From AGB Stars to Aspherical Planetary Nebulae
Recent Observational Highlights from the Far-IR and (Sub)mm to X-Rays
(part 2)

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Outline (part 2)

- **(Background) The formation of Aspherical Structure in Planetary Nebulae**
  (note: this material covered in SOFIA teletalk on 4/27/11)

- **Recent (selected) Observational Highlights from (sub)mm and far-IR to UV and X-Rays**
  1) X-rays: Chandra (CHANPLANS*) survey of nearby PN sample
  2) UV: GALEX discovery of "fuvAGB" stars (actively accreting binaries?)
  3) radio/ (sub)mm: dense waists, mm-sized grains in post-AGB objects
  4) far-IR (Herschel) and UV (GALEX): imaging of extended mass-loss history in AGB stars (e.g., spiral density structure, bow-shocks, rings)
  5) (sub)mm: surveys of outflows in PPNe
  6) detailed mm/submm studies of extreme outflows: Boomerang Nebula
  7) detailed far-IR studies of PNe - Herschel (HERPLANS*, NGC6781)
  8) SOFIA/GREAT study of the 3D Structure of PNe: "Ring Nebula" NGC6720

*CHANPLANS & HERPLANS: community-wide large projects on PNe (X-Rays, far-IR)
The Boomerang Nebula (most extreme example of AGB/pAGB mass-loss)

The coldest object in the universe (Sahai & Nyman 1997)

SEST data showed CO(1-0) absorption against CMB
(predicted, Sahai 1990)

Inner & Outer Outflow model

• Prodigious mass-loss rate for outer outflow
  (~$10^{-3}$ Msun/yr)
• But $L \sim 500$ Lsun!

Radiative momentum completely inadequate to drive outflow

Model shows $T_{\text{kin}} < 2K$
Boomerang Nebula: CO 1-0 (ALMA)

Note weak patchy emission on the periphery of the ultra-cold shell: **first direct evidence of grain photo-electric heating in an AGB CSE**

- Absorption over a large range of radial-velocity along line-of-sight to center
- Ultra-cold shell has radially-increasing expansion velocity explains puzzle of lower outflow velocity (35 km/s) in the central bipolar emission lobes, compared to that derived for ultra-cold shell from single-dish data (165 km/s) (velocity of material in bipolar lobes must be larger or equal to that in ultra-cold outflow, if former result from interaction with latter)
140" diameter region mapped (100", cyc 0)

- emission/absorption signal detected to much larger radii (>~ 55", need TP data to rule out artifacts due to missing UV coverage)
- circle = size of SN97 model ultra-cold outflow

~2/3 of absorption signal seen with single-dish resolved out (i.e., from smooth structures on angular scale > 35")

- > ~3 Msun in ultracold outflow (single-dish APEX/LABOCA continuum flux of 337 mJy consistent with estimate)
- expect r(1/2) ~10^{18} cm (~50")

(radius where CO abundance falls to 50% due to photodissociation by interstellar UV)
CO 3-2 (cycle 1, band 7)

- Central dense, dusty waist, likely expanding torus structure
- Hourglass shape of extended, diffuse optical nebulosity due to preferential illumination of largely round CSE!

- Complex spatio-kinematic structure at center, small line width - rotating disk?

Inner surface of lobe walls (unresolved) hotter than outer [also in CO 2-1, cyc 0]

Resolution ~0''.1
Beam 0''.37 x 0''.25

HST/ACS (Cracraft & Sparks ’07)
Polarized intensity 0.6 μm
pAGB mass-loss: Boomerang (continuum)

(Rayleigh-Jeans limit) if dust-absorption coefficient, $k \sim n^p$

$R(l_1/l_2) \sim (l_2/l_1)^{(2+p)}$, so $p \sim 0$

(without R-J): $p \sim 0.3$, $T_d \sim 30K$

(with extinction/reddening of starlight, somewhat higher $p$ and lower $T_d$ values allowed)

Grains must be very large!

Pollack+1992 (using laboratory data and theory) find

$p = 0.87$ for 3 mm grains at 100K

$p \sim 0$ for sizes $\sim 10$ cm

$M_d \sim 5 \times 10^{-4}$ $M_{\odot}$, or $M \sim 0.1$ $M_{\odot}$ assume gas-to-dust ratio=200, opacity

$k(1.3\text{mm}) \sim 1.5 \text{ cm}^2/\text{g}$

Peak fluxes, from images convolved to same resolution, i.e., 4".1 x 2".9

(black curve is fit with spectral-index=2)
Planetary Nebulae: Herschel & SOFIA

Large Herschel studies

MESS (PI: Groenewegen, PACS/SPIRE mapping, spectroscopy of selected evolved objects: GTO Key Prog., 330 hr)

