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LMC SMP 64: THE YOUNGEST PLANETARY NEBULA?

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ABSTRACT

The planetary nebula SMP 64 in the Large Magellanic Cloud is shown to possess several properties which set it apart from the general PN population. These are an extremely high central electron density, a strong radial density gradient, and a central star with a very low effective temperature, $T_{\rm eff} = 31{,}500$ K. However, the luminosity of the central star is 6400 $L_{\odot}$, implying a core mass of 0.62 $M_{\odot}$, typical of the Magellanic Cloud population of planetary nebulae. We conclude that the central star of SMP 64 has only just reached a temperature high enough to ionize a portion of the material ejected during the asymptotic giant branch evolution of the central star.

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

1. INTRODUCTION

The transitional stage of evolution from proto–planetary nebula (Pottasch 1984; Zijlstra 1989; Pottasch, Ratag, & Olling 1990) to normal planetary nebula (PN) is thought to occur on a relatively short time scale. As a consequence very few of these transitional objects have been unambiguously identified at optical wavelengths (Sabbadin 1986; Schwarz, Aspin, & Lutz 1989). Nonetheless, the evolution from AGB star to planetary nebula nucleus (PNN), the associated transition from slow superwind to fast, radiatively driven wind, and the rate at which this occurs all have a profound influence upon the subsequent dynamical evolution of the PN. It is therefore of considerable interest to identify such transitional objects in order to be able to draw conclusions about the final stages of evolution of the AGB, and about the subsequent excursion toward high stellar temperatures.

In recent years, we have been undertaking a systematic and detailed study of the Magellanic Cloud sample of PNs, and data on the diameters, fluxes, expansion velocities, and kinematics have been accumulated. More recently we have obtained spectrophotometric data (Meatheringham & Dopita 1991a, b), which have enabled us to determine the detailed physical and chemical properties of these nebulae (Dopita & Meatheringham, 1990, 1991a, b).

Among this sample, only one object in the LMC, SMP 64 (Sanduleak, MacConnell, & Philip 1978), emerged as having outstanding properties that perhaps qualify it as a genuine transition object. This object is the subject of this *Letter*.

2. OBSERVATIONS

Spectrophotometry of LMC SMP 64 was obtained on the night of 20 January 1988. The instrument used was the double-beam spectrograph on the 2.3 m telescope at Siding Spring with its 300 lines mm^{-1} gratings. With a dichroic beam-splitter cutting at 5500 Å, this gave complete spectral coverage from 3300–7500 Å. The detector was the 2CCD photon counting array (PCA) (Rodgers, Conroy, & Bloxham 1988). The exposure time was 2000 s. However, since the PCA saturates on bright lines, it was also necessary to take an additional 1000 s exposure with a neutral density filter transmitting 10% in order to obtain accurate relative fluxes for the brighter lines, particularly the hydrogen recombination lines. As a result of this process the absolute value of the Hβ flux obtained is not reliable, and we use the value measured by narrow-band imaging (Meatheringham & Dopita 1988). The data were all reduced using the IRAF spectral reduction package. Since the data fell on four different CCDs, these each had to be reduced separately and then combined into a single spectrum. The reduction process consisted of flat-fielding, data extraction, wavelength linearization, sky subtraction, reduction to flux, merging of CCDs, and summing of rows to extract individual spectra. The data from individual CCDs were merged and flux-calibrated against flux standard white dwarfs (Stone & Baldwin 1983; Baldwin & Stone 1984). The reduced spectrum is shown in Figure 1, and the reddening-corrected line intensities relative to Hβ are given in Table 1.

