Properties of the fullerene C\textsubscript{60}-containing PN Lin49 in the SMC; Explanations of strong near-IR excess

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Abstract. We performed a detailed spectroscopic analysis of the fullerene C\textsubscript{60}-containing planetary nebula (PN) Lin49 in the Small Magellanic Cloud (SMC). Lin49 is a C-rich and metal-deficient PN (Z\sim 0.0006) and its nebular abundances are in agreement with the AGB model for the initially 1.25 M\textsubscript{\odot} stars with the metallicity Z = 0.001 of Fishlock et al. (2014, [1]). By stellar absorption fitting with TLUSTY, we derived stellar abundances, effective temperature, and surface gravity. We constructed the photo-ionization model with CLOUDY in order to investigate physical conditions of Lin49. The model with the 0.005-0.1 \mu m radius graphite and a constant hydrogen density shell could not fit the \sim 1-5 \mu m SED owing to the strong near-IR excess. We propose that the near-IR excess indicates (1) the presence of extremely small carbon molecules or (2) the presence of high-density structure surrounding the central star.

1. C\textsubscript{60}-containing PN Lin49 in the SMC

Recently, \textit{Spitzer}/IRS mid-IR spectrum revealed that Lin49 is a C-rich dust PN, showing strong C\textsubscript{60} resonances at 17.4 and 18.9 \mu m and similar dust features such as the broad 11 \mu m and 30 \mu m features seen in the other C\textsubscript{60}-containing Magellanic Cloud PNe [2]. However, physical properties of the central star and the dusty nebula had been unknown. Therefore, we characterized Lin49 through abundance analysis, stellar absorption fitting, and photo-ionization modelling based on our own ESO/VLT X-SHOOTER UV to near-IR spectrum, the archived \textit{Spitzer}/IRS spectrum, and the UV to mid-IR photometry data.

2. Nebular abundances and Stellar absorption line analysis

The resultant elemental abundances are listed in Table 1. In comparison to heavy \alpha-elements S and Ar, Fe is highly depleted. It seems that S is not locked by dust grains such as MgS because the [S/H] abundance is comparable to the noble gas [Ar/H] abundance. According to
Table 1. Elemental abundances ($\log_{10}\epsilon$(H) = 12). The values in the last two columns are the predictions in the AGB models by [1] for initially 1.0 $M_\odot$ and 1.25 $M_\odot$ stars with $Z = 0.001$.

| X  | $\log_{10}\epsilon$(X) | $\log_{10}\epsilon$(X$_{\odot}$) | $\log_{10}(X/H)$ | $\log_{10}\epsilon$(X$_{1.0M_\odot,\text{model}}$) | $\log_{10}\epsilon$(X$_{1.25M_\odot,\text{model}}$) |
|----|---------------------------|-------------------------------|-----------------|--------------------------------|--------------------------------|
| He | 10.80 - 11.01             | 10.93 ± 0.01                 | -0.13 - +0.08  | 10.99                          | 11.01                          |
| C  | 8.46 ± 0.24               | 8.39 ± 0.04                  | +0.07 ± 0.25   | 8.06                           | 8.56                           |
| N  | 6.93 ± 0.02               | 7.86 ± 0.12                  | -0.93 ± 0.12   | 7.15                           | 7.26                           |
| O  | 8.11 ± 0.01               | 8.73 ± 0.07                  | -0.62 ± 0.07   | 7.58                           | 7.68                           |
| Ne | 7.18 ± 0.05               | 8.05 ± 0.10                  | -0.89 ± 0.11   | 6.89                           | 7.37                           |
| S  | 6.02 ± 0.01               | 7.16 ± 0.02                  | -1.15 ± 0.02   | 5.99                           | 6.00                           |
| Cl | 4.03 ± 0.05               | 5.25 ± 0.06                  | -1.22 ± 0.08   | 4.07                           | 4.08                           |
| Ar | 5.48 ± 0.11               | 6.50 ± 0.10                  | -1.02 ± 0.15   | 5.27                           | 5.28                           |
| Fe | 4.55 ± 0.04               | 7.46 ± 0.08                  | -2.91 ± 0.09   | 6.37                           | 6.38                           |

Figure 1. (left panels) (upper) Comparison between the CLOUDY model and observational data. The squares at 65, 90, and 120 $\mu$m are the predicted flux densities calculated by fitting the broad 30 $\mu$m feature. (lower) Closed-up plots for mid-IR wavelength. (right panel) Near-IR excess. The grey lines and the circles are the residual flux densities ($\Delta F_\lambda$) between the observed X-SHOOTER and Spitzer/IRS spectra and photometry bands and the corresponding values obtained from the CLOUDY model.

the chemical evolution model of the Milky Way halo by [3], the [S/Fe] and [Ar/Fe] are $\sim$+0.4 and $\sim$+0.3 in the [Fe/H] $<-1$, respectively. By applying this prediction to Lin49, we obtained the [Fe/H] = −1.55 and −1.32 from the observed [S/H] and [Ar/H], respectively. From the average [Fe/H] of −1.4 between them, we estimated Z to be $\sim$0.0006. Over 96% of the iron atoms in the nebula would exist as the dust grains. In the last two columns of Table 1, we list the predicted abundances in the AGB nucleosynthesis models by [1]. The observed abundances are in excellent agreement with the prediction of the 1.25 $M_\odot$ model. From the view of chemical abundances, we infer that the initial mass of the progenitor would be around 1.25 $M_\odot$.

