From AGB Stars to Aspherical Planetary Nebulae
Recent Observational Highlights from the Far-IR and (Sub)mm to X-Rays
Part 1

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Outline

• (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, X-Rays
  
  *2 community-wide large projects on PNe (X-Rays, Far-IR)*

• **Using SOFIA/GREAT to study the 3D Structure of PNe**: "Ring Nebula" NGC6720
Ordinary Stars (~1-8 Msun)

**AGB phase**

- Central (C+O) degenerate core, surrounded by He & H-shells (where nuclear-burning occurs), and a very large H stellar envelope

- cool (Teff < ~3000K), very luminous (~10^4 Lsun), have dusty, spherical expanding envelopes at low speeds (~5-20 km/s), but very large mass-loss rates (upto ~10^-4 Msun/yr)

- 3 chemistry types: O-rich, S-type, C-rich (C/O < 1, ~1, > 1)

(winds can be driven by radiation pressure on dust grains; grains drag the gas along via friction: radiative momentum L/c > ~ dM/dt x Vexp, but notable EXCEPTIONS, e.g., the Boomerang Nebula)
The Extraordinary Deaths of Ordinary Stars

- After most of the stellar envelope is lost due to mass-loss, heavy mass-loss ceases
- Central star begins its post-AGB evolution (towards hotter Teff) at constant L
- A planetary nebula (PN) is formed when Teff~30,000K by the ionization of the molecular outflow

**IRC10216 center**

- HST/WFPC2 0.6 µm
- HCN J=3-2 (ν=0,1,0), greyscale: continuum

**Dramatic transformation in the morphology and outflow velocity (~100 km/s) of the mass ejecta during the transition phase** – the pre-planetary nebula (PPN) phase; process likely initiated during late-AGB phase

**Circumstellar envelope of the AGB star IRC+10216 illuminated by Galactic starlight (CFHT V-band: Mauron & Huggins 2000)**

**IRC10216 center**

- eSMA: 4 hr integration, baselines 25-782 m, beamsize 0.4”x0.22” (Shinnaga et al. 2009)

**The PPN, CRL2688, as seen in scattered light (HST, 0.6 µm) Sahai+1998**
Three morphologically-unbiased HST surveys (*using rather simple selection criteria*) have observationally bracketed the evolutionary phase over which the transition from spherical symmetry to asphericity occurs:

1. **Young PN survey(s)** (compact, [OIII]/Hα < ~1) (e.g., Sahai & Trauger 1998; Sahai 2001-04 [IAU, APN meetings], Sahai, Morris & Villar 2011)

2. **Young PPN survey** (Sahai, Morris, Sanchez Contreras & Claussen 2007) [stars with heavy mass-loss: OH/IR stars (maser flux > 0.8 Jy) and C-rich objects; F25 > 25 Jy, IRAS F25/F12 > 1.4 i.e., lack of hot dust - AGB mass loss has stopped]

3. **Nascent PPN survey** [same as in (2), but 1 < F25/F12 < 1.4: earliest phase in PPN evolution] (Sahai et al. 2010)
45 nPPNe were imaged. 30% of these are resolved - aspherical structure is seen in 60% of the resolved objects.

In our PPN survey, fully 50% of our sample of 52 showed resolved morphologies, all of which were aspherical. The aspherical structure in the nPPN images (generally one-sided when collimated structures are seen) is very different from that observed in normal PPNs, which show diametrically-opposed, limb-brightened lobes.
HST Survey of Preplanetary Nebulae (PPNe)

(Sahai, S'anchez Contreras, Morris, Claussen, AJ, 2007)

Morphological classification scheme for PPNe

**Primary nebular shape**

- Bipolar, Multipolar
- Elongated, Irregular

**Secondary descriptors:** e.g., dusty waist, point-symmetry, halo

**Important** Point-Symmetric objects are NOT A PRIMARY CLASS

Point-symmetry found in all classes, except I(regular)
PNs: Primary Class B (bipolar)

27% (32/117 objects)

Adapted from Sahai, Morris & Villar (2011)
Primary Class L (collimated-lobe pair)

8.5% (10/117 objects)

