From AGB Stars to Aspherical Planetary Nebulae

An Observational Perspective

(invited review)

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Outline

1. Background: The Extraordinary Deaths of Ordinary Stars
2. Imaging Surveys (morphologies: AGB to PPNe)
3. Mass-Loss Phenomena (*focus on pre-PN phase*)

Extended Envelopes, Lobes (collimated ouflows), Central Region (dusty torii/disks, central star)

specific studies (highlighting different observational techniques)

Far-IR observations

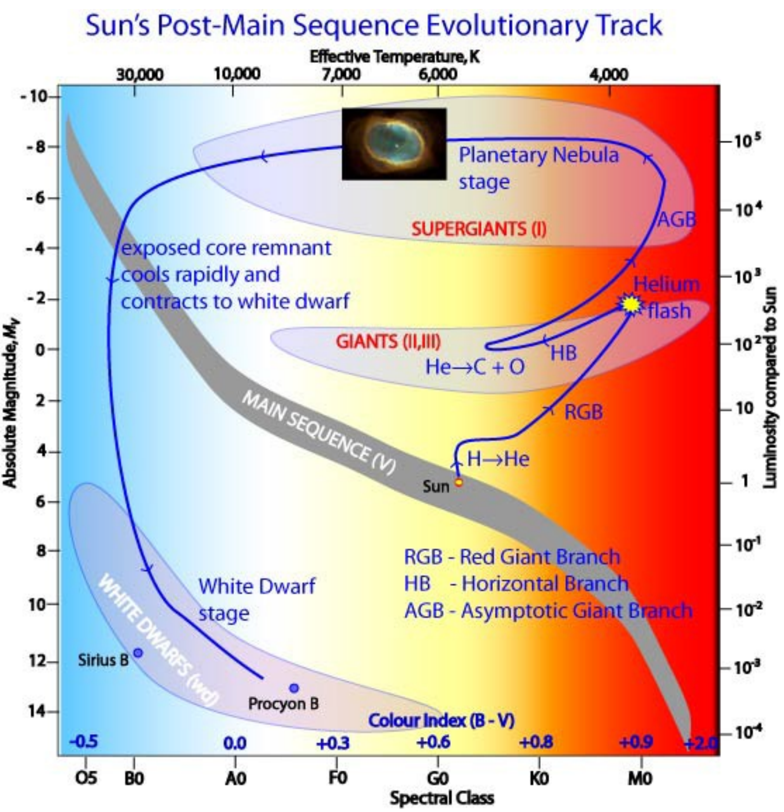
(sub)Mm-wave interferometry

X-Ray observations

UV observations

4. Summary

Ordinary Stars (~1-8 Msun)



(outreach.atnf.csiro.au)

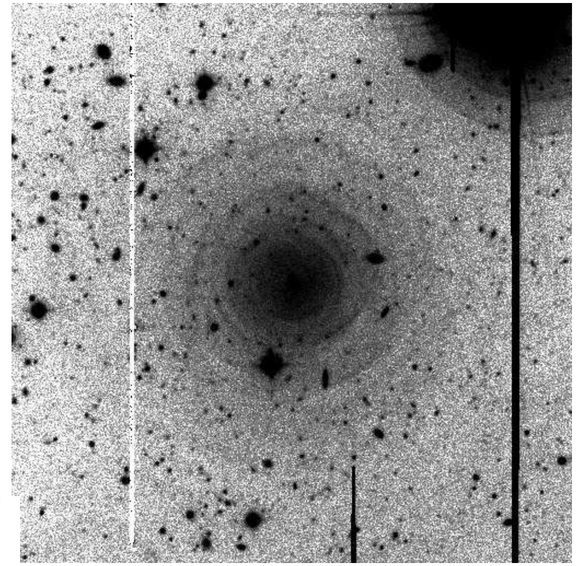
AGB phase

- 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 EXCEPTIONS, e.g., the Boomerang Nebula)

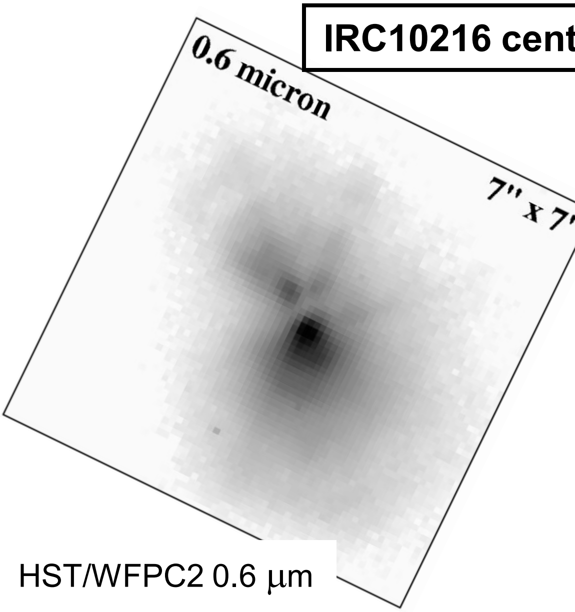
The Extraordinary Deaths of Ordinary Stars

- 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



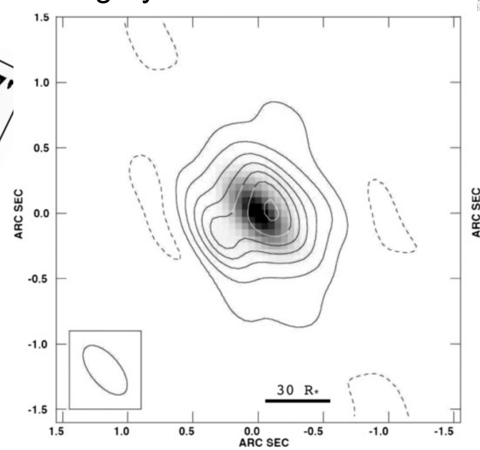
Circumstellar envelope of the **AGB star IRC+10216** illuminated by Galactic starlight (CFHT V-band*: Mauron & Huggins 2000*)

IRC10216 center



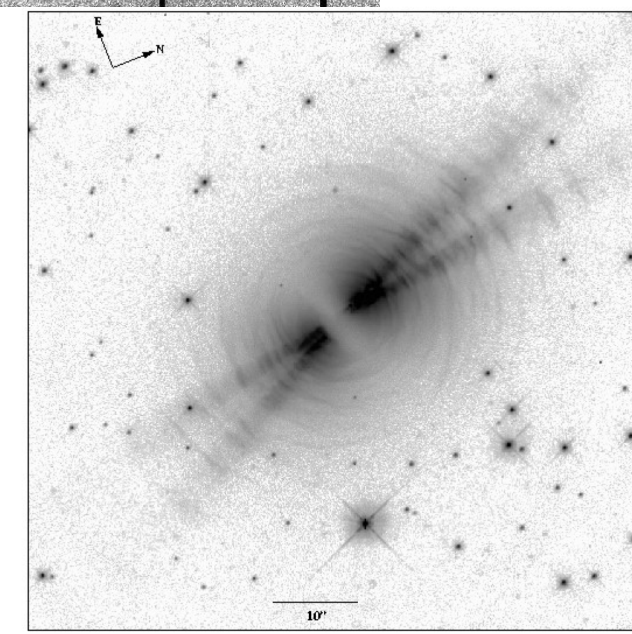
HST/WFPC2 0.6 μm

HCN J=3-2 (v=0,1,0), greyscale: continuum



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

A dramatic transformation in the morphology and outflow velocity (~100 km/s) of the mass ejecta occurs during the intermediate evolutionary phase – the pre-planetary nebula (PPN) phase; process likely initiated during late-AGB phase



CRL2688 (C-rich PPN) *(Sahai et al. 1998a)*

The **PPN, CRL2688**, as seen in scattered light (HST, 0.6 μm) *Sahai+1998*

From APN 1 to APN 6

Pre-HST/WFPC2 (APN I, Aug 1994, Oranim, Israel [*Harpaz & Soker 1995*])
"… It appeared that the needed theoretical interpretation had been found in the Generalized Interacting Stellar Winds (GISW) model." [GISW: hydrodynamical collimation of fast wind of CSPN by preexisting equatorially- density enhanced in AGB envelope] (*Frank 2000: APN II*)
Post-HST/WFPC2 (APN II [Aug 1999, MIT, Cambridge (*Kastner+2000*)] onwards)
APN III [Aug 2003, Mt. Rainier (*Meixner+2003*)]; APN IV [Jun 2007, La Palma, Spain]; APN V [Jun 2010, Bowness-on-Windermere, UK (*Zijlstra+2011*)] (also IAU PN Symposia #234 [Apr 2006 (*Barlow & Mendez+2006*)], #283 [Jul 2011 (*Manchado+2012*)])

- **A Paradigm Lost** "The new data indicate the purely hydrodynamic interacting stellar winds model can not recover the full variety of shapes and kinematics" (*Frank 2000: APN II*)
- **Grand Challenge** (*Kastner 2011: APN V conference summary*): construct a detailed set of binary star "decision trees" (as *Iben &Tutukov 1984* did or SN Type I progenitors) that apply to PNe and related objects (symbiotic nebulae) – *still unrealized*

Topics not covered [conference speakers covering these listed in blue]

- Magnetic fields/maser observations (Vlemmings, Olga, Sabin, Gonidakis)
- Proper Motion Studies (with HST/optical [Balick], or VLBI/masers)
- Abundances, isotope-ratios, chemistry, studies of photoionized/photodissociated regions (Ueta, Ladjal, Stanghellini, Guzman-Ramirez, Szcerba)
- Extragalactic post-AGB objects (Kamath)
- Long-slit optical spectroscopy (Pereyra, Lopez)
- Mid-IR Interferometry (mostly with VLTI) (Ohnaka, Paladini, Lykou)
- Distance determinations (Manteiga)
- WISE (Kronberger), AKARI, SOFIA (few results, but see Sahai, Werner+2014, this conference)

What Observations tell us about the AGB to PN transition

Old GISW paradigm inadequate: GISW could not explain few PNe with point-symmetry, collimated outflows or ansae (*Soker 1997,1990*)

- The mechanisms that shape PNe become operational significantly before the PN phase, i.e. the post-AGB phase (or very late AGB phase)

- The widespread presence of point-symmetry & multipolar structures in young PNe implies (episodic) collimated fast winds or jets **[CFW]**, operating during the pre-planetary or very late-AGB phase, are the primary agent for shaping most Planetary Nebulae (*dense equatorial torus may help in further confinement of fast outflows*) (*Sahai & Trauger 1998*)

- The morphological data (e.g. PNe with point-symmetric structures and/or ansae, quadrupolar or multipolar PNe), suggest that the fast winds/jets are collimated as they are launched

- *Formation of the dense waists in PNe likely occurs during the late AGB phase. Huggins (2007) infers that waists and lobes formed nearly simultaneously; waists a bit earlier* ***(****expansion timescales~few x 100 to 1000 yr****)***

- This stage is followed by further action of a very fast radiative wind from central star **[SRFW]**, & ionization during PN phase

- Fast (few x 100 km/s) molecular bipolar outflows in PPNe (*e.g. Bujarrabal et al. 2002*) with very large momentum-excesses indicate that these winds are not radiatively driven *(radiative momentum L/c << dM/dt x Vexp)*

Fundamental Questions

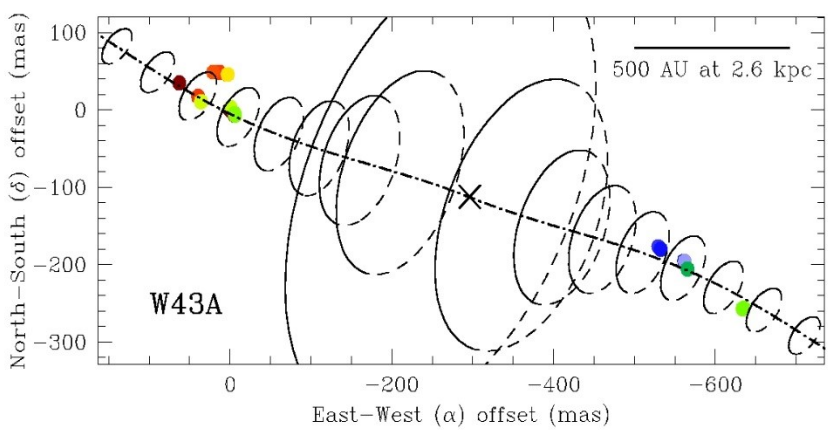
As stars evolve from the AGB to post-AGB phase:

- What factors govern AGB mass-loss rates (initial stellar mass, presence of companions, magnetic fields/rotation?)
- What factor(s) decide if a AGB object becomes a PPN or a dpAGB (or agbPPN)?
- What are the origins and properties of the fast outflows which shape PPNe and PNe (e.g., scalar momentum, episodicity)?
- What is the nature of the jet engine (i.e., launching & collimation mechanism)
- What is the origin and properties of equatorially-dense structures, i.e., the waists (bound/ expanding)?
- Is **Binarity** underlying cause for break in symmetry? (most likely) [CE ejection, accretion disk formation, rotation, magnetic fields]

- Are magnetic fields responsible (e.g., in launching, accelerating and collimating outflows)?

Although observations have provided estimates of the magnetic field strength and topology in select objects, the main problem is: are fields local, or global (IK Tau, polarization of thermal lines - *Vlemmings+2012*).

Post-AGB object: W43A toroidal magnetic fields (~mG) in maser spots (*Vlemmings et al. 2006*)



HST Surveys: PNe, PPNe, and nPPNe

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]/H$\alpha < \sim 1$) (*e.g., Sahai & Trauger 1998, Sahai, Morris & Villar 2011 [SMV11];* additional data*: Bulge PN survey - PI Zijlstra; survey of compact PNe in disk - PI Stanghellini; and a few from other GO programs*)
2. "young" PPN survey (*Sahai+2007; misc. PPNe sample Ueta+2000*) [stars with heavy mass-loss (based on IRAS fluxes): OH/IR stars (maser flux > 0.8 Jy) and C-rich objects; IRAS F25/F12 > 1.4 i.e., lack of hot dust - AGB mass loss has stopped]
3. Nascent PPN survey [same as above, but 1 < F25/F12 < 1.4: earliest phase in PPN evolution] (*Sahai, S'anchez Contreras+2011*)

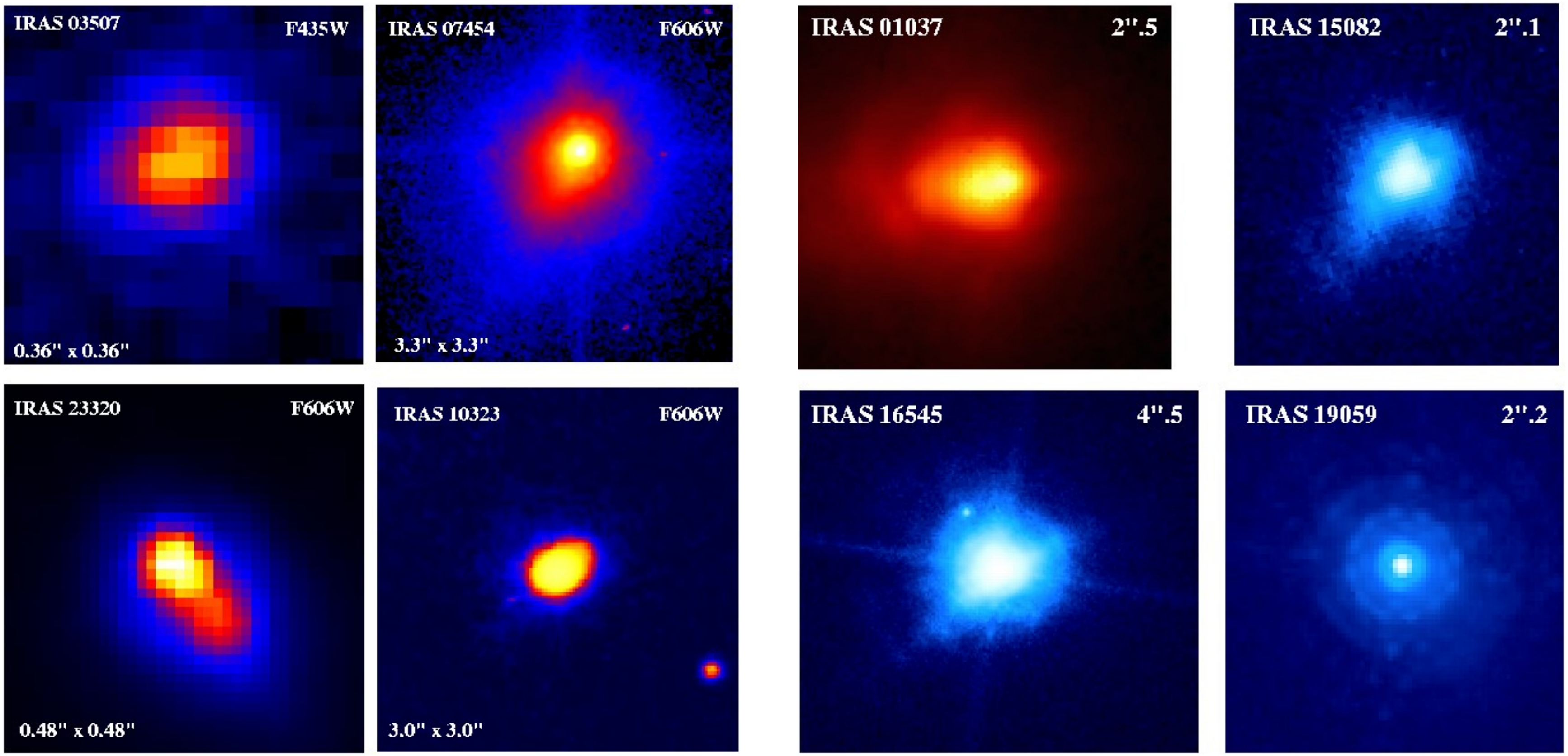
More categories of post-AGB or PPN-like objects; related objects:

