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Deconstructing *IRAS* 07027–7934

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Abstract. The planetary nebula *IRAS* 07027–7934 has a compact ionized core surrounded by a large cloud of matter believed to be of neutral gas and dust particles. A photoionization model of this ionized core is presented in this paper. The parameters $T_{\rm eff}$, R_*, and distance of the central star along with the radius of the nebula are derived by photoionization modeling. The nebula is found to have a much lower electron temperature than was estimated earlier but the electron density is very high, in broad agreement with previous result. The abundances derived for the first time point to a C/O ratio of >5 for the nebula, and the internal extinction caused by the ionized core, $E(B-V)$, is 2.

Key words. planetary nebulae: individual: *IRAS* 07027–7934 – planetary nebulae: photoionization modeling – stars: WC 11

1. Introduction

Among the planetary nebulae (PNe) with central stars of Wolf-Rayet Carbon type (WC), there are about half a dozen PNe that have been classified as [WC11]. Menzies & Wolstencroft (1990) obtained the first optical spectra of *IRAS* 07027–7934 (PN G291.3–26.2; also named Vo 1) and included it in the [WC11] subgroup based on the spectral characteristics. The PAH feature seen in IRAS LRS and the observation of strong OH maser emission at 1612 MHz by Zijlstra et al. (1991) indicated the simultaneous presence of carbon-rich and oxygen-rich dust. The object presents a stellar appearance in the optical and the ionized core was estimated to be $0\farcs3$ in diameter by Zijlstra et al. (1991). Here, I have derived the physical and chemical characteristics of Vo 1 by photoionization modeling.

2. Method of analysis and data

The approach to the problem of interpreting the available data on Vo 1 by way of computing a model is an optimal one. The data gathered from the literature basically consist of optical spectral line data of Menzies & Wolstencroft (1990), the $UBVR_{\rm c}I_{\rm c}JHKL$ photometry and H-alpha image of Zijlstra et al. (1991) and the IRAS fluxes at 12, 25, 60 and 100 μm. There is no UV (IUE) spectrum available for this nebula. The intensity distribution in H-alpha image (size $\sim 20''$) is non-Gaussian and the intensity beyond the ionized core is inferred to be mostly scattered light by neutral material and dust grains since the optical image (at 500 nm) is stellar (Zijlstra et al. 1991). Based on the split profile of OH, the difference between the observed CO and OH velocities and the off-centered location of the ionized core in the H-alpha halo, Zijlstra (2001) suggests that Vo 1 may have a bipolar morphology.

One needs the characteristics of the central star, like effective temperature, radius and distance, for photoionization modeling. On the other hand it is possible to invert the modeling methodology to get reasonable values (of these parameters) that are mutually consistent. Earlier estimates of T_* by Menzies & Wolstencroft (1990) and Zijlstra et al. (1991) were anywhere between 18 000 K and 28 000 K. A distance of 3–5 kpc was estimated through the measurement of $E(B-V)$ of close-by stars by Zijlstra et al. (1991). Rather than attempting a comprehensive model with limited data, a simpler modeling would be ideal as a first step toward interpreting them. The code used for this purpose is described in Surendiranath (1992) and Surendiranath & Kameswara Rao (1995). It essentially assumes a spherically symmetric and static nebula in steady state and allows the presence of dust grains mixed with the gas. The diffuse radiation field is treated under the on-the-spot (OTS) approximation. To take care of fluctuations in density, the code allows a filling factor of a value less than unity also. The approach to dust modeling is on the lines of Harrington et al. (1988) and Hoare & Clegg (1988). The grains are assumed to be heated by stellar and Ly α-line photons and assumed to emit like a blackbody under thermal equilibrium. Effects of scattering are not included and only grains of a single size are treated. In this work, only the ionized part of the nebula is considered for modeling, which implies that matching the observed nebular line fluxes is given a more serious consideration than matching the infrared radiation by dust though dust grains have been introduced in the ionized nebula of the model. See later for more discussion.

