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LM1-64: A HIGH EXCITATION PLANETARY NEBULA WITH WR NUCLEUS IN THE LMC

M. Peña[1,3], L. Olguín[1], M.T. Ruiz[2,4], and S. Torres-Peimbert[1,3]

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RESUMEN

Presentamos datos espectrofotométricos ópticos y ultravioleta de la nebulosa planetaria LM1-64 en la Nube Mayor de Magallanes. La nebulosa muestra un alto grado de ionización y la estrella central tiene emisión característica de estrellas WR del carbono. Los datos observacionales se combinan con modelos de estructura de ionización, para obtener la composición química y las condiciones físicas de la nebulosa, así como algunas características de la estrella central. A partir de los flujos de las líneas en emisión se encuentra T(O III) = 14 000 K, log He/H = 11.05 ± 0.05, log C/H = 8.83 ± 0.15, log N/H = 8.03 ± 0.20, log O/H = 8.31 ± 0.10, log Ne/H = 7.75 ± 0.10 y log Ar/H = 5.25 ± 0.20. El cociente C/O es mucho mayor que el valor solar y el del conjunto de nebulosas planetarias de la NMM, mientras que los otros elementos pesados tienen un comportamiento solar. LM1-64 es una de las planetarias más ricas en C de la NMM. La estrella central muestra emisión ancha en λ4650 debida a C III y C IV estelares. A partir de modelos de estructura de ionización, determinamos que su temperatura efectiva es del orden de 100 000 K y su gravedad es log $g \approx 5.0$. La magnitud aparente visual del objeto es 20.2 ± 0.50.

ABSTRACT

We present optical and UV spectra of the planetary nebula LM1-64 in the LMC. This is a high excitation planetary nebulae which shows evidence of having a WC central star. Broad and complex stellar emission at λ4650 (due to C III and C IV) is detected in the optical spectrum. We have measured all the emission line fluxes available and determined the physical parameters and chemical composition of the ionized gas. The derived values are T(O III) = 14 000 K, log He/H = 11.05 ± 0.05, log C/H = 8.83 ± 0.15, log N/H = 8.03 ± 0.20, log O/H = 8.31 ± 0.10, log Ne/H = 7.75 ± 0.10 and log Ar/H = 5.25 ± 0.20. LM1-64 shows a strong C enhancement in the envelope as result of the central star activity, while He, O and Ne are comparable to the average values reported for the LMC-PNe. From ionization structure models we have estimated the effective temperature of the central star to be ≈ 100 000 K and log $g \approx 5.0$. This temperature is much higher than the values reported for the known LMC-PNe with WR nucleus. The visual apparent magnitude of the object is 20.2 ± 0.50.

Key words: **MAGELLANIC CLOUDS — PLANETARY NEBULAE**

1. INTRODUCTION

LM1-64 was reported by Lindsay & Mullan 1963) as a probable planetary nebula in the LMC. pectrophotometric data obtained by us confirm his and show that LM1-64 is a high excitation PN vith a carbon WR nucleus. The reported sample of PNe with WR features in the Magellanic Clouds consists of only 5 objects, all of them showing low ionization degree. Monk, Barlow, & Clegg (1988) attribute spectral classes from WC4 to WC8 to their central stars.

The optical spectrum of LM1-64 shows very intense emission lines from high ionization species such as He II λ4686 and [Ne IV] λ4725. From the strength of these lines we should expect a stellar effective temperature of about 100 000 K for the progenitor. This is one of the largest temperatures suggested for a WR nucleus of a planetary nebula in the LMC. The only other very high temperature WR nucleus is N66 which recently showed evidence of undergoing a WR episode (Torres-Peimbert

Instituto de Astronomía, Universidad Nacional Autónoma de México.

Departamento de Astronomía, Universidad de Chile.

Guest Observer with the International Ultraviolet Satellite, operated by NASA.

Visiting Astronomer at CTIO, operated by AURA under ontract with the National Science Foundation.