3. RESULTS

3.1. *Physical Parameters of the Nebula*

An inspection of the spectral data for LMC SMP 64 in Table 1 and Figure 1 reveals that it possesses some extraordinary properties. First, the forbidden lines are very weak in comparison with the recombination lines. The [O III] λ5007/Hβ ratio would imply a extraordinarily low excitation. Using the definitions given in Dopita & Meatheringham (1990), this object would be assigned an excitation class of only 0.1. This result would be consistent with the presence of a strong stellar continuum, which also implies a low stellar effective temperature. We have applied the classical Zanstra method to determine the hydrogen Zanstra temperature according to the formulae given by Pottasch (1984), which relate the Hβ flux to the stellar continuum at Hβ (Meatheringham & Dopita 1991a). We have corrected the measured continuum for contamination by nebular continuum processes using the measured Hβ strength to scale these. As may be seen from Figure 1, there also exists the possibility of contamination by faint nebular forbidden iron lines. We estimate that this introduces a 5% uncertainty in our continuum estimate. With these figures we estimate an effective temperature of 31,500 $\pm$ 1500 K. This temperature would imply a spectral classification of about B0 for the central star.

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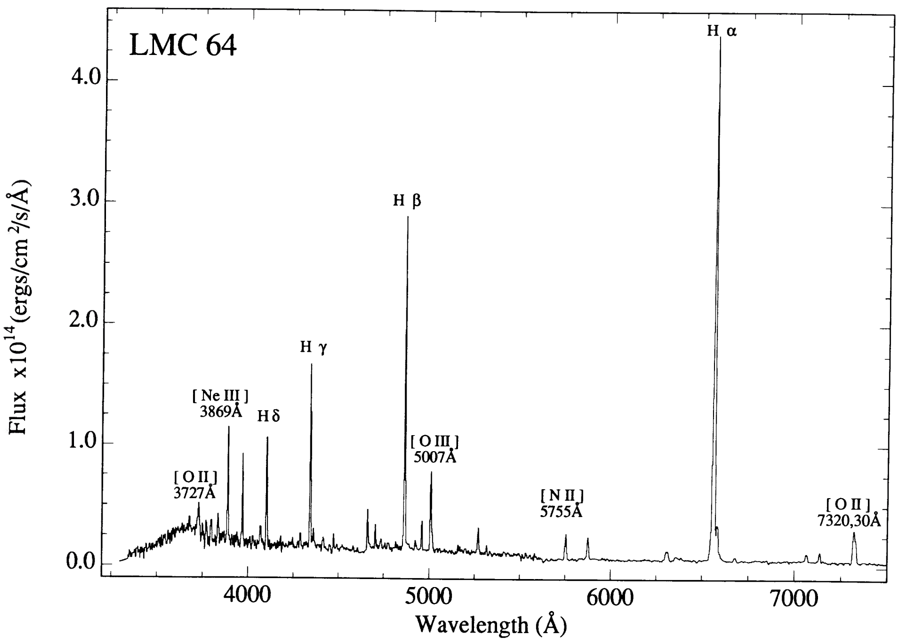

FIG. 1.—Observed spectrum of LMC SMP 64

The densities derived from line ratios of ions of different excitation potential indicate that a very steep outwardly decreasing radial density gradient exists in the ionized material. Taking simple one-zone models with an assumed temperature of 10,000 K, the following constraints on the local densities are implied. From the [O III] $\lambda4363/\lambda5007$ ratio, $n_e \approx 4.3 \times 10^6$ cm^{-3}; from the [N II] $\lambda5755/\lambda6583$ ratio, $n_e \approx 2.5 \times 10^6$ cm^{-3}; from the [O II] $\lambda(7318+7328)/\lambda(3726+3729)$ ratio, $n_e \approx 1 \times 10^5$ cm^{-3}; and finally, from the [S II] $\lambda(4069+4076)/\lambda(6717+6731)$ ratio, a lower limit of $n_e > 2 \times 10^5$ cm^{-3} is inferred.

