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EXTREMELY ENERGETIC PLANETARY NEBULAE IN THE LARGE MAGELLANIC CLOUD

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ABSTRACT

Highly energetic planetary nebulae have been identified in the Large Magellanic Clouds. These have higher expansion velocities than any of their galactic counterparts and appear to show directed expansion flows rather than having a spherically symmetric expanding shell. Comparison of their properties with similar, but less extreme, galactic planetaries suggests that these objects are highly luminous bipolar type I planetaries in which the central star is undergoing continued energetic mass loss but which is nevertheless insufficient to supply the energy and momentum of the nebula. We expect this class of objects to represent the upper end of the mass range of precursor stars which are able to evolve to the planetary nebula phase, and we present circumstantial evidence connecting them with the symbiotic stars.

Subject headings: galaxies: Magellanic Clouds — nebulae: planetary — stars: combination spectra

I. INTRODUCTION

The physical mechanisms which dominate the ejection and subsequent expansion of planetary nebulae are by no means fully understood. For example, during the asymptotic giant branch (AGB) evolution, it is likely that mass-loss rates are very high, but the cause of this is not yet certain (Wood and Cahn 1977; Renzini and Voli 1981; Renzini 1981*a*, *b*; Wood and Faulkner 1984).

Following the ejection of a massive shell, the subsequent evolution of expansion velocity and diameter is moderated by processes such as photoionization, resonance line trapping, radiation pressure on gas and grains, and the effects of a residual high-velocity white dwarf stellar wind on the ionized material.

For galactic planetaries, much attention has been given to expansion velocity/diameter correlations. However, these correlations are still capable of different interpretations. For example, Kwok, Purton, and Fitzgerald (1978) and Kwok (1982) suggest that both fast winds in the nebular phase and radiation pressure accelerate the expansion, a conclusion supported by an apparent dependence of expansion on mass of the central star (Robinson, Reay, and Atherton 1982; Phillips 1984). However, Sabbadin *et al.* (1984) argue for a model in which a high-velocity shell is ejected in a short time scale during the AGB evolution into a slower precursor wind and that this structure is subsequently made visible by photoionization during the planetary phase.

We have recently undertaken an extensive program to study the kinematics and dynamics of the Magellanic Cloud planetary nebulae. One aim of this project is to help disentangle the relative importance of these processes. Already, our study of the Small Magellanic Cloud objects has shown a good correlation between expansion velocity and excitation class (Dopita *et al.* 1985). We interpret this finding as indicating that the mass of the central star is a major determinant in the energetics of the nebular shell. This paper describes our results on three objects, classified as planetary nebulae in the Large Magellanic Cloud (LMC), which deviate markedly from the correlation in the high-velocity sense. These seem exceptional, rather than just being a tail of some distribution, and we shall present evidence to suggest that their white dwarf nuclei are among the most massive allowed by stellar evolution theory and are characterized by strong, continuing, high-velocity mass loss.

II. OBSERVATIONS

For our high-resolution work, we have used two telescopes, instruments, and photon-counting detector systems. On the 1 m telescope operated by the Australian National University we used the Perkin-Elmer echelle spectrograph with the two-dimensional photon counting array (2DPCA) (Stapinski, Rodgers, and Ellis 1981). Our observations on the 3.9 m Anglo-Australian Telescope (AAT) were made with the Royal Greenwich Observatory (RGO) spectrograph using the image photon counting system (IPCS) (Boksenburg 1972) at the focus of the 82 cm camera. The reduction procedure is described elsewhere (Dopita *et al.* 1985). Suffice it to say that the instrumental resolution of the two systems is almost identical (11.5 km s^{-1} for the 1.0 m telescope; 11.75 km s^{-1} for the 3.9 m FWHM).

