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OPEN SLIT ECHELLE SPECTROSCOPY OF PLANETARY NEBULA M 1-9[1]

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RESUMEN

Espectroscopía óptica de toda la nebulosa planetaria M 1-9, revela pronunciadas variaciones de densidad, una distribución de temperatura en la que $T_{\rm e}({\rm N}^{+})$ es mayor que $T_{\rm e}({\rm O}^{+2})$ y abundancias que indican que es una planetaria del halo, identificación validada por su alta velocidad radial y su distancia al plano galáctico. La masa ionizada es de 0.1 a 0.4 $M_{\odot}$. Un modelo de fotoionización con densidad uniforme (Cloudy, versión 10.00) reproduce la mayor parte del espectro, aunque la intensidad de [O III] 4363 Å es mucho mayor que la observada. En este modelo, las abundancias nebulares son más bajas que las obtenidas con técnicas usuales y la temperatura y luminosidad estelar son 84900°K y 1025 $L_{\odot}$, lo que significa que la progenitora probablemente fue una estrella de $\approx$1 $M_{\odot}$ en secuencia principal.

ABSTRACT

Optical spectroscopy of the entire planetary nebula M 1-9, reveals pronounced density variations, a temperature distribution where $T_{\rm e}({\rm N}^{+})$ is larger than $T_{\rm e}({\rm O}^{+2})$ and abundances indicating that it is a halo planetary nebulae, an association supported by it is very large radial velocity and distance to the galactic plane. The ionized mass is between 0.1 and 0.4 $M_{\odot}$. A uniform density photoionization model (Cloudy, version 10.00) reproduced most of the spectrum, but the intensity of [O III] 4363 Å is much larger than observed. In this model, nebular abundances are smaller than those derived using standard techniques and the stellar temperature and luminosity are 84900°K and 1025 $L_{\odot}$, which implies that the progenitor probably was a $\approx$1 $M_{\odot}$ zero-age main sequence star.

Key Words: ISM: abundances — ISM: individual objects (M 1-9) — planetary nebulae: general

1. INTRODUCTION

M 1-9 (PN G212.0+04.3, ARO 131, VV 31) is a small and distant planetary nebula (PN), with a heliocentric radial velocity of 136 ± 10 km s^{-1} (Schneider et al. 1983). Using the basic solar motion as given by Mihalas & Binney (1981), the local standard of rest radial velocity is 123 km s^{-1}. The minimum, maximum and mean values of distance estimates are 2.61, 11.58 and 6.4 ± 2.6 kpc respectively (Cahn, Kaler, & Stanghellini 1992; van de Steene & Zijlstra 1995; Zhang 1995; Phillips 2002, 2004, 2005; Stanghellini, Shaw, & Villaver 2008), which imply that the object is between 200 and 900 pc away from the galactic plane. Thus, the progenitor star probably was a Population II star. Central star magnitudes are $B = 15.7$ and $V = 15.6$, with an error margin between 0.25 and 0.5 magnitudes (Tylenda et al. 1991). There is no trace of molecular hydrogen emission in the near IR ($\lambda\lambda$ 1.6–2.5 μm) spectrum of M 1-9, which is made up entirely of hydrogen and He I recombination lines (Lumsden, Puxley, & Hoare 2001). Optical spectroscopy of M 1-9 can be found in Costa, Uchida, & Maciel (2004) and Henry et al. (2010), henceforth C04 and H10, where many PNe were observed in order to investigate radial abundance gradients in our galaxy. Regarding M 1-9, there are some differences between these two works, such as the electron temperature derived from the

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[1] Based on observations collected at the Observatorio Astronómico Nacional in San Pedro Mártir, B. C., México.

N^+ lines and the abundance of helium. These may be explained if different regions of M 1-9 were analyzed, a plausible explanation since both slits were just $2''$ wide.