2.1. Inputs to the model

Although the accuracy of absolute spectrophotometry of Vo 1 by Dopita & Hua (1997) is very high, I have avoided using

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these flux values to determine the reddening. The slit width had been kept at 5″ and this would have allowed scattered light from around the small nebula to enter the slit and one can not assume that the scattering was equal at, say H_α and H_β. It must be noted that Menzies & Wolstencroft (1990) find different $E(B-V)$ for different Balmer lines. The effect of scattering is important since the ionized core is small though the slit may be narrow. So to minimize this effect, I determined the $E(B-V)$ from the ratio of most closely spaced Balmer lines $H\delta$ and $H\epsilon$ and this value (1.14) agrees with the value adopted by Menzies & Wolstencroft (1990), 1.1. So taking this value for $E(B-V)$, all their line fluxes were dereddened with the help of Seaton's (1979) extinction curve, and then compared with the model fluxes. Menzies & Wolstencroft (1990) quote an error of ~30% in their measured $H\beta$ flux. So in matching the model fluxes to the observed spectrum, an accuracy better than this amount in the derived parameters may not be achieved.

The electron temperature T_e and electron density N_e estimated by Menzies & Wolstencroft (1990) were used as starting values for the modeling. The ratio of high precision measurements of the [S II] lines 6717 Å and 6731 Å by Dopita & Hua (1997) could have been used to determine the density, since any scattered light contribution would be equal in both lines as the wavelengths are very close. But the ratio falls beyond the range of linear part of the plasma diagnostic curve. The code requires only reasonable starting values since complete thermal equilibrium equations are solved to determine them at each radial point. The energy budget of Vo 1 by way of integrating the $UBVR_cI_cJHKL$ photometric fluxes along with the IRAS fluxes (from 0.36 μm to 100 μm) turns out to be $\sim 554\, d^2 L_\odot$, where d is the distance in kpc. In the absence of any atmospheric model for Vo 1, a blackbody is a reasonably good assumption for the central star (CS). For any given distance d in the range of 3–5 kpc, T_* and R_* have to be varied such that the bolometric luminosity is consistent with the observed value of $\sim 554\, d^2 L_\odot$ and the model nebular diameter is <1″ at that distance. The observed total emission in the infrared (from 1 μm to 100 μm) is nearly 98% of the observed bolometric luminosity. Vo 1 has been observed with ISO by various observers (see for example: Cohen 2001, Sczcerba et al. 2001). Cohen (2001) displays the spectrum in the range of 1–100 μm and identifies a number of dust emission features (PAHs and silicates).

All the observed IR emission must be coming from the dust grains present inside and outside the ionized part of the nebula. This suggests that part of the stellar radiation leaks out of the (ionized) nebula, since, only then could the dust present outside be heated. Zijlstra (2001) notes that since PAH emission requires a stronger UV radiation, the carbon-rich dust must be closer to the CS than the oxygen-rich dust. Thus it seems appropriate to consider the carbon-rich dust as being mixed with the gas in the ionized nebula. I have assumed the dust grains to be of amorphous carbon, and the filling factor to be unity which is quite reasonable for a compact high density nebula.

3. Discussion

In order to get a best fitting model, a number of models were run and each time the results were carefully scrutinized before introducing any change in the input parameters for the subsequent run. The input parameters of the best fitting model are the derived parameters of the PN Vo 1, and are shown in Table 1. A constant density was assumed for all the runs. The dust to hydrogen ratio by mass M_d/M_H is the dust to gas mass ratio M_d/M_g multiplied by 1.4. "***r***" denotes the fractional radial distance with $\boldsymbol{r} = 1$ defining the nebular outer radius. The nebular inner radius for all the runs was kept at 5.0×10^{13} cms (1.62×10^{-5} pc), while the outer radius as implied by the distance and angular diameter given in Table 1 is 1.32×10^{16} cms ($\sim 4.27 \times 10^{-3}$ pc). The model and observed fluxes (dereddened) are shown in Table 2.

Table 1. Parameters of the model.

Parameter	Value			
CSPN(BB)				
$T_{\rm eff}$	22 000 K			
Radius	6.5 $R_\odot$			
Nebula				
Const. density	$N_H = 5.445 \times 10^4$ cm^{-3}			
Abundance	H	He	C	N
	12.000	11.105	9.162	8.050
	O	Ne	S	Ar
	8.778	8.090	7.113	6.460
Size	0.″44 (diameter)			
Distance	4kpc			
Filling factor	1			
Dust	Amorphous Carbon			
M_d/M_H	9.0 d–2(0.012 r–0.1 r)			
	1.4 d–1(0.1 r–0.145 r)			
	2.01 d–3(0.145 r–1 r)			
Size distribution	single size			
Size	0.05μm			