The low-resolution spectrophotometric data on SMP 83 had previously been obtained on the AAT using the image dissector scanner (IDS) (Robinson and Wampler 1972). Data on all three objects had also been obtained using the IPCS on the RGO spectrograph with its 25 cm camera. The observing and reduction procedures are identical to those described by Webster and Smith (1983), except that a circular aperture was used for the SMP 83 observations in the place of the slit. This allowed all the nebular light to enter the spectrograph.

III. RESULTS AND DISCUSSION

Among the 44 planetaries we have observed in the SMC and the 88 we have already observed in the LMC, only three

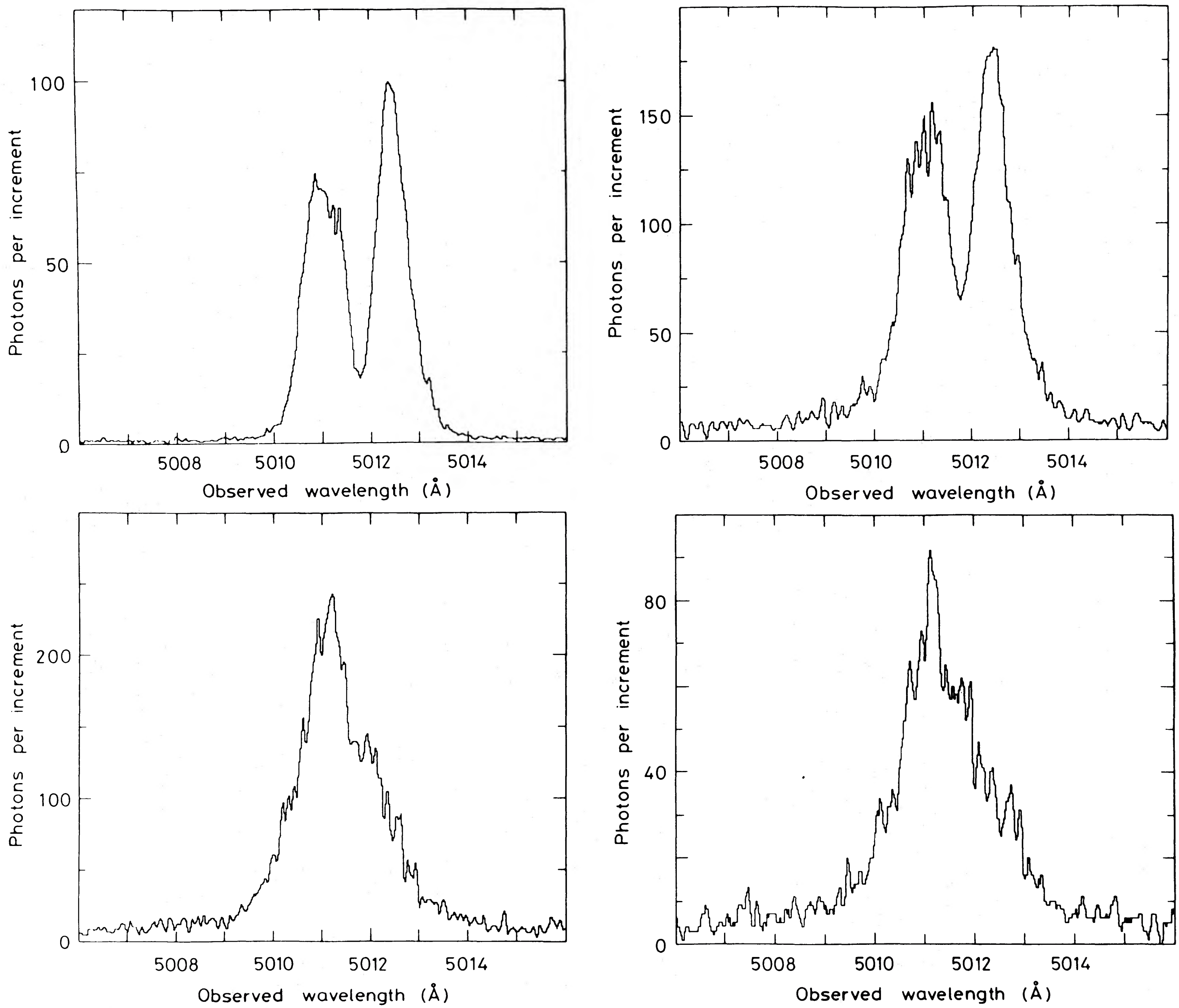

FIG. 1.—[O III] line profiles of SMP 11 and 83 (WS 35) as observed on the AAT 3.9 m telescope and MSSSO 1 m telescope. Full width at half-maximum is shown by a bar.