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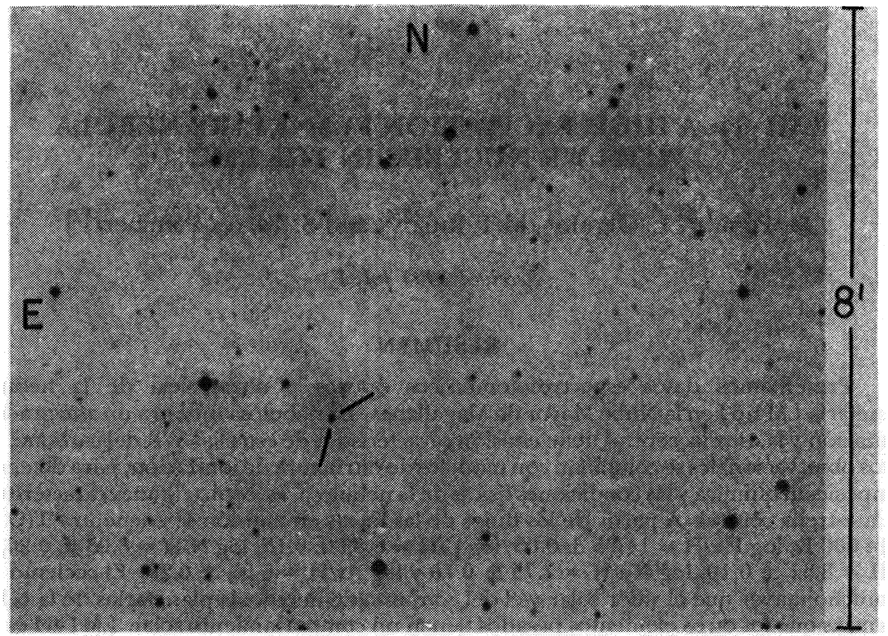

Fig. 1. Identification chart for LM1-64. The coordinates for this object are R.A. = 6^h 21^m 1.5^s, Dec = −66° 21′ 10″ (equinox 1950).

et al. 1993). The UV spectrum of LM1-64 shows very intense nebular C lines which give evidence of a high C abundance, presumably produced by stellar nucleosynthesis.

Due to the unusual features of LM1-64, we considered of great interest to make a detailed spectrophotometric study of it and to deduce nebular and stellar characteristics of this object.

In Figure 1 we present the identification chart for this object. Its equatorial coordinates are R.A. = 6^h 21^m 1.5^s, Dec = −66° 06′ 10″ (equinox 1950).

2. OBSERVATIONAL DATA

2.1. Optical Spectrum

Spectrophotometric data were obtained with the CTIO 4-m telescope equipped with an R-C spectrograph and a 2D-Frutti detector with grating

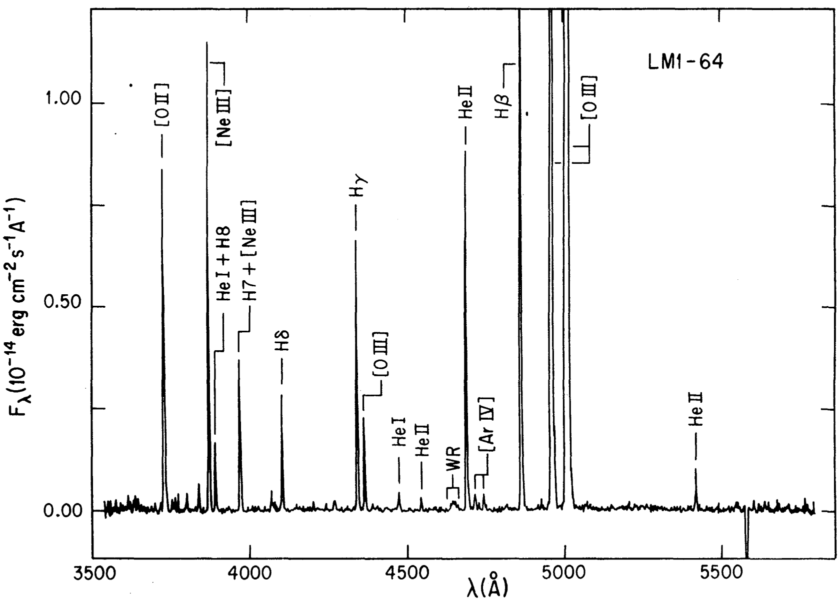

Fig. 2. Optical spectrum of LM1-64. The most important lines are indicated.

