# 1-D Dusty Photo-ionization Models of WR Planetary Nebulae NGC 2452 and IC 2003

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# 1-D Dusty Photo-ionization Models of WR Planetary Nebulae NGC 2452 and IC 2003

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**Abstract** We report dusty photo-ionization models for two Planetary Nebulae NGC 2452 and IC 2003, which have [WR] type central stars, using photo-ionization code Cloudy17. We used the medium resolution optical spectra and archival *IRAS* photometry to constrain our models. Further, the physical size of the ionized nebula derived using better known distance value from the literature and absolute $H_\beta$ flux were used as additional constrain. We examine the importance of photo-electric heating of the ionized gas by grains in these PNe: model which does not consider photo-electric heating fits the data better for NGC 2452 whereas in the case of IC 2003 the dust heating model fits better. We derive the elemental abundances of these PNe using the empirical method as well as through photo-ionization models. We obtain the values of N/O ratio for both PNe from dusty photo-ionization models which are lower than their respective values arrived using empirical methods. The central stars are assumed to be blackbodies and the photospheric temperatures derived respectively for NGC 2452 and IC 2003 from their best fit models are 182kK and 155kK and their respective luminosities are $630L_\odot$ and $1015L_\odot$. We propose that both the PNe were resulted from a lower mass progenitor of mass $\leq 2.8\mathrm{M}_\odot$.

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## 1 Introduction

The planetary nebula (PN; plural PNe) phase occurs when the low- and intermediate mass stars evolve after their AGB phase and before they complete their journey as white-dwarfs. PNe are shells of gas and dust that were ejected from their progenitors which are subsequently ionized by their hot central stars and show bright, characteristic emission lines. The physics of the nebula is important to be explored in order to understand the evolutionary status of its central star. Photo-ionization model describes the interaction of stellar ionizing photons with the nebula for a given density structure and plays a key role to discover the physical structure of the nebula. The constraints for photo-ionization modelling procedure are to reproduce the observed intensity ratios of important lines of different ionization stages, the size of the ionized region and also to reproduce the absolute fluxes of H$\beta$ and IR fluxes in *IRAS* bands. While the thermal and ionization structure of the nebula are constrained by the fluxes of [OIII] 5007Å and [NII] 6584Å lines, the flux ratio of [OIII] 4363Å/5007Å addresses all the heating and cooling processes in the nebula. Further, the nebular He II line at 4686 Å, which measures the stellar photons above 54.4 eV, can constrain the central star photospheric temperature. As abundance estimation from the classical empirical method using the ionization correction factors for unseen ions lack accuracy (Stasinska 1999), more reliable and accurate determination of He, C, N, Ne, S and Ar abundances requires tailored photo-ionization models. Apart from determining the ionization structures of a PN, such a model can also predict the electron density and temperature distribution in the nebula.

Grains are ubiquitous in PNe and they are well mixed with the gas component. As the gaseous nebula absorbs stellar photons in the Lyman continuum through photo-ionization, grains intercept the stellar radiation at shorter wavelengths and re-radiate at longer wavelengths. Dust in ionized plasma also plays an important role in heating and cooling of ionized gas which is known from Spitzer (1948); as grains compete with the gas in absorbing the hard UV photons from the central star, it can determine the thermal balance of the nebula (Dopita & Sutherland 2000). Presence of grains shrinks the size of an ionized nebula and results in a notable decrease in the H$\beta$ flux and increase in the IR continuum flux (Stasinska & Szczerba 2001).

Photo-ionization models of PNe were done earlier by taking only ionization of gas by stellar photons as the source of input energy to the surrounding nebula (Liu et al. 1995). Such models usually faced energy deficit in addressing the nebular thermal balance and could not address all the observed phenomena: in some cases it was quite severe, see for example, the case of H-poor PN IRAS

18333-2357 (Borkowski & Harrington 1991). Dopita & Sutherland (2000) first investigated in detail the importance of photo-electric heating from the grain surface which influences the strengths of the emission lines of the highly ionized species in UV. They found that very small grains (VSG or PAH) play a crucial role in nebular heating and cooling. As a result of this, the excitation balance and determination of the effective temperature of the central star are strongly affected. Grain physics is increasingly a non-linear function of charge for VSG population and the grain size and charge distributions should be considered in detail by resolving them in order to effectively address photo-electric heating (van Hoof et al. 2004). This method of computation, taking detail grain physics into account, will enhance the optical and UV lines of highest ionization stages (OIV] at 1402 Å, OV] at 1218 Å) and decrease the optical and UV lines of low ionization stages as discussed in van Hoof et al. (2004).