This paper is focused on analyzing M 1-9 using high dispersion optical spectroscopic observations of the entire nebula, thus avoiding the limitations imposed by narrow slit observations, where the photoionized region is not always fully sampled and it is difficult to apply photoionization models (Bohigas 2008). Observations are described in § 2. Standard procedures are used to reduce the data and obtain density, temperature and ion concentrations. In a manner rarely explored before, ion concentrations are also found assuming that most of the emission of the hydrogen recombination lines is not produced in the hot environment where most of the emission of forbidden lines is produced, but in a colder component, as may be evinced by Balmer ratios. All this is described in § 3, where the ionized gas mass and the Zanstra temperature of the exciting star are also calculated. Finally, in § 4 the spectrum is modeled using the Cloudy photoionization code, thus providing an additional estimate of nebular abundances as well as important insights on the properties and origin of the exciting star. Conclusions are presented in the final section.

2. OBSERVATIONS

Spectroscopy was carried out in January 2011, using the 2.1 m f/7.5 telescope at OAN, and the Echelle spectrograph with a 400 lines mm^{-1} cross disperser, no blocking filters and a 1.7 mm wide and 2.0 mm long slit ($\sim 22'' \times 27''$). The slit was fully open in order to minimize problems related to incomplete coverage (Bohigas 2008) and to capture all the emission produced by the objects that were observed during this campaign. The detector was a Thomson 2048×2048 pixel CCD, binned by a factor of two in both directions.

The spectral range, mean spectral resolution and dispersion are $\lambda\lambda$ 3650–6700 Å, ∼2.5 pixel and between 0.28 (red end) and 0.16 (blue end) Å/pixel (the binned pixel size is 30 μm). Fluxes were determined combining 26 exposures, each 600 s long. Data reduction was performed applying IRAF[2] standard procedures.

Results are reported in Table 1. Line fluxes were determined using standard stars Feige 66 and HD 93521 (1 Å data bins) with and without background subtraction. Mean fluxes relative to Hβ, along with the largest deviation for these measurements, are given under the column labeled as $F_{\rm obs}$. These deviations yield a rough estimate of measurement errors, since most line fluxes were measured at least four times: two standards, with and without background subtraction and, in some cases, the line could be measured in two spectral orders. For obvious reasons, deviations are not given for some weak and all atmospheric lines, which could not be measured more than twice. In this case, uncertainties may be as large as ∼50%.

Drawing a comparison between the theoretical and observed values of [O III] 5007/4959 and [N II] 6584/6548, it can be argued that the minimum error level is ∼5%. Since the flux of [Ne III] 3968 Å was not properly measured, as can be deduced by carrying out a comparison with the spectrum reported by H10, the reported [Ne III] 3869/3968 line ratio is obviously wrong (two times larger than the theoretical value).

Since PNe may have two components with very different temperatures (e.g., Liu et al. 2004), dereddening was performed using $I(\mathrm{H}\gamma)/I(\mathrm{H}\beta)$, the Balmer line ratio with the weakest density and temperature dependence. According to Storey & Hummer (1995), for densities smaller than 10^6 cm^{-3} and temperatures between 3000 and 15000 K, the mean case B value of this Balmer line ratio is 0.467 ± 0.008. De-reddening was done using Seaton's (1979) extinction law and assuming that $I(\mathrm{H}\gamma)/I(\mathrm{H}\beta) = 0.467$. De-reddened line fluxes appear under the label $I_{\rm obs}$ in Table 1. Line fluxes from the photoionization model that is discussed in § 4, are included in this table under the column labeled $I_{\rm mod}$.

Finally, the FWHM of the Hα line is $\sim 4\farcs3$. This implies that the slit used by C04 and H10 does not include the entire nebula, a fact that may explain some of the differences that are mentioned in the following lines.

3. DATA ANALYSIS

3.1. *Nebular densities and temperatures*

Electron densities and temperatures are shown in Table 2. These were calculated using IRAF's `temden` task (Shaw & Dufour 1994). Assuming that O^+ and N^+ coexist in the same nebular region, solutions for the electron temperature and density, $T_{\rm e}(\mathrm{N}^+)$ = 12902°K and $N_{\rm e}(\mathrm{O}^+)$ = 2016 cm^{-3}, were obtained self-consistently from [N II](6548+6584)/5755 and [O II]3726/3729. If the pressure is uniform, the temperature found from [O III](4959+5007)/4363 is $T_{\rm e}(\mathrm{O}^{+2}) = 10561$ K and $N_{\rm e}(\mathrm{O}^{+2}) = 2463$ cm^{-3}. The electron density derived from the [Cl III]5518/5538

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[2] IRAF is distributed by NOAO which is operated by AURA under contract to the NSF.