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PGL#1 in January, 1989. The spectral range etween 3500 and 5700 A was covered at 2.1 A esolution; we used a long slit 1.5″ wide, oriented E-/, and the aperture for extraction of the spectrum as 1.5″ × 1.5″. The exposure time was of 600 s. ky emission was subtracted using parts of the it that showed no evidence of nebular emission. lux standards from the list by Stone & Baldwin 983) and a He-Ar lamp were observed in order) calibrate the spectra in flux and wavelength. ata reduction was performed at CTIO La Serena omputing Facilities.

Figure 2 shows the calibrated spectrum. The ptical spectral features of LM1-64 correspond to a ery high excitation planetary nebula. The He II 4686/Hβ intensity ratio has a value larger than .50 and the collisionally excited lines at [Ne IV] 4725 and [Ar IV] λλ4711 and 4740 are clearly etected. The nebular recombination emission line t C II λ4267 is present and the stellar broad omplex emission feature at λ4650, due to C III and : IV, is also observable.

2.2. *Ultraviolet Spectrum*

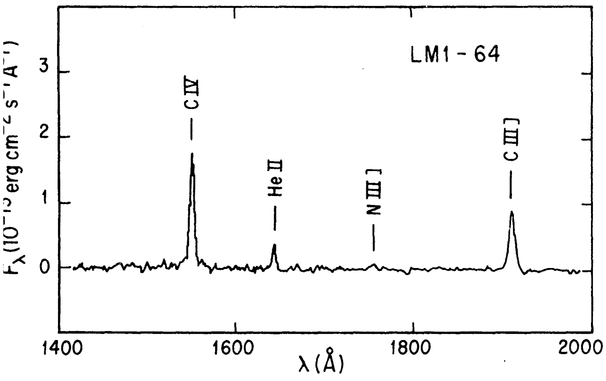
IUE ultraviolet data were obtained during 1989) derive the C abundance by means of the intense : IV λ1550 and C III] λ1909 doublets. Other lines etected are He II λ1640 and N III] λ1750. Fluxes f the UV lines, between 1200 and 2000 A, were ıeasured from the merged *IUE* spectra resulting rom the large aperture low resolution exposures WP 39573 (180 min) and 39576 (115 min). Data eduction was performed with the *IUE* Regional)ata Analysis Facility. The calibrated UV spectrum ; plotted in Figure 3.

3. REDDENING AND PHYSICAL CONDITIONS

In Table 1 we present the optical measured uxes, F(λ), relative to Hβ. The uncertainties in the line flux ratios are less than 10% for the lines with log F(λ)/F(Hβ) ≥ −13.50, approximately 20% for the lines with log F(λ)/F(Hβ) ≥ −15.00 and larger for the fainter ones. Due to the narrow entrance slit used in the optical, the spectrum is expected to be affected by wavelength-dependant atmospheric dispersion. This effect is similar to that produced by interstellar extinction and both are corrected in the same way, by fitting the observed Balmer decrement to the theoretical one. We have used the theoretical computations by Hummer & Storey (1987) for case B, assuming an electron temperature of 14 000 K as derived from the [O III] λλ4363/5007 line intensity ratio and an electron density of 1000 cm^{-3}. A logarithmic reddening correction, C(Hβ) = 1.20 is derived and a similar value can be deduced from the He II recombination lines. By applying this correction to the optical lines, we reproduce the theoretical Balmer decrement up to H10 with a precision better than 10%, therefore we are confident that the line ratios are well corrected. We have used the reddening law by Whitford (1958) assuming that, in the optical region, the wavelength extinction law in the LMC is the same as in our galaxy. The dereddened line intensities, I(λ), are also presented in Table 1.

The UV line fluxes, relative to He II λ1640, are presented in Table 2. The intense C lines and He II λ1640 have uncertainties less than 10%, and we attribute an error of around 20% to the N III] λ1750 line flux. Since, due to the optical treatment, we have lost the information about the extinction, we have used the value of the galactic extinction toward the object as a minimum value. According to Burstein & Heiles (1982) this is C(Hβ) ≈0.10. We have dereddened the UV lines relative to He II λ1640, using the UV galactic reddening law by Seaton (1979). Subsequently we have related the UV lines to Hβ by assuming that, for an electron temperature of 14 000 K, the theoretical He II λλ1640/4686 intensity ratio is 6.94 (Seaton 1978; Hummer & Storey 1987). This allows us to correct for the difference in size between the optical slit and the *IUE* large aperture and to minimize the uncertainties due to the unknown reddening value. In this way the uncertainties in the UV to Hβ intensity ratios are about 0.1 dex.