A considerable fraction (about 15%) of the central stars of PNe (CSPNe) show Wolf-Rayet phenomena ([WR] stars hereafter), which are similar to the massive WR stars (Acker & Neiner 2003). It is essential to understand their evolutionary status and resolve how it differs from that of the normal PNe in order to fully understand the evolution of low- and intermediate mass stars. PNe around [WR] stars ([WR]PNe) provide this opportunity as the result of the process governing the evolution of [WR] stars are imprinted in these PNe. The electron temperatures of PNe derived from the Balmer jump is always smaller than the temperature derived from collisional excitation lines. Larger negative temperature gradient and higher deficit of thermal energy in photo-ionization models are often observed for [WR]PNe (Stasinska & Szczerba 2001). A comprehensive analysis of the IR properties of all known [WR]PNe and a sample of non-[WR]PNe were made using archived photometric data of $2MASS$, $IRAS$, $WISE$ and *Akari* by Muthumariappan & Parthasarathy (2020, MP20 hereafter) which shows differences between them. For example, [WR]PNe show higher IR luminosity, larger dust mass than the non-[WR]PNe. MP20 also discussed the presence of large amount of VSG in [WR]PNe compared to that in non-[WR]PNe which can significantly influence the thermal structure of the nebula. Presence of large amount of VSG in the H-poor environment of IRAS 18333-2357 was also discussed earlier (Borkowski & Harrington 1991, Muthumariappan & Parthasarathy 2013). It is very likely that the photo-electric heating can play a significant role in determining the thermal structure of [WR]PNe in particular. This needs to be explored.

We present here accurate dusty photo-ionization models for two [WR]PNe, namely, NGC 2452 and IC 2003 by incorporating dust component in the radiative transfer computation. We aim to address the significant contributions of grain heating and cooling mechanism, in addition to photo-ionization, for the thermal balance in these nebulae. Such models were not worked out for the above mentioned PNe. For comparison, we also present models which include dust component but consider only photo-ionization as the source of nebular thermal energy. We thus also aim to estimate more accurate values for the effective temperatures and luminosities of their central stars.

## 2 Observations and data analysis

Medium resolution optical spectroscopic observations of [WR]PNe NGC 2452 and IC 2003 were made using the Opto-mechanics Research (OMR) grating spectrograph attached with the 2.34m VBT located at the Vainu Bappu Observatory, Kavalur in Tamil Nadu, India. Observations were made with a clear and stable sky condition on $28^{th}$ January 2018. The slit of the spectrograph has a length of $2.8'$ and its width was set at $2''$. The slit position was chosen such that it covers the whole optical nebula and it passes through the central star, which is a required condition to constrain the nebular parameters accurately. We have used 600 lines/mm grating and have taken the spectra in two different wavelength region settings. The blue region setting has a wavelength coverage from 3800Å to 6300Å and the red region setting covers the wavelength region from 5800Å to 8200Å . The overlapping spectral region is used in scaling the line fluxes of the blue and red frames. The data was recorded on a CCD detector having an array of 4k $\times$ 4k square pixels with a pixel size of 16$\mu$m. The wavelength dispersion across a pixel is 2.5Å providing a spectral resolution of 2000 at 5000 Å . The integration time for each spectral frame is 45 min with the telescope guided by an auto-guider to overcome from any drift in the sky. Adequate number of bias frames and tungsten lamp flat frames were taken along with the observations for performing the CCD corrections. We have also recorded spectral lamp frames (FeAr for blue region and FeNe for red region spectral settings) for wavelength calibration and spectro-photometric standards were taken along with the target sources which are required for flux calibration.

The spectral data were reduced and analyzed using the $IRAF$ data analysis package following the standard procedure. After correcting for the CCD signatures using bias and flat frames, spectra were extracted from the target frames, from the wavelength calibration frames and from the spectrophotometric frames. Wavelength calibration of the target spectra and standard star spectra were done using wavelength calibration frames and then they were subjected to the interstellar reddening correction with their respective $c_{H\beta}$ values derived from the Balmer lines in the spectrum. Following this, the target spectra were finally flux calibrated using the spectro-photometric fluxes of standard star from which the emission lines fluxes were measured .

## 3 Photo-ionization modeling

Atomic and ionic emission line fluxes were measured from the calibrated target spectra by fitting a gaussian to each line profile. Table 1. and Table 2. list the measured emission line fluxes relative to H$\beta$ flux (which is taken as 100) for the PNe NGC 2452 and IC 2003. Optical emission line fluxes of different ions are used to derive approximate values of nebular electron temperature ($T_e$), electron density ($n_e$) and the ionic abundances of different species using the Nebular Empirical Analysis Tool ($NEAT$, Wesson et al. 2012). $NEAT$ uses the built-in values of ionization correction factors (ICFs) to estimate the abundances of unseen ions and finds the total elemental abundance. It has been observed that the abundance values derived from weaker emission lines can be overestimated or underestimated. Table 3. shows the values of $T_e$, $n_e$ and elemental abundances of the PNe derived from $NEAT$. These derived empirical values are used to model the ionized regions of PNe.

