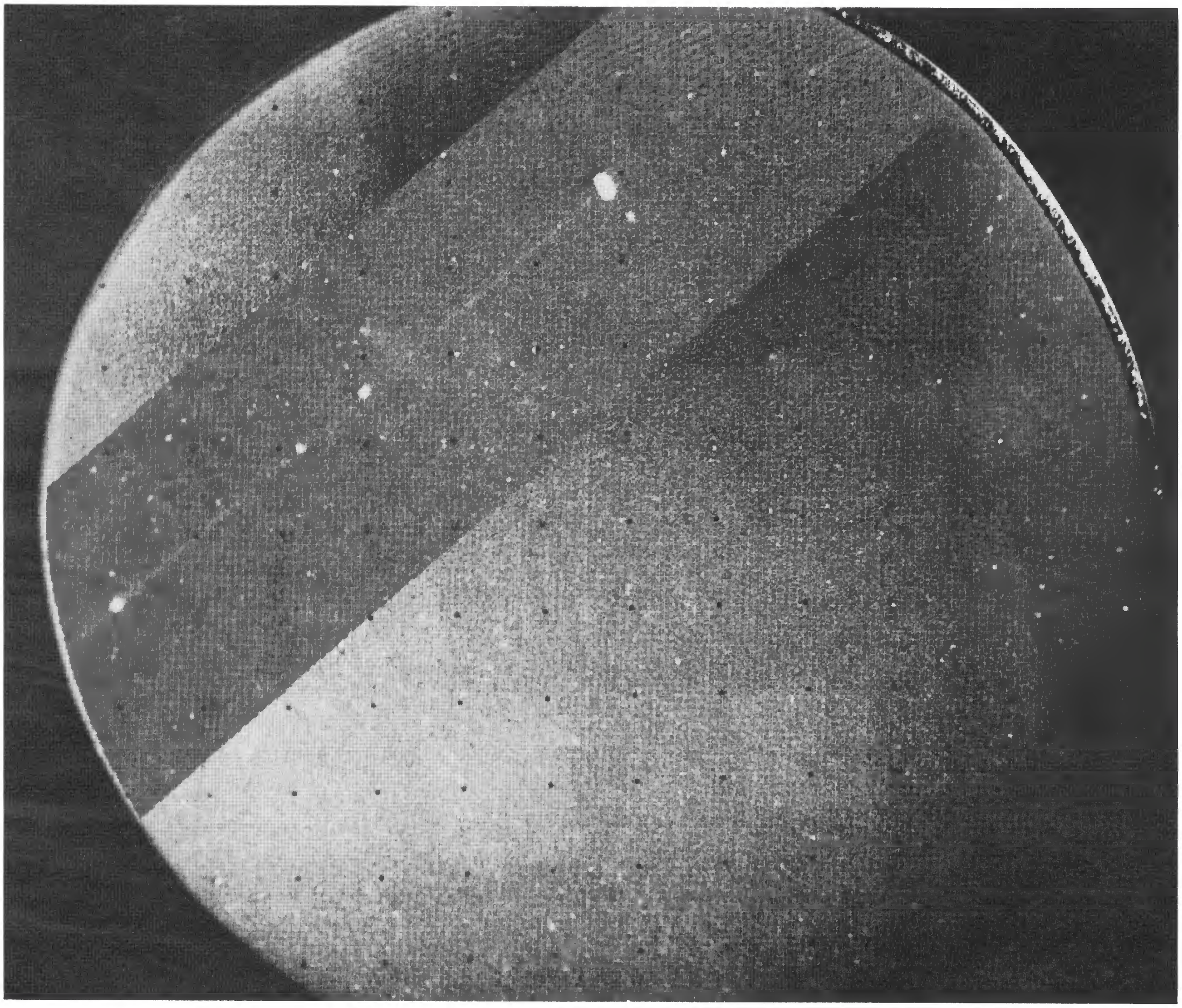

FIG. 1.—UV spectrum of LMC P40, obtained with the *IUE* short-wavelength spectrograph. The exposure time for this observation (SWP 14032) was 320 minutes. Wavelength increases from upper right to lower left. The four strongest emission lines are geocoronal Lyα (*upper right*), C IV λ1550, λ1640 He II, and λ1909 C III] (*lower left*). A continuum is seen extending from Lyα to longward of λ1909. Reproduced from a reduced *IUE* "Photowrite" transparency, in which the photometric scale has been linearized and geometric corrections have been applied. Correction for the wavelength-dependent instrumental response has not been made here.