HERPLANS (Ueta+2014 PACS/SPIRE mapping, spectroscopy of 11 high-exc PNe from CHANPLAN sample: OT1 Large Prog., 197 hr)

Goals: thermal dust emission, far-IR lines (ionic/atomic/molecular gas) and derive Tdust, Mdust, Te, ne, ionic/elemental abundances

Important "legacy value" of dataset for PN studies! (but no kinematic information)

• SOFIA project to map velocity-resolved fine-structure line emission in nearby PNe to determine their 3D structures

select bright objects from ISO survey by Liu et al (2001), angular sizes larger than SOFIA beam (17.5” at 158 μm)

Selected NGC6720 for Cycle 0+1

flux [CII]158 μm=6.8 x 10^{-12} erg/cm^2/s, optical shell ~ 90 x 60 arcsec^2 (large, but not too large, can be (strategically) mapped in few hours

(props: 81-0065, 01-0138: Sahai, Morris, Werner)
NGC6781 (PACS/SPIRE continuum)

- 10' x 10' broadband maps at 5 wavelengths 70-500 μm (beam 5.6"-36"), 0.02 mJy/arcsec^2 rms
- PACS IFU spectroscopy (5 x 5 grid covering 47" x 47", beam 9.6"-13")
- SPIRE FTS spectroscopy (SSW: 194-342 μm, SLW: 316-672 μm)

(Schwarz & Monteiro 2006)

(D=0.95 kpc)

(Ueta+2014)
NGC6781: Dust Model

Far-IR SED based on HERPLAN data

\( \text{T}_{\text{dust}} = 36 \pm 2 \text{ K}, \beta = 1 \pm 0.1 \)

\[(Ueta+2014)\]

Dust Temperature, Column Density (M_{\odot}/\text{pix}), \beta
NGC6781: Far-IR Spectrum

Spectrum over complete PACS/SPIRE wavelength coverage (51-672 μm), from central spaxel (black) and rim spaxel (grey). Various ionic, atomic and molecular lines marked.

- Gas/Dust 195 +/- 110; Shell Mass 0.86 Msun (0.54 ionized, 0.12 atomic, 0.2 mol)
- Spatially resolved abundances, ratios (C/O, N/O) from far-IR lines
- Progenitor star mass >~1.5 Msun

(Ueta+2014)
First detection of OH+ in PNe

OH+ important for interstellar chemistry (e.g., formation of water, oxygen-bearing species)

Mapping reveals that the OH+ rotational emission is produced in the PDRs

Found only in stars with Teff > 100000 K

High-energy photons (soft X-rays) may be responsible for OH+ production (e.g., as in ultraluminous galaxies)

Aleman+2014 (also Etxaluz+2014)
GREAT mapping of [CII]158 $\mu$m in PNe

• Obtain spatially and velocity-resolved spectra of the [CII]158 $\mu$m line (detected by ISO with 70” beam) to probe 3-D structure

Why [CII]158 $\mu$m?

• Low critical density, hence line is easily excited both in and outside the PN shell

In contrast, optical forbidden lines arise mostly from dense, ionized PN shell, whereas molecular lines arise from dense equatorial region outside PN shell.

• [CII]158 $\mu$m emission fluxes for a good fraction of the 28 PNe studied by Liu et al. yield masses which are significantly larger than those probed by molecular lines (not surprising as molecular gas expected to survive only in very dense, dusty parts of the PNe).

• [CII]158 $\mu$m, together with [OI]63 and 146 $\mu$m, is a primary coolant of Photodissociation Regions (PDRs). PNe, with their relatively well-defined physical structures, are probably the best astrophysical laboratories for studying PDRs.
The Ring Nebula NGC6720

• Evolved, oxygen-rich PN, D=0.7 kpc
• Central star (Teff=120,000 K) starting on cooling track, kinematic age ~7000 yr (e.g., O’Dell 2007)
• Gas in halo is recombining, H2 molecules forming on dust grains in high-density knots/filaments (van Hoof+2010)
3D Structure: Models

Bright “Ring” seen in optical images

old models

- Torus (1960)
- Flat Ring (1970)
- Cylinder (1974-75)
- Spheroid (1983)
- Ellipsoid (1997)

also

Two halos surround bright ring
- Inner halo: structured
- Outer halo: smooth, circular

Models: Two Broad Classes

(1) Prolate Ellipsoid

(2) Bipolar, seen nearly pole-on

Molecular Line Studies (CO, H$_2$) lead to models with elements of both classes

(1) Prolate ellipsoid: Guerrero et al. (1997)

Most modern models based on velocity-resolved multi-slit optical spectroscopy
3D Structure: Class 1 model

Opaque reconstruction in [OIII] and [NII] at mean flux levels (O’Dell et al. (2007))