objects stand out as having extraordinary internal dynamics. In the catalog of Sanduleak, McConnell, and Phillips (1978) these have numbers SMP 11, 83, and 94 are all in the LMC. The object SMP 83 is also identified as N66, LM1 52, and W5 35 in the catalogs of Henize (1956), Lindsay and Mullan (1963; Table 1), and Westerlund and Smith (1964), respectively. The planetary SMP 94 is also known as S170 and LM2 44 in the catalogs of Henize (1956) (who classified it as a stellar object) and of Lindsay and Mullan (1963; Table 2).

For two of these objects, good quality line profiles have been obtained at [O III] λ5007 with both telescopes, and we present these in Figure 1 to allow the reader to judge the reality of the weaker features. SMP 83 shows a two-component profile with a projected expansion velocity of 105 km s^{-1} (as defined in Dopita *et al.* 1985), whereas SMP 11 has an expansion velocity of 98 km s^{-1}. The outermost real components spread over some 225 km s^{-1} in the case of SMP 83, and 250 km s^{-1} for SMP 11. For SMP 94, only a low signal-to-noise profile has been obtained under very poor observing conditions on the 1 m telescope, and so SMP 94 is not presented here. However, this shows evidence for a four-component structure in which the outer components equal or exceed a velocity of expansion of 100 km s^{-1}.

These velocities are extraordinarily large, and exceed anything found in the rest of our sample by some 40 km s^{-1}. To emphasize the peculiar position of these planetaries, we have plotted them in Figure 2 on the expansion velocity/excitation class correlation found by Dopita *et al.* (1985) for the SMC. The solid line is the SMC correlation, and the dashed lines enclose all SMC planetaries. From our as yet unpublished data we have no reasons to suspect that the overall LMC correlation is any different. Clearly, the motions in these planetaries are a factor of 2 larger than that which would be consistent with their excitation class.

In order to better understand this phenomenon, we shall now discuss each object in turn.

a) LMC SMP 83 (WS 35)

The spectrophotometry of this planetary, along with the others, is given in Table 1. From these data and others available in the literature, we give a summary of its properties in Table 2. The strength of the [Ne V] and He II lines suggests a stellar temperature well in excess of 10^5 K (Webster 1976*a*).

As pointed out by our referee, the [Ne V] line intensity with respect to Hβ is very strongly geometry dependent (Koppen 1983). With favorable geometry, such as a filled uniform sphere, a lower limit of order 1.15×10^5 K is indicated. However, if the ionized material is confined to a shell, as is more likely the case in this nebula, the true temperature may be as high as 1.8×10^5 K. In any event, we regard these estimates of the stellar temperature to be a more reliable value than the He^{++} Zanstra temperature which relies on an uncertain continuum measurement. Indeed, there is little evidence that the optical continuum arises from anything other than the