TABLE 1

M 1-9 SPECTRUM

ID	$F_{\rm obs}$	$I_{\rm obs}$	$I_{\rm mod}$
[O II] 3726	42.80±4.54	59.60	52.11
[O II] 3729	23.20±2.78	32.27	35.01
H 10 3798	4.48±1.51	6.09	5.34
H 9 3835	6.98±1.47	9.36	7.31
[Ne III] 3869	21.90±2.63	29.08	29.15
H 8+He I 3889	14.90±1.56	19.66	18.66
[Ne III] 3968	3.57±0.25	4.60	8.79
Hϵ 3970	12.10±0.85	15.56	15.91
He I 4026	2.07±0.50	2.62	2.14
[S II] 4070	0.66±0.20	0.83	1.11
Hδ 4102	19.80±0.85	24.52	25.95
Hγ 4340	39.80±1.59	46.72	47.05
[O III] 4363	2.85±0.19	3.33	6.39
He I 4388	0.52±0.06	0.60	0.57
He I 4471	4.32±0.10	4.86	4.60
Mg I 4571	0.30	0.33	
He II 4686	0.31	0.33	0.33
He I 4713	0.56±0.04	0.59	0.75
Hβ 4860	100.00±0.00	100.03	100.00
He I 4922	1.36±0.10	1.33	1.23
[O III] 4959	151.00±2.72	146.74	156.51
[O III] 5007	460.00±9.20	440.96	471.10
He I 5016	3.07±0.82	2.93	2.80
[Cl III] 5518	0.25	0.21	0.33
[Cl III] 5538	0.42	0.35	0.32
[N II] 5755	1.70±0.06	1.34	1.34
He I 5876	18.00±0.27	13.76	13.85
[O I] 6300	2.93	2.06	2.21
[S III] 6312	1.29±0.06	0.90	0.81
[O I] 6364	0.72	0.50	0.70
[N II] 6548	28.30±1.05	18.99	17.95
Hα 6563	427.00±11.10	285.76	289.14
[N II] 6584	78.20±2.11	52.20	52.97
F(Hβ)[a]	2.65±0.09		
C(Hβ)	0.54		
I(Hβ)[a]		9.19±0.31	

[a] F(Hβ) and I(Hβ) in 10^{-12} erg cm^{-2} s^{-1}.

line ratio, $N_{\rm e}({\rm Cl}^{+2}) = 12504$ cm^{-3}, was obtained assuming that $T_{\rm e}({\rm O}^{+2})$ is the mean temperature of the region where Cl^{+2} is the predominant chlorine ion.

It is worth noticing that C04 and H10 determined very similar numbers for $T_{\rm e}({\rm O}^{+2})$, 10992 and 10440°K, but significantly smaller values for $T_{\rm e}({\rm N}^{+})$, 10435 and 11490°K. They also find that the density derived from [S II]6717/6731 (4516 and 7084 cm^{-3}), is substantially larger than the one obtained in this paper from the density dependent O^{+} line ratio. H10 also find a very similar density from the chlorine line ratio, 13810 cm^{-3}, a pleasant surprise since these lines are rather weak and were poorly measured. Thus, there is a reasonable consensus for the

TABLE 2

ION CONCENTRATIONS

Line ratio	Value	N_e (cm^{-3})
[O II]3726/3729	$1.85^{+0.47}_{-0.37}$	2016^{+1629}_{-842}
[Cl III]5518/5538	$0.60^{+0.02}_{-0.02}$	12504^{+1126}_{-1046}
ID	Ratio	T_e (°K)
[N II](6548+6584)/5755	$53.13^{+3.57}_{-2.93}$	12902^{+404}_{-434}
[O III](4959+5007)/4363	$176.49^{+16.29}_{-14.26}$	10561^{+293}_{-291}