3.1. Nebular environment

The model runs of electron density and temperature are shown in Fig 1. The mean density $\overline{N}_e$ turns out to be 5.54×10^4 cm^{-3} compared to 6.3×10^4 cm^{-3} obtained by Menzies & Wolstencroft (1990). The mean temperature $\overline{T}_e$ is much lower (6900 K) than what was derived by them (16 000 K). The nebular abundances (from Table 1) indicate a C/O ratio of more than 5. In Fig. 2 the nebular ionization structure for various ions is plotted. The internal extinction caused by the nebula is estimated as $E(B-V) \sim 2$ mag. This is the extinction in the ionized nebula only. There may be additional extinction in the surrounding neutral region which would have been included in the foreground extinction. The above value is much higher than the value derived from Balmer lines. The photometry of close-by stars by Zijlstra et al. (1991) yielded a value between 0.3 and 0.6 depending on the spectral type used and for a distance of 3 kpc. Since this object is at a high galactic latitude, one would expect most of the extinction to be internal and not interstellar. Photometry of close-by stars in general gives an estimate of extinction in the direction of the object and hence would not account for any circumstellar extinction. Therefore this observed value must be viewed with caution. The model value of

Table 2. The emission line fluxes ($H\beta$ = 100).

Wavelength (Å)	Ion	Model flux	Obsd. flux (dereddened)
6563	H i	293.4	221.5
4340	H i	46.4	47.5
4101	H i	25.6	21.4
3970	H i	15.7	13.0
5876	He i	4.0	7.0
7065	He i	0.4	1.9
3889	He i	2.7	13.8
6678	He i	1.1	3.8
4922	He i	0.4	3.8
4471	He i	1.4	8.4
4686	He ii	0.0	4.6
4267	C ii	0.2	25.3
5755	[N ii]	1.6	9.1
6548	[N ii]	34.3	26.2
6584	[N ii]	101.0	90.4
6300	[O i]	0.9	12.9
6363	[O i]	0.3	4.5
3727+29	[O ii]	28.0	28.2
7321+22	[O ii]	5.3	25.3
7331+32	[O ii]	4.3	20.7
5007	[O iii]	5.2	0.0
4068	[S ii]	5.9	14.0
4076	[S ii]	1.9	10.0
6717	[S ii]	1.7	1.4
6731	[S ii]	3.8	3.7

Absolute Hβ flux.
Model: 2.6×10^{-12} ergs cm^{-2} s^{-1}.
Obsn: $2.7 \pm 0.8 \times 10^{-12}$ ergs cm^{-2} s^{-1}.

Table 3. The nebular radio continuum.

Frequency (GHz)	Model flux (mJy)
4.0000E–01	7.7553E+00
1.0000E+00	7.1184E+00
5.0000E+00	5.9996E+00
1.0000E+01	5.5178E+00
1.5000E+01	5.2360E+00
1.6000E+01	5.1911E+00

2 is an indication of high nebular extinction and may be taken as an upper limit.

Some of the observed He and C lines are stellar and one can make out a P-Cygni like profile for them in the spectra observed by Dopita & Hua (1997). So the model fluxes in these lines indicate that the nebular contribution is very small. The model infrared excess (IRE) is 73.3. The total dust emission of the model in the IR is only $\sim 135 d^2 L_\odot$, a small fraction of what is observed. The total emission in Ly α is $\sim 2 d^2 L_\odot$, pointing to its negligible role. The fraction of the stellar luminosity utilized for heating of dust is ~0.24. Table 3 gives the radio spectrum predicted by the model for any comparison with future observations.