STECHER *et al.* (*see* page L42)

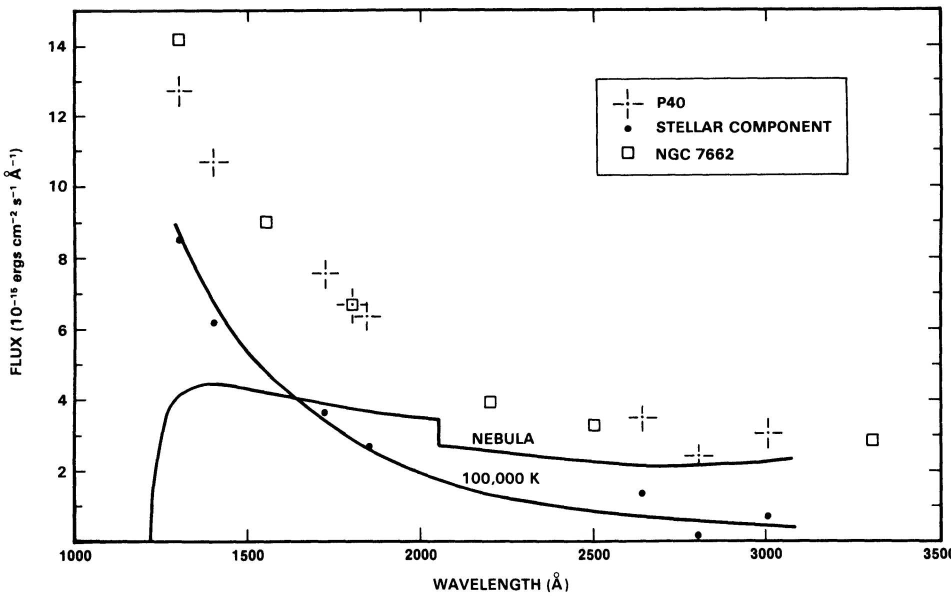

FIG. 2.—Derivation of the intrinsic stellar continuum of LMC P40. Data points identified as "P40" represent the observed continuum fluxes, corrected for instrumental response and interstellar extinction. Similar data for NGC 7662 (Harrington *et al.* 1982) are shown. A hydrogen emission continuum, scaled to represent the nebular contribution according to the observed nebular Hβ line flux, is shown and has been subtracted from the "P40" points to yield the stellar fluxes. A solid curve representing blackbody emission at 100,000 K is shown for comparison.

dominates at shorter wavelengths only. Since the observations of P40 are most secure, the discussion will concentrate on this object. We model the nebular component as the sum of H^0 two-photon emission and Balmer continuum radiation (Bohlin, Harrington, and Stecher 1978, hereafter BHS), using the flux distribution computed for the high-excitation PN NGC 7662 (which has a similar emission-line spectrum) by Harrington *et al.* (1982), scaled to the P40 Hβ flux. This quantity (Osmer 1976), corrected for extinction, is $\log I(\mathrm{H}\beta) = -12.60$, where the flux is in ergs cm^{-2} s^{-1}. Subtracting the nebular component from the extinction-corrected continuum yields the observed intrinsic stellar continuum shown in Figure 2.