Finally, there are also a number of lines in the 4700–5300 Å region which are not usually seen in PNs. These can be mostly identified as [Fe III]; they appear in relative intensities that are similar to those seen in FU Ori stars, or in some T Tau stars, and are indicative of a dense plasma, possibly excited by collisions. Some of these lines do appear in the very dense high-excitation nebula NGC 7027 (Kaler et al. 1976) but are absent in other dense, low-excitation nebulae such as BD+30, NGC 3629, or Vy 2-2. Since the strength of the [Fe III] lines with respect to the forbidden lines of other elements commonly seen in PN increases strongly with density, the observation of strong [Fe III] lines implies that there must exist a very dense zone in LMC SMP 64 ($n_e \gg 10^6$ cm^{-3}).

3.2. *Photoionization Modeling*

We have used the generalized modeling code MAPPINGS (Binette, Dopita, & Tuohy 1985) to compute the emission-line spectra of models in photoionization equilibrium using the procedure which is described in detail by Dopita & Meatheringham (1991a). Briefly, we have assumed "average" LMC abundances in the nebula from Dopita & Meatheringham (1991a) and have adopted a blackbody photon distribution for the central star, with a sharp cutoff at the He$^+$ ionization limit.

Nebulae with steep outward density gradients are very sensitive to small changes in the ionizing flux from the central star. In the case of a nebula with an r^{-2} density gradient, for example, in the absence of absorption, the local ionization parameter will remain constant with radius. However, the absorption of the ionizing radiation will drop off with the recombination rate, or as r^{-4}. Thus, if the ionizing radiation is not absorbed in a thin shell, then it never will be. In the case of a young planetary nebula with a secularly increasing flux of ionizing radiation, the ionization front will be initially trapped in a narrow zone near the inner boundary of the nebula, but, if it succeeds in ionizing a zone with a thickness comparable with its inner radius, the ionization front will rapidly sweep out to ionize the remainder of the nebulosity.

In the case of LMC SMP 64, the very large difference between the densities derived from high- and low-ionization species indicates that not only is the radial density gradient steep, but also that the extent of the ionized structure is large compared with its inner radius. However, the existence of [O I] lines is a sure indication that the nebula is ionization, rather than density, bounded. The steepest stable density gradient for which these conditions can be met was found to be an $r^{-1.7}$ law. In the modeling we have used a power-law index of both -1.5 and -1.7.

Generally, for low-excitation PNs, the excitation temperature is determined by the [O III] to Hβ ratio, the [Ne III] to Hβ ratio, and, allowing for the collisional de-excitation of the [O II] lines, the ratio of the [O I], [O II], and [O III] lines. However, in the case of LMC SMP 64, this procedure does not work well, because of the very large density gradient in the nebula, and a laborious process of trial and error fitting was necessary. In Table 1 we present two representative models which both gave a reasonable fit to the observed spectrum. Clearly we are not reproducing the intensities of the low-excitation species very well, but, given the fact that we have not altered the abundances from the mean of the LMC PN in any way, the fit is quite acceptable. Nonetheless, with this procedure, some concern about the uniqueness of the "best-fit" model must remain.

Regardless of the details of the density structure in the model, the stellar parameters are well determined, as are the luminosity through the observed Hβ flux and the temperature