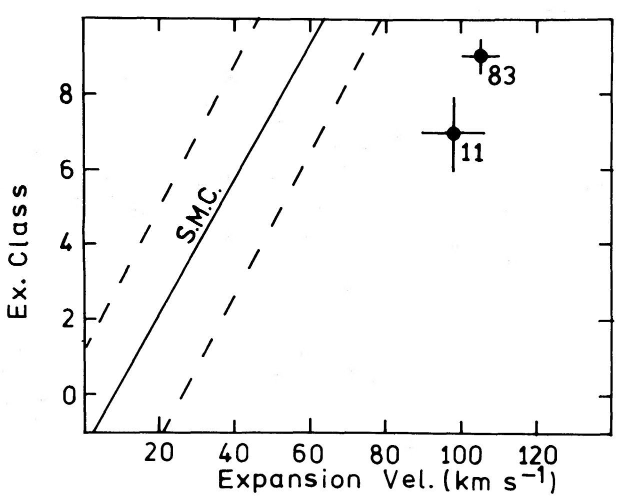

FIG. 2.—Expansion velocity of SMP 11 and 83 compared with the expansion velocity/excitation class correlation found by Dopita *et al.* (1985) in the SMC. Dashed lines enclose all observed objects in the SMC.

TABLE 1

SPECTROPHOTOMETRIC RESULTS

λ	ION	OBJECT NAME SMP 11	SMP 83	SMP 94
3426	[Ne V]	...	195 b	20 b
3727, 9	[O II]	...	107 b	<3
3868	Hβ, [Ne III]	...	90 b	11 b
3969	[Ne III]	...		20 a
4340	Hγ	...	52 a	50 a
4363	[O III]	...	18.7 b	9.1 b
4686	He II	50 c	68 b	62 a
4712	He I, [Ar IV]	...	6.5 c	2 c
4740	[Ar IV]	...	6.1 c	1 c
4861	Hβ	100 c	100 a	100 a
4959	[O III]	130 b	262 a	18 a
5007	[O III]	440 b	791 a	54 a
5876	He I	...	5.4 c	7 b
6563	Hα	...	285 a	371 a
6584	[N II]	...	125 c	<2
6717	[S II]	...	17 b	<2
6731	[S II]	...	17 b	<2

NOTES.—Fluxes given with respect to $I(H\beta) = 100.0$. Corrected for reddening. Quality: a, <10% error; b, 10%–20%; c, 20%–40%.

TABLE 2

PARAMETERS OF SMP 83 (WS 35)

Stellar Parameters:			
Luminosity of central star	$6 \times 10^4 L_\odot$		
Temperature of central star			
He^{++} Zanstra temperature	8×10^4 K		
Excitation temperature	1.5×10^5 K		
Inferred mass of central star	1.2–1.3 $M_\odot$		
Hydrogen burning	1.2–1.3 $M_\odot$		
Helium burning	0.8–0.9 $M_\odot$		
Nebular Parameters:			
Excitation class (Feast 1968 System) ... (see Morgan 1984)	9		
log flux in Hβ	-12.65 ergs cm^{-2} s^{-1} mean		
Electron temperature	1.6×10^4 K		
Mean Electron Density			
[Ar IV] lines	10^4 cm^{-3}		
[O II] lines	3×10^3 cm^{-3}		
Inferred nebular mass	0.35 $M_\odot$		
Inferred nebular diameter	0.19 pc		
Approximate Nebular Abundances:[a]			
Abundance by number	He/H	O/H	N/O
SMP 83	0.11 ± 0.03	2.2×10^{-4}	0.65
⟨LMC⟩	0.11	2.7×10^{-4}	0.1

[a] Derived from nebular model with blackbody central star and uniform density.

nebular processes. The absolute He II $\lambda4686$ flux is the largest measured, implying a very luminous central star. The luminosity derived, $6 \times 10^4\ L_\odot$, makes this perhaps the most luminous and among the hottest of the planetary nuclei in the Clouds, although WS 40 may rival it (Stecher *et al.* 1982). With the Paczyński (1971) evolutionary tracks, a mass of 1.2–1.3 $M_\odot$ is predicted for the central star.

As far as the nebular abundances are concerned, the oxygen abundance is normal for an LMC planetary, while the nitrogen shows a factor of 6 enhancement. This puts SMP 83 in the class of type I planetaries, the group defined by Greig (1971) and Peimbert (1978) as typified by high nitrogen and helium abundances, and usually by hot central stars and bipolar morphology.