4. dpAGB: disk-prominent post-AGB objects – central star post-AGB spectral type, radial-velocity binary, and most (or all) of circumstellar mass in a circumbinary disk structure (little or no extended nebulosity) (*e.g., van Winckel 2003*) – *numerous*

5. agbPPN: CSE has properties typical of PPNe, but central star has an AGB spectral type (e.g., OH231.8+4.2) – *these are rare*

6. Symbiotic stars with PN-like (M2-9) or PPN-like nebulae (R Aqr) – *these are rare*

Nascent PPNe (nPPNe)



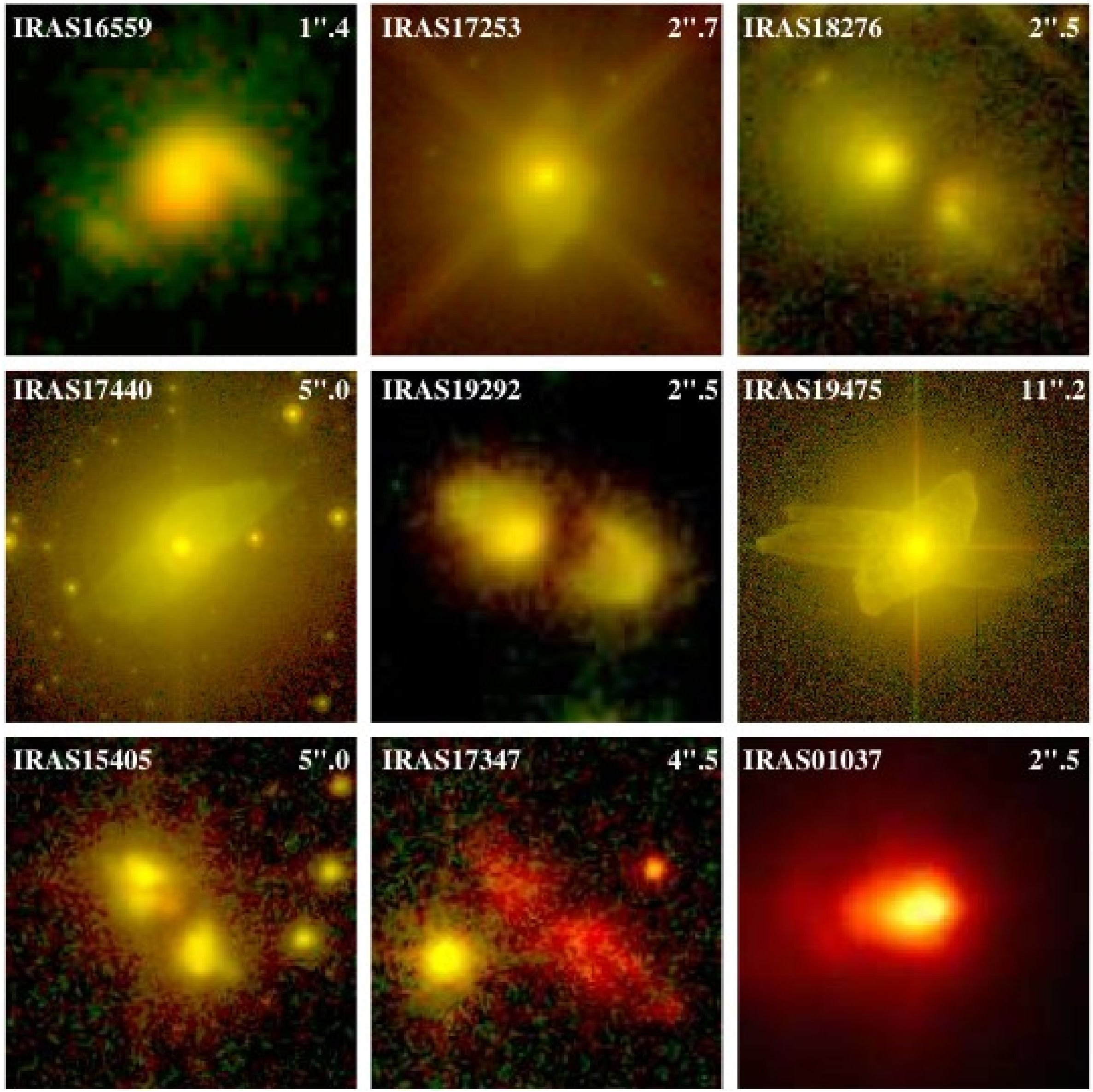
nPPN survey: 45 objects imaged, 30% resolved, 60% of these show aspherical structure (*Sahai, S'anchez Contreras+2011*)

Compare **PPN survey** (52 objects imaged, 50% resolved, 100% of these aspherical)

Aspherical structure in the nPPNe (generally one-sided when collimated structures are seen) is very different from that observed in normal PPNe, which show diametrically-opposed, limb-brightened lobes or an elongated shell => beginning of aspherical mass-loss

V Hya: best-studied nPPN – multi-epoch HST/STIS data show one-sided, very fast (240 km/s), collimated, knotty outflow (*Sahai,Morris+2003*) slowing down and fading over a period of 12 years (*Sahai, Morris+2014, in prep*)

Pre-Planetary Nebulae



From our (unbiased) HST imaging surveys, we have found

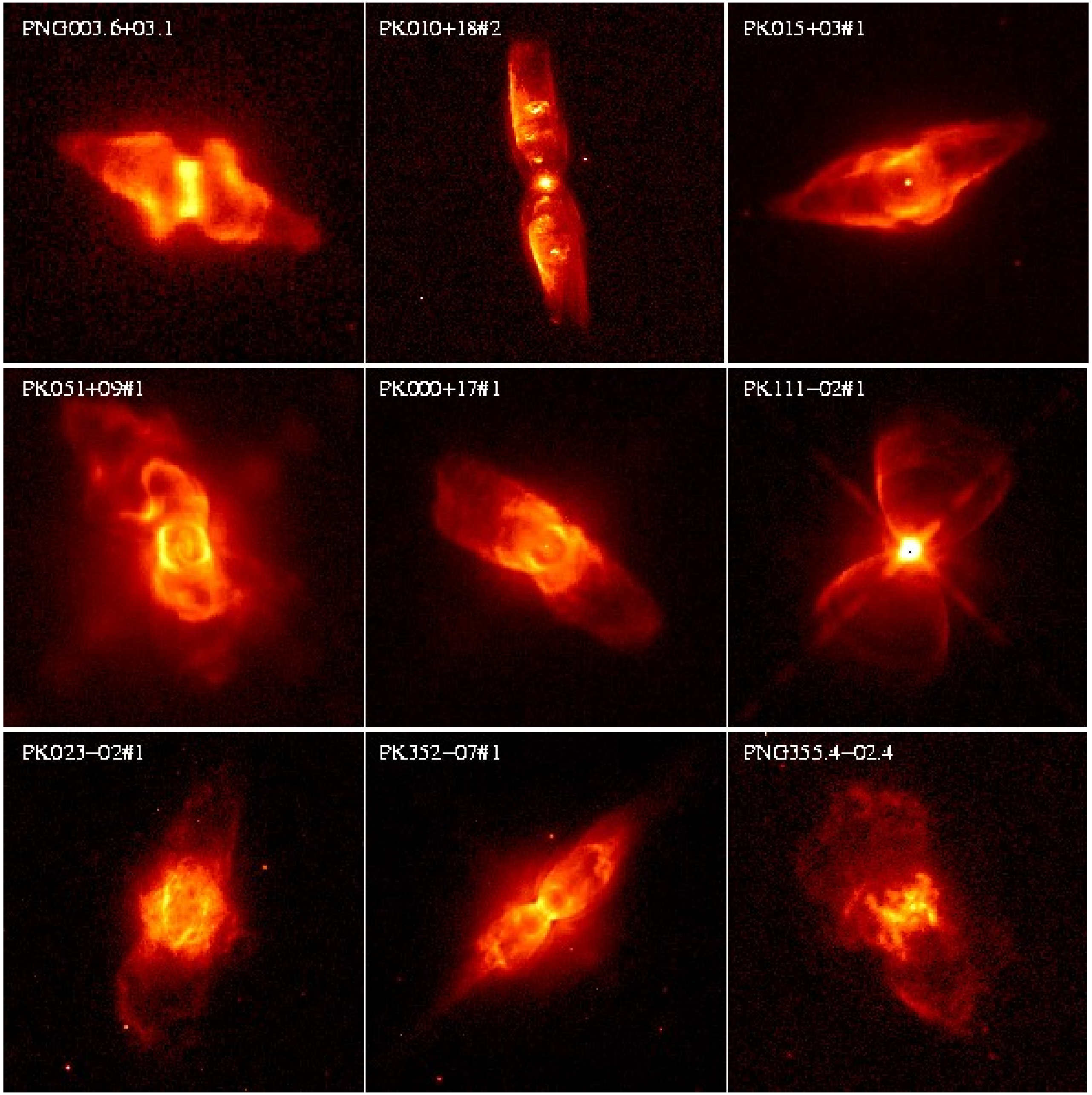
1) PPNe (like young PNe), also show similarly aspherical morphologies.

2) (compare) nPPN IRAS01037 (lower right corner) – a very late AGB star: shows aspherical structure in its inner region

Survey resulted in a detailed morphological classification scheme

Sahai, S'anchez Contreras, Morris, Claussen 2007

Primary Class B (bipolar)



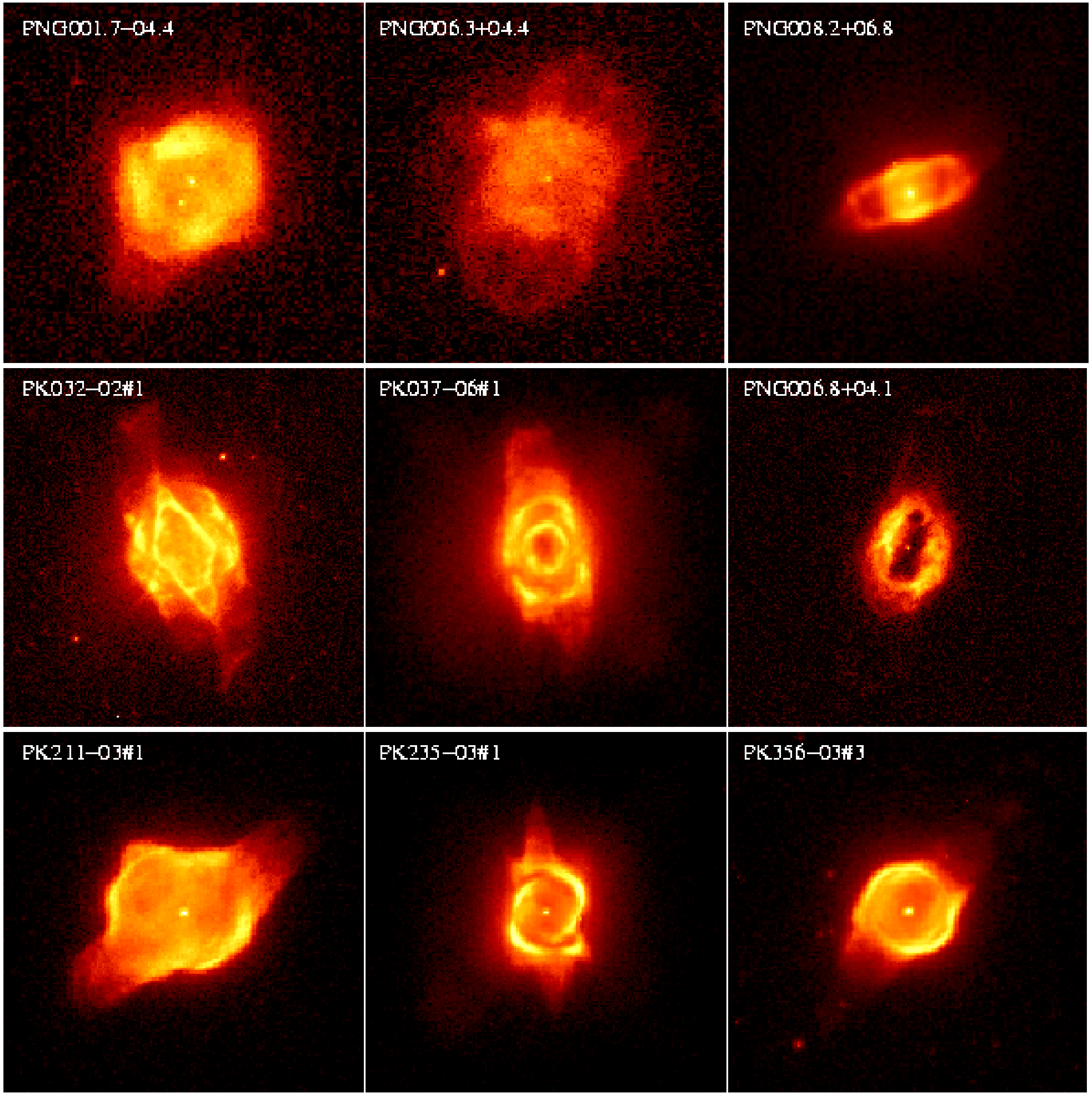
Morphologically unbiased survey with HST/WFPC2 in Hα (and/or [NII])

28% (33/119 objects)

Note: require lobes to be *pinched-in* where they join the waist region)

Adapted from SMV11

Primary Class L (collimated-lobe pair)

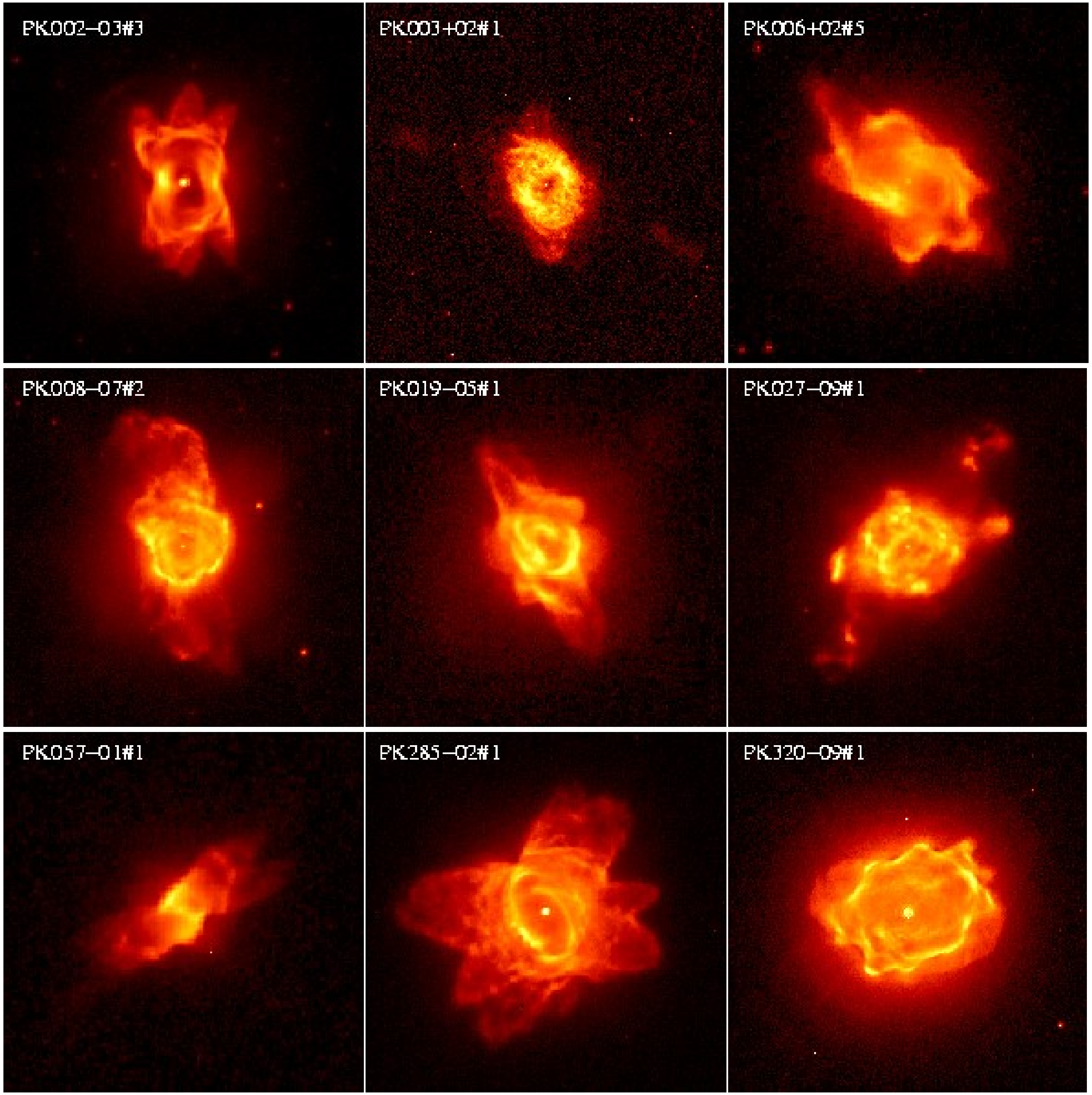


8.5% (10/119 objects)