TABLE 3

ION CONCENTRATIONS

Ion	Line	Std	2C
He^+	5876	0.0931	0.0906
He^{+2}	4686	0.0003	0.0004
$N^+ \times 10^{-5}$	6584	0.565	1.043
$O^0 \times 10^{-6}$	6300	1.633	3.013
$O^+ \times 10^{-5}$	3727	1.722	3.177
$O^{+2} \times 10^{-4}$	5007	1.286	1.983
$Ne^{+2} \times 10^{-5}$	3869	2.367	3.649
$S^+ \times 10^{-7}$	4069	0.889	1.640
$S^{+2} \times 10^{-6}$	6312	1.128	1.912
$Cl^{+2} \times 10^{-8}$	5528	2.327	3.943

highly excited region of the nebula, but significant differences on the density and temperature of the less excited gas that presumably lies at the nebular periphery.

Interestingly, at a density of 2016 cm^{-3} the dereddened Hα/Hβ and Hδ/Hβ ratios indicate that the mean temperature of the gas producing the hydrogen recombination lines is between 9900 and 2900°K (Storey & Hummer 1995), which suggests that, in addition to the hot gas where forbidden line emission is mostly produced, there may be a colder component where recombination lines are important cooling agents.

3.2. *Nebular abundances from ionization correction factors*

Ion abundances are given in Table 3. The concentration of helium ions was calculated following Aller (1984), taking into account collisional effects on the He I lines (Kingdon & Ferland 1995). The other concentrations were determined using IRAF's `ionic` task (Shaw & Dufour 1994). Two approaches were used to estimate ion concentrations.

In the standard approach (under header Std), concentrations relative to H^+ were calculated assuming that the temperature of ionized hydrogen is equal to the temperature of the ion whose abundance is to be determined: $T_e(N^+)$ for N^+, O^0, O^+ and S^+, the average of $T_e(N^+)$ and $T_e(O^{+2})$ for He^+, S^{+2} and Cl^{+2} and $T_e(O^{+2})$ for He^{+2} , O^{+2} and Ne^{+2}. The electron density is assumed to be equal to $N_e(O^+)$ in all cases. With the exception of He^{+2}, all ion abundances reported in Table 3 are smaller than in H10. Differences are larger for low ionization species N^+, O^+ and S^+. To a certain extent, this is due to the fact that a larger value of $T_e(N^+)$ is found in this paper. Except for He^+, the same remark applies when concentrations are compared to those published in C04.

Since there can only be one mean temperature for ionized hydrogen, this often used procedure is clearly inconsistent and prone to errors, though these will not be larger than ∼15% as long as the temperature is between 9000 and 15000°K. But this approach can no longer be used if there is a colder component, since the emissivity of Balmer lines is greater at lower temperatures, whereas forbidden lines are much weaker. Thus, the weighted mean temperature of the region where hydrogen recombination lines are emitted is substantially different from the mean temperature of the region where most of the emission from forbidden lines is produced.

Ion concentrations given under header 2C in Table 3, were calculated using the aforementioned temperatures for the forbidden lines, but assuming that the weighted mean temperature for Balmer line emission is $T_e(H^+) = 6400$°K, the mean value of the temperature prescribed by Hα/Hβ and Hδ/Hβ. The relative abundance of both helium ions, which is also determined from recombination lines, is calculated using the emissivity of helium lines at $T_e(H^+)$. This assumption will probably overestimate the abundance of He^{+2}, since this ion exists in a hotter environment. As before, since emissivities have a weak density dependence, all ion abundances were determined assuming that the electron density is equal to $N_e(O^+)$. As expected, ion concentrations of heavy elements relative to H^+ are larger when a cold component is included, since a large fraction of the hydrogen Balmer line emission will be produced in this region. Notice that ion abundances will be somewhat smaller when forbidden line emission in the cold component is included.