The revised 1D code Cloudy 17.02 (Ferland et al. 2017) was used to construct the dusty photo-ionization models of NGC 2452 and IC 2003. The code determines the ionization, temperature and chemical state of PNe and predicts their emission line spectra. It has the provision to compute grain heating in determining the thermal balance of the nebula, which are required for this study. The code can resolve the sizes and charges of VSG to compute effectively the photo-electric heating. The opacity file required for the code as an input can be computed separately for a desired grain nature (amorphous silicate and amorphous carbon), grain size distribution and for a dust-to-gas mass ratio. We construct dusty photo-ionization models of PNe with and without considering the grain heating. The distance to these PNe were estimated by Frew et al. (2016) with reasonable accuracy (better than 30%). This helps us to fit better our models to the observed fluxes. Accurate distances are essential to constrain the fundamental parameters of the central star like luminosity and in turn to place it accurately in the HR diagram.

The approximate values of $T_e$, $n_e$ and elemental abundances of the PN derived using $NEAT$ are used as the initial values for the Cloudy models. The input stellar spectrum is described by the black body function for a given stellar effective temperature ($T_{eff}$). The initial values of $T_{eff}$ and the dust colour temperature $T_{dust}$ were taken from the literature. The $IRAS$ fluxes at 12-, 25-, 60- and 100$\mu$m bands are obtained from the NASA IPAC Infrared Science archive (available at *http.irsa.ipac.caltech.edu*) to constrain the far-IR emission from the dust component in the nebula. The size of the nebula and its distance taken from Frew et al. (2016) are supplied to Cloudy17. The dust opacity at different wavelengths are calculated for amorphous silicate and amorphous carbon grains considering the MRN grain size distribution and are used for our computation. The minimum size of the grain $a_{min}$= 0.00035$\mu$m and the maximum grain size $a_{max}$ = 0.25$\mu$m and the size distribution is resolved with 30 size bins. The low value of $a_{min}$ is chosen to account for the photo-electric heating of the ionized nebula by the VSG grain population effectively. The input parameters $T_{eff}$, $n_e$, $T_{dust}$, ionic abundances are varied around their initial values and the inner radius of the ionized nebula $R_{in}$, stellar luminosity $L_*$, nebular filling factor and the dust-to-gas mass ratio are

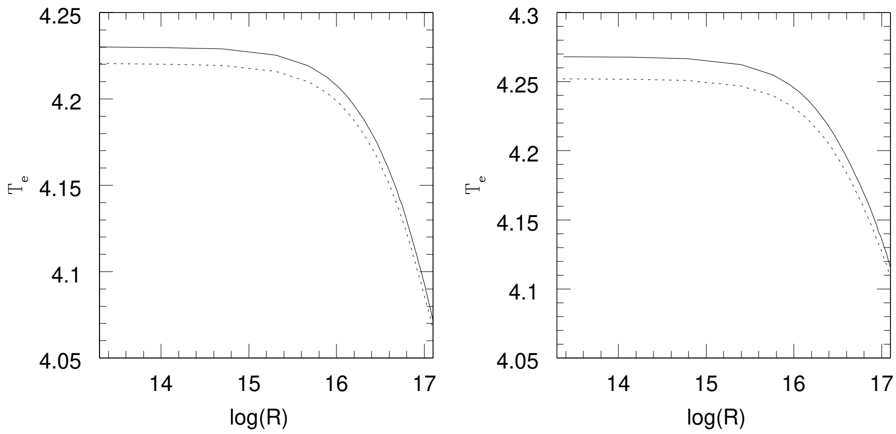


**Fig. 1** Radial temperature plot of NGC 2452 (left) and IC 2003 (right). Solid line is for the grain heating and dotted line is for the no grain heating model.

taken as free parameters to obtain the best fit model. The density is assumed to be constant within the ionized region. The emission line flux ratios of [OIII] at 4959 Å and 5007 Å, [NII] at 6583 Å and He II at 4686 Å relative to H$\beta$ are optimized with their respective observed values to obtain the final model. Optimization of the physical size of the optical nebula and the absolute flux of H$\beta$ and *IRAS* fluxes at 25- and 60$\mu$m are also used. The best fit models were judged using the $\chi^2$ minimization technique by finding the net $\chi^2$ value, which is the addition of $\chi^2$ values that correspond to the optimization of absolute flux, relative flux, angular diameter and IR photometry.

The model output provides the synthetic spectra with optical emission line fluxes and *IRAS* continuum fluxes. The 12$\mu$m *IRAS* band is contaminated by the IR emission features and since our model does not consider the IR emission features, we do not use the flux at this band as a constrain for the models. Dust continuum of ionized region of a PN is traced better by the 25- and 60$\mu$m bands.

## 4 Results

In this section we present the results obtained from 1D dusty photo-ionization Cloudy models constructed for [WR] PNe NGC 2452 and IC 2003. From the models of these PNe which were made with and without considering the grain heating, we discuss the importance of grains in thermal balance of these PNe.