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

Adapted from SMV11

Primary Class M (multipolar)



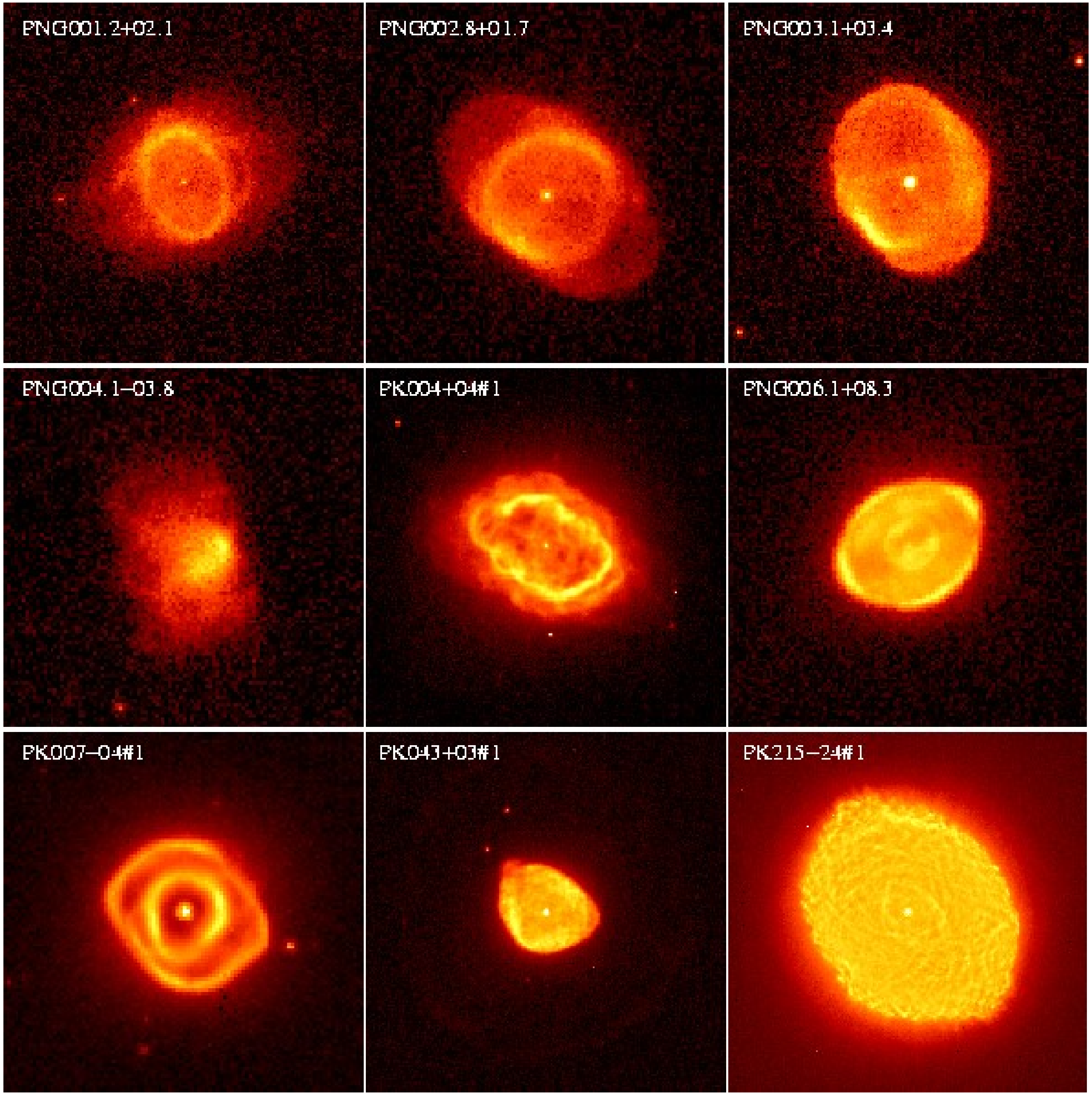
19% (23/119 objects)

(Two or more primary lobe pairs whose axes are not aligned)

Lobes generally (but not always) distributed in a point-symmetric manner around center

Adapted from SMV11

Primary Class E (elongated)



31% (36/119 objects)

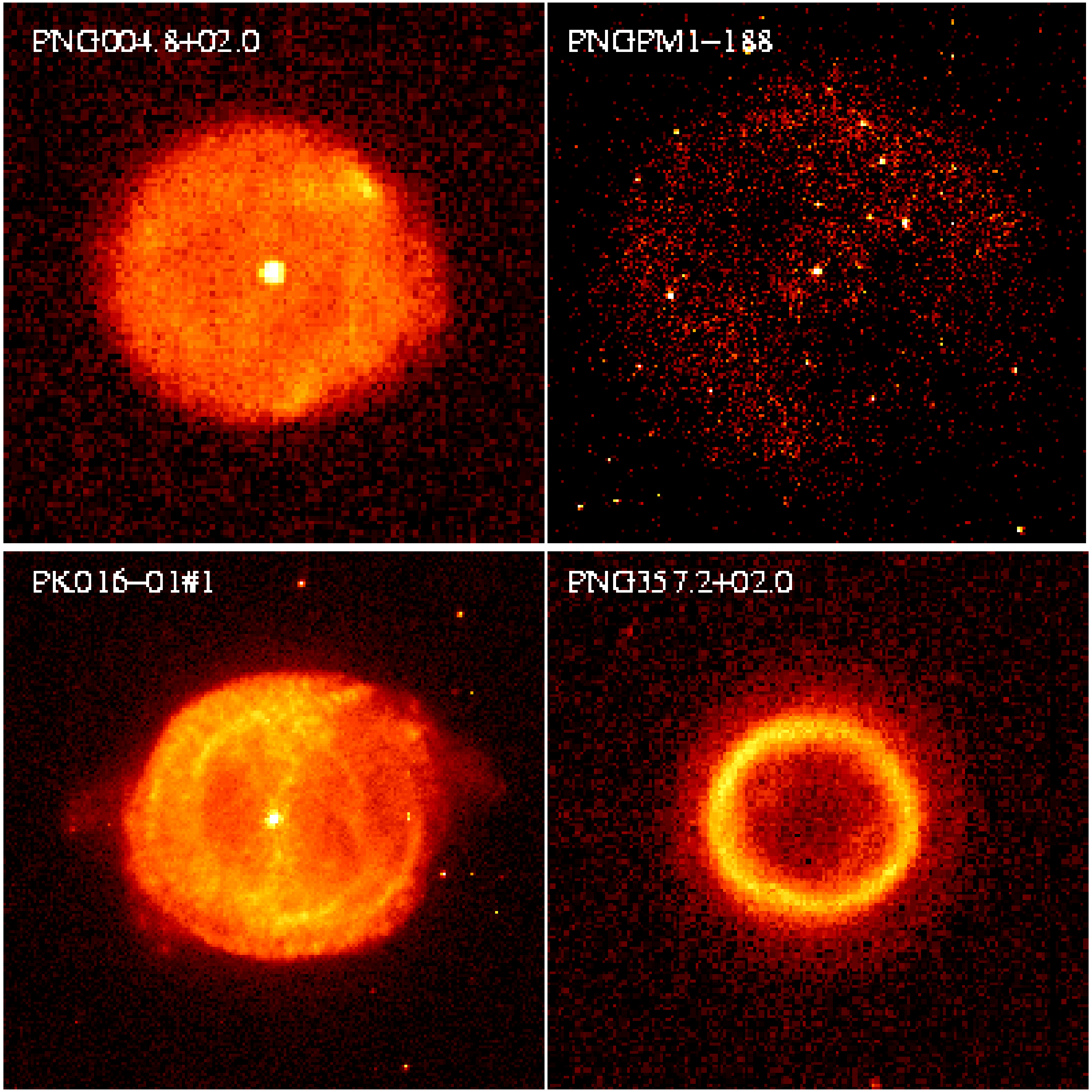
<u>Note</u>: class-B, class-L can look like class-E due to insufficient angular resolution and unfavorable orientation

Action of fast wind; fading of lobes relative to waist may produce the following MORPHOLOGICAL evolution in PNe

B => L => E

Adapted from SMV11

Primary Class R (round)



3.4% (4/119 objects)

Maximum asymmetry of primary shell less than 10%

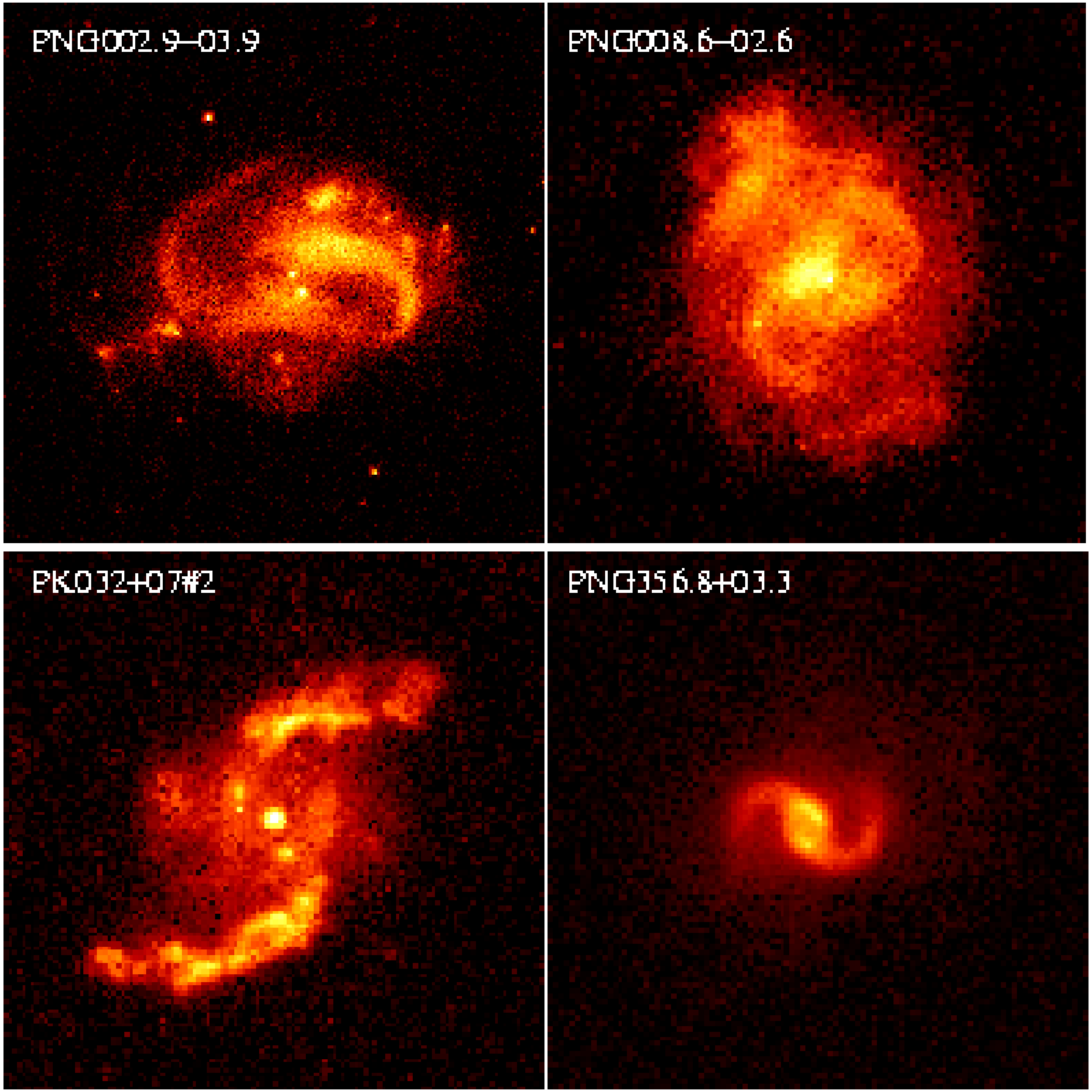
Why no Round PPN

(i) A fast wind is needed in order to carve out a cavity and produce a shell for an object to be observable as a PPN

(ii) Single stars do not develop the collimated fast winds which produce aspherical PPN, and develop the very fast (radiatively driven) wind only when the central star is hot enough (and then one gets a round PN)

Adapted from SMV11

Primary Class S (spiral-arm)



3.4% (4/119 objects)

Most prominent nebular structure has a 2-armed spiral shape

Morph. Class. scheme: minimal prejudice regarding underlying physical causes

In many cases, physical causes readily suggested by geometry, along with kinematical studies of some systems

Kinematical studies (e.g. Miranda, Lopez [SPM database], and collaborators) very important for dealing with prsojection effects, and recovering full 3D geometry

Adapted from SMV11

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 structrure 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*

Scheme developed for classifying pre-planetary nebulae (Sahai +2007) extended to young PNe.

Require 3 more Primary Classes, several new secondary descriptors

Scheme applied after construction to new sample of compact PN by Stanghellini/Shaw et al. (in SMV11)

Scheme proved to be comprehensive, there was NO NEED to invent NEW descriptors

***bcr:** formed by highly-flared equatorial disk which has been 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*

Inner bubbles: reverse shocks

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*

ps common: 45% objects show ps

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*

h(d): ionization front outside main nebula, in progenitor AGB envelope

Table 4:: **Statistics**

Classification	Number[1]	Fraction[1]	Number[2]	Fraction[2]
	$R_{exc} \leq 1$		All Objects	
B	27	0.28	33	0.28
M	18	0.19	23	0.20
E	32	0.34	37	0.31
I	6	0.063	8	0.068
R	4	0.042	4	0.034
L	7	0.074	10	0.085
S	2	0.021	4	0.034
		Point Symmetry		
B, ps[3]	12	0.44	14	0.45
M, ps[4]	15	0.83	19	0.83
E, ps[5]	13	0.41	15	0.42
ps[4]	42	0.44	53	0.45

1 2 3 4 5 6

[1]Number of objects in given class, and as a fraction of the total (96) for which the [OIII]λ5007/Hα flux ratio, $R_{exc} \leq 1$,

[2]Number of all objects in given class, and as a fraction of the total sample (119)

[3]Number of point-symmetric objects in class B, and as a fraction of the total in class B

[4]Number of point-symmetric objects in class M, and as a fraction of the total in class M

[5]Number of point-symmetric objects in class E, and as a fraction of the total in class E

B+M+L fraction is > ~55%!

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*

Ground-Based Surveys

1) PNe (see APN V review by *Parker+Frew 2011*)

- SuperCOSMOS Hα survey (AAO/UK Schmidt Tel) of southern Galactic plane (*Parker+2005*): >~1000 new PNe (MASH-I & MASH-II catalogs: *Parker+2006, Miszalski+2008*)
- IPHAS Hα survey (2.5m Isaac Newton Tel) of northern Galactic plane (*Drew+05*): 155 new PNe (*Corradi+Sabin 2012*)
- VPHAS+ ongoing extension of IPHAS to the southern Galactic plane
- DSH catalog (Deepskyhunters - mostly amateur astronomers) : use POSS-I and POS-II to identify visual candidates in areas complementary to above; sent to professionals for Hα imaging (*Jacoby+2010*)
- Bulge PNe (*Miszalski+2009a,b*)

Advantage over HST: (i) much larger number of objects, so better statistics, especially for "rare" classes, (ii) better at finding rare objects: e.g., round PNe (these are generally very faint), PNe with binary central stars showing evidence of mass-transfer (*Hen 2-39: barium central star* - *Miszalski+2013*), (iii) interesting objects more amenable for detailed studies (*too numerous to reference here!*)

Disadvantage: (i) low angular resolution means young PNe cannot be resolved, (ii) for older PNe, extended lobes get fainter and may be "lost", resulting in misclassification

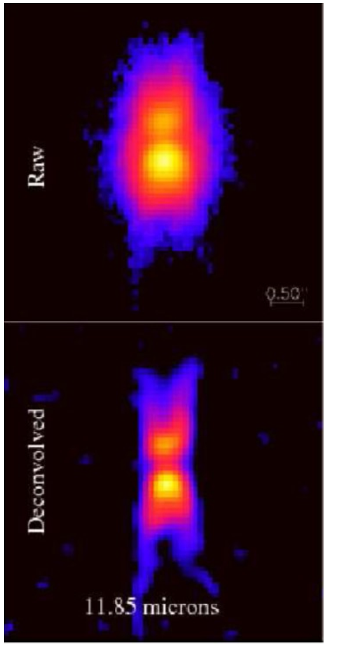
Ground-Based Surveys (continued)

2) PPNe

- *Mid-IR:* 85 AGB or post-AGB objects [11 AGB stars, 62 PPNe, 8 RV Tauri stars in several filters at 8-18 μm with VISIR/VLTI, T-Recs & Michelle/Gemini-S,N] (*Lagadec+2011*)
- ALL resolved PPNe (28) depart from spherical symmetry; AGB stars unresolved

Angular resolution ~0.4” at μm; images are usually deconvolved – introduces uncertainty into the fidelity of the structures

Comparison with HST: HST has an obvious advantage when object optically visible, but for objects with high foreground extinction (e.g., the water-fountain PPN W43A), mid-IR imaging better.