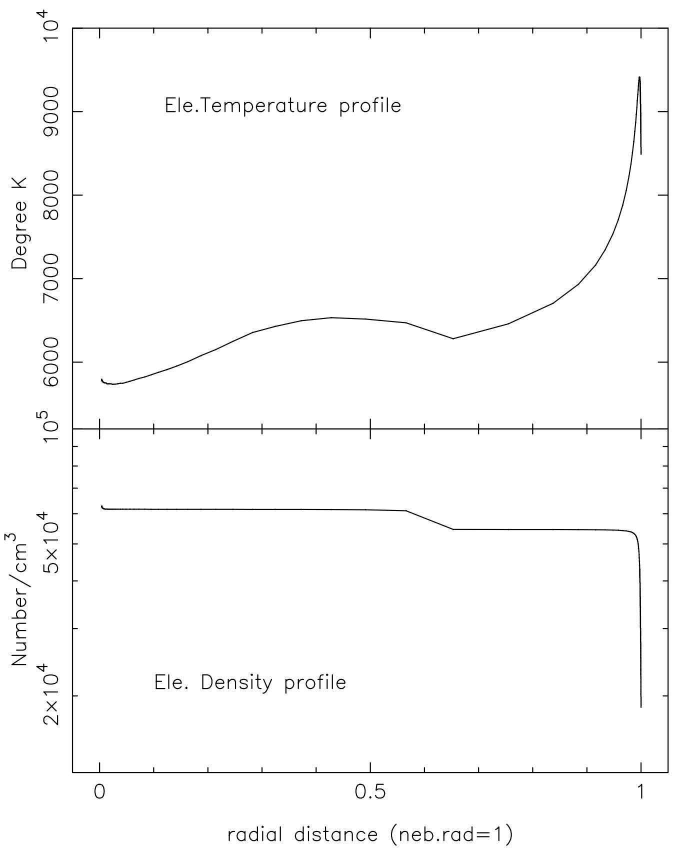

Fig. 1. $T_{\rm e}$ and $N_{\rm e}$ across the nebula.

Table 4. The IRAS fluxes.

Band μ	Model flux (Jy)	obs. flux (Jy)
12	6.43E+00	2.75E+01
25	4.03E+00	7.78E+01
60	1.72E+00	3.62E+01
100	3.95E–01	1.27E+01

3.2. Central star

De Marco & Crowther (1999) compared application of blackbody and model atmosphere energy distribution in modeling M 4–18 and showed that the H-deficient non-LTE model atmosphere has a sharp cutoff near the He ionization limit. They claimed better overall agreement of their model with observations for the latter. Models with $T_{\rm eff}$ in the range 22 000 K to 30 000 K, have also been tried for Vo 1, but were not satisfactory, even after experimenting with changes in other parameters. One of the main problems faced is that the model flux in the line [O iii] 5007 Å cannot be suppressed to a very low value, while obviously any model atmosphere in which the radiation below the He ionization limit is zero will not produce this line.

3.3. Dust

In Fig. 3, the IR radiation of the model versus the observations are shown, while Table 4 gives the model and observed IRAS fluxes. Figures 4 and 5 show the observed ISO spectrum.

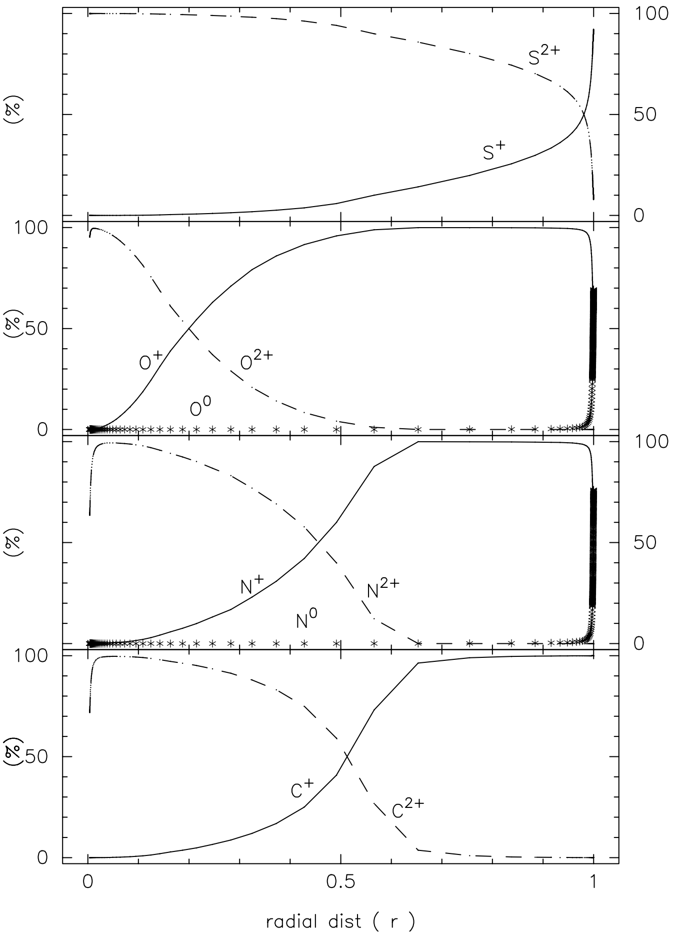

Fig. 2. Ionization structure across the nebula.