Triaxial ellipsoid (radii 0.1,0.13,0.20 pc), seen nearly pole-on: equatorial region, denser & optically thick, polar-regions optically thin.
3-D Structure: Class 2 Model

Kwok et al. 2008 proposed

Triple bi-conical shape (seen pole-on) & central torus (bright optical ring)
Model apparently accounts for both bright ring and halo structure
*(motivated by edge-on triple biconical structure inferred for NGC6853)*

Which model is correct? Under the binary framework, ellipsoidal shapes results from interactions with sub-stellar companions, whereas bipolar shapes require interaction with stellar-mass companions *(Soker 1996)*
Modest program for Cyc 0,1

Mapped positions in CII

major and minor axis (+diagonals), including positions on and away from the bright optical shell

8 in Cyc 0 (green circles)
9 in Cyc 1 (green dashed circles)

Total integration time / position typically

6 min (Cyc 1, Tsys~2600K)
17 min (Cyc 0, Tsys~4500K)

Supplementary APEX data at selected positions for

CO 3-2, 2-1 (white dashed circles) and $^{13}$CO 2-1
Mass(PDR)~0.1 Msun (within <88" diameter region)

Abund Ratio Cl/CO > 6.5 in optical shell region

using published CO 2-1 data

we proposed that best model for NGC6720 is a multipolar PN (seen pole-on) with a barrel-shaped central region (a secondary classifier in PN morphological scheme of SMV12)
"Starfish Twins"

These multipolar PNe give an idea of what NGC6720 might look like at more edge-on orientations.
Generally, there appears to be an odd symmetry in the velocity-structure about the nebular center (e.g. 7 & 7A, 8 & 8A)

But exceptions as well (e.g., 4Ci & 4CiA, 4Di & 4DiA)

(spiky features due to bad channels)
**NGC6720**

CII, CO and $^{13}$CO

(CO data from APEX 12-m)

**CONCLUSION**

data are broadly consistent with model proposed in *Sahai+2012*

(O'Dell+2013 abandon ellipsoidal model, adopt our model to fit optical data)

but detailed spatio-kinematic modeling still needs to be done

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**Compare CII and CO line profiles** (*beam-size for CO similar to CII SOFIA beam*)

(a) total velocity extent similar (~50 km/s)

(b) widely-separated red- and blue-shifted components ($V_{lsr}$ ~16 km/s, -12 km/s) at locations on the bright optical shell (*pos 3 & 8A*), (but) CO also shows low-velocity components near systemic velocity ($V_{lsr}$ ~ 0 km/s)

(c) narrower emission at systemic velocity beyond optical shell (*pos 4*)
Summary

What we have learnt from observations

• The transition from sphericity (AGB) to asphericity (PN) on “large-scales” is observationally/phenomenologically reasonably well-characterized (outflow velocities, mass-loss rates, momentum rates are being determined for an ever-increasing sample)

• The central regions are much less understood (dense dusty waists: torii and/or disks; central stars: binary or single, their offsets from geometric center of nebula)

• Extreme objects: very large “AGB” mass-loss rate (Boomerang), very large momentum rates (e.g., IRAS19374, IRAS22036, Boomerang)

Some directions for future observations

1) Far-IR velocity-resolved mapping of nearby planetary nebulae (SOFIA: note ISO data show [OI] 63 \(\mu m\) line often much stronger than [CII] 158 \(\mu m\) line)

2) (Sub)mm and cm-wave interferometry with dense uv-coverage, high angular resolution, polarization: ALMA, VLA (masses of dust and gas in torii/disk, expansion/rotation, magnetic fields)

3) UV spectroscopy/photometric monitoring of accretion activity (HST/ COS)

4) X-Ray Studies: AGB stars, central stars of PPNe (none detected so far) and PNe

5) Mid-IR Interferometry and imaging (e.g., VLTI, JWST)
Extra Slides
model 1 versus model 2

- **Model 1**: minor axis and major axis represent regions with very different physical and kinematical properties:
  - minor axis lies along a dense equatorial region, optically-thick to UV
  - major axis lies along polar axis, optically-thin to UV
- **Model 2**: both minor axis and major axis lie in (or near) the equatorial plane and represent regions with similar physical and kinematical properties

Major difference in expected line-profiles for above models:

- **Model 1**: systematic velocity-gradient along major axis
  - line profiles outside the optical shell should be centrally-peaked at systemic velocity
- **Model 2**: no systematic velocity-gradient along major axis
  - line profiles outside the optical shell should show double-peaked profiles with blue- and red-shifted peaks due to emission from the approaching and receding bicones, respectively.
Schematic Models for Bipolar PPNe/PNe

Balick & Frank 2002, AnnRevA&A

a1-4: possible formation mechanisms of PPN, PN lobes
1) GISW
2) Magnetized Wind Blown Bubble (e.g., Garcia-Segura+2005)
3) Disk/star magneto-centrifugal winds (both disk and star produce collimated outflows)
4) Episodic/precessing jets

3 & 4 produce point-symmetry

b1, b2: creating dense waist/ torus/disk
1) Common envelope evolution =>massive torus?
2) Accretion disk formation (Bondi accretion/ Roche lobe overflow) =>small (light) disk?