Water-fountain PPN IRAS15445-5449 (has synchrotron jet: Perez-Sanchez+2013)

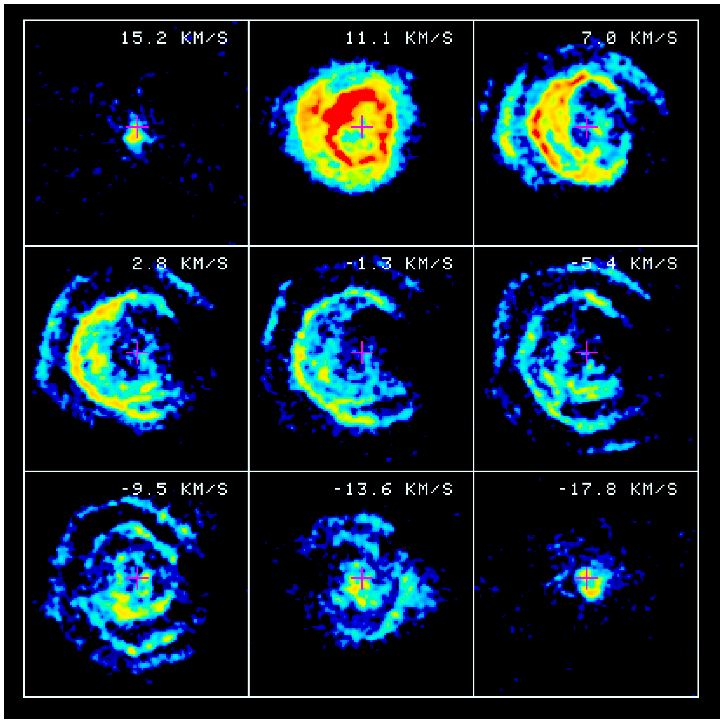
3) AGB circumstellar envelopes (CSEs)

- *Mm-wave: Neri+1998* – 36 AGB+12 pAGB; CO 1-0 with PdBI, CO 2-1 with 30m (5”-12”): CSEs mostly round, 30% show asymmetry; *Fong+2006* – 2 AGB, 5 PPNe, 1 PN with BIMA+12m NRAO (5.6”), *Castro-Carrizo+2010* – 45 AGB+pAGB mapped in CO 1-0,2-1 with PdBI +30m (~1”-4”), 16 reported, reach similar results
- *Optical:* 22 CSEs with high dM/dt using NTT (EMMI, EFOSC2: B, V, I filters) (*Mauron+Huggins 2013*)
- 15 CSEs detected (*dust illuminated by Galactic starlight*)
- ~50% round (E<1.1), ~20% elliptical (E>1.2). Results consistent with flattening due to a binary companion => *extended CSE structure signature of hidden binary at center!*

AGB Mass-Loss: *extended CSE structure signature of hidden binary at center*

"Circular Arcs" or Archmidean Spiral Structure

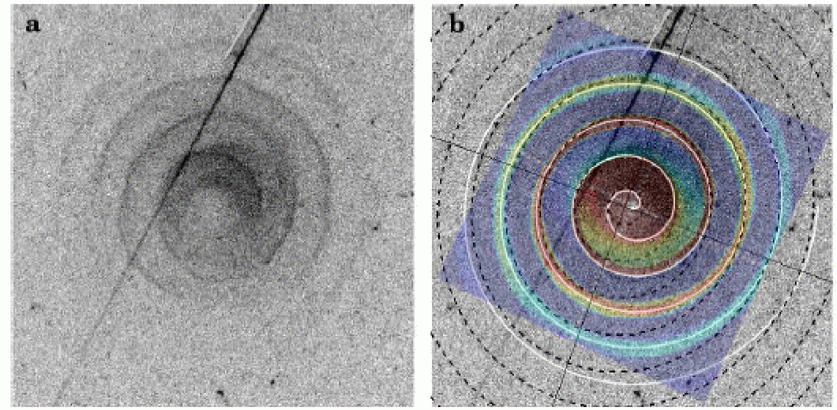
First seen in many well-known AGB/pAGB objects with HST (IRC 10216, CRL 2688, NGC 6543, NGC7027)



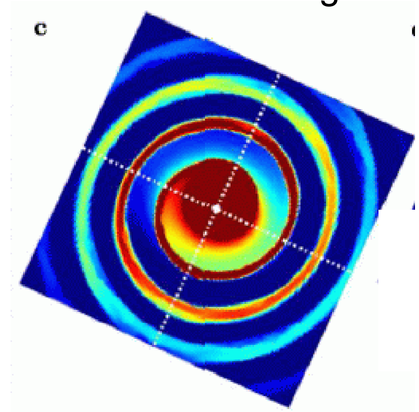
CIT-6 HC3N J=4-3 (36.39 GHz)
beam ~0.7" x 0.6", panel size 21"
Claussen, Sjouwerman, Rupen et al. 2011)

a one-armed spiral in the center?
(inferred by *Dinh-V-Trung & Lim 2009*, from a lower-resolution map)

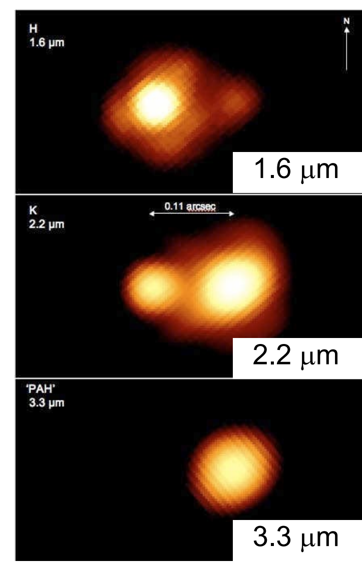
Spiral structure can be induced by a companion
(first shown by *Mastrodemos & Morris 1999*)



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



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



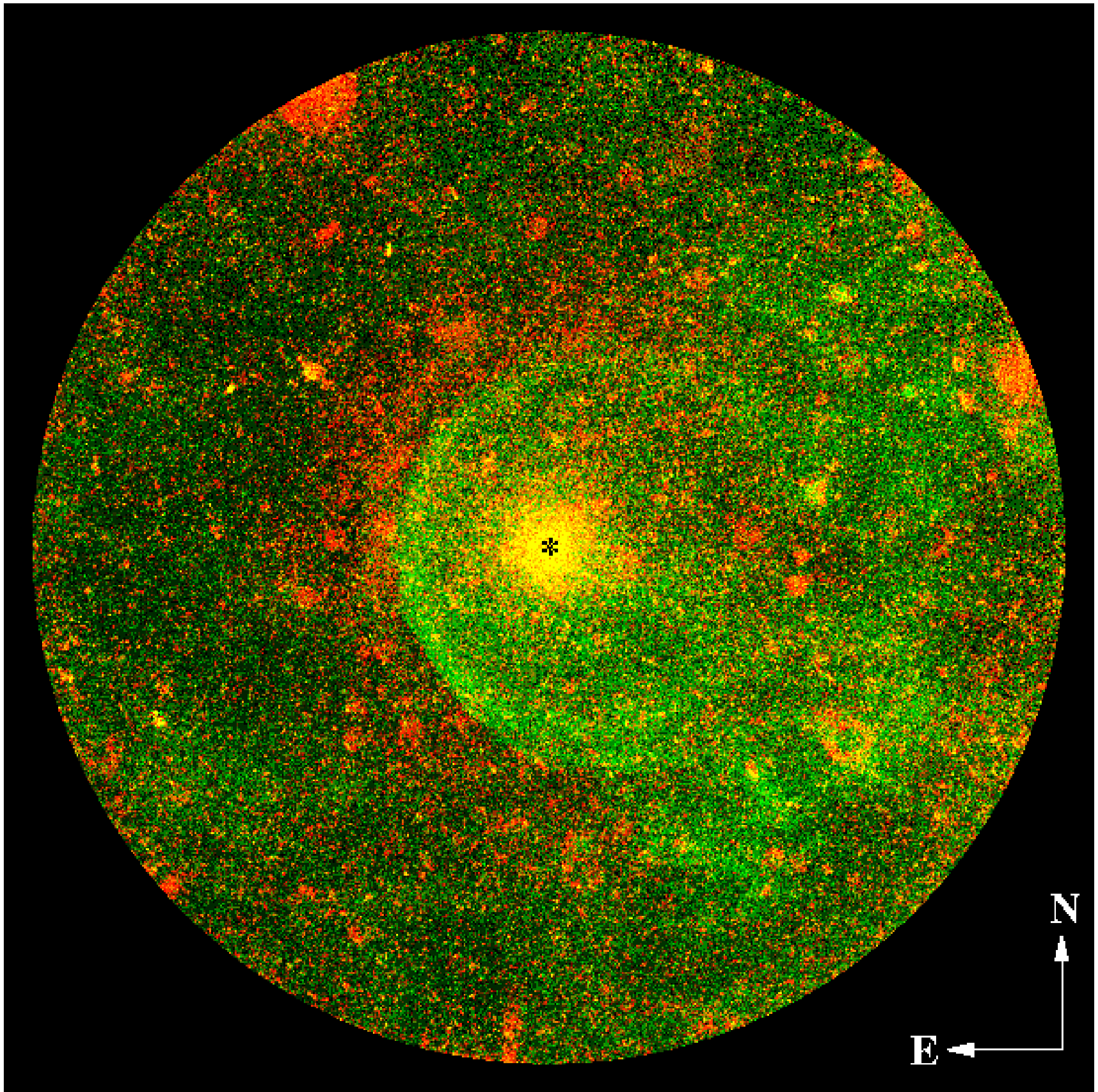
Central binary in CRL3068 (Keck AO: *Morris+2006*)

(more on such structures, e.g., R Scl (Maercker+2012) in Ramstedt , this conference)

AGB mass-loss: Total Mass of Ejecta

(mass~R_{out}, outer boundary probed via signature of ISM interaction)

GALEX FUV/NUV image of IRC10216 (*Sahai +Chronopoulos 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)

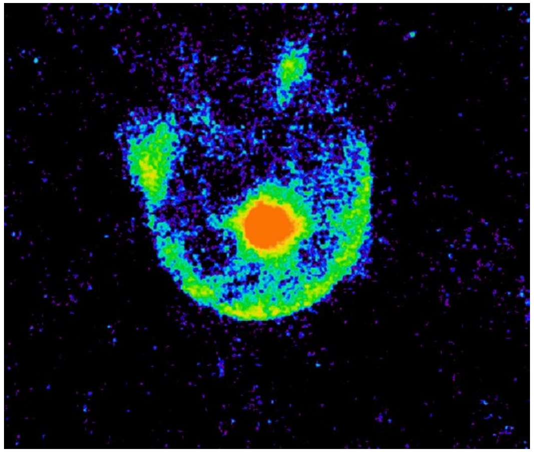
Envelope Mass (*taking dM/dt=2 x 10^{-5} Msun/yr, d=130 pc*) is > ~1.4 Msun

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

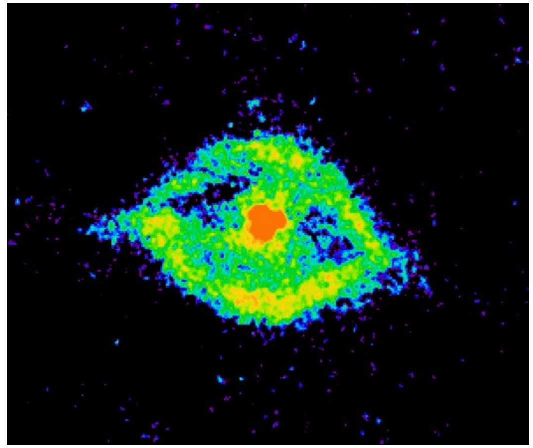
e.g., Bow-shocks in R Cas, R Hya, α Ori, Ueta+2010 (& references therein)

Asymmetries in the Extended Envelopes of AGB Stars:

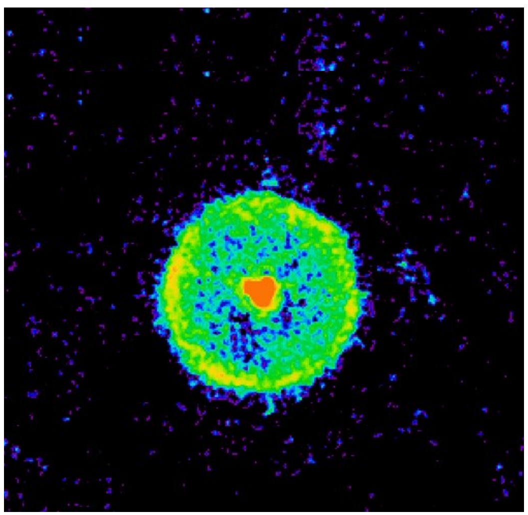
Herschel PACS imaging



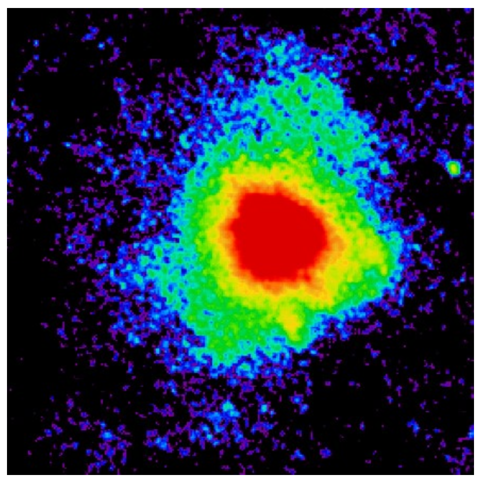
Fermata: UU Aur



Eyes: VY Uma



Rings: AQ And



Irregular: V Cyg

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:

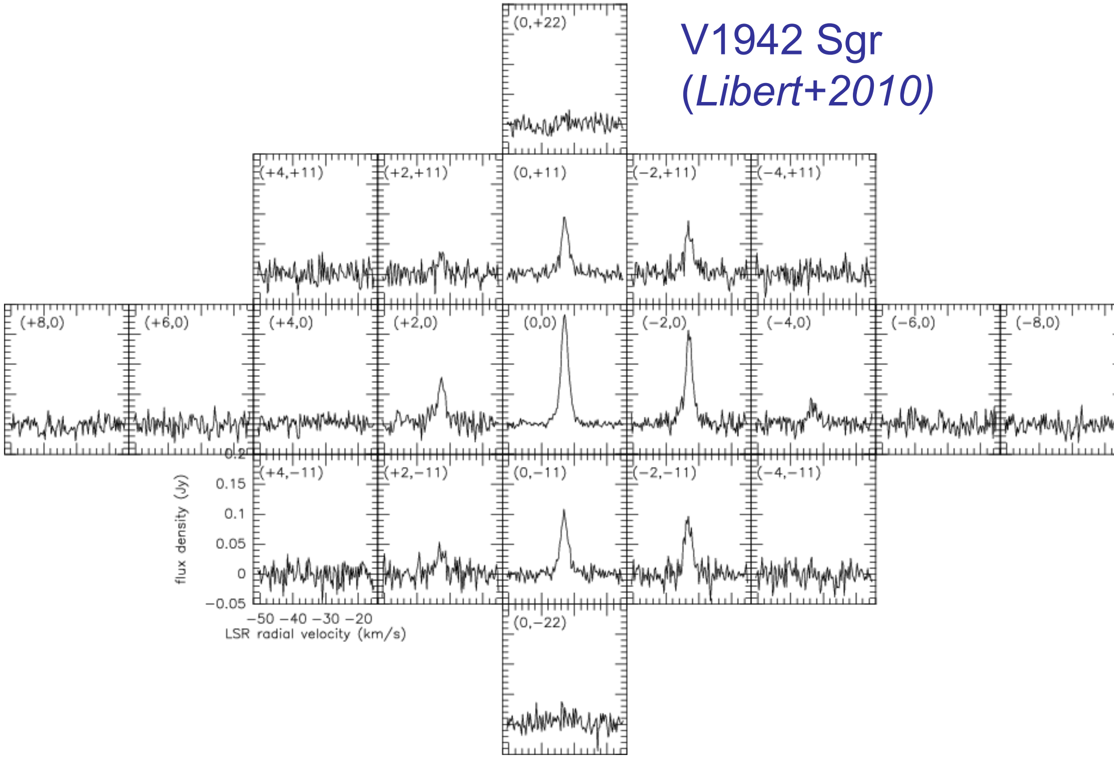
- *Fermata* and *eyes* due to bow-shock interactions of the AGB winds with the ISM
- *Eye*-class tentatively associated with (visual) binaries
- *Rings* do not appear in M-type stars, only for C or S-type stars, consistent with their origin being a thermal pulse
- 3 stars (R Scl, TX Psc, U Cam) show *rings* , and evidence of bow-shock interaction