The conventional diagnostic line ratios have been analyzed. The relevant references to the atomic parameters to derive physical conditions and chemical composition are from the compilation by Mendoza (1983) or later. From the [O III] λλ4363/5007 intensity ratio, we derived an electron temperature T(O III) = 14 000 ± 1000 K. The error corresponds to the uncertainties in the line fluxes. An uncertain electron density can be derived from the weak [Ar IV] λλ4711/4740 lines; for this we have subtracted the contribution of [Ne IV] λ4715 and



ig. 3. Ultraviolet spectrum of LM1-64 resulting from ıe low dispersion exposures SWP 39573 (180 min) and WP 39576 (115 min).

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TABLE 1

OBSERVED AND PREDICTED LINE INTENSITIES RELATIVE TO Hβ[a]

λ_0 (A)	Ion	f_λ^b	log F(λ)/F(Hβ)	log I(λ)/I(Hβ)	Model
3726+29	[O II]	+0.315	−0.35	+0.03	−0.14
3760	O III	+0.300	−1.73	−1.37	...
3771	H 11	+0.295	−1.90	−1.55	...
3798	H 10	+0.290	−1.65	−1.30	...
3835	H 9	+0.280	−1.51	−1.18	...
3869	[Ne III]	+0.270	−0.31	+0.02	+0.08
3889	He I + H 8	+0.265	−1.11	−0.79	...
3967+70	[Ne III] + H 7	+0.235	−0.65	−0.37	...
4069	[S II]	+0.210	−1.61	−1.36	...
4102	Hδ	+0.200	−0.83	−0.59	...
4200	He II	+0.170	−1.90	−1.69	...
4267	C II	+0.155	−1.80	−1.62	...
4342	Hγ	+0.135	−0.50	−0.34	...
4363	[O III]	+0.130	−0.94	−0.78	−0.75
4471	He I	+0.105	−1.61	−1.48	−1.49
4541	He II	+0.080	−1.82	−1.73	...
4650	C III	+0.050	WR	...	...
4686	He II	+0.045	−0.33	−0.28	−0.28
4711+15	[Ar IV] + He I	+0.040	−1.65	−1.58	...
4725	[Ne IV]	+0.040	−2.03	−1.98	−2.40
4740	[Ar IV]	+0.030	−1.59	−1.56	−1.62
4861	Hβ	+0.000	+0.00	+0.00	+0.00
4921	He I	−0.015	−2.02	−2.04	...
4959	[O III]	−0.020	+0.54	+0.53	+0.55
5007	[O III]	−0.030	+0.83[c]	+0.82[c]	+1.05
5411	He II	−0.115	−1.25	−1.39	...
C(Hβ)[d]		1.20	...	...	...
log F(Hβ)		−13.00	...	...	...
T(O III)		...	...	14000	13950

[a] The uncertainties are less than 10% for the lines with log F(λ)/F(Hβ) ≥ −13.50, around 20% when log F(λ)/F(Hβ) ≥ −15.00 and larger for the fainter ones.
[b] Reddening law from Whitford (1958).
[c] Saturated.
[d] C(Hβ) includes the interstellar extinction and the atmospheric dispersion.

He I λ4713 emission lines to [Ar IV] λ4711; we have assumed that, under the physical conditions of LM1-64, log [Ne IV] λλ4711/4725 = −0.20 and log He I λλ4713/4471 = −0.93. From this, a logarithmic value of −0.23 is derived for the [Ar IV] line intensity ratio, which corresponds to log n_e = 4.07 ± 0.10. This value could be representative of the density in the knots and condensations of the inner part of the nebula. We have adopted a rms value of 1000 cm^{-3} as representative of this object.