TABLE 1

A. Comparison of Reddening-corrected Line Fluxes LMC 64 with Models

Ion Identity	λ (Å)	Observed	Model A	Model B
[O II]	3727	18.7	5.1	24.2
H9	3835	11.1	7.8	7.8
[Ne III]	3869	<3.0	6.3	5.5
H8 + He I	3889	29.8	15.6	15.3
[Ne III] + H7	3967, 70	18.3	18.3	17.7
[S II]	4069, 76	4.7	0.7	0.8
Hδ	4102	27.9	26.3	26.2
Hγ	4340	45.6	47.2	47.1
[O III]	4363	4.5	5.6	5.1
He I	4471	3.4	2.0	1.8
[Fe III]	4658	10.4	...	...
[Fe III]	4701	6.8	...	...
[Fe III]	4734	4.6	...	...
[Fe III]	4755	2.0	...	...
?	4778	3.9	...	...
?	4815	1.5	...	...
Hβ	4861	100.0	100.0	100.0
[O III]	4959	8.0	10.4	9.7
[O III]	5007	24.6	30.1	28.0
[N I]	5199	1.7	...	...
[Fe III]	5270	10.2	...	...
[Fe II]?	5318	2.9	...	...
[N II]	5755	12.3	5.1	2.5
He I	5876	9.7	5.3	5.4
[O I]	6300	2.3	...	0.1
[S III]	6312	6.5	4.8	4.1
[O I]	6363	3.3	...	...
[N II]	6548	3.2	4.3	6.7
Hα	6563	285.1	279.0	280.0
[N II]	6584	9.8	12.8	19.9
He I	6678	1.9	1.5	1.4
He I	7065	3.9	0.7	0.6
[Ar III]	7135	4.6	4.5	4.4
[O II]	7320	15.0	28.0	26.3
[O II]	7330	10.0	22.8	21.1
log ($L_{H\beta}$) ergs s^{-1}		35.01	35.01	35.01

B. Model Parameters

Parameters	Model A	Model B
Inner radius (cm)	8.00E14	8.00E14
Outer radius (cm)	6.85E15	3.38E16
H density at inner edge (cm^{-3})	8.66E06	8.08E06
Power index of density law	−1.50	−1.70
Luminosity of central star ($L_\odot$)	6460	6770
Temperature of central star (K)	31500	310000

from the degree of excitation. The fact that the [O III] λ5007 line is observed but that we only have an upper limit on the strength of the [Ne III] lines at λ3868 and λ3967 puts very strong constraints on the temperature of the central star. The [O III] lines become weaker than 2% of Hβ below $T_{\rm eff} \approx$ 29,000 K, and the [Ne III] lines become this faint below $T_{\rm eff} \approx$ 31,500 K for LMC abundances.

On the basis of these models, and from the observed Zanstra temperature, we adopt the following parameters for the central star:

$$\log (L/L_\odot) = 3.82 \pm 0.06 \; ; \quad T_{\rm eff} = 31{,}300 \pm 600 \text{ K} .$$

4. DISCUSSION

There are three possible origins for LMC SMP 64. It may either be a very young PN on its way across the H-R diagram, or else it may be a star on the zero-age main sequence (ZAMS), surrounded by a compact H II region. A third possibility is that it is a symbiotic star. We believe that this can be immediately discounted on the grounds that the spectrum contains no lines of highly ionized species, none of the characteristic emission bands such as the one at 6830 Å, or any signs of a companion cool star which would have shown up as a red excess cut up by the TiO bands. None of the objects in the Allen (1984) atlas have a spectrum which resemble this object. A further (somewhat weaker) constraint is the fact that the Hα line is not broadened in any way.

According to the theoretical ZAMS of Maeder & Meynet (1987), if it is a young star, then its luminosity implies a mass of $11 \pm 1\ M_\odot$. It should then have an effective temperature of only 27,000 ± 1200 K, and a spectral classification of B0.5–B1.0. Stars either approaching the ZAMS, or leaving it, will have lower temperatures at this luminosity. Thus, although the implied ZAMS temperature is only slightly cooler than what is observed for LMC SMP 64, this difference is sufficient to discount the possibility that we are dealing with a young object, at a high degree of probability. An identification of Wolf-Rayet features in the spectrum would have helped to confirm our hypothesis that it is a young PNN. Unfortunately no such features appear.

On the basis that we are dealing with a genuinely young PN, we may place it on the H-R diagram to determine the core mass from theoretical tracks (Schönberner 1981; Wood & Faulkner 1986). This has been done in Figure 2, where we have also plotted the positions of the other PNs in the Magellanic Cloud for which we have detailed photoionization models (Dopita & Meatheringham 1991a, b). The core mass implied is $0.62 \pm 0.02\ M_\odot$, typical of the general population of PNs in the Magellanic Clouds.