We fit stellar absorption lines with the O-type star grid model OStar2002 by [4] using the non-LTE model stellar atmospheres modeling code TLUSTY [5]. We determined the effective temperature ($T_{\text{eff}}$) of 30 500 ± 500 K, the surface gravity ($\log g$) of 3.29 ± 0.06 cm s$^{-2}$, and the $\epsilon$(He,C,N,O,Si) of 10.9 ± 0.3, 9.0 ± 0.3, 7.6 ± 0.3, 8.6 ± 0.1, and 6.8 ± 0.3, respectively.
3. Photo-ionization modeling; finding of the near-IR excess

Using the photo-ionization code CLOUDY [6], we investigated physical conditions of Lin49. As the SED of the ionization/heating source, we used the central star’s spectrum synthesized by the TLUSTY and varied its intrinsic luminosity ($L_*$) to match the observed nebular elemental abundances, gas emission line fluxes, and broad band fluxes/flux densities. We supposed that the infrared continuum is due to graphite grains; we adopted the radius $a = 0.005-0.1\mu m$ and the $a^{-3.5}$ size distribution. We derived the gas and dust masses of $0.11 M_\odot$ and $4.3\times10^{-5} M_\odot$, respectively. The dust temperature is in the range from 79 K to 825 K. We determined the core-mass of $0.53-0.57 M_\odot$. The location of the derived $L_*$ and $T_{\text{eff}}$ on evolutionary tracks of post AGB stars with $Z = 0.001$ of [7] indicates that the initial mass is $1.0-1.5 M_\odot$, consistent with our inference from the nebular abundances.

In Fig. 1 left, we present the observed and the modelled SEDs. The predicted SED could not fit the near-IR SED owing to the strong near-IR excess. To focus on the near-IR excess, we examined the differential spectra and photometry points between the observations and the CLOUDY model (Fig. 1 right); the near-IR excess peaks at $\sim2-3\mu m$ and its SED can be fitted by a single blackbody temperature of 1250 K. Limited to the SMC C

4. Interpretations for the near infrared excess

At the moment, we deduced two possibilities that the near-IR excess SED indicates (1) the presence of the extremely small molecules and/or (2) the high-density structure nearby the central star.

4.1. Stochastic heating by extremely small particles

Under the usual dust grain size (e.g., $\gtrsim 0.01\mu m$), dust temperatures are determined by solving an energy balance equation between the radiative heating owing to the central star and the cooling of grains. In such size grains, individual quantum events are not important. While, in extremely small grains which compose of 100 atoms or less, single photons would cause them to heat up significantly for very short time scale. This mechanism is known as stochastic heating, and has been proposed for the reflection nebulae NGC7023 and NGC2023 [9] and PNe e.g., IC418 [10]. Interestingly, these reflection nebulae and IC418 show mid-IR C\textsubscript{60} PNe, SMP24 shows the near-IR excess; [8] found that a hotter dust component ($\sim1000$ K) is necessary to fit the observed SED down to $1\mu m$, apart from the hot dust component ($\sim270$ K).

4.2. High density structure nearby the central star

In Section 3, we assumed that Lin49 does not have any sub-structures surrounding the central star but a normal density nebula only. However, the blackbody minimum emitting radius of the 1250 K component ($\sim2$ AU) suggests that near-IR component would emit from sub-structures nearby the central star. A similar idea was proposed for the near-IR excess at the central
Figure 2. (left panel) The explanation of the two density shell model. The central star is located in the geometrical center of two spherical nebulae, so called high density shell and low density shell. As the ionization and heating source, we used the spectrum of the central star (CSPN) synthesized by the TLUSTY fitting. (right two panels) (upper) Comparison between the observed SED plots and the predicted SED by the two density shell model. (lower) Closed-up plot for mid-IR wavelength. The dust temperature was in the range from 79 K to 1453 K. The lines and symbols in both of panels are as defined in Fig. 1 left.

position of IC418; [12] took the near-IR JHK images of IC418 and found excess at the central position after subtracting out the contribution from the central star. They argued that the excess indicates a possible compact shell interior to the main shell. We tested this interpretation for the near-IR excess in Lin49. When we assumed two density shells as explained in Fig. 2 left, we can well fit the near-IR excess (Fig. 2 right). The (binary) disk rather than the shell could stably harbor the near-IR emitters nearby the central star for a long time, although we did not detect any narrower absorption lines from the cooler stellar components. Assuming the high density disk, the Keplerian rotational velocity was 4 km s$^{-1}$ at 31 AU from the central star.

Several SMC and Galactic C$_{60}$ PNe show the near-IR excess. It would be worth investigating these PNe in order to characterize properties of dust, small molecules, and the central star of C$_{60}$ PNe and also understand the C$_{60}$ formation in the circumstellar environment.

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