Detailed modeling using hydrodynamical simulations to fit stand-off distance, shape, density distribution, e.g., Villaver+2012

Bow-shock: Standoff distance

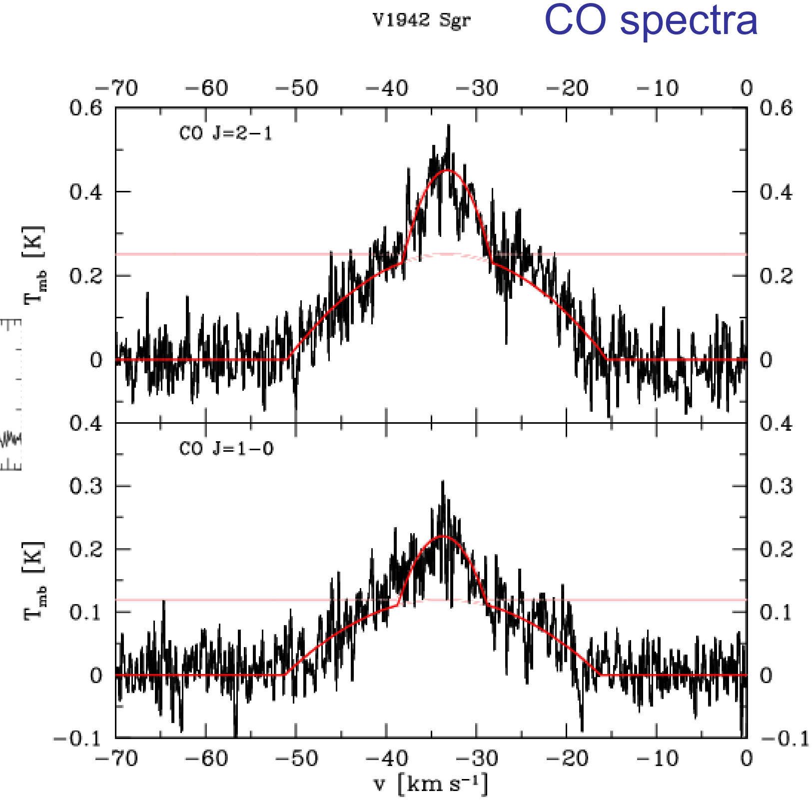
$\sim (dM/dt \; V_{exp} / n_{ISM})^{0.5} / V_*$ (V_* is velocity relative to ISM)

HI Observations



V1942 Sgr
(*Libert+2010*)

CO spectra



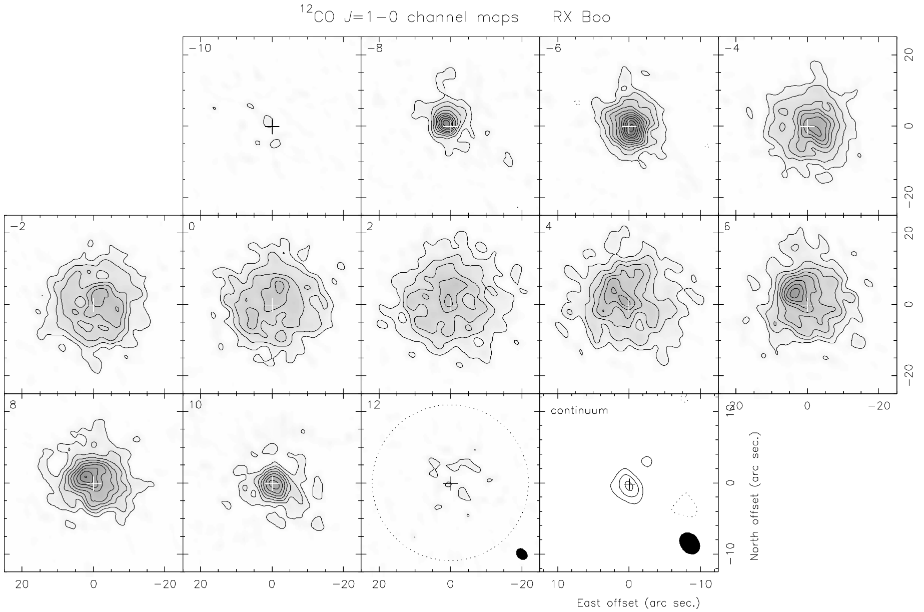
HI observations (Nancay Radio Telescope: 4’x22’ beam, VLA: 55”-100” beam) complementary to CO in getting a complete description of the CSE of an AGB star

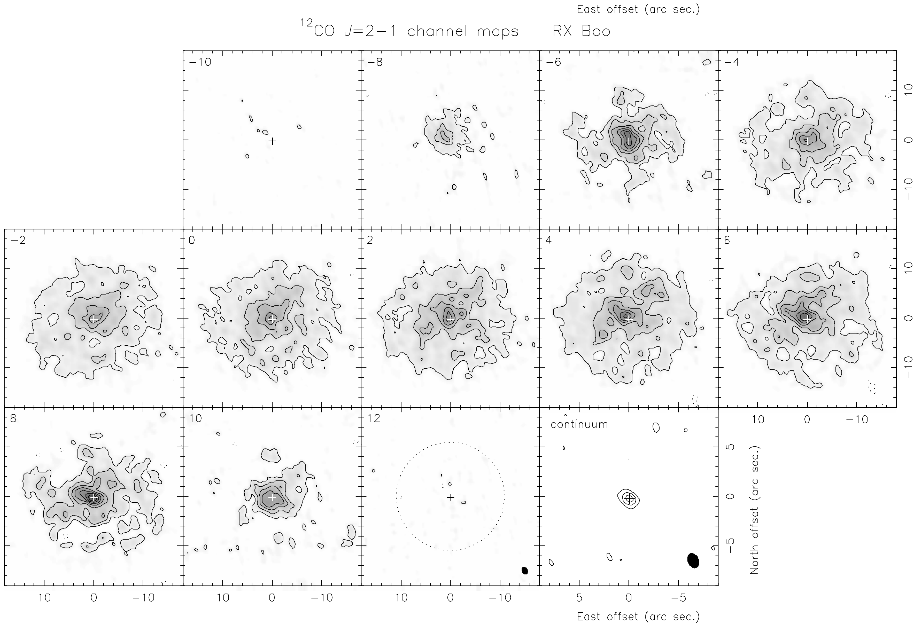
in RS Cnc, which also shows similar CO profiles & HI emission – CO from equatorial torus & outflow, HI from extended structure in NW direction in HI (opposite to that of proper motion), size 18’, mass 0.02 Msun, likely interaction with ISM over 2-3 x 10^5 yr for dM/dt 10^{-7} Msun/yr

VLA survey by *Matthews+2013* of 11 AGBs finds HI CSEs with masses ~0.015-0.055 Msun, and evidence of interaction with ISM

(many papers: e.g., Matthews+2013 and references therein)

AGB mass-loss: RX Boo (O-rich, SRb)





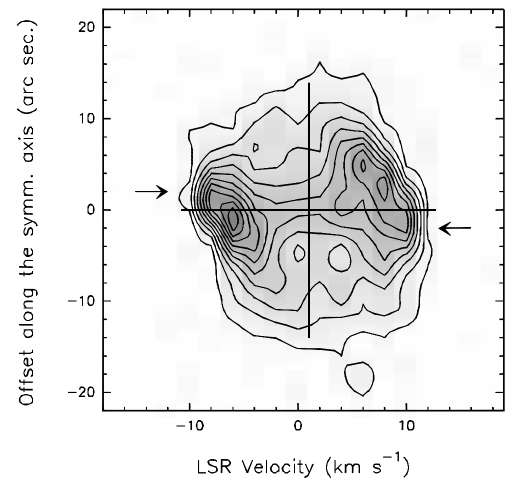
(COSAS study: *Castro-Carrizo+2012***)**

- Overall shape roughly round, but evidence of axial symmetry (PA ~50 deg)

(i) Clumpiness in density? preferential photodissociation by IS UV may amplify this effect (CSEs of low-mass loss rate objects affected more)

(ii) Clumpiness in temperature?

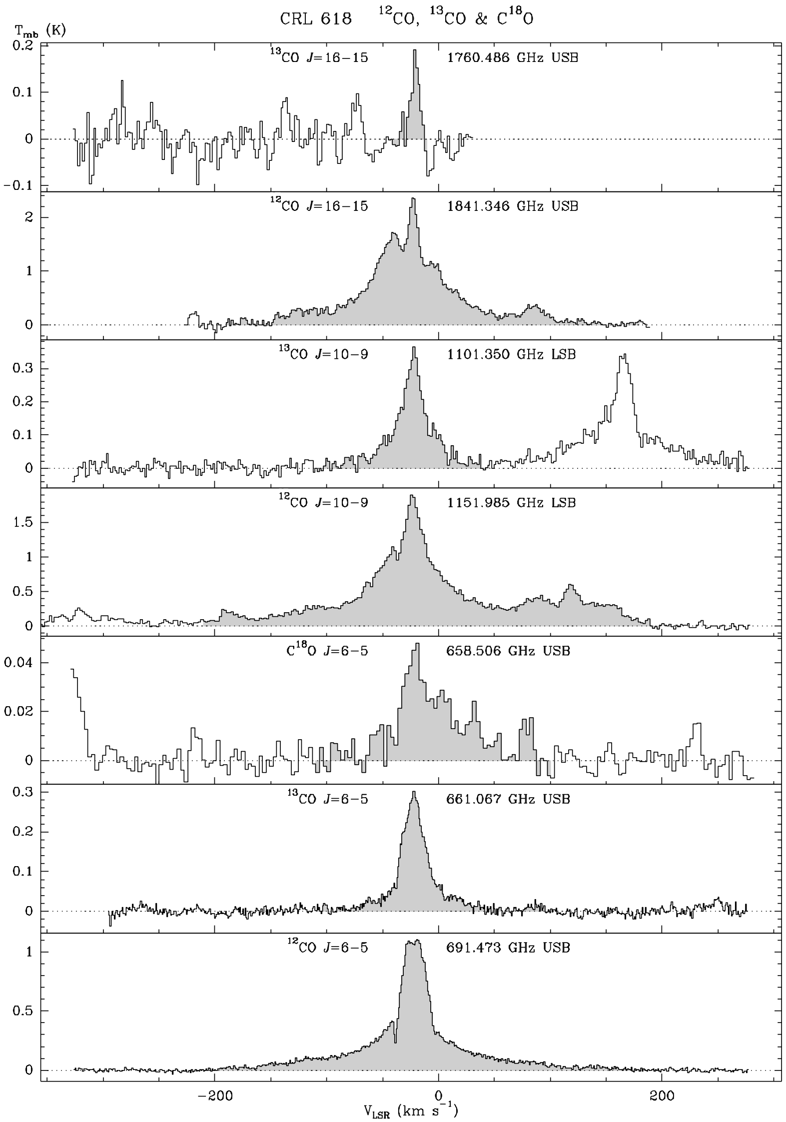
Would be useful to compare dust distribution (scattered light) to CO maps



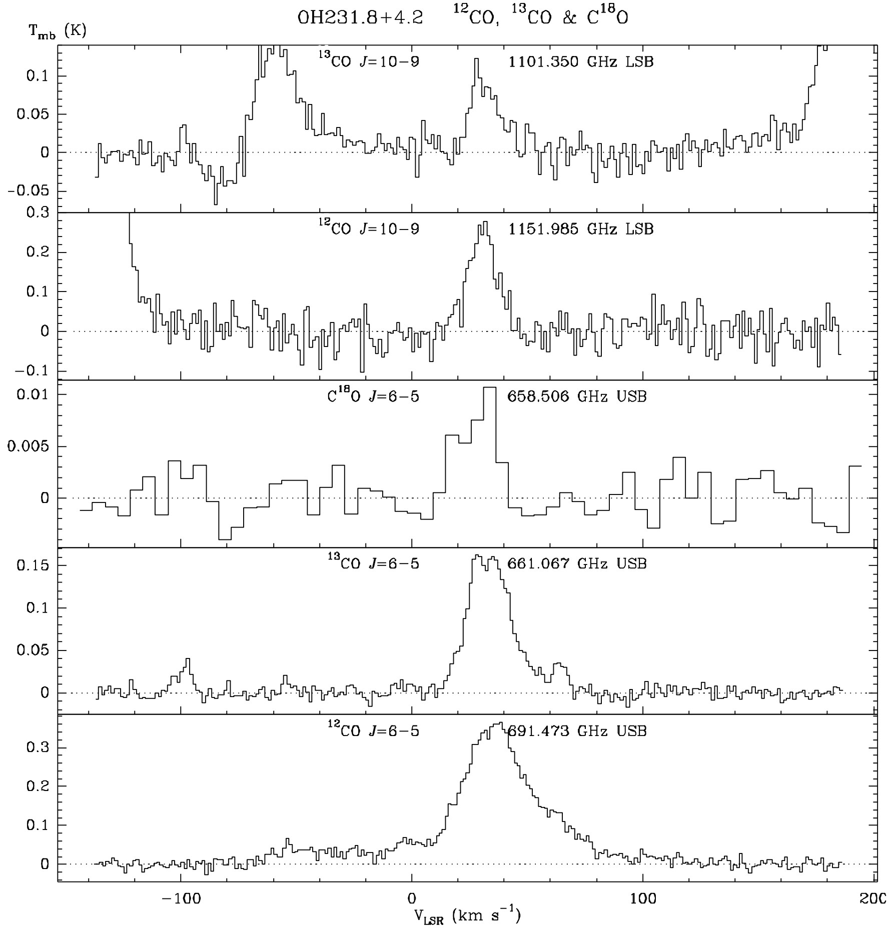
pAGB mass-loss: Herschel/HIFI observations

PPNe and PNe (**HIFI Key Herschel Program,** *Bujarrabal+2012*))

CRL618



OH231.8+4.2



Wide profiles, sometimes very extended wings

Submm & Far-IR lines from CO, ^{13}CO, H_2O (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)

pAGB mass-loss OPACOS Survey

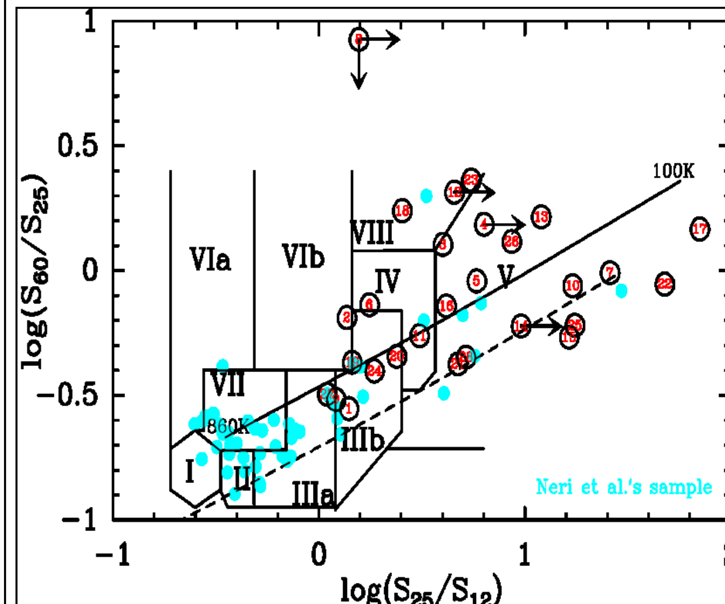
S'anchez Contreras & Sahai 2012

Many interferometric CO mapping papers by Bujarrabal, Alcolea , S'anchez Contreras, Castro-Carrizo & colleagues on post-AGB objects such as M1-92, M2-56, CRL618, IRAS19475, Red Rectangle …

20 pPNe (+5 AGBs, 2 PNe)