Adapted from Sahai, Morris & Villar (2011)

Note: closely related to class-B (but do not show pinched-in appearance where lobes join the waist region)
Primary Class M (multipolar)

20% (23/117 objects)

Adapted from
Sahai, Morris & Villar (2011)
Primary Class E (elongated)

31% (36/117 objects)

Adapted from Sahai, Morris & Villar (2011)

Note: class-B, L can look like class-E due to insufficient angular resolution and unfavorable orientation
Primary Class R (round)

3.4% (4/117 objects)

Adapted from
Sahai, Morris & Villar (2011)
Primary Class S (spiral-arm)

3.4% (4/117 objects)

adapted from Sahai, Morris & Villar (2011)
Secondary characteristics important:

(a) **Point-symmetry** => secular trend such as precession or wobble in the orientation of the central engine or a collimated outflow

Note: different kinds of point-symmetry possible

(b) **Ansae** => impact of jet on slow-moving prior wind

(c) **Waist** => equatorial outflow or bound disk

(d) **Inner Bubbles** => reverse shocks, very hot gas

(e) **Barrel-shaped central Regions** => evolution of waist under impact from very fast wind from CSPN?

**Table 4: Statistics**

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<th>Fraction$^1$</th>
<th>Number$^2$</th>
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<td>ps$^4$</td>
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B+M+L (extreme asphericity) fraction > ~55%!
Collimated (episodic) fast winds/jets (CFWs), operating during the very late-AGB phase, interacting with round AGB circumstellar envelopes, are the primary agent which initiate the formation of aspherical shapes and structures (Sahai & Trauger 1998)

- highly collimated lobes, multipolar morphologies imply that fast outflows are probably born collimated (i.e. collimated at or very near the launch site)
- point-symmetry implies a secular trend in the orientation of the central driver of the CFWs (precession and/or wobble)
- very large momentum-excesses indicate that CFWs are not radiatively driven (e.g. Bujarrabal et al. 2002)
PN shapes/shaping: Primary Physical Processes (2)

- Dense waists seen in PPNe & PNe likely form during the late AGB phase. Huggins (2007) infers that waists and lobes formed nearly simultaneously, with waists forming a bit earlier (expansion timescales~few 100 to 1000 yr)

- (a) ionization by hot central star, (b) action of Spherical, Radiatively-Driven, Fast Wind (SRFW) (speed ~1000 km/s) from central star on the pre-shaped PPN is responsible for further morphological changes of the PN structure

lobe structures preserve shapes/geometries (since main morphological classes same in PPNe and young PNe)

**major change** due to expansion/ionization of dusty waist (SFRW, hot central star): waists become brightest components, central stars become visible
Fundamental Questions

- What are the origins and properties of the CFWs (~few x 100 km/s) (e.g., scalar momentum, episodicity)?

- What is the origin and properties of equatorially-dense structures, i.e., the waists (bound/ expanding)? Physical mechanism is unknown - possibly common envelope ejection, or Bondi-Hoyle accretion of matter from AGB wind into a disk (determination of waist masses could provide a constraint)

- Is Binarity the underlying cause? [can lead to CE ejection, accretion disk formation, rotation, magnetic fields]
PNe & their Central Stars (X-Ray Emission)

CHANPLANS: First systematic survey of nearby (<~1.5 kpc) PNe with radii <~ 0.4 pc
CXO Cyc 12 (570ks) +14 (670ks) (e.g., Kastner+2012)

Hot-bubble X-ray emission from NGC3242 (top) and 7009 (bottom) overlaid on HST images (Kastner+2012)

IC418

Inner-bubble in [OIII]5007 (green), Hα (red) HST image (SMV11)
Hot-bubble in Xrays: CXO image (blue), Hα (green), [NII] (red) (Ruiz+2013)

- **(Expected)** Shocked gas due to a fast (~1000 km/s) wind from hot central star, interacting with slow wind ejecta, should produce a hot bubble at temperatures $T_x > 10^6$ K
- **(New)** X-ray luminous central stars in 50% of PNe (70% for known binary CSPNe) - emission much harder (>~0.5 keV) than expected from stellar photosphere (100-200 kK)

Probe of processes related to central star (binarity and/or magnetic fields, or self-shocking winds as in O stars)
fvuAGB Stars (UV and X-Ray Emission)

Binaries with actively accreting main-sequence companions?