There is a fascinating suggestion by Sanduleak (1977) that SMP 83 may vary irregularly over 0.9 mag. However, its spectrum is unlike any symbiotic or emission-line star, and the gross features of its spectrum are apparently invariant over the last 20 yr.

Since the nebular spectrum is strongly dominant over the stellar continuum, such variability cannot be ascribed to the star itself. For the nebula, the minimum time scale of variability is set by the recombination time scale $\sim 10^4/n_e$ and the light travel time across the nebula. These are of order 3 and 1 yr, respectively. However, such nebular variations would imply enormous fluctuations in the light of the central star, for which there is no known theoretical cause. Until such variability can be confirmed, we think it more likely that an instrumental or identification problem is the source.

Although SMP 83 is unresolved, the [O III] line profile strongly suggests a bipolar morphology, since spherically symmetric expanding gas shells produce single-component line profiles, whereas the observed line profile is clearly split into two components separated by 85 km s^{-1}. Such a well-defined splitting requires that the majority of the emitting gas is moving in two oppositely directed streams which, from their separation in velocity, may well be seen in a nearly "end-on" orientation.

The nebular mass of SMP 83 can be estimated from the absolute Hβ flux and the density, knowing the distance and the electron temperature. However, the density from the [Ar IV] doublet differs from that given by the [O II] doublet (Table 2). Indeed, the density of the two lobes differs. From our [O II] profile we find that the approaching lobe has a density of 4800 cm^{-3}, whereas the receding lobe has a density of 1200 cm^{-3}. A systematic difference between [Ar IV] densities and [O II] densities was found by Webster (1976*b*) for a large sample of planetaries, and she showed that the [O II] density is more reliable for the estimation of nebular mass.

The high density derived for the [Ar IV] zone is characteristic and seems to have its origin more in uncertain atomic physics than in any intrinsic property of planetary nebulae. Czyzak *et al.* (1980) point out that other observed line intensity ratios are quite inconsistent with theory, and this may result from poorly determined collision strengths or transition rates. SMP 83 appears to fall on the Webster relationship, so we have used the [O II] density to derive the mass given in Table 2 (0.35 $M_\odot$).

In fact, SMP 83 is certainly centrally condensed. The diameter determined by Speckle interferometry in the [O III] line is only 0.081 pc (Wood, Bessell, and Dopita 1985). If this figure is combined with the Hβ flux, a lower limit for the nebular mass is established at 0.07 $M_\odot$.

b) LMC SMP 94

Compared with the previous object, the most striking feature of the spectrum presented in Table 1 is the complete absence of low excitation lines, [O II], [N II], [S II], and so on, and the remarkably weak [O III] lines. This was remarked upon by Morgan (1984), who found it by consequence very difficult to classify. In part, the weak [O III] $\lambda4959$, $\lambda5007$ lines are a consequence of collisional de-excitation in this extraordinarily dense object. The observed [O III $\lambda4363/\lambda5007$ ratio of 0.17 ± 0.02 is not permitted for any temperature if the electron density is less than 10^5 cm^{-3}. Assuming that the electron temperature is in fact 15,000 K, a more representative value for LMC planetaries, implies a density of 2.3×10^6 cm^{-3}.

We suspect this object of being a symbiotic star since, although we see no trace of a red companion in our spectrum, there is a weak resolved feature at 6830 Å which is an unidentified emission band characteristic of these objects (Allen 1980, 1984). An infrared detection of a stellar continuum or a high-resolution Balmer line profile would be required to settle the issue.

c) LMC SMP 11

The only information available in the literature on SMP 11 is a description of the emission-line spectrum on objective prism plates. (Morgan 1984; Sanduleak, McConnell, and Phillips 1978). Morgan gives it excitation class 4 and remarks that [O III] is slightly weak for this class. Our spectrometric data are of very poor quality, being obtained in cloudy conditions with bright moonlight. However, the firm detection of He II suggests that the true excitation class may be nearer 7. The [O III] profile is illustrated in Figure 1, and, while it has a single peak, it shows a lot of real structure and extended wings over ~ 250 km s^{-1}. The profile can be interpreted in two ways. Either it is composed of two broad components of unequal intensity separated by ~ 60 km s^{-1}, or it has a triple component structure composed of a slowly (~ 30 km s^{-1}) expanding shell superposed on a two-component profile with a characteristic expansion velocity, like SMP 83, near 100 km s^{-1}.