Properties of the Sources in Our Survey OPACOS

Source (IRAS No.)	Other Names	Object[a] Class	Spectral Type	Morphology[b] (Opt./NIR)	Chemistry[c]	f_{12}/f_{25}	f_{60} (Jy)	d[d] (kpc)
03206+6521	OH 138.0+7.2	AGB	M?	S	O	0.71	37.5	3.4
18055−1833	V* AX Sgr	PPN	G8Ia	S	O	0.73	33.1	2.0
18135−1456	OH 15.7+0.8	PPN	G5-K0	S	O	0.25	158	2.5
18167−1209	OH 18.5+1.4	PPN	F7	S	O	<0.16	21.3	7.0
18276−1431	OH 17.7−2.0	PPN	A0-K5	B	O	0.17	120	3.0
18348−0526	OH 26.5+0.6	AGB	M	†	O	0.57	463	1.1
18420−0512	OH 27.5−0.9	PPN	M1	B,ml	O	0.04	26.2	6.0
18460−0151	OH 31.0−0.2	PPN(wf)	…	†	O	<0.64	<277	7.0
18560+0638	OH 39.7+1.5	AGB	M	†	O	0.83	101	1.4
19024+0044	OH 35.3−2.6	PPN	G0-5	M	O	0.06	42.5	10
19134+2131		PPN(wf)	…	B	O	0.32	8.56	8
19234+1627	PN G051.5+00.2	PN	…	E	…	<0.22	15.5	9.5
19255+2123	OH 56.1+2.1,K3-35	PN	>60kK	B	O	0.08	48.2	4.0
19292+1806	OH 53.6−0.2	PPN	B?	B	O	<0.10	28.8	5.0
19306+1407		yPN	B0-1	B	C+O	0.06	31.8	5.5
19374+2359		yPN	B3-6	B	O	0.24	70.9	11
19475+3119	HD331319	PPN	F3	M	O	0.01	55.8	3.5
19548+3035	RAFGL2477	PPN	M6	S	C+O	0.69	46.7	4.0
19566+3423		AGB	…	S	C+O	0.42	49.0	9.0
20000+3239	GLMP 963	PPN	G8I(simb)	E/B	C	0.21	30.0	3.0
20462+3416	LS II+34 26	yPN	B1.5	E	O	:0.02	12.1	2-5
22036+5306	GLMP 1052	PPN	F4-7	B	O	0.18	107	4.0
22177+5936	OH 104.9+2.4	AGB	M	S	O	0.54	90.7	2.4
22223+4327	V448 Lac	PPN	F8Ia	B	C	0.06	22.4	4.0
22568+6141	PN G110.1+01.9	yPN	B0	B	…	0.12	20.8	6.0
23166+1655	AFGL3068, LL Peg	AGB	C	spiral	C	0.91	248	1.1
23304+6147	GLMP 1078	PPN	G2Ia	B(M?)	C	0.19	26.6	4.0



Objects have extended, cool dust shells

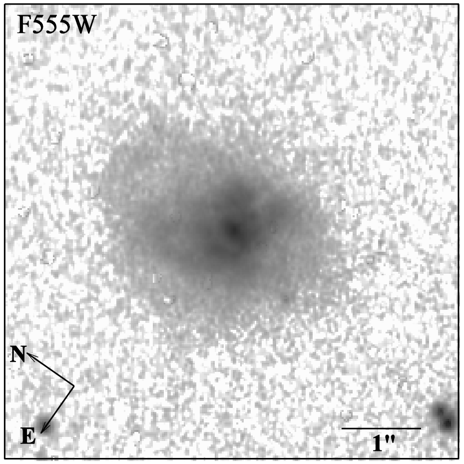
SUMMARY OF OBSERVATIONAL RESULTS

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*)

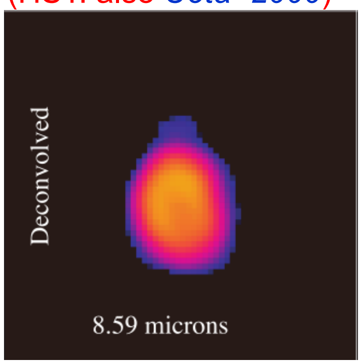
Discovery of an extreme object, IRAS19374

OPACOS Survey: Extreme PPNe - IRAS19374+2359

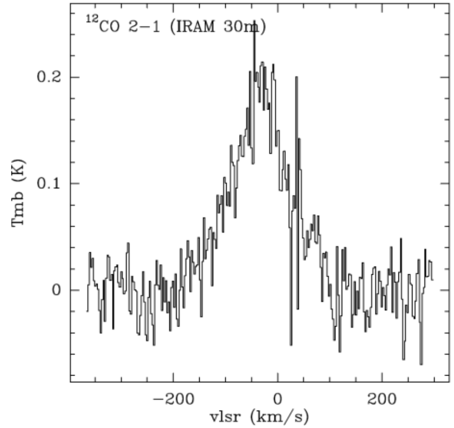
✓**such "extreme" sources offer the most stringent tests for theoretical models**

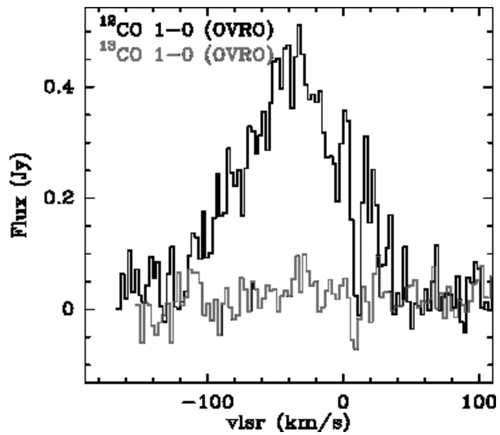


(HST: also *Ueta+2000*)

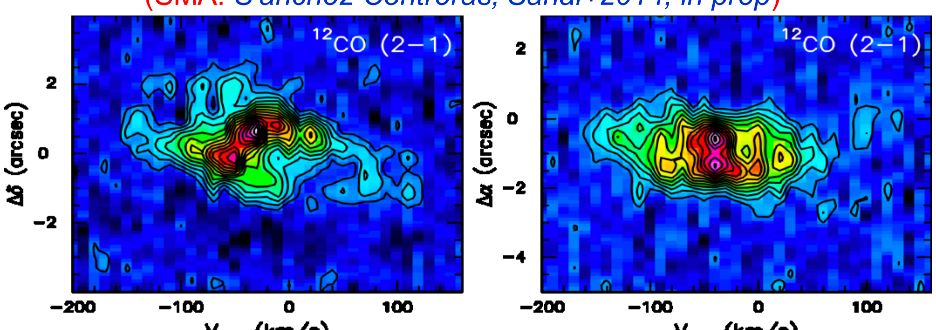


(mid-IR/VLT: *Lagadec+2011*)





(SMA: *S'anchez Contreras, Sahai+2014, in prep*)



•broad CO emission line has a triangular shape.

•wing-dominated profile differs from those seen in most PPNe (intense, narrow line-core and weak broad wings)

(follow up with SMA and IRAM-30m)

•CO 2-1 IRAM-30m spectrum shows a similar wing-dominated profile with an even larger full velocity extent (FWZI~300 km/s)

(for D= 11 kpc, L=8 10^4 Lsun)

•kinematical age: outflow ~800 tan(*i*)=1100 yr, torus ~1500/tan(*i*)=1100 yr (if, assume i≈54°)

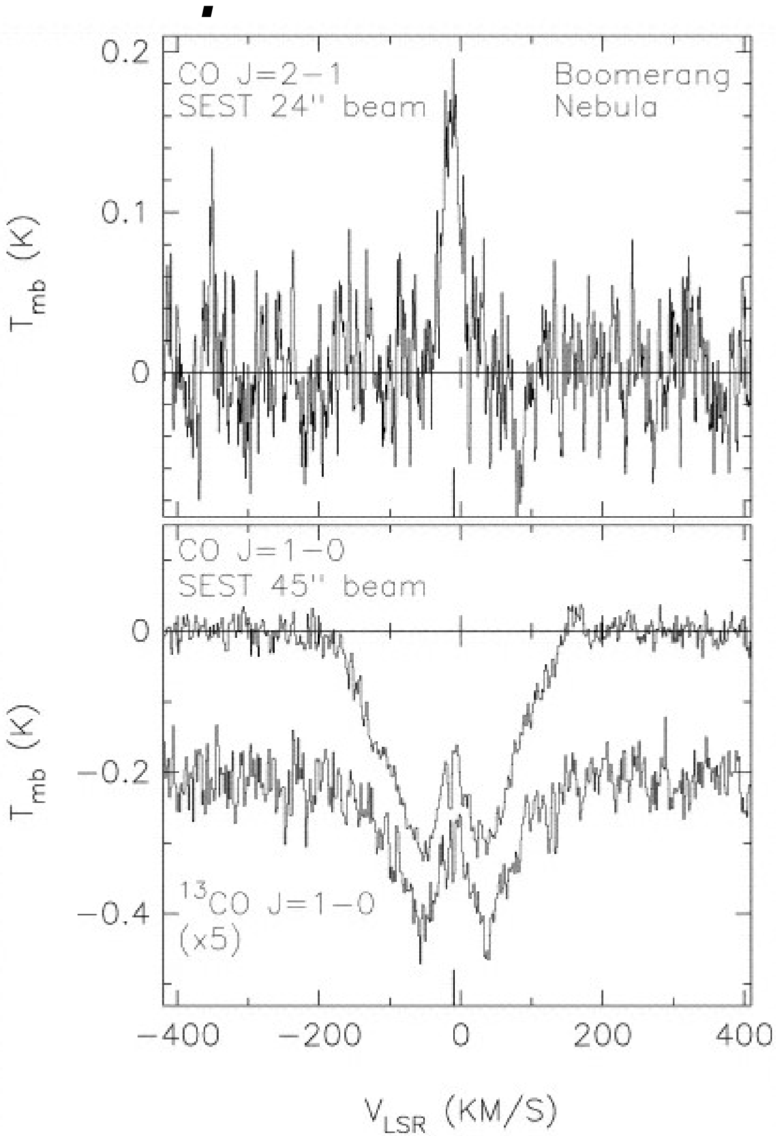
•total outflow mass ~1 Msun

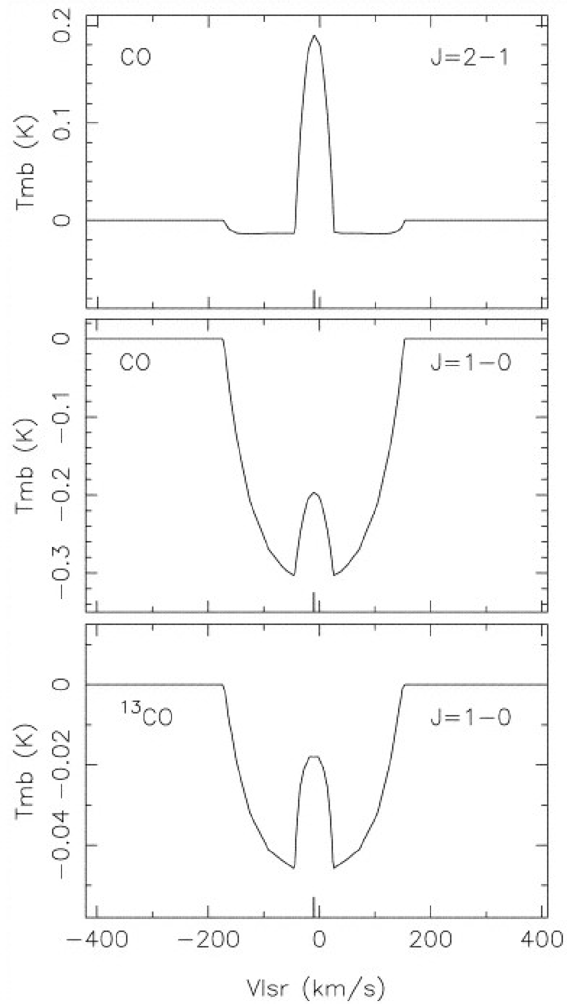
linear momemtum carried by the outflow of >45 Msun km/s (unprecedentedly large)

•CO wings arise in bipolar structures - **most of the molecular gas in the massive, slow AGB wind of IRAS 19374 has been accelerated by the shock interaction with a fast, post-AGB jet.**

pAGB mass-loss: The Boomerang Nebula

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 ouflow***

(~10^{-3} Msun/yr)

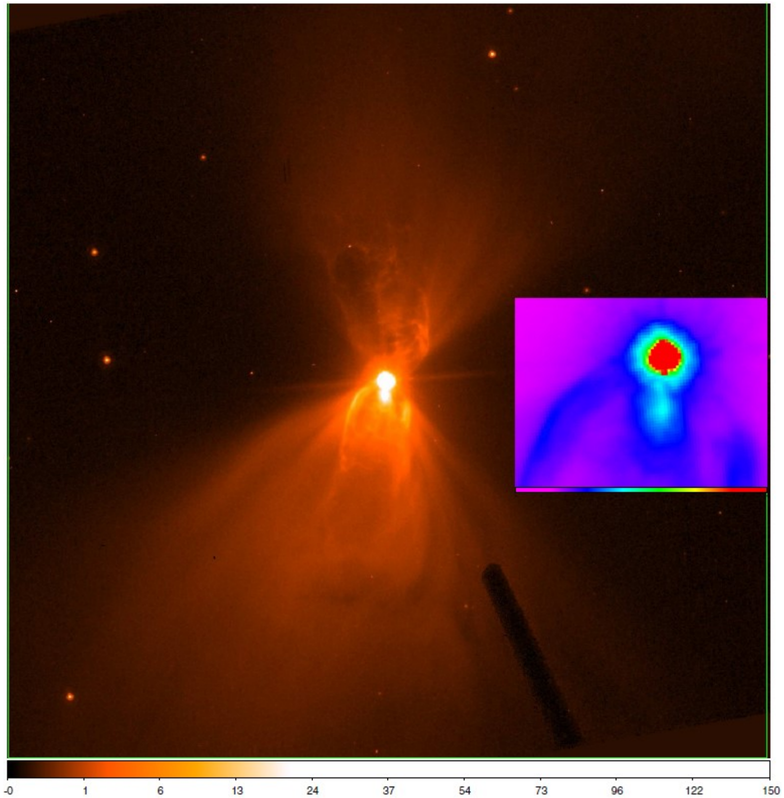
- ***But L~500 Lsun!***

Radiative momentum completely inadequate to drive outflow

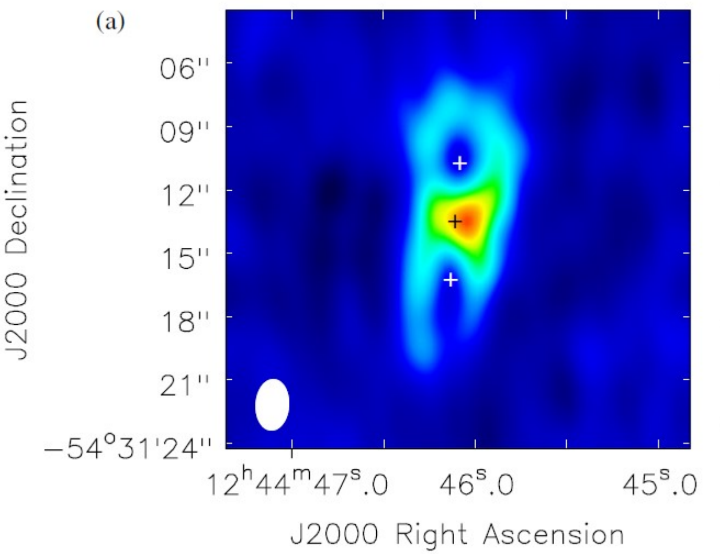
Model shows T_{kin} < 2K

pAGB mass-loss: Boomerang Nebula

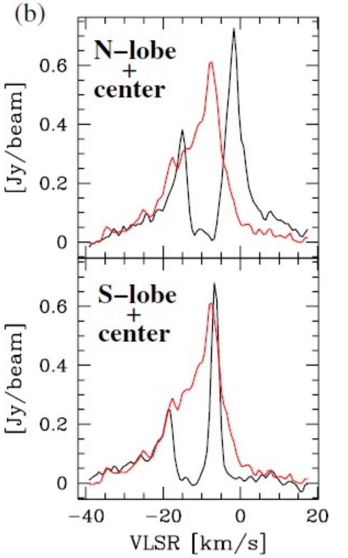
(Sahai, Vlemmings, Nyman, Huggins: Cycle 0 ALMA project: *Sahai+2013*)



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



CO 2-1 image (systemic velocity)