**Table 1** Observed and model derived emission line fluxes and *IRAS* continuum fluxes of NGC 2452

| Wavelength (Å) | Line ID | Observed flux | Model A flux | Model B flux |
|---|---|---|---|---|
| 3868 | [Ne III] | 87.50 | 79.54 | 80.15 |
| 3967 | [Ne III] | 25.90 | 25.03 | 24.91 |
| 4340 | H$\gamma$ | 40.42 | 46.79 | 46.80 |
| 4363 | [OIII] | 18.77 | 20.54 | 19.31 |
| 4686 | He II | 43.72 | 41.65 | 41.73 |
| 4711 | [ArIV], He I | 6.84 | 7.04 | 6.69 |
| 4740 | [ArIV] | 9.08 | 5.35 | 5.09 |
| 4861 | H$\beta$ | 100.00 | 100.00 | 100.00 |
| 4959 | [OIII] | 542.90 | 606.61 | 588.43 |
| 5007 | [OIII] | 1720.00 | 1811.28 | 1756.95 |
| 5411 | He II | 7.09 | 3.60 | 3.61 |
| 5755 | [NII] | 2.04 | 3.71 | 3.68 |
| 5876 | He I | 7.08 | 17.75 | 17.73 |
| 6312 | SIII | 3.20 | 1.97 | 1.91 |
| 6548 | [NII] | 49.49 | 62.46 | 62.62 |
| 6563 | H$\alpha$ | 306.20 | 288.49 | 288.18 |
| 6584 | [NII] | 180.00 | 187.70 | 189.50 |
| 6678 | HeI | 5.39 | 4.77 | 4.77 |
| 6716 | [SII] | 24.20 | 27.68 | 27.39 |
| 6731 | [SII] | 32.75 | 34.00 | 33.78 |
| 7065 | He I | 4.16 | 6.54 | 6.51 |
| 7136 | [ArIII] | 60.89 | 66.18 | 65.48 |
| 7319 | [OII] | 7.48 | 7.84 | 7.72 |
| 7330 | [OII] | 5.07 | 12.84 | 12.64 |
| 7751 | [ArIII] | 10.66 | 15.79 | 15.62 |
| F(25$\mu$ m) | dust cont. | 5.01 Jy | 5.05 | 4.59 |
| F(60$\mu$ m) | ,, | 6.59 Jy | 8.71 | 7.92 |
| F(100$\mu$ m) | ,, | 9.78 Jy | 1.32 | 1.20 |

## 4.1 NGC 2452

The PN NGC 2452 has a WR-type central star with a sub-type of WO1 (Weidmann & Gamen 2011) and the effective temperature of the stellar photosphere was reported as 141kK by Kingsburgh & Barlow (1994). This PN belongs to an excitation class of 10 (MP20). The estimated values of mean dust temperature, dust-to-gas mass ratio and IR excess by MP20 have their respective values of 90K, $2.6\times10^{-3}$ and 3.2. The distance to this PN and the angular diameter of its optical nebula are respectively 3.3kpc and 15$''$, as given in Frew et al. (2016).

Pena et al. (1998) made spatially resolved long-slit spectro-photometric observations of NGC 2452, covering different knots of this PN. Photo-ionization models of four different regions of ionized nebula were constructed by them, assuming a constant density, using the code PHOTO (Stasinska 1990). The input radiation field of the central star, which is taken to be located at a distance of 4kpc, is described by a model atmosphere with an effective temperature of 158kK. However, this study did not include the dust component of the nebula in the radiative transport computation. Pena et al. (1998) noted that the chemical composition of He, N and possibly C are enhanced in the nebula indicating a massive progenitor ($M_{initial} \geq 2.8M_{\odot}$) for this PN. They did not find any abundance variation within the nebula. They found that the electron temperature derived from Balmer discontinuity matches with the temperature arrived using [OIII] line ratio and hence the nebula does not show large temperature fluctuations which is observed in some PNe. The dust chemistry of the nebula was not known; the C/O ratio of the gas phase nebula was given as 0.76 by Kingsburgh & Barlow (1994) indicating an O-rich dust. However, Pena et al. (1998) argue from their analysis of gas phase abundances for a C-rich environment in this nebula. Hence, we have computed dusty photo-ionization models of the nebula for both the cases; taking the dust component as amorphous carbon and amorphous silicate.

We derived the interstellar reddening factor from the Balmer lines of our spectrum of NGC 2452, which has a value of $c_{H\beta} = 0.36$ . The empirical values of $T_e$, $n_e$ and elemental abundances of the PN were obtained using $NEAT$ program which are given in Table 3. The value of $T_{eff}$ from Kingsburgh & Barlow (1994) was used as the initial value for modelling. Several models were run considering silicate and carbon as the grain chemistry to obtain the best fit model to the observations. The input parameters and the derived parameters of NGC 2452 for the models we have worked out are listed in Table 4. along with their respective $\chi^2$ values of the fit. The stellar spectrum of the best fit model is described by a black body function with $T_{eff} = 182$kK. We find that the amorphous carbon model fits the observed parameters relatively better than the silicate model. Further, as seen from their $\chi^2$ values, the amorphous carbon model which does not consider dust heating as an additional source of input energy for the thermal balance of the nebula (model B) fits better with the observations than the one which considers dust heating (model A). However the difference between these two cases is not large implying that the grain heating in NGC 2452 is not significant. The observed and the model derived optical emission line fluxes with respect to the H$\beta$ flux (=100) and the IR continuum fluxes at 25$\mu$ and 60$\mu$ bands of $IRAS$, are compared in Table 1. As can be seen from the table, the model reproduces the fluxes reasonably well. However, it differs by a large value at the $IRAS$ 100$\mu$m band. This could be explained as follows: the grains inside the ionized gas is warmer than the grains in the outer neutral regions and the dust temperature derived by MP20 is the overall average including ionized and neutral regions whereas our photo-ionization model provides the 100$\mu$m flux from the ionized gas alone. The parameters of NGC 2452 and its central star derived from our models are given in Table 4. The size of the photo-ionized region and the absolute $H_\beta$ flux derived by the model matches with the observations quite well. The mean temperature of the dust component is derived to be 83K, which is lower than the value arrived from a modified blackbody fit to the *IRAS* fluxes by MP20 (90K). Dust-to-gas mass ratio derived from the Cloudy model matches with the value obtained by MP20 ($2.6\times10^{-3}$).