Effective temperature.—The derived stellar continuum is in the Rayleigh-Jeans regime; we compare it with blackbody flux distributions and estimate $T_{\mathrm{eff}} = 100{,}000$ K, consistent with the resemblance of the line spectrum (Paper I) to that of NGC 7662 (BHS; Harrington *et al.* 1982). A 100,000 K blackbody spectrum is matched to the data in Figure 2.

Zanstra temperature.—We compare observed and theoretical ratios of $Q(\lambda_1, \lambda_2)$, the ratio of the number of ionizing continuum photons beyond λ_1 and the continuum flux at λ_2. The observed ratio, 0.30, for the He II/continuum ratio $Q(228, 1640)$ is taken from the measured ratio of the λ1640 emission line to the local continuum and so is independent of the extinction law. (We derived the extinction at λ1640 from the ratio of the observed lines at λ1640 and λ4686; the error in this ratio due to uncertainties in subtracting the weak local continua is very small. To find the λ1640 stellar flux, the unreddened nebular flux at λ1640 was calculated from the unreddened Hβ line flux. At Hβ, the reddening correction is not very sensitive to the choice of extinction law. Thus, the Zanstra temperature is likewise insensitive. Note, however, that, if the galactic extinction law had been applied to derive the stellar continuum of Figure 2, the flux at the shortest wavelength would be about 30% smaller than shown.) We assume that He^+ is the only absorber below λ228. From Figure 4 of Bohlin, Harrington, and Stecher (1982), for the Hummer and Mihalas (1970) models with normal He/H ratios, we find for $5 < \log g < 7$ that $93{,}000 \text{ K} < T_{\mathrm{eff}} < 108{,}000$ K, with higher temperatures (by about 10,000 K) for He-rich atmospheres computed by Wesemael *et al.* (1980). Thus, within the uncertainties in $\log g$, a Zanstra temperature of 10^5 K is compatible with the continuum flux shown in Figure 2 and with the estimated $\log g$ suggested below.

Stellar radius.—The nebular model yields a predicted Hβ flux that, for fixed temperature, is proportional to $(R_*/D)^2$. (D is the distance of the exciting star of radius R_*.) For P40 we take distance modulus $m - M = 18.63$ (Crampton 1979), while for the SMC, $m - M = 19.1$ (Crampton and Greasley 1982). Then $R_* = 0.76$ $R_\odot$, 0.67 $R_\odot$, and 0.72 $R_\odot$, respectively, for P40, N2, and N5, as computed with the Cassinelli (1971) $T =$

95,066 K model. For consistency with $T_{\rm eff} = 10^5$ K for P40 and N5, the radii of these stars should be reduced by a factor of 0.927 to 0.70 $R_\odot$ and 0.67 $R_\odot$ respectively. The radius also depends on the nebular filling factor.

Luminosity.—From the effective temperature and the stellar radius (since $L = 4\pi R^2 \sigma T_{\rm eff}^4$), the luminosity $L_* = 4.47 \times 10^4\ L_\odot$ for P40, or since $M_{\rm bol}({\rm Sun}) = 4.75$, $M_{\rm bol} = -6.88$.

Mass.—A minimum mass can be estimated from the Eddington limit for a PN central star (Kutter and Savedoff 1969),

$$L_{\rm edd} = \frac{4\pi GMc}{\kappa} = 10^{4.11}\left(\frac{ML_\odot}{\kappa M_\odot}\right). \qquad (1)$$

In computed models, at vanishing optical depth, the opacity approaches $\kappa_{\rm es} = 0.199(1 + X)$ where X is the hydrogen mass fraction. The minimum mass then follows from the measured luminosity; for $X = 0$, $M > 0.690\ M_\odot$, while for normal abundances ($X = 0.772$, Cameron 1982), $M > 1.16\ M_\odot$. Since the LMC and SMC PN show no enhanced He compared to the Sun, the latter value is an appropriate estimate of the minimum mass of the P40 central star. It also agrees with $M_* = 1.2\ M_\odot$, estimated from L_* and $T_{\rm eff}$ compared with theoretical tracks in the H-R diagram as noted in the paragraph below on the initial mass.