4. THE CENTRAL STAR AND THE IONIZATION STRUCTURE OF THE NEBULA

From the flux at 5480 A we derive an apparen visual magnitude of 20.2 ± 0.5 mag for the whol object (star + nebula) which implies a dereddene visual magnitude fainter than 17.9 ± 0.5. Adoptin a distance modulus of 18.45 for the LMC (va den Bergh 1989), we derive an absolute visua magnitude fainter than −0.8 for this object. It can b shown that the nebular continuum is contributin

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TABLE 2

OBSERVED AND PREDICTED UV LINES INTENSITIES

λ_0 (A)	Ion	f_λ^a	log $F_\lambda/F(\lambda 1640)$	log $I_\lambda/I(H\beta)^b$	Model
1550	C IV	1.18	+0.71	+1.27	+0.93
1640	He II	1.14	+0.00	+0.56	+0.56
1750	N III]	1.12	−0.50	+0.04	−0.13
1909	C III]	1.23	+0.54	+1.11	+1.18

[a] Reddening law from Seaton (1979).

[b] log F(He II λ1640) = −12.69. The value of the galactic reddening is C(Hβ) = 0.10. We have adopted He II I(λ1640)/I(λ4686) = 6.94.

ore than 50% to the visual flux at 5480 A, erefore the central star should have a visual ›solute magnitude fainter than 0.0 mag, which is ›nsistent for a PN nucleus. In this way we discard e possibility of it being a Population I WR star.

The He II Zanstra temperature, as derived from e He II λ4686 emission line, is higher than 80 000 for a black body distribution and using NLTE mosphere models by Clegg & Middlemass (1987) e derive also a temperature higher than 80 000 ıd a surface gravity log $g \approx 5.0$. This is a very high mperature for a PN-WR nucleus compared with e known planetary nebulae with WR nucleus in e Large Magellanic Clouds, which have spectral pes WC4/5 (Monk et al. 1988).

The high temperature in LM1-64 PNN is only ›mparable to the nucleus of N66 which in the last w years seems to have initiated a WR episode at had not been detected before (Torres-Peimbert al. 1993; Peña & Ruiz 1988). WR and stellar nission features in the galactic PNN have been udied by Smith & Aller (1969), Aller (1976), Heap 982), Méndez & Niemela (1982) and others (see éndez 1991 and references therein). They have und that the WR characteristics spread in a wide nge from relatively cool stars with spectral type 'C11 to very hot ones, with spectral types WC2 WC3 and effective temperature higher than)0 000 K. The spectral characteristics and the nization degree of LM1-64, which has excitation ass around 7, are similar to those in IC2003 and GC 2867 (Torres-Peimbert & Peimbert 1977; Aller al. 1981) whose central stars have been classified WC3 by Méndez (1991). According to this we ntatively attribute a classification of WC3 to the ntral star of LM1-64.

To study stellar and nebular parameters we have ılculated a grid of nebular ionization structure ıodels using central stars with effective tempera- ıres ranging from 80 000K to 110 000K and log from 4.5 to 5.5. The stellar energy distributions were taken from the NLTE models with He/H = 0.10 calculated by Clegg & Middlemass (1987). The stellar parameters were established in order to fit the excitation level given by the He II λ4686/He I λ4471 and [O III] λ5007/[O II] λ3727 emission line ratios. We have used the computer code described by Torres-Peimbert, Peimbert, & Peña (1990).

In Tables 1 and 2 we have included the line intensities predicted by our best fit ionization structure model. It was calculated assuming spherical symmetry, uniform density and homogeneous chemical composition. The ionizing flux corresponds to a central star with effective temperature of 100 000 K, log g = 5.0 and stellar radius of 0.3 $R_\odot$. The physical parameters of the model are: density of 500 cm^{-3}, filling factor of 1, chemical abundances of log C = 8.80, log N = 8.05, log O = 8.32, log Ne = 7.75, log S = 5.90, log Si = 5.90, log Ar = 5.3 (in the scale of log H = 12.00). In this simple model, the most important emission lines, except the C ones, are fitted within 10% and the electron temperature and ionization degree of the nebula is very well reproduced.

The main discrepancy of the model predictions with the observations occurs in the C lines. The C III] λ1909 is predicted approximately a factor of 1.17 higher and C IV λ1550, a factor of two lower than observed. Moreover the possible presence of a small amount of dust mixed with the ionized gas would reduce the C IV resonant line emission, increasing the discrepancy (Hummer & Kunasz 1980). A different value of the extinction or a different reddening law, such that by Nandy et al. (1981) for the LMC do not improve the discrepancies. We propose that these discrepancies can be explained in terms of chemical inhomogeneities in the nebula which are affecting the C lines (see § 5). Besides the C IV line may be enhanced by stellar emission. High resolution UV spectroscopy would be necessary to separate the stellar contribution from the nebular emission.