The abundances derived empirically using *NEAT* program match with the previous determination published by other groups (Kingsburgh & Barlow 1994, Pena et al. 1998). As the carbon lines are not present in the optical spectra, for our model we have taken the carbon to be 1.1 times more abundant than oxygen, as derived by Pena et al. (1998). The model derived elemental abundances, which are listed in Table 4. are mostly in agreement with the values of previous determinations. However, our dusty photo-ionization model shows somewhat larger (0.15) He abundance and the N/O ratio is reduced by about a factor of 2 than the values obtained from the empirical methods and from the dust-free photo-ionization model of Pena et al. (1998). We do not get a good fit to all the observed parameters if we impose to keep the values as derived by the empirical method. The N/O value derived by our best fit model is lower than the theoretical value of 0.8 which is required for type-I PNe (Peimbert 1967) suggesting a lower mass ($\leq 2.8M_{\odot}$) progenitor for NGC 2452. However, the N/O value given by our empirical calculation and also by other groups suggest the PN to be near the Type-I limit. The radially outward temperature profile of the nebula is shown for model A and model B in Fig 1., which tells that the dust heating model has a maximum jump in $T_e$ at the $R_{in}$.

## 4.2 IC 2003

IC 2003 is a PN which has a WR type central star of sub-type WC3 (Weidmann & Gamen 2011). From their *IUE* observations, Feibleman (1997) suggested that the central star of the PN belongs to 'O VI' sequence with an effective temperature of 112kK. The central star temperature was derived by Koppen (1983) using nebular He II to H$\beta$ line ratio as 158kK. This PN belongs to an excitation class of 9 as found from the emission line fluxes of H$\beta$, [OIII] and He II lines in our spectrum and using the spectral classification scheme of PNe given by Gurzadyan & Egikyan (1991). The nebula shows clearly a C-rich dust chemistry: the C/O ratio of the gas phase abundance is 2.07 (Kingsburgh & Barlow) and the *Spitzer*-IRS spectrum of IC 2003 shows the presence of PAH features. The distance to IC 2003 and the angular diameter of its optical nebula are given by Frew et al. (2016); their values are respectively 4.33kpc and $9''$.

Photo-ionization model of the PN IC 2003 was worked out earlier by Koppen (1983) by matching the ionic emission line fluxes in UV, optical and IR. The dust component of the PN was not considered in his model and hence the *IRAS* continuum fluxes were not reproduced. Further, he did not try to reproduce the low-excitation features as this lies outside the limitation of the models. The optical size of the nebula and its absolute H$\beta$ flux were not taken as constraints. The author has used the blackbody stellar flux distribution and

**Table 2** Observed and model derived emission line fluxes and *IRAS* continuum fluxes of IC 2003

| Wavelength (Å) | Line ID | Observed flux | Model A flux | Model B flux |
|---|---|---|---|---|
| 3868 | [Ne III] | 79.20 | 78.96 | 77.07 |
| 3969 | [Ne III] | – | 1.14 | 1.11 |
| 4340 | H$\gamma$ | 46.30 | 46.82 | 46.83 |
| 4363 | [OIII] | 17.00 | 21.05 | 19.77 |
| 4686 | He II | 31.50 | 31.04 | 31.20 |
| 4711 | [ArIV], He I | 4.70 | 5.34 | 5.12 |
| 4741 | [ArIV] | 3.70 | 4.04 | 3.87 |
| 4861 | H$\beta$ | 100 | 100 | 100 |
| 4959 | [OIII] | 447.5 | 527.46 | 513.75 |
| 5007 | [OIII] | 1542 | 1574.42 | 1534.00 |
| 5411 | He II | 3.79 | 2.69 | 2.70 |
| 5517 | Cl III | 3.51 | 3.67 | 3.61 |
| 5537 | Cl III | 2.78 | 3.73 | 3.66 |
| 5577 | OI | 2.13 | 1.15 | 1.13 |
| 5876 | He I | 9.20 | 12.86 | 12.83 |
| 6300 | OI | 4.80 | 39.30 | 38.42 |
| 6312 | SIII | – | 0.10 | 0.095 |
| 6548 | NII | 4.91 | 6.42 | 6.37 |
| 6563 | H$\alpha$ | 300.00 | 290.00 | 289.50 |
| 6584 | [NII] | 19.18 | 18.96 | 18.77 |
| 6678 | HeI | 1.81 | 3.42 | 3.42 |
| 6716 | [SII] | 1.01 | 0.90 | 0.87 |
| 6731 | [SII] | 1.48 | 1.09 | 1.07 |
| 6890 | HeII | 0.89 | 0.32 | 0.32 |
| 7006 | Ar V | 2.23 | 1.48 | 1.43 |
| 7065 | He I | 5.98 | 4.92 | 4.90 |
| 7136 | [ArIII] | 24.40 | 33.35 | 32.90 |
| F(12$\mu$ m) | dust cont. | 0.47 | | |
| F(25$\mu$ m) | " | 4.14 | 2.94 | 2.68 |
| F(60$\mu$ m) | " | 3.41 | 5.06 | 4.60 |
| F(100$\mu$ m) | " | 11.71 | 0.80 | 0.73 |