We cannot exclude the possibility that SMP 11 is also a symbiotic star, since the [O III] line profiles in a small sample of symbiotics measured by Webster and Taaffe (1984) typically have line widths of order 100 km s^{-1}.

d) Comparison with Galactic Planetaries

The remarkable nature of SMP 83 (WS 35) and, if confirmed as a planetary, SMP 11 is emphasized by comparison with the galactic planetaries (e.g., Sabbadin *et al.* 1984). The only objects which deviate in the sense of high velocity of expansion are NGC 2392 (the Eskimo nebula) which achieves a maximum expansion velocity of ~ 75 km s^{-1} (Wilson 1950; Reay, Atherton and Taylor 1983), He 2-111 (Webster 1978), and NGC 6302. For NGC 3292 the observations suggest a prolate or bipolar double-shell structure oriented with its long axis in the line of sight.

Very high velocities were observed in a faint bipolar giant halo about He 2-111 by Webster (1978): This nebula is an extreme type I object with very intense nitrogen lines and a well-developed bipolar or biconical structure in the inner regions. The giant halo is expanding into material ejected at an earlier phase by the central star, since this also shows very strong [N II] lines. The range of velocities in this object is 400 km s^{-1}, and the kinetic energy of the giant shell is 3×10^{46}–1×10^{49} ergs. However, if He 2-111 was placed at the distance of the LMC, it is unlikely that the giant halo would be detected, owing to its low emissivity relative to the core. From the nebular mass of SMP 83, we derive a minimum kinetic energy of between 1 and 7×10^{46} ergs in the ionized material at the current time. Since the inferred radius is $\sim$0.1 pc, the dynamical age is at least 950 yr, compared with the age of less than 2700 yr for He 2-111. Thus, if energy is input continuously, SMP 83 will achieve the energy content of He 2-111 at a comparable age.

The possibility of a continuous injection of energy via stellar winds is suggested by the case of NGC 6302. This is again a luminous, high-excitation, bipolar, nitrogen-rich type I planetary nebula, but is seen with its major axis almost in the plane of the sky. Meaburn and Walsh (1980) discovered an 800 km s^{-1} wide component of the [Ne v] λ3426 line in the nebular core and showed that lower excitation lines in the outer parts have components extending from -186 to $+140$ km s^{-1}. This nebula has a dense equatorial ring which has been observed in neutral hydrogen (Rodriguez and Moran 1982), and also in the infrared (Lester and Dinerstein 1984). In both NGC 6302 and He 2-111 the observations are consistent with the idea that a dense ring serves to confine the nebula in the equatorial plane in the presence of a strong stellar wind, allowing a directed flow to develop along the polar directions. However, the very broad [Ne v] line in NGC 6302 is unlikely to be the result of a stellar wind seen directly, since this would demand extreme mass-loss rates (Barral *et al.* 1982).

In the case of SMP 83, we can estimate the mass loss and velocity of a radiation-driven wind, provided that the Lamers (1981) relation (derived for Population I stars) is valid and that (Castor, Abbott, and Klein 1975) the ratio of $V_{\rm wind}/V_{\rm esc} \approx 3.0$. Perinotto (1983) finds this to be true for a limited sample of planetary nuclei observed with *IUE*, at least to one order of magnitude. Using the figures given in Table 2 we find