Chemical abundances determined from ionization correction factors (ICF) given by Kingsburgh & Barlow (1994) are presented in Table 4. Column headers Std and 2C indicate which set of ion concentrations was used. The table includes mean non-type I PN abundances (under header PN Not-I) compiled by Bohigas (2008), and the mean solar abundance of these elements, as reported by Lodders (2003) and Asplund, Grevesse, & Suval (2005).

These abundances, as well as most of those reported by C04 and H10, are substantially smaller than the mean abundances of non-type I PN, which indicates that the star that eventually produced M 1-9 was older and lighter than type II PN main sequence progenitors (the majority of non-type I objects). The most important discrepancy in these three abundance sets is the very low helium abundance reported by C04 (0.065), which is almost surely wrong.

Regardless of which of these abundance sets is considered, and taking into account its large local standard of rest radial velocity and distance from the galactic plane, it is likely that M 1-9 is a halo (type IV) planetary nebula (Peimbert 1990; Howard, Henry, & McCartney 1997), associated to a ~1.0 $M_\odot$ low metallicity Population II progenitor star. The case for a halo planetary nebula is weaker if M 1-9 is made up of a hot and a cold component, since abundances are substantially larger in this case (under column labeled 2C in Table 4), though the abundance criterion may be incorrect if a substantial number of halo planetary nebulae have a hot and a cold component. Notice that M 1-9 was classified as a type IIb, type II and type III PN by C04, H10 and Quireza, Rocha-Pinto, & Maciel (2007).

3.3. *Nebular mass and central star temperature and visual magnitude*

Since the entire nebula is included in the slit, the ionized hydrogen mass can be estimated from

$$M(\mathrm{H}^+) = \frac{4\pi D^2 I(\mathrm{H}\beta) m_\mathrm{H}}{\langle N_\mathrm{e}\rangle E_{42}}\,, \qquad (1)$$

where D is the distance to the object, $I(\mathrm{H}\beta)$ is the Hβ flux corrected for reddening, m_H is the proton mass, $\langle N_\mathrm{e}\rangle$ is the mean electron density and E_{42} is the effective recombination emissivity of the Hβ line. If the mean temperature of the H^+ region is 11731°K, the mean value of $T_\mathrm{e}(\mathrm{N}^+)$ and $T_\mathrm{e}(\mathrm{O}^{+2})$, the nebula is in pressure equilibrium, so that $N_\mathrm{e} = 2240$ cm^{-3}, and the distance to M 1-9 is 6.4 ± 2.6 kpc, then $M(\mathrm{H}^+) = 0.155^{+0.151}_{-0.100}$. If there is a cold component and the mean temperature and density in the H^+ region are 6400°K and 4104 cm^{-3}, then $M(\mathrm{H}^+) = 0.050^{+0.049}_{-0.032}$. Considering helium, the ionized gas mass is ~37% larger.

TABLE 4

CHEMICAL ABUNDANCES FROM ICF

Element	Std	2C	PN Not-I	Solar
He	0.093	0.091	0.109±0.005	0.082
N $\times10^{-5}$	4.79	7.57	15.3±5.49	6.40
O $\times10^{-4}$	1.46	2.31	4.35±0.84	4.74
Ne $\times10^{-5}$	2.69	4.25	12.4±3.53	7.17
S $\times10^{-6}$	1.79	2.92	8.67±2.42	14.7
Cl $\times10^{-8}$	2.33	3.94	1.42	2.49

Kaler & Jacoby (1989) provide simple formulae to estimate the effective temperature and visual magnitude of central stars of optically thick PNe, from He II(4686)/Hβ and the Hβ flux. They argue that a PN can be regarded as optically thick if ([O II] 3726 + [O II] 3729)/H$\beta \geq 1$. The observed value is slightly less than this lower limit (0.92). Assuming that M 1-9 is optically thick, the temperature and visual magnitude of the central star are $T_* \simeq 80000$°K and $V \simeq 16.7$. The central star temperature is two times larger than the value given by Lumsden et al. (2001), but nearly identical to the one predicted by the photoionization model (next section). The visual magnitude is considerably larger than in Tylenda et al. (1991), where they find that $V = 15.6 \pm 0.5$ with a somewhat larger extinction constant (0.8 vs 0.54).