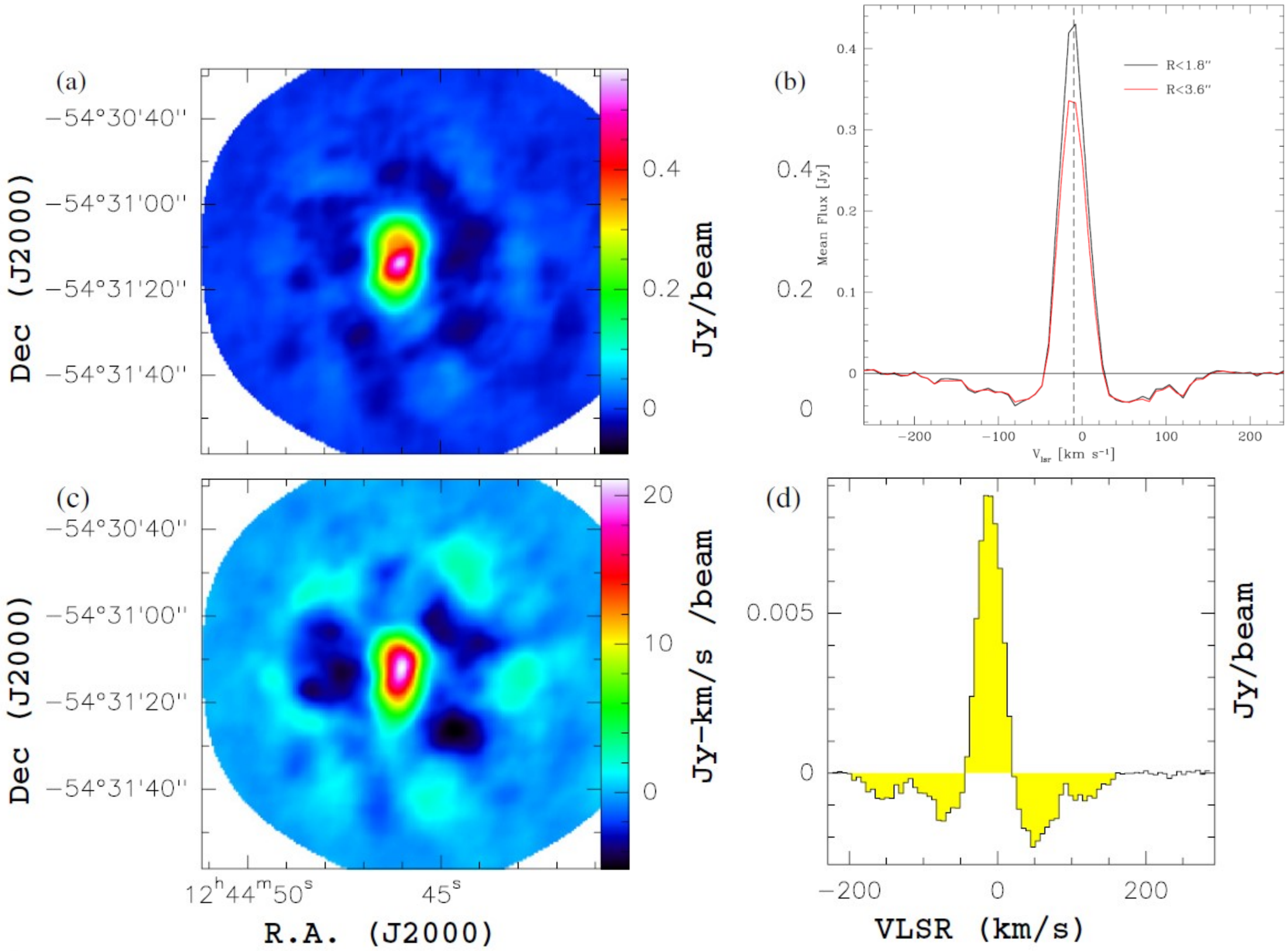


spectra

- 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

hourglass shape of extended, diffuse optical nebulosity due to preferential illumination of largely round CSE

Boomerang Nebula: CO 1-0 (ALMA)



- Absorption over a large range of radial-velocity along line-of-sight to center
- ultra-cool shell has radially-increasing expansion velocity

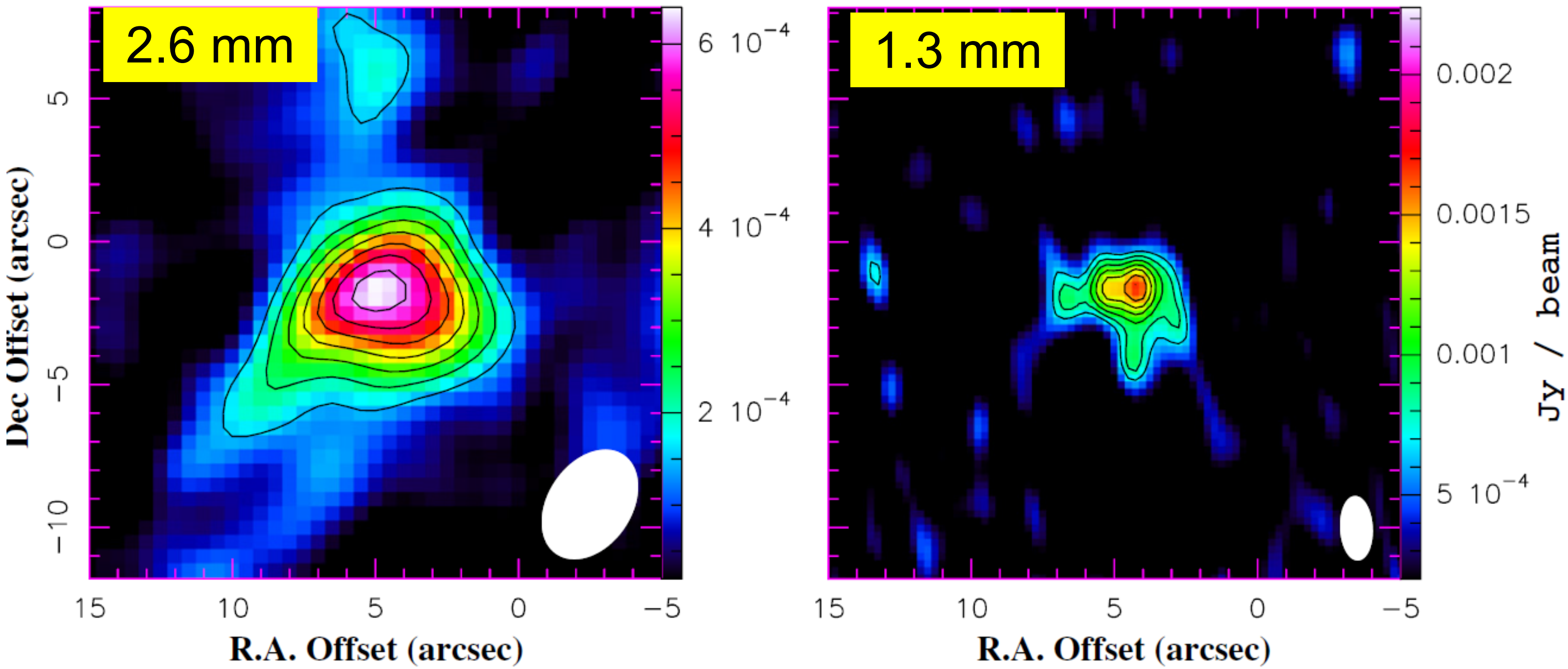
explains puzzle of lower outflow velocity (35 km/s) in the central bipolar emission lobes, compared to that derived for ultra-cold shell from single-dish data (165 km/s)

(velocity of material in bipolar lobes must be larger or equal to that in ultra-cold outflow, if former result from interaction with latter)

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

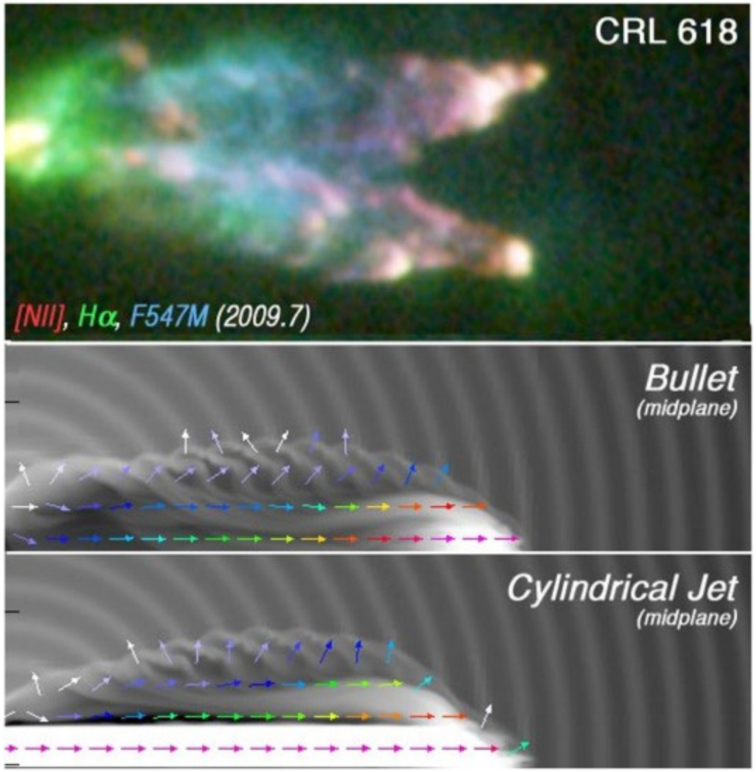
(without R-J): for p = 0.6, 1, 1.5, get T_d*= 45K, 9.5K, 5.0K and* r_d*=1.9"*

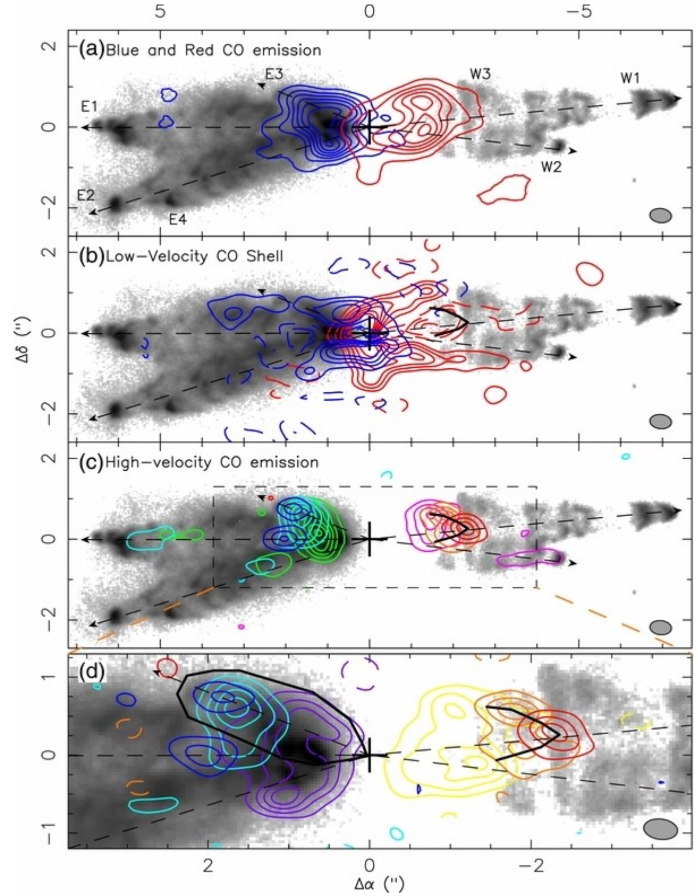
Assuming opacity $\kappa(1.3mm)$ *~ 1.5* cm^2/g

M_d*~ 3.5 x* 10^{-4} ***Msun**, or M~ 0.07 **Msun** (assume gas-to-dust ratio=200)*

expansion time scale for dust region ~ 420 yr => Mass-loss rate ~1.7x10^{-4} M_{sun}*/yr*

CRL 618: Multi-wavelength high-resolution observations and hydrodynamical models





Red -22 to 158

Blue -194 to -22

Red -17 to 9

Blue -35 to -27

R1 128 to 151

R2 94 to 120

R3 70 to 89

B1 -183 to -161

B2 -158 to -132

B3 -132 to -114

R4 28 to 42

B4 -84 to -71

Balick+2013: Measure proper motion of 0.5” in 7 years from HST images.

- Favor a model in which a spray of high-speed (300 km/s proper motion) clumps were launched ~100 yr ago, creating the multipolar morphology.

also study of expandin g HII region,Tafoya+2013

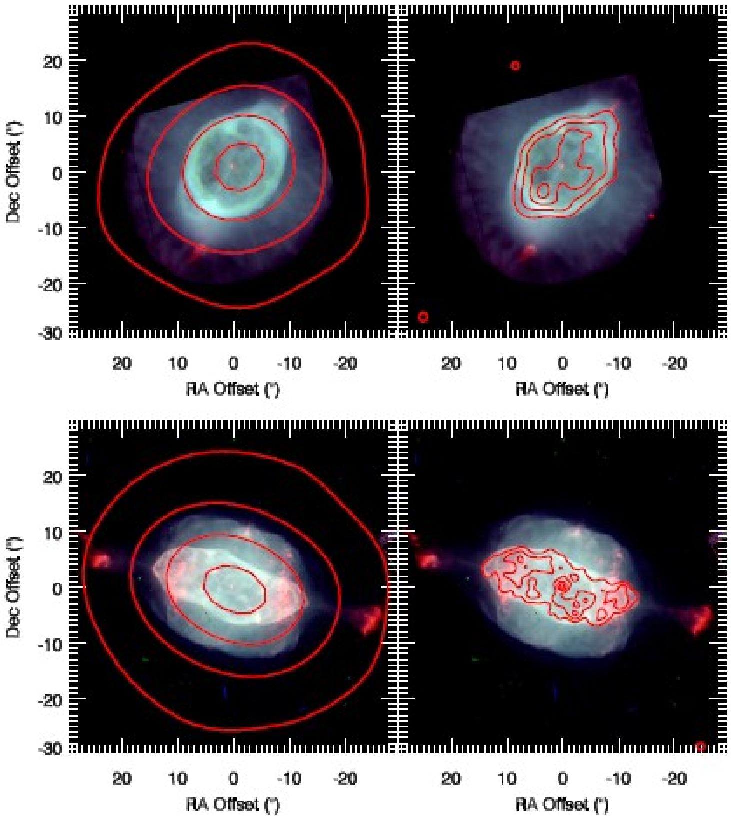
Lee+2013a,b: SMA observations of outflows and dense core at 0.8 mm with ~0.3” to 0.5” resolution.

- Outflows (CO J=3-2, HCN J=3-2): Two episodes of bullet-like ejections, ~105+/-40 yr and ~45+/-25 yr
- Dense core: dM/dt~10^{-3} Msun/yr, V ~ radius, unexplained isotope ratios $^{12}C/^{13}C$~9 (decreasing from ~40 in extended CSE), $^{14}N/^{15}N$~150, large (mm-size) grains

X-Ray emission from PNe

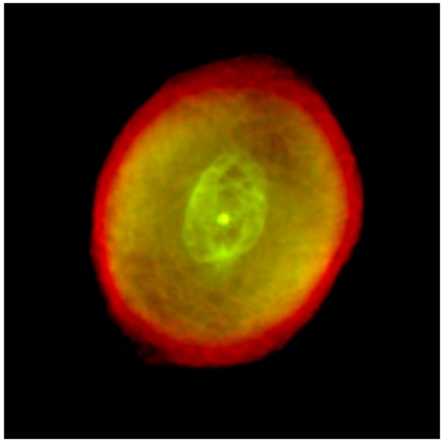
- shocked gas due to a fast (~1000 km/s) wind from hot central star, interacting with slow wind ejecta, should produce a hot bubble at temperatures Tx >> 10^6 K

XMM *Chandra*

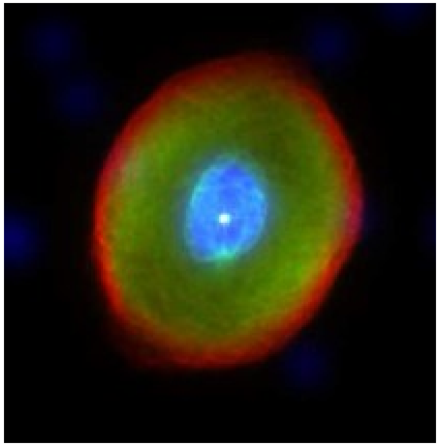


Hot-bubble X-ray emission from NGC3242 (top) and 7009 (bottom) overlaid on HST images (*Kastner+2012*)

IC418 (see detailed photoionzation model in *Morisset+Georgiev 2009*)



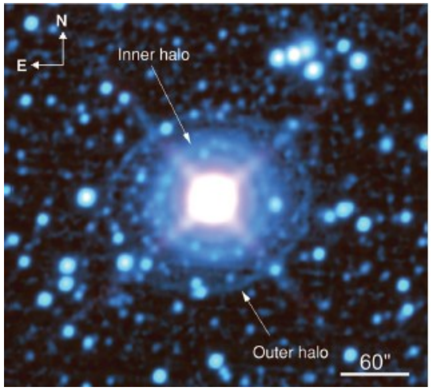
Inner-bubble in [OIII]5007 (green), Hα (red) HST image (*SMV11*)



Hot-bubble in Xrays: CXO image (blue), Hα (green), [NII] (red) (*Ruiz+2013*)

CHANPLANS: First systematic survey of nearby (<~1.5 kpc) PNe with radii <~ 0.4 pc, Chandra Cyc 12 (570ks) +14 (670ks)

This program builds upon a large number of earlier smaller efforts using CXO and XMM (e.g., see references in Kastner+2012)



WISE image of IC418 (W1, 3.4 μm: blue-green, W2 , 4.6 μm : red) showing inner and outer halo (*Ramos-Larios+2012*)

X-Ray Emission from PNe

Kastner+2012 have analyzed results for a total of 35 PNe (21 CHANPLAN + 14 from previous studies)

(1) Probe of wind-wind interactions (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 Tx >> 10^6 K)