$$\log \dot{M} \approx -6.4 \text{ yr}^{-1} ,$$

$$V_{\rm wind} \approx 3400 \text{ km s}^{-1} .$$

Such a high velocity wind would not be able to blow a "classical" (e.g., Castor, McCray, and Weaver 1975) mass-loss bubble, since a stellar wind shock would not develop. Instead, if the ion Larmor radius is sufficiently large, the high-velocity stellar wind ions can penetrate directly into the planetary nebula gas a distance determined by Coulomb interactions (Dopita, Binette, and Tuohy 1984). For SMP 83 this distance is of order 10^{16} cm. In this scenario, the momentum of the stellar wind is transferred directly to the thermalized stellar wind and entrained nebular gas. On this model, some 2000–13,000 yr would be required to build up the excess 50 km s^{-1} observed in the ionized gas. This time scale is considerably longer than the dynamical age of order 1000 yr derived above, and this appears to rule out direct acceleration by stellar winds. However, this "direct impingement" model may still explain the broad [Ne v] lines seen in NGC 6302. These would arise at the inner edge of the nebula in the interaction zone where the gas pressure of the nebula is approximately equal to the ram pressure of stellar wind as in equation (3) of Barral *et al.* (1982). If the wind parameters are similar to those of SMP 83, then the [Ne v] lines arise from a region in which the ratio of entrained gas to stellar wind material is $\sim$10:1.

A fundamental problem associated with SMP 83, and which may equally apply to the galactic type I bipolar nebulae discussed above, is that the dynamical ages inferred from observations are considerably longer than the fading and cooling time scales derived from simple theory (e.g., Paczyński 1971) which are typically less than 100 yr. Stecher *et al.* (1982) suggested that what we see may represent a "fossil" nebula, the central star having already faded. However, the density of SMP 83 is sufficient to ensure that the nebular ionization conditions remain reasonably well related to the current temperature of the central star, and this is still both hot and bright. An increase in the time scale over which the nucleus remains hot and bright can be achieved in helium-burning models (Wood and Faulkner 1985). For example, a helium-burning star of mass $\sim$0.9 $M_\odot$ can achieve the parameters observed for SMP 83 after $\sim$300 yr and remain above 10^4 $L_\odot$ for a further $\sim$300 yr. This seems to us to represent a more acceptable solution to the time scale problem.

Given that the stellar wind is unlikely to have produced the high-velocity motions in SMC 83, and also that the momentum in the radiation field is likewise insufficient to accelerate the nebular shell within the dynamical time scale, then we are forced to postulate that both the bipolar structure and the high-velocity expansion were established before the object became a planetary nebula, during the AGB phase of evolution of the central star. If so, then it may well have looked like OH 0739$-$14: a dusty nitrogen-rich galactic bipolar and OH/IR source with a binary star nucleus of which one component is an M9 III variable star. Cohen, Dopita, and Schwartz (1985) have shown that the lobes of the reflection nebula are currently expanding at $\sim$80 km s^{-1}, being driven by a hot stellar wind into denser material ejected at low velocity in an earlier phase of evolution. This object is, in turn, probably related to the symbiotic phenomena in which hot gas is generated by accretion of a red giant wind onto a white dwarf companion. Indeed, an increasing number of galactic symbiotic stars are now recognized as showing bipolar mass flow with velocities as high as 200 km s^{-1}. Examples include HM Sge, BF Cyg, V1016 Cyg, and R Aqr (Solf 1983, 1984). Thus we have an intriguing, circumstantial, but suggestive link between these energetic bipolar type I planetaries and the symbiotic stars which may well repay further investigation.

IV. CONCLUSION

A rare class of rapidly expanding planetary nebulae have been identified in the Large Magellanic Cloud. One of these, SMP 83 (WS 35) is identified as a luminous type I planetary with a rather massive central star, which almost certainly has bipolar symmetry. This LMC planetary resembles in many respects He 2-111 or NGC 6302 in the Galaxy. In such objects, the white dwarf winds, although important in the dynamics, are not sufficient to explain the energy and momentum content of the nebular gas. We therefore postulate that the bipolar morphology and outflow were already established when these objects became planetaries. This suggests a possible relationship between type I bipolar planetaries and symbiotic stars.

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