- **Search for binarity using FUV emission in AGB stars:** Large and variable UV flux most likely related to accretion activity in a binary (Sahai +2008)
- Pilot studies with XMM/Chandra to search for X-Ray Emission from fvuAGB Stars: 50% detection rate (Sahai+2014, in prep), energetic X-ray SEDs (coronal gas, Tx >30 MK, likely produced in an accretion shock, confined by magnetic fields in vicinity of AGB star/disk)

**Y Gem:** highest FUV flux amongst ~100 AGB stars with GALEX FUV fluxes (Sahai,Neill +2011)

- Largest UV flux amongst all FUV-excess AGB stars (M8)
- UV flux very large, decreased dramatically from 2006 to 2008
- FUV/NUV flux ratio > 1
- **CO 2-1 line emission shows narrow profile** (FWHM=3.4 km/s) – likely arises in a large (~300 AU) disk, rather than a outflow (e.g., Jura & Kahane 1999)
- **Hα** profile variable on time-scales of days to months; radio emission shows thermal (ionized gas) & non-thermal emission
- Very energetic, variable X-ray SED (Tx~50-150 MK), Fe 6.3-6.9 keV line emission - X-rays scattered by disk?
pAGB Objects (Dusty Equatorial Waists)

Dusty Waists - important morphological component of post-AGB objects

2 major classes of post-AGB objects

(a) PPNe different in their morphologies (have extended outflows)

(b) disk-prominent post-AGB objects (dpAGB): (radial-velocity) binary stars and circumbinary disks (lack extended nebulae). (e.g., AC Her, U Mon, RV Tau unresolved, <1”-2”: Sahai, Claussen, Schnee, & Morris 2011)

- 2 Different OBSERVED Manifestations of such structures

1. Large (~1000 AU) Torii
   i) Dark band obscuring central star in a bipolar/ multipolar object (mostly PPNe); in some cases, an outer radial edge is detected
   ii) Bright toroidal or barrel-shaped regions (in most PNe)

2. Medium-sized (~10-50 AU) Disks

Disks in dpAGB objects (e.g., proposed from SED/spectral modelling: e.g., de Ruyter+2005; van Winckel +2008, Gielen+2007; direct detection - interferometric visibilities with VLTI & modelling, e.g., Lykou+2011, Keplerian disk with CO interferometric observations (Red Rectangle) e.g., Bujarrabal+2013)
The origin of these circumbinary disks and large dusty waists is a mystery current models based on Bondi-Hoyle accretion from an AGB wind around a companion only produce small-sized (~1 AU) accretion disks (Mastrodemos & Morris 1998, 1999).

But, the waist regions of PPNe and dpAGBs share many observational similarities

a) Submm excesses: large (millimeter-size) grains

b) Crystalline silicate features (e.g., seen in Spitzer spectra: Gielen+2007)

So, in both PPNs and dpAGBs, the mineralogy and grain sizes show that dust is highly processed.

- Probe the mass/kinematics of the dust/waist structure => test formation models
  - low mass & Keplerian rotation (e.g. due to accretion around a companion from AGB wind)
  - large mass & expansion, if Common Envelope ejection in a binary, equatorial mass-outflow

WAIST LIFETIME > TIME-SCALES FOR DUST PROCESSING, GRAIN GROWTH (> ~ 2000 yr, Jura 2001)
Confirm presence of substantial masses of very large (mm-size) grains
β at mm wavelengths lower in dpAGBs (<0.4) than PPNe (~1)

Extended study in progress using SMA, CARMA, ALMA, ATCA, VLA (huge increase in sensitivity): *Sahai, Patel, Gonidakis et al 2014, in prep*
AGB Mass-Loss: **extended CSE structure signature of hidden binary at center**

“Circular Arcs” or Archmidean Spiral Structure

First seen in many well-known AGB/pAGB objects with HST (IRC 10216, CRL 2688, NGC 6543, NGC7027)