Surface gravity.—Since $M_{\rm edd} \sim \kappa L$, the stellar surface gravity must be $\log g > 4.586 + 4 \log T_5 + \log(1 + X)$ (Wesemael *et al.* 1980). For $X = 0.772$, $\log g > 4.835$, while for $M = 1\ M_\odot$ and $R = 0.70\ R_\odot$, $\log g = 4.75$, documenting the conservative choice we have made for M_*.

Absolute flux.—Since we estimate $R_* = 0.70\ R_\odot$ and $T = 10^5$ K, from the known distance we have the means, via the Hummer and Mihalas (1970) model atmosphere no. 201, to compute the absolute flux in the continuum at λ1640. Alternatively, the two models, one for the PN sensitive to $\lambda < 912$ Å (for the flux at Hβ) and the other for the stellar atmosphere (which predicts the continuum at λ1640) are inconsistent with $T_5 = 1$. For $F({\rm H}\beta) \sim T^3$ and $F(\lambda 1640) \sim T$, we estimate compatibility at $T = 1.14 \times 10^5$ K, a temperature indistinguishable from 1.00×10^5 K in the data of Figure 2. The models allow us to estimate the unreddened stellar flux at λ5475, the effective wavelength of the V system: $F(V) = 4.88 \times 10^{-17}$ ergs cm^{-2} s^{-1} Å^{-1}. Then, for $A_v = 0.40$ mag for P40 [corresponding to $c = 0.19$, $E(B - V) = 0.13$, and $R = 3.1$], $m_v = 19.76$ for the Hayes and Latham (1975) calibration. Thus these stars are the faintest visual objects measured by UV spectroscopy.

Initial mass.—Recent models cover evolution from the asymptotic giant branch through mass loss (in winds) and on to the onset of PN formation. From the assumption that the observed L_* is substantially the same as that at the rapid mass loss phase we can find the likely nature of the progenitor star. From Figure 8 of Renzini and Voli (1981), we estimate the initial mass $M_i = 3.7\ M_\odot$, core (= present) mass $M_c = M_* = 1.2\ M_\odot$, and mass in PN plus central star $M_T = 2.55\ M_\odot$ or $2.03\ M_\odot$ depending on the assumed boundary condition (case A or case B). In comparison, from Figure 1 of Iben (1981) we estimate $M_i = 4\ M_\odot$, $M_* = 1.13\ M_\odot$, and $M_T = 2.7\ M_\odot$. Both the Renzini-Voli theory and the Iben theory yield $M_c > M_{\rm edd}$, but the total mass that each predicts is larger than $M_{\rm edd} + M_{\rm PN}$ or $M_* + M_{\rm PN}$. ($M_{\rm PN} \sim 0.33\ M_\odot$.) The theories encompass larger PN masses than those applicable here or indeed those generally observed.

Expansion age.—The radius of nebula P40 is 0.091 pc (the model computed in Paper I has been corrected to take account of R_* determined above and the Crampton 1979 distance modulus). For an assumed expansion velocity of 20 km s^{-1}, appropriate to young PN (Bohuski and Smith 1974), the present age of the nebula, $t_{\rm exp}$, is 4450 years. For N2 and N5, the revised radii are 0.043 pc and 0.092 pc, and the ages are 2100 and 4500 years.

Stellar parameters were computed for the nuclei of N2 and N5 in the same way as for P40 and are listed in Table 1.

