Dust Chemistry as a Tracer of Evolutionary Status Among Post-AGB Stars

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Image credit: Very Large Telescope, ESO
Summary

• Stellar Evolution
• From AGB Star to Planetary Nebula
• From AGB to PN: Morphology
• From AGB to PN: Chemistry
• The Morphology – Chemistry connection
• Spectral Diagnostics
• Observations
• Sample Data
Stellar Evolution

Massive Stars

White Dwarf

Black Hole or Neutron Star

Intermediate-Mass Stars

Planetary Nebula

ISM
(nearly 80% by mass comes from the envelopes of Intermediate Mass Stars)

Main Sequence

Supergiant

Supernova

Intermediate-Mass Stars
(approx 90% of stars)

Massive Stars
Intermediate-Mass Stellar Evolution

Intermediate Mass Stars
- $0.8 \, M_\odot < M_{ZAMS} < 8 \, M_\odot$
- Main Sequence to Giant or Supergiant phase (He burning)
- AGB phase: nuclear fusion in shells
AGB $\rightarrow$ Proto PN $\rightarrow$ PN

The Dark Age

Proto Planetary Nebula
Emission from hot dust
Central star obscured

AGB Star
Nuclear burning in shells
Helium flashes/Thermal Pulsation

Planetary Nebula
Central Star visible/ ionizing stellar envelope
From AGB to PN: Morphology

Heavy mass loss leads to obscuration of the central star. When the light re-emerges, the nebulae have a completely different morphology. This is correlated with the dust chemistry, which determines the density and opacity of the dust.

Post-AGB star IRAS 22272+5435 at N band
(Image credit: COMICS)

Proto-PN Frosty Leo at K band
(Image credit: ESO)
From AGB to PN: Chemistry

Oxygen-Rich vs. Carbon-Rich

• The binding energy of Carbon Monoxide = 11.1 eV means CO forms first, leaving only the more abundant element to form other molecules

• All AGB stars start out O-rich; a Third Drege-Up can provide enough Carbon to turn the envelope C-rich a
O-Rich vs. C-Rich AGB Stars

Two competing mechanisms in AGB stars:

- Third Dredge Up: a pulse-driven convection zone reaches into the He burning shell, carrying $^{12}$C enriched material to the surface.

- Hot Bottom Burning: during the quiescent inter-pulse phase, the convective envelope extends into the H burning shell leading to CNO cycling of the envelope. Depletes $^{12}$C in favor of N, Li, O, $^{13}$C

Partial pressures of a few atomic and molecular species as a function of the C/O ratio (Marigo 2002)
The opacity of the dust is strongly correlated to the constituent chemistry. In model atmospheres by Gustaffson & Hoffner (2004), the contributions to opacity are shown for several molecules. Left: Solar C/O ratio, right, C/O ratio -1.1.
In Planetary Nebulae, Stanghellini et al. 2002 established a connection between morphological type, galactic latitude (hence progenitor mass), and dust chemistry.

**Chemistry-Morphology Connection**

![Apparent spatial distribution of the sample PNs (Galactic longitude vs. Galactic latitude): circles, Round PNs; asterisks, E PNs; filled squares, B PNs; open squares, BC PNs.](image)

**TABLE 3**

<table>
<thead>
<tr>
<th>Morphology</th>
<th>$\langle \text{He/H} \rangle$</th>
<th>$\langle \text{O/H} \rangle$</th>
<th>$\langle \text{N/H} \rangle$</th>
<th>$\langle \text{Ne/H} \rangle$</th>
<th>$\langle \text{Ar/H} \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>1.10 (18)</td>
<td>3.61 (16)</td>
<td>1.71 (14)</td>
<td>0.96 (16)</td>
<td>1.29 (7)</td>
</tr>
<tr>
<td>E</td>
<td>1.20 (33)</td>
<td>3.34 (32)</td>
<td>1.51 (31)</td>
<td>0.87 (32)</td>
<td>1.28 (27)</td>
</tr>
<tr>
<td>BC</td>
<td>1.39 (9)</td>
<td>3.22 (8)</td>
<td>1.92 (6)</td>
<td>1.36 (5)</td>
<td>0.60 (4)</td>
</tr>
<tr>
<td>B</td>
<td>1.49 (16)</td>
<td>4.05 (13)</td>
<td>5.66 (13)</td>
<td>0.94 (11)</td>
<td>1.36 (9)</td>
</tr>
</tbody>
</table>

**Notes.**—He/H abundances are multiplied by 10; O/H, N/H, and Ne/H abundances are multiplied by $10^4$; Ar/H abundances are multiplied by $10^5$. Statistical sample in parentheses for each entry.