noted that it yields too high an electron temperature for the nebula.

We derive the interstellar reddening factor from the Balmer line ratio of our spectrum for this PN. Its value is $c_{H\beta} = 0.38$ and is in good agreement with previous determination (0.37, Marionni & Harrington 1981). The empirically derived values of $T_e$, $n_e$ and elemental abundances of IC 2003 using *NEAT* are given in Table 3., which agree with the values obtained previously by other authors. These values and the $T_{eff}$ of the central star from Koppen (1983) were taken as the initial values for our model and they were varied nearby. As the carbon lines are not detected in our optical spectrum, we have taken that the carbon abundance as twice of the oxygen abundance (C/O of gas phase nebula is 2.07). The free parameters for the models are $L_*$, filling factor and

**Table 3** Nebular diagnostics derived using empirical method

| *NEAT* parameters | NGC 2452 | IC 2003 |
|---|---|---|
| $n_e$ | 5248 | 1862 |
| $T_e(k)$ | 9583 | 9970 |
| He/H | 0.121 | 0.11 |
| N/H | $2.72\times10^{-4}$ | $4.5\times10^{-5}$ |
| O/H | $4.3\times10^{-4}$ | $4.01\times10^{-4}$ |
| Ar/H | $6.8\times10^{-6}$ | $4.5\times10^{-6}$ |
| S/H | $1.26\times10^{-5}$ | $1.24\times10^{-6}$ |
| Cl/H | – | $1.00\times10^{-6}$ |
| Ne/H | $3.02\times10^{-5}$ | – |

$R_{in}$. Several models were calculated with amorphous carbon dust grains. The models which were examined with and without incorporating dust heating in the thermal balance of the ionized gas are model A and model B respectively. Best fit models in both cases were judged using the net $\chi^2$ value, as done for NGC 2452. The stellar and the nebular parameters derived by our models for IC 2003 are shown on Table 4. As seen from the $\chi^2$ value in Table 4, model A, which considers dust heating, fits better with the observations than model B, which does not consider dust heating, though the difference is not large. This may imply that grain heating in IC 2003 is not very significant. The mean dust component temperature is 83K and the dust-to-gas mass ratio is $2.6\times10^{-3}$ as derived by model A. Fig 1. shows the outward radial temperature profile of the ionized nebula for model A and model B; the dust heating model shows maximum jump in $T_e$ at $R_{in}$ than the model without dust heating.

Table 2. lists the optical emission line fluxes relative to H$\beta$ flux (= 100) and the continuum flux at 25$\mu$ and 60$\mu$ bands of *IRAS* derived by model A and model B which are compared with their observed values. As can be seen from the table, the model A reproduces the emission line and IR continuum fluxes reasonably well. However, as noted for the case of NGC 2452, the derived dust continuum flux at the 100$\mu$m band differs significantly from observations. The derived value of the nebular electron density matches with previous estimations (Feibelman 1997, Stanghellini et al. 1995). The elemental abundances from our photo-ionization models are listed in Table 4. which are in general good agreement with the empirically derived values. The empirical abundances match well with the abundances derived by other groups (Kingsburgh & Barlow 1994). However, dusty photo-ionization model produces a little higher He abundance and the nitrogen abundance is significantly lower, giving a lower N/O (1.4 times) ratio, than the values obtained empirically and by dust free photo-ionization models of Koppen (1983). However, all the given values of N/O values are lower than the theoretical value of 0.8 required for type-I PNe.

