Photoionization modelling of the Wolf-Rayet planetary nebulae IC 4663 based on multiwavelength observations

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Abstract. Observations of the central star planetary nebulae (CSPN) IC 4663 revealed its spectral features similar to WN sequence of massive Wolf-Rayet (WR) stars. Because CSPN IC 4663 spectrum is dominated by broad He II and N V emission lines, it is classified as [WN3] spectral type. The similarity on the central stars composition of O(He) and IC 4663 provides evidence for evolutionary sequence [WN] → O(He). Evolution of CSPN IC 4663 followed evolution low-mass star, but experienced born-again scenario when it enters white dwarf phase. So it goes back to Asymptotic Giant Branch (AGB) phase. To investigate central star properties, the nebula and its evolutionary status, we constructed the spectral energy distribution (SED) model by using photoionization code CLOUDY based on data set from optic to far-IR wavelength (~3 − 100 µm) and include the Postdam Wolf-Rayet (PoWR) stellar model atmosphere. The comparison between the nebular abundances from photoionization model result and AGB model gives initial 3$M_\odot$ star with Z = 0.02. The nebula ionized mass derived from the photoionization model also consistent with the prediction from AGB model.

Keywords: Photoionization modelling and Wolf-Rayet planetary nebulae IC 4663

1. Introduction
Some of the central stars of planetary nebulae (CSPN) have H-deficient atmosphere and spectral features similar to massive Wolf-Rayet (WR) stars. This phenomenon can be explained by a scenario called “born again scenario” suggested by [4], when last helium thermal pulse occurs after the star left the thermally pulsing AGB (Late Thermal Pulses/LTP) or H-burning has almost come to the end on the early white-dwarf cooling branch (Very Late Thermal Pulses/VLTP). Observations of the CSPN IC 4663 revealed that it has [WN3] spectral features. The similarity on the composition of O(He) and IC 4663 central star suggested a secondary evolutionary sequence of H-deficient star [WN] → O(He) [6]. To gain insight about the progenitor star of this planetary nebulae (PN) and its evolutionary status, we constructed a photoionization model by using archival data from optic to far-IR (~3 − 100 µm).
2. Data
For constructing a photoionization model, we looked for the observational data and its derivation that represents the ionizing sources and ionized gas from the archival data. We used spectra from [6] that were observed by using Gemini Multi-Object Spectrograph (GMOS) on Gemini South, with wavelength coverage of the spectra is from 3767 – 5228Å. We adopted the nebular abundances derived from [5] as input parameter into the model and used data from APASS, 2MASS, WISE, AKARI/IRC and IRAS to constraint the model. For dereddened $F(\text{H} \beta)$ of entire nebula, we used from [7] and get the value about -10.92. Distance (3.5 kpc) and diameter (14.4′′) of the PN is adopted from [8].

3. Photoionization Modelling
Spectral energy distribution (SED) fitting between observational data and model is done by using CLOUDY C13.05 [3]. For the input parameters of ionizing source, we used Postdam Wolf-Rayet (PoWR) stellar model atmosphere [10] to derive the central star properties and the result is showed on Table 1. We varied 14 parameters ion the model ($T_{\text{eff}}$, inner radius, hydrogen density, elemental abundances, dust mass fraction and filling factor) and showed these in Table 2. The spectra from [6] are used as constraints to optimize the model by using ‘optimize lines’ method on CLOUDY. On the first model, we used $T_{\text{eff}} = 140000\text{ K}$ and $\log g = 6.1$ adopted from [6]. Nevertheless, the higher excitation lines such as [Ne III] and [O III] are overestimated on this model. On the other hand, model with $T_{\text{eff}} = 125000\text{ K}$ and $\log g = 6.0$ from PoWR result is consistent with the observation data. The best-fit model is the model with minimum reduced $\chi^2$ calculated from broadband fluxes, broadband flux densities and dereddened integrated flux of entire nebulae that is included on the input parameters. The $\chi^2$ value for the best-fit model is 3.75.

![Figure 1](image.png)

**Figure 1** Comparison of SED between the CLOUDY model and observational data of IC 4663.
Table 1. PoWR model atmosphere results for IC 4663

| Parameters | Value     |
|------------|-----------|
| $T_*$      | 125000 K  |
| $v_\infty$ | 1600 km/s |
| $\log g$   | 6.0 cm/s^2|
| $\log L/L_\odot$ | 3.5 |

Table 2. Parameters From CLOUDY Best-Fit Model

| Parameters | Value     |
|------------|-----------|
| $T_{\text{eff}}$ | 125000 K  |
| $\log g$   | 6.0 cm/s^2|
| $\log L/L_\odot$ | 3.1 |
| $r_{\text{in}}$ | 0.04''   |
| $n_H$      | 1000 cm/s^3|
| $m_d/m_g$  | 4.23(-4) $M_\odot$|
| He/C/N/O/Ne/S/Cl/Ar | 11.08/8.55/8.4/8.7/8.4/7.2/5.38/7.13 |
| filling factor | 0.63 |

4. Results and Discussions

Figure 1 shows the plots between observed SED and the predicted SED from CLOUDY model. It is showed, however, that for the mid-IR part, the continuum does not show amorphous silicate bump although C/O < 1 indicates this PN is O-rich dust type. This should be confirmed by mid-IR spectroscopic observation. We do not find any mid-IR spectroscopic observation for this PN to constrain the model on the mid-IR emission line fluxes and dust continuum. Therefore, we cannot derived the dust-mass precisely and determine its dust type.

The nebular abundances of He/C/N/O/Ne/S from the model compared with the predictions from AGB model by [5] gives initially $3M_\odot$ star with Z = 0.02. From the model result, we also derived the gas-mass ($1.2M_\odot$). This result is also consistent with [5]. By using VLTP evolutionary tracks from [1], we get the core mass (0.625$M_\odot$), which also originated from a progenitor star with an initial mass $3M_\odot$. As a comparison, CSPN Abell 48 that had been classified as [WN5] by [9] is also suggested from $\sim 3M_\odot$ progenitor star [2]. But, Abell 48 is confirmed to be C-rich star which is different with IC 4663 that has C/O < 1. From the AGB nucleosynthesis prediction, the star with initial mass about $1.2 - 3M_\odot$ should be C-rich star. This can be confirmed by using mid-IR spectroscopic to see if IC 4663 is O-rich, C-rich or dual chemistry PN.

5. Conclusions

A new photoionization model for IC 4663 has been constructed by using CLOUDY and observation data from optical to far-IR. The input parameters for the central star properties are derived by using PoWR atmosphere model and give $T_{\text{eff}} = 125000$ K and $\log g = 6.0$ that are consistent with observation data. The comparison between nebular abundances from the model result with AGB model and born-again scenario evolutionary track suggested this PN is originated from $3M_\odot$ progenitor star.
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