IV. DISCUSSION

The distances of the Magellanic Clouds are more reliably known than the distances of galactic PN. The latter may individually be uncertain by factors of 2. Thus, it would appear that the masses of $\gtrsim 1\ M_\odot$ derived for the three stars discussed above establish with some confidence the existence of specific PN nuclei significantly more massive than 0.6 $M_\odot$. The luminosities are well above $L_{\rm edd}(M = 0.6\ M_\odot)$ for any composition. Can the stellar mass estimates, M_*, be in error? If unspecified events had recently disturbed the stars so that the observed luminosities, L_*, do not represent the quasi-equilibrium luminosities treated in the Iben (1981) and Renzini and Voli (1981) evolutionary scenarios, L_* may be higher than the luminosities described by the mass-luminosity relation. This follows since the thermal relaxation time, $t_{\rm kel} \sim \kappa M/4\pi Rc \sim 4000$ yr, for a mean opacity $\kappa \sim 1$ cm^2 g^{-1} over the star, and thus is comparable to the estimated ages of the PN. However, if only the atmosphere is disturbed, the relaxation time is smaller. Thus, since $M_{\rm edd}$ depends on a dynamical argument, we establish $M > M_{\rm edd}$, but the relation between L_* and M_* depends partially upon the details of recent processes and may not be reliable.

Kaler (1982) recently analyzed a large sample of PN nuclei in the Galaxy and found several objects well above 0.6 $M_\odot$, but the individual determinations are not very accurate because of uncertainty in the distances.

The nucleus of the PN A63 is an eclipsing binary star, with a likely mass of 0.9 $M_{\odot}$ (Bond, Liller, and Mannery 1978). In the PN A46, the mass of the nucleus (also a binary member) may be as large as 1.1 $M_{\odot}$ (Bond 1982). The two available observational procedures most likely to give accurate masses for individual PN nuclei, the study of eclipsing binary stars and the application of the mass-luminosity relation to stars of known distance, confirm the existence of central stars with $M \sim 1\ M_{\odot}$.

Selection favors the observation of luminous PN in the Clouds, since PN surveys are limited primarily by brightness in the Clouds (Jacoby 1980), but surveys in the Galaxy tend to select unobscured, high-density PN. The central stars discussed here may be among the most massive ones in the LMC and SMC.

Although stellar evolution theory predicts the formation of C stars with a bolometric magnitude of -6.50 (Iben 1981), none that bright are observed (Cohen *et al.* 1981). However, the three central stars discussed here have $M_{\text{bol}} \sim -6.8$, and therefore their predecessor red giants had $M_{\text{bol}} \sim -6.8$. The red giants were C stars, since the ejected envelopes, observed as PN, have $N(\text{C})/N(\text{O}) \sim 2$ in the gas phase (Paper I). Perhaps C stars so luminous are veiled by grains formed from the high-C content (Iben 1981), or their appearance is distorted by mass loss. Radiation pressure on the grains may cause them to be ejected along with the envelope gas which is well coupled to the grains (Krishna Swamy and Stecher 1969; also see Kwok 1980). An ionized nebula would then develop from the ejecta.

According to Iben and Renzini (1982), the fading time (during which the stellar luminosity drops to one-tenth of its value at the time when $T_{\text{eff}} \approx 30{,}000$ K and significant nebular ionization can occur [Paczynski 1971]) varies as $t_f \sim M^{-9.6}$, where $t_f = 15{,}000$ yr for $M = 0.6\ M_{\odot}$. For the P40 central star, with $M_* \sim 1.2\ M_{\odot}$, $t_f \sim 20$ yr! However, if $M_{\odot} = 0.90\ M_{\odot}$, $t_f \sim 300$ yr. The interval from core-envelope separation to maximum core temperature is much longer than t_f. For stars as massive as those considered here, the short duration of t_f ensures that the number detectable as PN nuclei on their horizontal tracks at any one time must be small.

Note that an extreme upper limit on the distances of the Clouds can be derived by pretending that the observed stars are actually the brightest conceivable C-O cores, namely objects at both the Chandrasekhar mass limit and the corresponding Eddington luminosity limit (for $X = 0.772$). In that case, the theoretical luminosity, compared with the observed L_*, would require that the distance moduli of the LMC and SMC be increased by ~ 0.18 mag from the Crampton (1979) and Crampton and Greasely (1982) values. The Magellanic Clouds, then, are no more than 1.08 times more distant than presently believed.

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