Regrettably, we have no measurement of the expansion

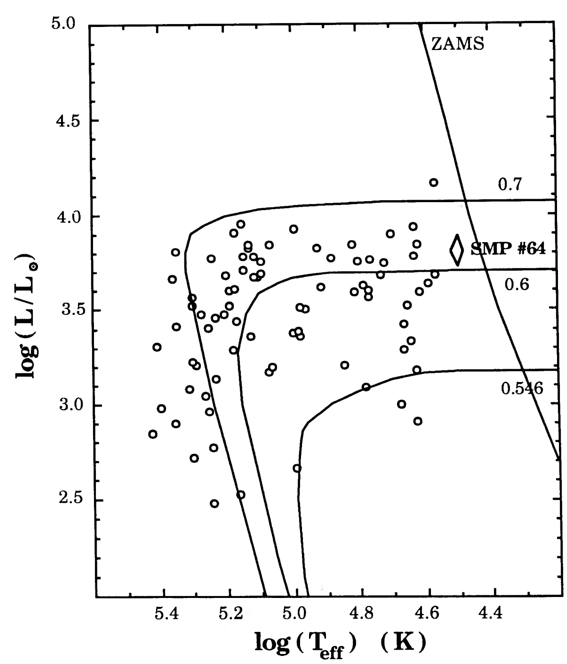

Fig. 2.—Position of SMP 64 on the H-R diagram is shown as an error diamond. The zero-age main sequence is indicated, as are theoretical tracks for PNN core masses of 0.7, 0.6, and 0.546 $M_\odot$. Open circles are Magellanic Cloud PNs for which we have constructed detailed models.

velocity of the nebula. However, for other Magellanic Cloud PNs we have found that the expansion velocity is well correlated with the position of the PNN on the H-R diagram through (Dopita & Meatheringham 1991a)

$$(V_{\rm exp}/{\rm km\ s^{-1}}) = -128 \pm 4 + 38 \pm 2[\log (T_{\rm eff}) - 0.25 \pm 0.05 \log (L/L_{\odot})] ;$$

to the extent to which LMC SMP 64 is typical (!), we can infer an expansion velocity of only 7 km s^{-1}.

If the density gradient is the result of a stellar wind during the AGB phase, then the mass-loss rate implied by our model is of order 1.8×10^{-7} ($V_{\rm exp}$/km s^{-1}) $M_{\odot}$ yr^{-1}, or about 1.3×10^{-6} $M_{\odot}$ yr^{-1} with our assumed expansion velocity. However, we believe that this hypothesis is unlikely given the very short dynamical ages this would imply.

If we define a dynamical age as the time for matter to expand at constant velocity to reach the ionization front, then the age of the nebula is only 310 yr. The time taken for matter to flow from the central star to the inner radius at this velocity is much shorter, only 37 yr! These estimates depend on assumed expansion velocity of 7 km s^{-1}, which is in some sense a lower bound, since higher outflow velocities than this are generally found in the AGB precursor stars (Kastner et al. 1990). If this is the case, then the time-scale problem becomes even more oppressive, and such time scales are shorter than any reasonable time scale for the central star to evolve from the AGB to the current position of the star on the H-R diagram (Schönberner 1979, 1983; Wood & Faulkner 1986). A similar problem of time scale was noted by Sabbadin (1986) in the case of Vy 2-2. A possible solution to this problem would exist if the mass of residual hydrogen on the PNN is reduced to a very low value during the transition to the blue, since the evolutionary time scale is very sensitive to this quantity. However, a reduction by the amount required would then imply exceedingly short time scales for evolution in the PN phase.

We therefore believe that it is much more likely that the ionized material is being constantly replenished by ionization of a reservoir of dense gas close to the star. The existence of fairly strong forbidden iron lines in the spectrum of LMC SMP 64 is probably an observational indication that such a dense reservoir exists. If this reservoir had an appreciable radial extent, as in the case of an equatorial disk, for example, then the mass-loading of the ionized flow would ensure that the radial density gradient was shallower than the r^{-2} law.

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