Physical Properties of Fullerene C60-Containing PN Lin49 in the SMC; Explanations of Strong Near-IR Excess

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New detection of the C60 bands in Lin49

X-SHOOTER guide camera image
Known Properties of “Galactic” C60 PNe

- Cool central star and metal deficient nebula, about MC metallicity
- The origin (i.e., initial/current mass) of C60 PNe is unclear due to

1. Surface gravity (Log g)
2. Distance

Study on MC C60 PNe can overcome these problems

- useful for Galactic C60 PNe as well as MC C60 PNe

We investigate properties of Lin49

<table>
<thead>
<tr>
<th>Objects</th>
<th>&lt;Teff&gt;</th>
<th>&lt;log g&gt;</th>
<th>&lt;[Ar/H]&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galactic C60 PNe (11 objects)</td>
<td>38600</td>
<td>3.80</td>
<td>-0.60</td>
</tr>
<tr>
<td>C60 SMC PNe (7 objects)</td>
<td>37600</td>
<td>?</td>
<td>-0.97</td>
</tr>
<tr>
<td>Lin49 in the SMC</td>
<td>30500</td>
<td>3.29</td>
<td>-1.07</td>
</tr>
</tbody>
</table>

With VLT X-SHOOTER and Spitzer IRS spectra, we derive:

- Nebula abundances
  - Compare with AGB model predicted abundances and estimate the initial mass

- Central star's Teff and log g

- Dust and gas mass & core mass of the central star
  - Through CLOUDY (Ferland 1998) SED fitting. Use the synthesized spec by TLUSTY. Obtain $L^*$, then core-mass $M^*$

$$M^* = g \frac{L^*}{4\pi G \sigma \text{Teff}^4}$$
Nebular Abundances

The abundances could be explained by the initially 1.25 Msun with $Z = 0.06$ Zsun AGB models of Fishlock et al. (2014)

\[ \varepsilon(X/H) = \log \frac{n(X)}{n(H)} + 12 \]

<table>
<thead>
<tr>
<th>X</th>
<th>$\varepsilon(X/H)$</th>
<th>[X/H]</th>
<th>AGB model</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>10.99</td>
<td>+0.06</td>
<td>11.01</td>
</tr>
<tr>
<td>C</td>
<td>8.67</td>
<td>+0.28</td>
<td>8.56</td>
</tr>
<tr>
<td>N</td>
<td>6.93</td>
<td>-0.93</td>
<td>7.26</td>
</tr>
<tr>
<td>O</td>
<td>8.11</td>
<td>-0.62</td>
<td>7.68</td>
</tr>
<tr>
<td>Ne</td>
<td>7.18</td>
<td>-0.89</td>
<td>7.37</td>
</tr>
<tr>
<td>S</td>
<td>6.02</td>
<td>-1.15</td>
<td>6.00</td>
</tr>
<tr>
<td>Cl</td>
<td>4.03</td>
<td>-1.22</td>
<td>4.08</td>
</tr>
<tr>
<td>Ar</td>
<td>5.48</td>
<td>-1.02</td>
<td>5.28</td>
</tr>
<tr>
<td>Fe</td>
<td>4.55</td>
<td>-2.91</td>
<td>6.38</td>
</tr>
</tbody>
</table>
With VLT X-SHOOTER and Spitzer IRS spectra, we derive:

- Nebula abundances
  - compared with AGB model predicted abundances and estimated the initial mass of $\sim 1.25 \text{ M}_{\odot}$

- Central star's Teff and log g

- Dust and gas mass & core mass of the central star
  - Through CLOUDY (Ferland 1998) SED fitting. Use the synthesized spec by TLUSTY. Obtain $L^*$, then core-mass $M^*$

$$M^* = g L^* / 4\pi G \sigma \text{Teff}^4$$
Stellar absorption fitting with TLUSTY
Teff=30500 K and Log g = 3.29 cm s^{-2}
With VLT X-SHOOTER and Spitzer IRS spectra, we derive

- Nebula abundances
  - compare with AGB model predicted abundances and estimate the initial mass
- Central star's Teff and log g
- Dust and gas mass & core mass of the central star
  - Through CLOUDY (Ferland 1998) SED fitting. Use the synthesized spec by TLUSTY. Obtain L*, then core-mass M*

\[ M^* = g \, L^* / 4\pi \, G \, \sigma \, \text{Teff}^4 \]
SED model with CLOUDY

Central Star
TLUSTY synthesized spectrum
Teff = 30500 K
Log = 3.29 cm s^{-2}

Dusty Nebula
Rin = 0.0004 pc
Rout = 0.069 pc
nH = 4770 cm^{-3}
0.005-0.1\mu m
graphite
The NIR-IR data cannot be fitted with a normal ISM grain size.
Near-IR Excess; Stochastic heating by small particles?

For extremely small grains, a photon energy $E_{ph}$ produces the difference between the max and min temperatures $\Delta T$ written by

$$\Delta T = E_{ph}/3Nk$$

($N$: the number of the atoms in a molecule)

(Sellgren 1984; Whittet 2003)

the radiation peak energy of the central star is $\sim$13.05 eV, $N$ is $\sim$40-60
Near-IR Excess; High density component nearby the central star?

**Central Star**
TLUSTY synthesized spectrum  
$T_{\text{eff}} = 30500 \text{ K}$  
$\log = 3.29 \text{ cm s}^{-2}$

**High density nebula**
$R_{\text{in}} = 0.0002 \text{ pc}$  
$R_{\text{out}} = 0.0004 \text{ pc}$  
$n_{\text{H}} = 47800 \text{ cm}^{-3}$  
0.005-0.1μm graphite

**Low density nebula**
$R_{\text{in}} = 0.0004 \text{ pc}$  
$R_{\text{out}} = 0.069 \text{ pc}$  
$n_{\text{H}} = 4770 \text{ cm}^{-3}$  
0.005-0.1μm graphite
Near-IR Excess; two component model can fit the observation.

Core-mass: 0.58 Msun
Luminosity: 6320 Lsun
Gas mass: 0.11 Msun
Dust mass: 4.14x10^{-5} Msun
Dust temp: 80-1420 K
Summary

Near-IR excess

- Stochastic heating by small particles?
  - What's type of particle? C60 precursors? smaller fullerene? (e.g., C36; Piskoti et al. 1998, Nature)

- High-dens. component nearby the central star?
  - Shell? flatten envelope? How did a ~1.25M sun star create?

- Is there a connection to C60 formation?
  - Near-IR excess is seen in C60 PNe