(Recent) “Impulsive” Models

- Intermediate Luminosity Transient Event (ILOT): accretion onto ms companion => (several month-long) episodic event, producing linear radial-velocity curve in ejecta; jets produce bipolar structure (Akashi+Soker 2013)

- Magneto-Rotational Explosion: ejection along polar axis and in equatorial plane (Matt+2006)
### PRIMARY CLASSIFICATION

**Nebular Shape:**
- **R**: Round
- **B**: Bipolar
- **L**: Collimated Lobe Pair
- **M**: Multipolar
- **S**: Spiral-Arm
- **E**: Elongated
- **I**: Irregular

### SECONDARY CLASSIFICATIONS

**Lobe Shape:**
- **o**: lobes open at ends
- **c**: lobes closed at ends

**Central Region:**
- **w**: central region shows an obscuring waist
- **t**: central region is bright and has a toroidal structure
- **bcr**: central region is bright and barrel shaped
- **bcr (c)**: barrel has closed ends
- **bcr (o)**: barrel has open ends
- **bcr (i)**: irregular structure present in barrel interior

**Central Star:**
- ****: central star evident in optical images
- ***(nnn)**: star is offset from center of symmetry, nnn is max offset in milliarcsec

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**Extension of PPNe classification scheme**
(items in red are new descriptors needed for PNe)

- Minimal prejudice regarding underlying physical causes (although in many cases, physical causes readily suggested by geometry, along with kinematical studies of some systems)

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**bcr**: more highly-flared equatorial disk, expanded by CSPN fast wind
SECONDARY CLASSIFICATIONS

Other Nebular Characteristics:

- **an**: ansae
- **ml**: minor lobes
- **sk**: a skirt-like structure present around primary lobes
- **ib**: an inner bubble is present inside the primary nebular structure
- **wv**: weave-like or patchy microstructure
- **rg**: multiple projected rings on lobes
- **rr**: radial rays are present
- **pr**: one or more pairs of diametrically opposed protrusions on the primary geometrical shape
- **ir**: additional unclassified nebular structure not covered by the primary/secondary classifications

Point Symmetry:

- **ps(m)**: two or more pairs of diametrically opposed lobes
- **ps(an)**: diametrically opposed ansae present
- **ps(s)**: overall geometric shape of lobes is point-symmetric
- **ps(t)**: waist has point-symmetric structure
- **ps(bcr)**: barrel-shaped central region has point-symmetric structure
- **ps(ib)**: inner bubble has point-symmetric structure

Halo:

- **h**: halo emission is present (low-surface-brightness diffuse region around primary structure)
- **h(e)**: halo has elongated shape
- **h(i)**: halo has indeterminate shape
- **h(a)**: halo has centro-symmetric arc-like features
- **h(sb)**: searchlight-beams are present
- **h(d)**: halo has a sharp outer edge, or shows a discontinuity in its interior
pAGB mass-loss: Boomerang Nebula
(Sahai, Vlemmings, Nyman, Huggins: Cycle 0 ALMA project: Sahai+2013)

- CO 2-1 (and 1-0) emission region bipolar (lobes have bubble structure), and oriented along same axis, as the optical hourglass shape
- Central dense, dusty waist, likely expanding torus structure

HST/ACS 0.6 μm: note knotty “jet” (inset)

CO 2-1 image (systemic velocity) spectra

• Central dense, dusty waist, likely expanding torus structure
• hourglass shape of extended, diffuse optical nebulosity due to preferential illumination of largely round CSE
Boomerang Nebula: Continuum Emission

Low value of emissivity-index, $p$, implies millimeter-sized grains

Rayleigh-Jeans limit: $R(\lambda_1/\lambda_2) \sim (\lambda_2/\lambda_1)^{2+p}$, hence $p=0.5$
(without R-J): for $p = 0.6, 1, 1.5$, get $T_d = 45K, 9.5K, 5.0K$ and $r_d=1.9”$

Assuming opacity $\kappa(1.3\text{mm}) \sim 1.5 \text{ cm}^2/\text{g}$

$M_d \sim 3.5 \times 10^{-4} \text{ M}_{\odot}$, or $M \sim 0.07 \text{ M}_{\odot}$ (assume gas-to-dust ratio=200)

Expansion time scale for dust region $\sim 420$ yr $\Rightarrow$ Mass-loss rate $\sim 1.7 \times 10^{-4} \text{ M}_{\odot}/\text{yr}$