4. PHOTOIONIZATION MODEL

The spectrum of M 1-9 was re-analyzed using version 10.00 of the Cloudy photoionization code (Ferland et al. 1998) with its default optimization method (Subplex; Rowan 1990). Photoionization models assume equilibrium conditions, which imply that the smallest timescales must be associated to atomic processess. In this photoionization model the longest timescale of an atomic process is 76.7 yr, much less than the probable age of M 1-9.

The incident continuum was assumed to be produced by a halo abundance He-Ni Rauch (2003) model photosphere for central stars of planetary nebulae, which was slightly better than any solar abundance model from the same author. The stellar temperature and luminosity, T_* and L_*, were left as free parameters. The gravity (g_*) was selected from the condition that the mass of an equivalent black body,

$$M_* = \frac{g_* L_*}{4\pi\sigma G T_*^4} \qquad (2)$$

is between 0.5 and 1.0 $M_\odot$.

The nebula was assumed to be a static sphere surrounding the central star and letting no inward-directed diffuse line or continuum radiation escape, which implies that the covering factor is equal to one. The inner radius was a free parameter and the default cosmic ray background was included.

The total hydrogen density, N(H), was assumed to be uniform and was treated as a free variable. This assumption is obviously at odds with observations, but better results could not be obtained from simple power law density distributions, nor assuming uniform pressure. No attempt was made to simulate a PNe with two well defined temperature (and density) components. Grain abundance was assumed to be uniform and equal to Cloudy's standard value. The AGB grain set was used in this model.

The abundances of helium, nitrogen, oxygen, carbon, neon, sulfur and chlorine were left as free parameters. Abundances for other elements were taken from Cloudy's PN set and were kept fixed. Considering their small importance in the structure of photoionized regions, lithium, beryllium, boron, scandium, titanium, vanadium, chromium, manganese, cobalt. copper and zinc were not included.

Model runs were set to optimize the intensities of [O II] 3726,3729 Å, [Ne III] 3869 Å, He II 4686 Å, [O III] 5007 Å, [N II] 5755,6584 Å and He I 5876 Å with respect to Hβ. Model runs produced worst results when they were also set to optimize [O III] 4363 Å. No carbon line could be used to tie up the abundance of carbon, since none was observed. But changes in the carbon abundance made an important difference in the overall quality of the modeled spectrum, since it is a major cooling agent. Calculations were stopped when [O I]6300/Hβ reached the observed value.

Line intensities for the best modeled spectrum are presented in Table 1 under the column labeled as $I_{\rm mod}$. Excepting [O III] 4363 Å ([Ne III] 3968 Å was not properly measured), observed line intensities are reasonably well reproduced by the photoionization model. Excluding this line, the mean difference between observed and modeled line intensities is 10.7%. The photoionization model prescribes a much higher intensity for the blue O^{+2} line and, consequently, a larger than observed value for $T_{\rm e}(O^{+2})$ (13005 vs. 10561°K). This discrepancy was also found when model runs were also set to optimize [O III] 4363 Å. There is a very good agreement between the modeled and the observed value for $T_{\rm e}(N^{+})$ (12893 vs 12905°K). Since N(H), the total hydrogen density (ionized, neutral and molecular), is a free parameter in this uniform density model, the electron density sensitive [O II]3729/3727 line ratio could not be successfully reproduced (1.49 vs. 1.85).

TABLE 5

MODEL PARAMETERS

L_* ($L_\odot$)	1025
T_* (°K)	84900
g_* (cm s^{-2})	10^6
$R_{\rm o}$ (pc)	0.077
N(H) (cm^{-3})	2165
log L(Hβ) (erg s^{-1})	34.445
He	0.089
C $\times 10^{-4}$	10.0
N $\times 10^{-5}$	3.02
O $\times 10^{-4}$	0.97
Ne $\times 10^{-5}$	1.11
S $\times 10^{-6}$	1.15
Cl $\times 10^{-8}$	3.88

The most important parameters of this photoionization model are presented in Table 5. Notice that the stellar temperature is nearly identical to the one found using the method devised by Kaler & Jacoby (1989).