**Table 4** Central star and nebular parameters of NGC 2452 and IC 2003 derived from dusty Photo-ionization models.

| Model Parameters | NGC 2452 model A | NGC 2452 model B | IC 2003 model A | IC 2003 model B |
|---|---|---|---|---|
| $T_{eff}$ (kK) | 182 | 182 | 155 | 155 |
| $L_*(L_{sun}$ | 630 | 603 | 1008 | 1015 |
| D (kpc) | 3.32 | 3.32 | 4.33 | 4.33 |
| $n_e cm^{-3}$ | 2140 | 2140 | 1862 | 1862 |
| $T_e$ (K) | 13200 | 9970 | 9980 | |
| $R_{in}$ (cm) | $7.16{\times}10^{16}$ | $7.16{\times}10^{16}$ | $8.3{\times}10^{16}$ | $8.3{\times}10^{16}$ |
| $R_{ion}$ | | | | |
| Diameter(") | 12.27 | 12.10 | 10.12 | 10.14 |
| (observed) | (15.0) | (15.0) | (9.0) | (9.0) |
| $F_{H\beta}$ | $1.17{\times}10^{-11}$ | $1.11{\times}10{-}11$ | $1.21{\times}10{-}11$ | $1.22{\times}10{-}11$ |
| (observed) | $(1.1{\times}10^{-11})$ | $(1.1{\times}-11)$ | $(1.3{\times}10^{-11})$ | $(1.3{\times}^{-11})$ |
| $m_d/m_g$ | $2.72{\times}10^{-3}$ | $2.72{\times}10^{-3}$ | $2.01{\times}10^{-3}$ | $2.01{\times}10^{-3}$ |
| He/H | 0.15 | 0.15 | 0.118 | 0.118 |
| C/H | $8.50{\times}10^{-4}$ | $8.50{\times}10^{-4}$ | $9.78{\times}10^{-4}$ | $9.78{\times}10^{-4}$ |
| N/H | $2.79{\times}10^{-4}$ | $2.79{\times}10^{-4}$ | $4.91{\times}10^{-5}$ | $4.91{\times}10^{-5}$ |
| O/H | $6.17{\times}10^{-4}$ | $6.17{\times}10^{-4}$ | $4.89{\times}10^{-4}$ | $4.89{\times}10^{-4}$ |
| Ar/H | $5.15{\times}10^{-6}$ | $5.15{\times}10^{-6}$ | $2.50{\times}10^{-6}$ | $2.50{\times}10^{-6}$ |
| S/H | $4.10{\times}10^{-6}$ | $4.10{\times}10^{-6}$ | $1.65{\times}10^{-7}$ | $1.65{\times}10^{-7}$ |
| Cl/H | – | – | $4.23{\times}10^{-7}$ | $4.23{\times}10^{-7}$ |
| Ne/H | $7.51{\times}10^{-5}$ | $7.51{\times}10^{-5}$ | $5.60{\times}10^{-5}$ | $5.60{\times}10^{-5}$ |
| $\chi^2$ (relative.flux) | 0.637 | 0.312 | 0.26 | 0.60 |
| $\chi^2$ (absolute.flux) | 1.65 | 0.14 | 2.23 | 2.10 |
| $\chi^2$ (ang. diameter) | 4.94 | 5.7 | 1.59 | 1.70 |
| $\chi^2$ (IR photometry) | 1.29 | 0.59 | 5.00 | 5.50 |
| $\chi^2$ (net) | 8.51 | 6.78 | 9.00 | 9.90 |

Hence we propose a lower mass ($\leq 2.8M_\odot$) progenitor for IC 2003.

## 5 Discussion

PNe around [WR] central stars, when compared to the normal PNe, show relatively larger amount of hot dust component which are very small in size and they thermally fluctuate in the hard UV radiation of the central star (MP20). These grains are expected to play a significant role in heating the nebula through emitting photo-electrons. IC 2003 shows PAH features and hence this confirms the presence of small grains inside the ionized gas, whereas the mid-

IR spectrum of NGC 2452 is not available in the literature to directly trace the presence of this grain population. Our model on NGC 2452 with amorphous carbon grains fits the observations better when dust heating is not considered as an input energy source. For IC 2003, on the other hand, the model which considers grain heating shows a better fit with the observations. However, including dust heating does not make a very significant difference in both PNe.

The radial temperature plots of our models show that the electron temperature in the inner edge of NGC 2452 is 370K larger in the dust heating model when compared with the no dust heating model, which is only 2.25% more. For the PN IC 2003 the dust heating model shows 670K larger than the no dust heating model at the inner edge, which is 3.75% more. The size distribution of VSG population has significant impact on the photo-electric heating of the nebula; this can provide as high as 16% additional energy to the ionized gas if the grains are carbonaceous (van Hoof et al. 2004). Different size distributions are required to be tried out, giving more mass to the VSG population to see if more dust heating is essential. However, our model fits reasonably well to the optical and IR data implying that the heating and cooling mechanisms of the ionized gas are taken into account with reasonable accuracy and hence dust heating in IC 2003 using different VSG size distributions may not be significantly larger than what is obtained from this study.