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5. CHEMICAL ABUNDANCES

5.1. Heavy Elements

To derive ionic abundances from the emission lines, we have adopted a two temperature zone model and an electron density of 1000 cm^{-3}. We used T(O III) for the calculations of O^+, He^+, C^{++}, N^{++}, O^{++}, Ne^{++} and A^{+3}; for the higher ionization stages, He^{++}, C^{+3} and Ne^{+3} we have used an electron temperature of 15 000 K as predicted by the best ionization structure model computed for LM1-64. The resulting ionic abundances are presented in Table 3. The errors in the ionic abundances include the errors introduced by the line intensities, relative to Hβ, and the uncertainty in the electron temperature.

It is noticeable that a C^{++} abundance a factor of 8 higher is derived from the λ4267 recombination line than that from the λ1909 collisional excitation line. Similar behaviour has been found in some galactic PNe, such as BB-1 (Peña et al. 1991, 1993) and NGC 4361 (Torres-Peimbert et al. 1990). Peimbert, Storey, & Torres-Peimbert (1993) have also found this type of discrepancies in O^{++} ionic abundance determinations derived from collisionally excited lines compared to that from recombination lines for some galactic H II regions. They have attributed them to temperature fluctuations of the order of 0.04 or higher within the nebula.

In the case of C^{++} in LM1-64, it can be shown that a line temperature T(λ1909) $\approx$ 10 000 K would be necessary to obtain similar ionic abundance determinations from both procedures. This value, compared with T(O III) = 14 000 K represents an extremely large fluctuation that would require very extreme density fluctuations or shock wave mechanisms. The only way to reconcile the C^{++} abundance derived from the recombination line with the one derived from the collisionally excited line is to assume large carbon inhomogeneities as those proposed by Torres-Peimbert et al. (1990) for NGC 4361 which seems to have an inner very carbon rich shell surrounded by an outer shell with solar abundances. Carbon inhomogeneities have been also reported in the galactic PN NGC 40 by Bianchi & Grewing (1987) who find evidence of an extremely C rich material in the inner edge of the nebula surrounding the WC central star. We propose that similar inhomogeneities could be present in LM1-64 and we will adopt the C^{++} ionic abundance as given by the collisional excitation line as a lower limit to the abundance.

Total abundances can be obtained from the derived ionic concentrations and some standard formulae for the ionization correction factors i_{cf} (e.g. Peimbert & Torres-Peimbert 1977). Alternatively the i_{cf} can be obtained from an ionization structure model. We have applied both procedures and found that the results agree very well. Therefore we have adopted the ionization correction factors as derived from our best fit model.

The expressions used for each element are:

$$N(C)/N(H) = 1.31\ [N(C^{++}) + N(C^{+3})]/N(H^+)\ ,$$

$$N(N)/N(H) = 1.48\ N(N^{++})/N(H^+)\ ,$$

$$N(O)/N(H) = 1.42\ [N(O^+) + N(O^{++})]/N(H^+)\ ,$$

$$N(Ne)/N(H) = 1.30\ [N(Ne^{++}) + N(Ne^{+3})]/N(H^+)$$

$$N(Ar)/N(H) = 1.71\ N(Ar^{+3})/N(H^+)\ .$$

5.2. Helium Abundance

The He^+/H^+ abundance was calculated using the He I $\lambda\lambda$4471 and 4921 lines. We have taken into account the contribution to the observed intensity of the He I triplet line λ4921 resulting from the collisional excitation of the 2^3S state of the He I. According to the computations by Peimbert & Torres-Peimbert (1987), in LM1-64 the λ447 line intensity is enhanced by a factor of 1.067 due to collisional effects. A similar correction factor is obtained if the correction formulae by Smits (1991 or Clegg (1987) are used. We have adopted the He^+/H^+ abundance by taking the average of the abundances from the He I $\lambda\lambda$4471 (as modified with Peimbert & Torres-Peimbert correction) and 492 lines.

In Table 4, we present total abundances for He, C, N, O, Ne and Ar. The errors include the uncertainties in the ionic abundances. For comparison we have also included the solar values and the chemical composition derived by different authors for the bulk of the planetary nebulae in the Magellanic Clouds.