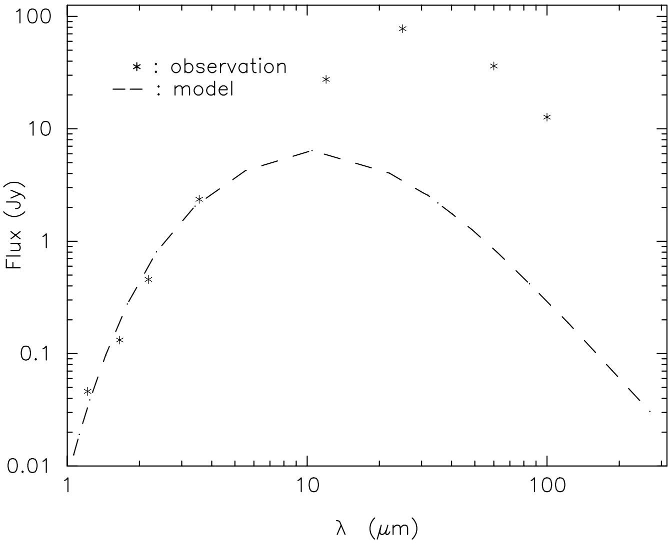

Fig. 3. Dust radiation from the model.

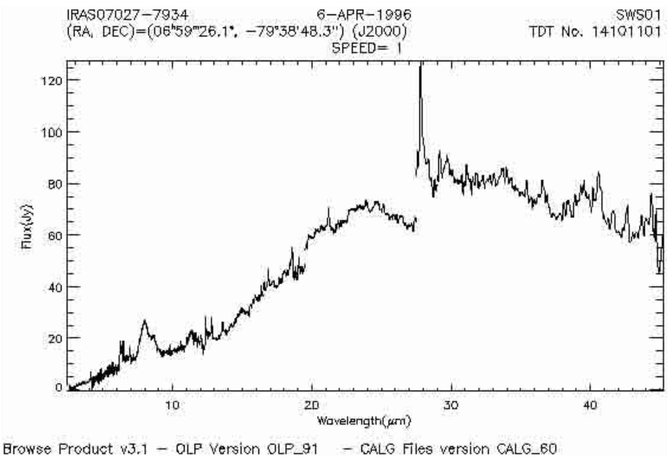

Fig. 4. ISO SWS01 observation of Vo 1.

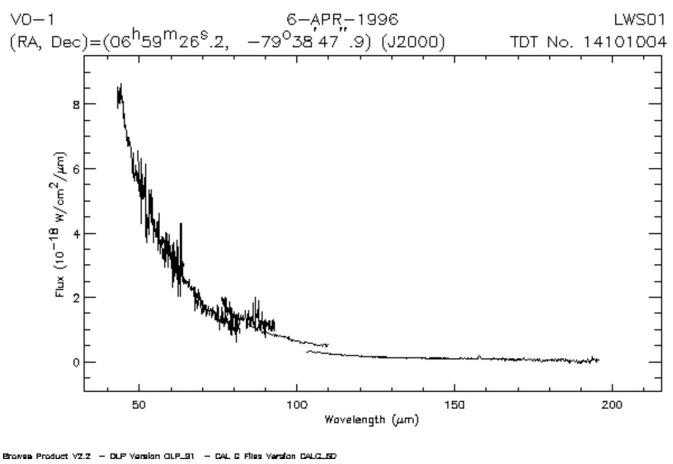

Fig. 5. ISO LWS01 observation of Vo 1.

As mentioned earlier, the main focus was on ionization structure. Dust grains were included to make them compete along with gas for UV photons, so that ionization structure does not get skewed. De Marco & Crowther (1998) could not find a satisfactory combination of parameters that could reproduce the observed nebular properties of CPD −56°8032 and He 2–113. One of the reasons they suggest for this is the likely presence of dust inside the nebula which their models did not take into account. Therefore, even if matching the model IR radiation to observation is not given importance in the case of Vo 1 here, the presence of dust grains is a requisite. Only grains of constant (but arbitrary) size have been included, and the radial packing of dust grains and grain radius were adjusted to give the maximum dust IR radiation possible. Also, the presence of dust grains was allowed inside the nebula starting from a radial distance at which they would not evaporate. The code incorporates a switch to halt the program if dust temperature exceeds a preset limit at any radial point and this facility helps to determine the radial distance from where the presence of dust grains is allowed.