Model abundances are markedly smaller than those that were found using mean temperatures and ionization correction factors (listed under column labeled Std in Table 4). Thus, the model also supports the conclusion that M 1-9 is a halo planetary nebula, though the abundance of carbon is slightly larger than the largest carbon abundance found in halo PNe (Howard et al. 1997).

Some properties of the zero-age main sequence progenitor star of M 1-9, can be estimated finding which theoretical evolutionary tracks of PN nuclei are closest to the exciting star in an HR diagram. When compared to models produced by Vassiliadis & Wood (1993, 1994), the exciting star is closest to a 23000 year old H burning shell PN nucleus, produced by a solar metallicity, 1 $M_\odot$ zero-age main sequence star (but the exciting star is three times more luminous than this PN nucleus). When compared to Blöcker's (1995) models, the exciting star is closest to a 6500 year old He burning shell PN nucleus, produced by a 1 $M_\odot$ zero-age main sequence star (but he exciting star is 40% less luminous than this PN nucleus). Bear in mind that these authors have different age definitions for their models, and that both of these have no direct relationship to the dynamical age of a planetary nebula.

From the outer radius of the model nebula, R_o, and assuming a nebular mean expansion velocity of 10 km s^{-1}, the dynamical age of the PN model turns out to be close to 7500 years. If the outer radius defines the FWHM of the Hα line profile ($4\farcs3$), the photoionization model implies that the distance to M 1-9 is equal to 3.7 kpc, substantially less than the mean distance estimate, 6.4 ± 2.6 kpc. At this distance, given the intrinsic Hβ luminosity $L(\mathrm{H}\beta)$, the Hβ line intensity of the photoionization model would be 1.7×10^{-11} erg cm^{-2} s^{-1}, 1.85 times larger than the observed, reddening corrected, intensity. The outer radius (and distance) would have to be $\sim$40% larger in order to reproduce the observed Hβ line intensity and the FWHM of the Hα line profile (conversely, $L(\mathrm{H}\beta)$ would have to be smaller). This implies that the constant density model is not the best solution and/or the stopping criterion that defines the outer radius of the model nebula, based on the rather uncertain value of [O I]6300/Hβ, fails to include the whole nebula.

5. CONCLUSIONS

Optical spectroscopic observations of the entire planetary nebula M 1-9 show that the object has large density variations and a temperature structure where $T_e(\mathrm{N}^+)$ is larger than $T_e(\mathrm{O}^{+2})$, which may indicate that cooling is more efficient in the region where O^{+2} is the predominant oxygen ion. A higher density in this region is a plausible explanation.

Abundances determined with the standard procedure indicate that M 1-9 may be a halo planetary nebulae, an association that is supported by its very large radial velocity and great distance from the galactic plane. If this is so, the progenitor was a low metallicity population II star with a main sequence mass close to 1 $M_\odot$. Since the ionized nebular mass is between 0.1 and 0.4 $M_\odot$, this implies that there is almost no molecular gas and that most of the ejected material is within the $4\farcs3$ defined by the FWHM of the Hα line profile. On the other hand, the abundances of nitrogen, oxygen, neon and sulphur would be almost twice as large if there is a second cold component in M 1-9, casting some doubts on the identification of M 1-9 as a halo PN.

A uniform density model produced with version 10.00 of the Cloudy photoionization code (Ferland et al. 1998), reproduced rather accurately most of the spectrum of M 1-9, but the intensity of [O III]4363 line turned out to be much larger than observed. Consequently, $T_e(\mathrm{O}^{+2})$ is overestimated in the photoionization model, which indicates that a uniform density model is far from being an adequate simplification. Unfortunately, models were not better when simple power law density distributions were used.

In the photoionization model, the stellar temperature is slightly larger than the one found using the Zanstra method (Kaler & Jacoby 1989), model abundances are markedly smaller than those derived using standard techniques, and the progenitor star is a $\approx$1 $M_\odot$ zero-age main sequence star (Vassiliadis & Wood 1993, 1994; Blöcker 1995). All these supports the notion that M 1-9 is a halo planetary nebula produced by a low mass population II star.

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