Another point to noted here is the values of N/O ratios derived for the ionized gas of PNe from our dusty photo-ionization models. While the values we derived using the empirical method agree well with those given by other authors for the PNe NGC 2452 and IC 2003, the model derived N/O value is lower by a factor of 2.0 for NGC 2452 and by a factor of 1.5 for IC 2003. This needs to be investigated to understand how the inclusion of grain heating in the ionized gas affects the estimation of N/O ratio, as this ratio constraints strongly the progenitor mass of the PN. Type I PNe are resulted from those progenitors which have experienced envelope burning resulting conversion of dredged-up primary carbon to nitrogen. These nebulae have N abundance that exceeds the total N + C abundance of H II region in the host galaxy; in our galaxy N/O $\geq$ 0.8 (Kingsburgh & Barlow 1994). Though for IC 2003 the N/O value obtained by our models and by other groups are significantly lower than 0.8, which is required for a lower mass progenitor, for NGC 2452 our model value is much smaller than 0.8 whereas earlier determinations by other group were close to this limit.

## 6 Conclusions

We have performed using Cloudy 17.02 the dusty photo-ionization models of planetary nebulae NGC 2452 and IC 2003 which have WR-type central nuclei. Optical medium resolution spectrum and *IRAS* continuum band fluxes of the

PN were used as constrains. Using better known distances to these PNe, their absolute sizes and H$\beta$ fluxes were reproduced. Models were calculated with and without considering the photo-electric heating by VSG population in addition to photo-ionization. We conclude the following:

1) NGC 2452 model fits well with the observations if we take amorphous carbon as the grain chemistry and do not include photo-electric heating.

2) IC 2003 model with amorphous carbon fits better with the observations if we include photo-electric heating as an additional energy source.

3) The N/O ratio derived from our models are lower than those values we derive from the empirical method. With the N/O values obtained from the dusty photo-ionization models we propose that NGC 2452 and IC 2003 are Type II PNe and both should have resulted from low mass ($\leq 2.8M_{sun}$) progenitors.

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## 8 Statements & Declarations

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b) Competing interests: The authors have no relevant financial or non-financial interests to disclose

## Figures

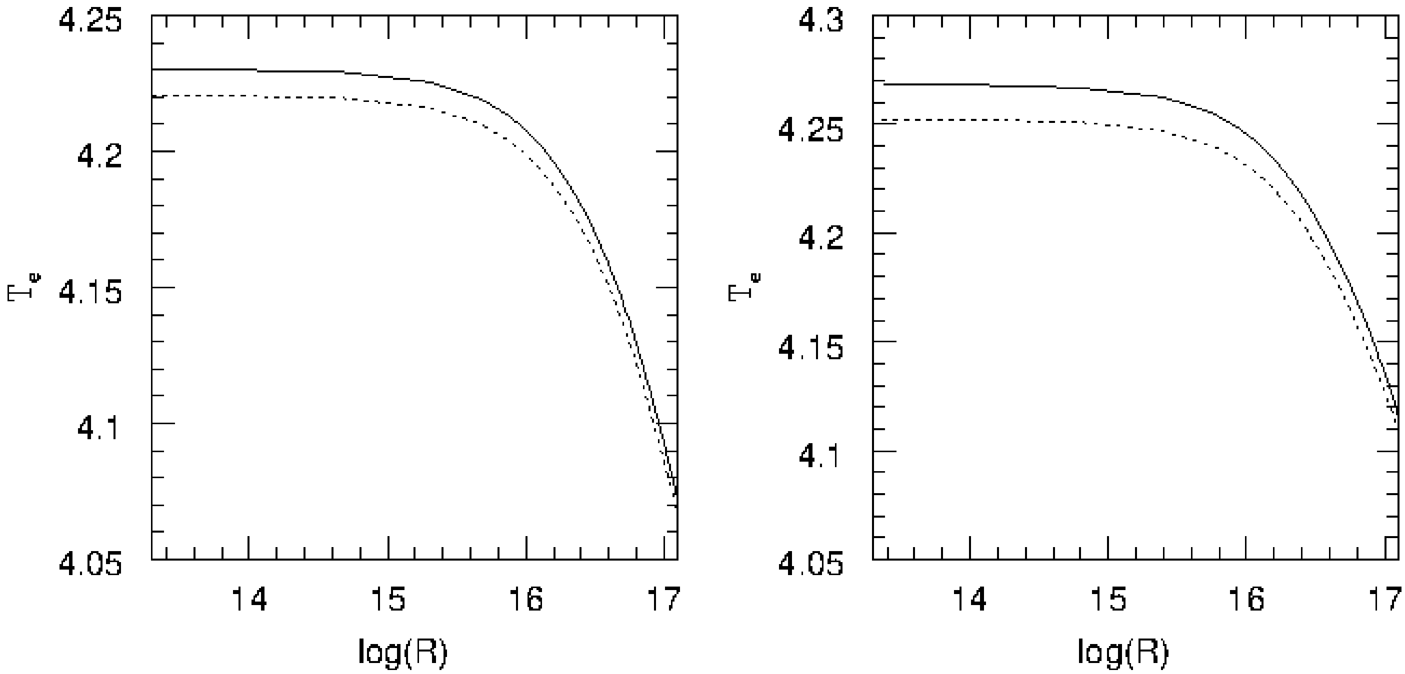


**Figure 1**

Radial temperature plot of NGC 2452 (left) and IC 2003 (right). Solid line is for the grain heating and dotted line is for the no grain heating model.

## Supplementary Files

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- muthuWRPNe.zip