Spiral structure can be induced by a companion
(first shown by *Mastrodemos & Morris 1999*)

**CIT-6 HC3N J=4-3 (36.39 GHz)**
beam ~0.7” x 0.6”, panel size 21”
Claussen, Sjouwerman, Rupen et al. 2011)
a one-armed spiral in the center?
(inferred by *Dinh-V-Trung & Lim 2009*, from a lower-resolution map)

**CRL3068 HST image:** Morris+2006, Mauron & Huggins 2006

Hydro simulation:
comparable mass binary system, orbital plane inclined by 50 deg (*Kim & Taam 2012*)

(see also ALMA observations of *R ScI*, Maercker+2012)
AGB mass-loss (duration, total mass of ejecta)
(mass~$R_{\text{out}}$, outer boundary probed via signature of ISM interaction)

GALEX FUV/NUV image of IRC10216 (Sahai +Chronopoulous 2010)

- AGB CSEs much larger than traced in CO (photodissociated by Interstellar UV)
- Scattered light from dust traced further out with deep optical imaging (200” for IRC10216)
- even further out, HI observations useful (but difficult!)

Bow-shock shows evidence of interaction with ISM at radii 500”-1000” (termination shock to bow-shock)

Envelope Mass ($\frac{dM}{dt}=2 \times 10^{-5} \text{ M}_\odot \text{yr}^{-1}$, $d=130 \text{ pc}$) is $> \sim 1.4 \text{ M}_\odot$

Such observations provide, for the first time, a physical outer boundary to the CSE resulting from dense, heavy AGB mass-loss

e.g., Bow-shocks in R Cas, R Hya, $\alpha$ Ori, Ueta+2010 (& references therein)
AGB mass-loss (duration, total mass of ejecta)

Astrosphere of carbon star CIT 6
(Sahai & Mack-Crane 2014)

Total Envelope Mass > ~0.3 Msun
Object moving North thru Warm Ionized Medium at >~ 39 km/s

Puzzling Features
Double-arc structure, detailed shape of astrosphere not well explained by models

- Higher mass-loss rate in past?
- Inclination?
- Object has entered relatively dense clump of WIM recently

FUV GALEX image of CIT 6 (24'.75 × 24'.75)
(location of the central star: *)
AGB Mass Loss (duration, total mass of ejecta)

Herschel PACS imaging

Cox+2012: PACS 70 and 100 µm imaging (part of the MESS Key program: PI Groenewegen)

For 43/56 nearby (<0.5 kpc) AGB and supergiants:

• Fermata and eyes due to bow-shock interactions of the AGB winds with the ISM

• Eye-class tentatively associated with (visual) binaries

• Rings do not appear in M-type stars, only for C or S-type stars, consistent with their origin being a thermal pulse

• 3 stars (R Scl, TX Psc, U Cam) show rings and evidence of bow-shock interaction

Bow-shock: Standoff distance

$$ \sim \left( \frac{dM/dt \ V_{\exp}}{n_{\text{ISM}}} \right)^{0.5} / V^* $$  (V* is velocity relative to ISM)
pAGB mass-loss: Herschel/HIFI observations
PPNe and PNe \(\text{HIFI Key Herschel Program, Bujarrabal+2012}\)

**CRL618**
- Submm & Far-IR lines from CO, \(^{13}\)CO, H\(_2\)O (and others)
- Warm fast winds (CRL618: >200K, CRL2688: 100K)
- Cold fast winds (OH231.8+4.2, NGC6302: 30K)

=> **cooling of the fast wind with age**: fast outflow in
CRL618 is young (100 yr), in OH231.8, older (1000 yr)
SUMMARY OF OBSERVATIONAL RESULTS

Circumstellar $^{12}$CO: 24 detections (+ 3 upper limits) - sample of PPNe with CO data significantly enlarged - envelope spatially resolved in ~18/24 objects - asymmetries and velocity gradients in all; broad wings in line profiles for ≥ 50% (=> signatures of fast post-AGB outflows)

Surveys lead to discoveries of extreme objects, e.g., IRAS19374, which have very large momentum excesses, and thus provide the most stringent tests of theoretical models