3.4. Accuracy of the results

The overall fit of the model fluxes to observations seems good, although there is some scatter. Since we consider $T_{\rm eff}$, R_* and distance of the CS as derived parameters their accuracies are estimated respectively as ±400 K, ±0.1 $R_\odot$ and ±0.1 kpc. The He I lines are underestimated and increasing the abundance was found to be unhelpful. In the case of oxygen, both the red [O II] and [O I] lines are weak in the model. The observed higher strength of the former led to the high $T_{\rm e}$ value of

Table 5. Grid of model fluxes showing effect of variation of abundance.

Abundance	Flux											IRE	$\overline{T_e}$	$\overline{N_e}$
	C II 4267	[N II] 5755	[N II] 6548	[N II] 6584	[O II] 3727	[O II] 3729	[O III] 5007	[S II] 4068	[S II] 4076	[S II] 6716	[S II] 6731		K	cm^{-3}
C = 8.861	0.1	1.5	34.2	101.8	20.5	6.4	4.9	4.9	1.6	1.4	3.1	75.6	6900	55 400
C = 9.463	0.3	1.2	30.7	90.3	17.3	5.4	5.2	4.4	1.4	1.3	2.9	73.8	6700	55 700
N = 7.749	0.2	0.8	18.3	53.8	22.4	6.9	5.3	5.0	1.6	1.4	3.1	76.9	7000	55 400
N = 8.351	0.2	1.8	51.6	151.8	12.7	3.9	4.2	3.3	1.1	1.1	2.4	68.5	6400	55 500
O = 8.477	0.1	1.45	33.6	98.9	9.8	3.0	3.4	4.6	1.5	1.3	3.0	74.5	6900	55 400
O = 9.079	0.1	1.2	30.9	91.0	34.3	10.6	5.7	4.4	1.4	1.3	2.9	72.9	6700	55 300
S = 6.812	0.2	1.6	36.5	107.3	22.2	6.9	6.2	2.4	0.8	0.7	1.5	75.9	7000	55 400
S = 7.414	0.1	0.9	25.0	73.7	12.2	3.8	3.0	6.5	2.1	2.1	4.7	67.9	6300	55 300

The fluxes are w.r.t. $H\beta = 100$ units; the abundance values represent either a reduction or enhancement by a factor of 2 w.r.t. the best fitting model values of Table 1.

Menzies & Wolstencroft (1990). The line C II 4267 Å is also very weak in the model. Increasing the carbon abundance increases the line marginally but affects fluxes of other lines. As mentioned earlier, the presence of dust complicates the ionization structure. Additionally the dust model adopted here is very simplified. I have not considered a distribution of sizes which would be more realistic and modelled only the ionized core neglecting the dust outside. The radial distribution of dust grains in the nebula is also very arbitrary. Lack of availability of a model atmosphere for Vo 1 is another weak point and the large error in the observed fluxes could mislead the model. Finally the extent of stellar contamination in some of the nebular lines is also unknown.

In Table 5, a grid of model fluxes of C, N, O and S lines are shown against abundances of these elements that have been varied (ie. either decreased or increased by a factor of two) w.r.t. the best fitting model abundances of Table 1. The last three columns show the infrared excess (IRE), average T_e and average N_e. Except as in Col. 1, all other input parameters were kept the same as in Table 1 while experimenting with these variations.

4. Conclusions

With limited observations available on Vo 1, an optimal approach has been made to derive mutually consistent values of the effective temperature, radius and distance of the central star by photoionization modeling. The nebular parameters have also been derived. The C/O ratio in the nebula is more than 5 and the nebular internal extinction $E(B - V)$ is 2. The uncertainties could be reduced with more accurate and comprehensive observations of the central star and the nebula which would justify the effort of more complex modeling. In particular, the spectrum used here was recorded with an intensified Reticon detector by Menzies & Wolstencroft (1990) and so there is a need for accurate CCD observations with a narrow slit.

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