Average abundance ratios for the different morphological classes. Argon and Neon are constant throughout the stellar lifetime and are thus good baselines.
ISO SWS spectra of an O-rich (top, showing silicate features) and a C-rich star (bottom, showing PAH features). The middle spectrum is a peculiar case showing features of both O-rich and C-rich chemistry (Yamamura et al. 1999).

Synthetic stellar spectra at varying C/O ratios. (Gustafsson et al. 2003)
Observations

Three programs with Spitzer Space Telescope’s Infrared Spectrograph (IRS) and Infrared Array Camera (IRAC) including 75 targets:

- Post-AGB Stars
- Transition Objects
- “Dual Dust” Planetary Nebulae
Observations

• Observations of the same sample were taken with the twin Magellan 6.5-meter Telescopes in Chile
  – MMIRS Near Infrared spectra
  – PANIC Near Infrared Narrowband Imaging
## IR Dust Chemistry Diagnostics

<table>
<thead>
<tr>
<th>Spectral Feature</th>
<th>Wavelength</th>
<th>Diagnostic 1</th>
<th>Diagnostic 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicates (amorphous)</td>
<td>10-18 μm</td>
<td>Dust chemistry, evidence of grain growth processing</td>
<td>Changes from emission (AGB) to absorption (p-AGB) and back to emission (PPN)</td>
</tr>
<tr>
<td>Polycyclic Aromatic Hydrocarbons</td>
<td>6.2 &amp; 7.7 μm</td>
<td>Dust Chemistry</td>
<td>Shock heated gas</td>
</tr>
<tr>
<td>MgS</td>
<td>30 μm</td>
<td>Peak position/width change with temperature of underlying continuum</td>
<td></td>
</tr>
<tr>
<td>H₂ (imaging)</td>
<td>2.12 μm</td>
<td>Photoionization Regions/Shock heating,</td>
<td></td>
</tr>
<tr>
<td>Br γ (imaging)</td>
<td>2.16 μm</td>
<td>Ionized gas</td>
<td></td>
</tr>
</tbody>
</table>
Sample (Raw) Data

NGC 6369: Resolved for the first time with PANIC

NGC 6369 Near Infrared Spectra taken with MMIRS
Thanks to Joe Hora and the Smithsonian Predoctoral Program for making this research possible!

Sunset at Las Campanas Observatory, Chile
The Pivotal PPN phase

Possible shaping mechanisms that could account for the geometries seen in Planetary Nebulae:

1. An inherently asymmetric “equatorially enhanced” wind
2. “Choked” spherically symmetric winds – pre-existing circumstellar disk
3. Polar jets

A Young PN
Credit: R. Sahai & J. Trauger (JPL)
The Pivotal PPN phase

Possible shaping mechanisms that could account for the geometries seen in Planetary Nebulae:

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Need extreme magnetic field or rapid stellar rotation
neither are expected or observed in evolved stars
The Pivotal PPN phase

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2. “Choked” spherically symmetric winds – pre-existing circumstellar disk
3. Polar jets

Can be produced with a binary companion, but the binary fraction is too small to account for all of the bipolar nebulae.

A Young PN
Credit: R. Sahai & J. Trauger (JPL)
Shell Remnants from Stellar Pulsation

Proto Planetary Nebula NGC 1705
Image credit: NASA & Hubble Heritage Team (STScI/AURA), W. Sparks (STScI) & R. Sahai (JPL)

The Cat’s Eye Planetary Nebula
Image credit: R. Corradi, Z. Tsvetanov, Hubble WFPC2, NASA, ESA, and STScI/AURA