TABLE 3

IONIC ABUNDANCES

λ_0 (A)	Ion	log (X^{+m}/H^+)
4471 + 4921	He^+	-1.17 ± 0.03
4686	He^{++}	-1.34 ± 0.03
1750	N^{++}	-4.14 ± 0.20
4267	C^{++}	-2.57 ± 0.05
1909	C^{++}	-3.77 ± 0.10
1550	C^{+3}	-3.46 ± 0.10
3869	Ne^{++}	-4.49 ± 0.06
4725	Ne^{+3}	-5.00 ± 0.15
3726 + 29	O^+	-4.89 ± 0.10
4959	O^{++}	-3.88 ± 0.08
4711 + 40	Ar^{+3}	-6.98 ± 0.15

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TABLE 4

TOTAL ABUNDANCES AND COMPARISON WITH THE MEAN VALUES FOR MC-PNe AND THE SOLAR VALUES[a]

Element	LM1-64	Model	<SMC PN>[b]	<LMC PN>[b]	Sun[c]
He	11.05 ± 0.05	11.05	10.92 ± 0.06	10.94 ± 0.04	11.00
C	8.83 ± 0.15[d]	8.80	8.79 ± 0.30	8.70 ± 0.35	8.56
N	8.03 ± 0.20	8.05	7.51 ± 0.16	7.98 ± 0.24	8.05
O	8.31 ± 0.10	8.32	8.15 ± 0.16	8.41 ± 0.17	8.93
Ne	7.75 ± 0.10	7.75	7.38 ± 0.24	7.68 ± 0.19	8.09
Ar	5.25 ± 0.20	5.30	5.60 ± 0.20	5.90 ± 0.20	6.58

[a] In units of 12 + log X/H.
[b] C, N, O and Ne from Walton et al. (1991); He and Ar from Monk et al. (1988).
[c] Solar values from Grevesse & Anders (1989).
[d] A C value of 9.60 is obtained using C^{++} from λ4267.

6. DISCUSSION AND CONCLUSIONS

By comparing the chemical composition derived ›r LM1-64 (Table 4) with the solar values and the ılk of the Magellanic Cloud PNe, it is found that M1-64 shows O and Ne similar to that in the LMC-Ne and a very enhanced C abundance, with a C/O ıtio much higher than unity. N abundance appears so slightly enhanced, although this is a very ncertain result that needs further confirmation. dditionally the He abundance is 20 per cent larger ıan in the bulk of LMC-PNe; nevertheless He is ot as enhanced as in the extreme type I LMC-PNe 7 and P9 (Aller et al. 1987). Helium to hydrogen ıtios of 0.133 and 0.152 are derived for P7 and P9 om Aller et al. data, after correction for collisional ffects.

C/O abundance ratios significantly higher than nity have been reported for several samples of MC-Ne (Aller et al. 1987; Walton et al. 1990). The igh C abundances have been ascribed to the third regde-up episode whereby the products of the iple-α reaction are brought up to the surface late ı the evolution of AGN stars. The results by /alton et al. show that the C/O ratio increases ith decreasing initial metallicity, being higher in ıe SMC-PNe. In this scheme, we find that the C/O ıtio in LM1-64 is higher than the average reported ›r LMC-PNe, corresponding to the fact that the ' abundance is 0.1 dex lower than the average ılue. Furthermore we have found evidence ›r the possible presence of large C abundance ıhomogeneities within the nebula which would nply an even higher C/O ratio. Evidently the /C central star in LM1-64 has largely enriched its nvelope with freshly made carbon during the third regde-up. According to evolutionary models by enzini & Voli (1981), the initial mass of the central star should have been in the range between 2 and 5 solar masses.

By means of an ionization structure model fitting the observations, we have derived an effective temperature of 100 000 K, a luminosity of 6900 $L_\odot$ and a radius of 0.3 $R_\odot$ for the central star of LM1-64. Comparison of these values with theoretical evolutionary tracks for helium-shell burning stars by Wood & Faulkner (1986) implies a mass lower than 0.6 solar masses for this star.

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Lorenzo Olguín, Miriam Peña, and Silvia Torres-Peimbert: Instituto de Astronomía, UNAM, Apartado Posta 70-264, 04510 México, D.F., México.
María Teresa Ruiz: Depto. de Astronomía, Universidad de Chile, Casilla 36-D, Santiago, Chile.

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