- Although such hot bubbles observed in about 30% of PNe, temperature Tx ~ 10^6 K, Lx~10^{30}-10^{32} erg/s: heat conduction (*Ruiz+2013* demonstrate this using data+models for 3 PNe with detected OVI, signature of a 10^5 K conduction layer), rapid evolution of fast wind properties, or energy-absorbing pick-up ions (as known for solar wind)?
- X-rays come from bright-rimmed inner bubbles, radii < 0.15 pc (age < 5000 yr) (recall "ib" morphological descriptor as signature of a reverse shock in *SMV2011*!), most of the host PNe don't show 2.1 μm H_2 emission

(2) Probe of processes related to central star (binarity and/or magnetic fields)

- About 50% of PNe have X-ray luminous central stars (fraction is 70% for known binary CSPNe); in almost all, the emission is much harder (>~0.5 keV) than expected from the photosphere (100-200 kK) of the hot star
- Most host PNe have elliptical/round shapes, and don't show 2.1 μm H_2 emission

Binarity: accretion onto a compact companion, coronal emission from a late-type companion "rejuvenated" by accretion of AGB material (however non-binary models such as internal wind shocks, infall from a debris disk, or non-LTE photospheric emission also possible)

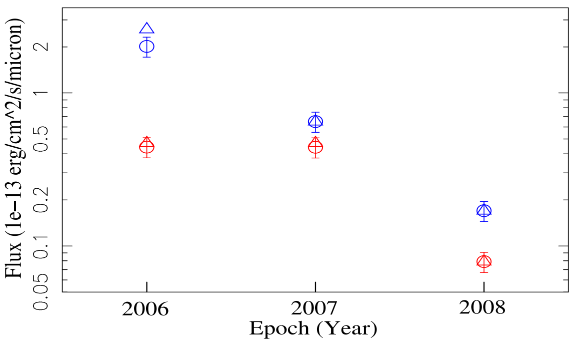
Note: PPNe are generally not detected in X-Rays; only exception is He 3-1475, which has a ~2000 km/s collimated outflow (Sahai+2003) => CFWs, unlike SRFWs, interact with a smaller mass of ambient CSE, do not produce enough X-ray emitting gas

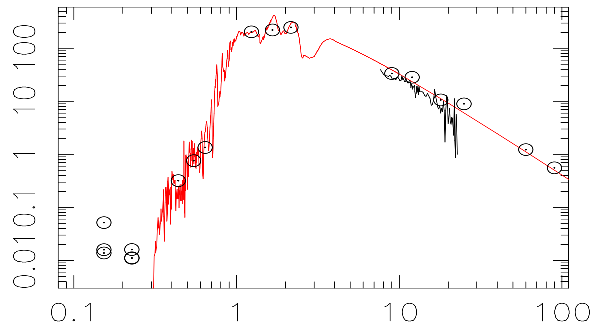
fuvAGB Stars: Binaries with actively accreting main-sequence companions?

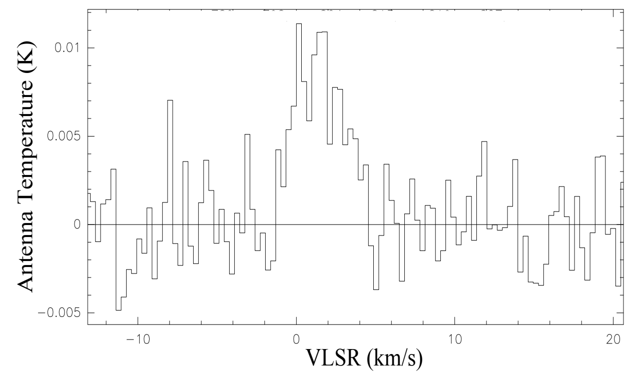
Search for binarity using FUV emission in AGB stars: Large and variable UV flux most likely related to accretion activity in a binary (*Sahai +2008*)

We have begun a pilot study with XMM/Chandra to search for X-Ray Emission from fuvAGB Stars (two fuvAGB stars, R Uma & T Dra are known X-ray sources: *Ramstedt+2012*)

Y Gem – a nascent dpAGB star? fuvAGB star with highest FUV flux amongst ~100 AGB stars with GALEX FUV and/or NUV fluxes (*Sahai,Neill +2011*)

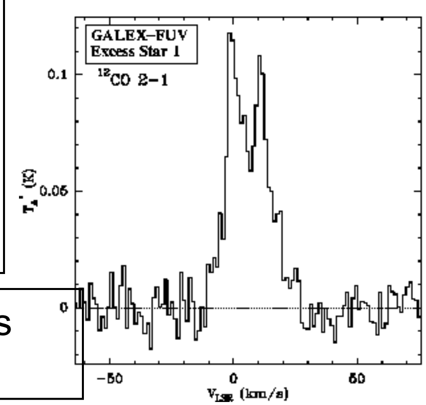


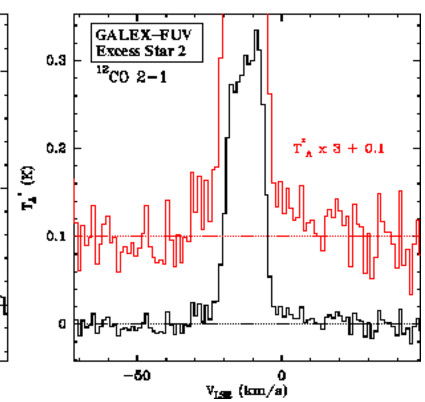




- Largest UV flux amongst all FUV-excess AGB stars (M8)
- UV flux very large, decreased dramatically from 2006 to 2008
- FUV/NUV flux ratio > 1
- **CO 2-1 line emission shows narrow profile** (FWHM=3.4 km/s) – likely arises in a large (~300 AU) disk, rather than a outflow (*e.g., Jura & Kahane 1999*)
- Hα profile variable on time-scales of days to months; radio emission shows thermal (ionized gas) & non-thermal emission

CO 2-1,1-0 survey (IRAM30m) of small sample of fuvAGB stars shows outflows (*Sahai, Sanchez Contreras, Gil de Paz+2014, in prep*)





pAGB mass loss: Dusty Equatorial Waists

Dusty Waists - important morphological component of post-AGB objects

- 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*)

pAGB mass loss: Dusty Equatorial Waists

- 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*)

PPNe appear to be different in their morphologies, compared to

dpAGB objects with (radial-velocity) binary stars and circumbinary disks, which appear to lack extended nebulae. *89 Her & HD44179 show weak extended nebulosity, generally no nebulosity seen optically, or in mm-wave continuum/CO emission* [AC Her, U Mon, RV Tau unresolved, <1”-2”: *Sahai, Claussen, Schnee, & Morris 2011*]

But, the waist regions of PPNe share many observational similarities with binary pAGBs

a) Submm excesses: large 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*)

pAGB mass-loss: Pilot Study of Continuum Emission from Dusty Waists

Table 1: Radio and Millimeter-Wave Fluxes of post-AGB Objects

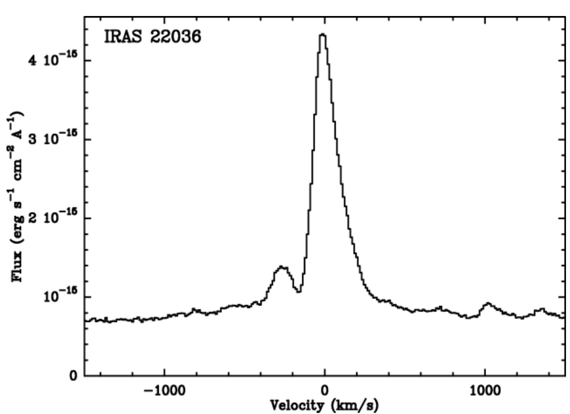
Source	X μJy(σ)	Ka μJy(σ)	Q μJy(σ)	3 mm[a] mJy(σ)	1.3 mm[b] mJy(σ)	0.85 mm mJy(σ)	D[c] kpc	M_d $10^{-2}M_\odot$
RV Tau	...	270 (50)	(107)	3.9(0.2)	...	50.3 (3.6)[d]	2.2	0.1
U Mon	...	(100)	(169)	15(0.3)	100(14)	182 (2.6)[d]	0.77	0.064
AC Her	(46)	...	...	4.6(0.4)	38(1)	99.4 (3.8)[d]	1.1	0.072
IRAS16342−3814	(162)	(168)	(254)	...	277 (13)[e]	602 (90)[f]		
IRAS17150−3224	...	(240)	(213)	...	158 (10)[e]	...		
IRAS18135−1456	(66)	(82)	(169)	12 (1.4)[g]	...	...		
IRAS18276−1431	...	(108)	(157)	11 (3.2)[g]	...	...		
IRAS19548+3035	(45)	...	...	6 (1.1)[g]	...	...		
IRAS20000+3239	(44)	...	...	6 (1.1)[g]	11.4(1.7)[h]	30.9 (2.5)[i]		
IRAS22036+5306	1010 (62)	1180 (55)	1230 (81)	8.4 (0.7)[j]	...	290 (40)[j]	2	2.2

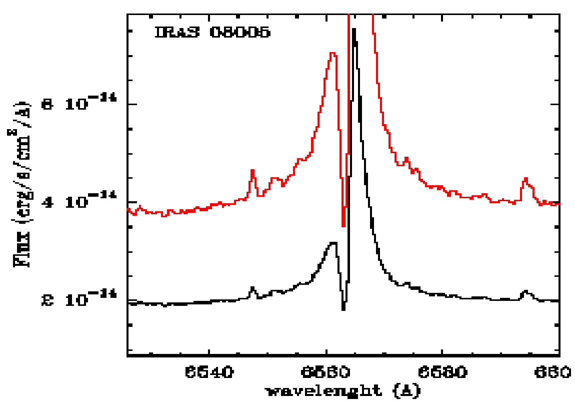
[a] Beam sizes for RV Tau, U Mon, & AC Her 3 mm observations are 2″.4×1″.5, 2″.4×2″.1, & 2″.4×1″.5, respectively

[b] Beam sizes U Mon & AC Her 1.3 mm observations are 2″.2×0″.9 & 2″.0×1″.8, respectively

[extended study in progress using SMA, CARMA, ALMA, ATCA, VLA (huge increase in sensitivity): *Sahai, Patel, Gonidakis et al 2014, in prep*]

(from the central regions of these waist) Hα P-Cygni profiles with very broad wings in PPNe



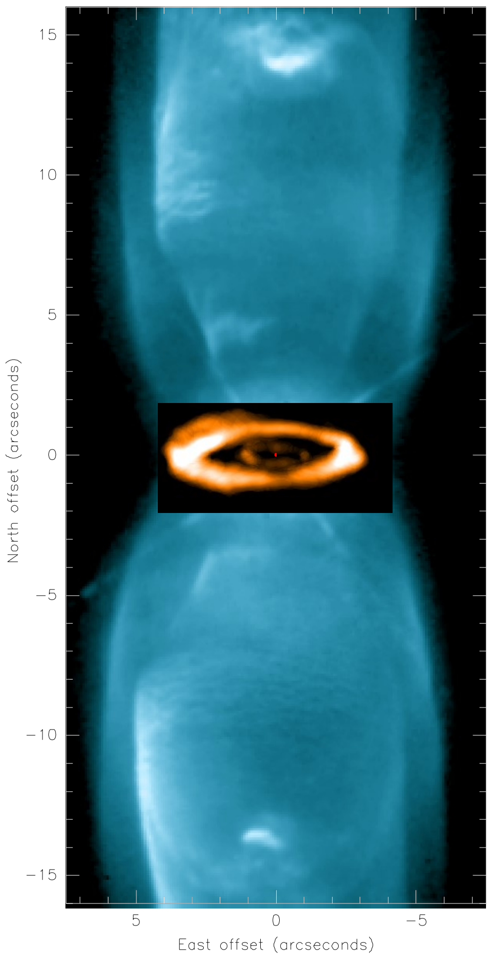


(early work by Van de Steene, Wood & van Hoof 2000, preliminary survey at Mt. Palomar by Sahai & S'anchez Contreras 2004, followed by Keck survey by S'anchez Contreras+2008)

Emission from central ionized disk + Raman scattering in fast, neutral outflow (Sahai, S'anchez Contreras+2011)

pAGB mass-loss: M2-9

(Castro-Carrizo+2012)



Large grains (> 1 μm) in central ring region and lobes => disk wind? (Werner+2014)

Young PN (size120” x 12”)

(Rotating, ionizing beam from star inferred to explain brightness variations in knots along lobe edges => binary at center, P~90 yr e.g., *Doyle et al. 2000*)

•^{12}CO 2-1 mapping with IRAM PdBI (beam 0.8” x 0.4”)

•Two expanding (Vexp =7.8 & 3.9 km/s), coaxial rings within the equatorial waist seen in optical images (*outer ring was imaged earlier at lower resolution: Zweigle et al. 1997*)

•Rings ejected ~500 years apart, ejection period outer ring ~40 yr+/- 30 yr

•Systemic velocity of outer ring differs from inner one by 0.6 +/-0.1 km/s, centers offset by 0.35”

⇒Central star responsible for mass-ejection is a BINARY

Companion mass <~0.2 Msun (assume M_p ~0.5-2 Msun)

Separation ~20+/-5 AU, too large for common envelope interaction or being a symbiotic system

Binarity

1. Central Stars of PNe (CSPN) (review by *de Marco 2009*)

Photometric variability: due to presence of cool companion (e.g., *Bond +2000*: 10-15% of ~100 CSPNs have P <~ 3 days; Miszalski+ (2009a,b) used OGLE II, III and doubled the sample, inferred small orbit size implies that these must have undergone CE evolution); dearth of object with P > 3 days

Radial-velocity: studies (e.g., *Afsar & Bond +2005, Sorensen & Pollacco 2004*) could not find periodic variations, so wind variability remains viable explanation

Infrared-excess: signature of a cool (M-type) companion (*Douchin, this conference*)

(e.g., *de Marco+2013*: I-band & some J-band photometry in 27 CSPN: 8 detections, but low significance (<2σ).

2. Post-AGB:

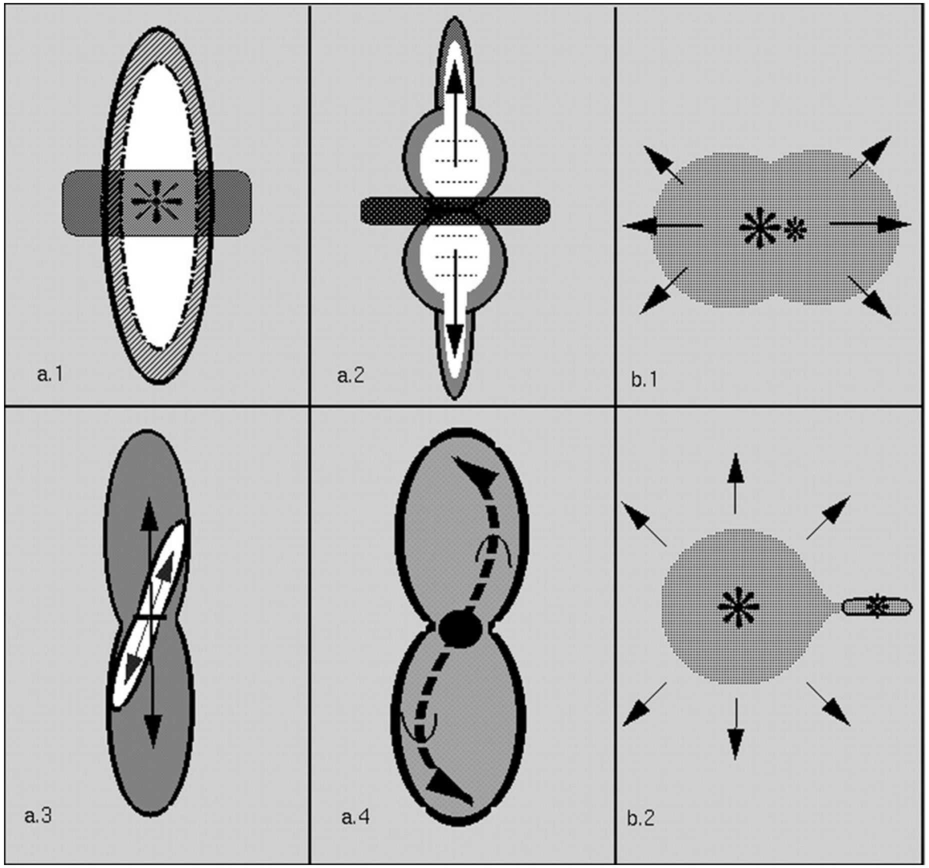
PPNe: RV surveys mostly inconclusive (variations have same period as pulsation: e.g., *Hrivnak+2013*)

dpAGB: RV surveys show that ALL objects are binaries (*e.g., van Winckel+2008*)

3. AGB stars: variability due to pulsations of red giant make it impossible to use the above techniques. But we can use UV observations to detect a hot source (star and/or accretion disk) with Teff >~6000K and L > 1 Lsun with S/N > 10

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*)

Summary

What we know (well or not so well) from Observations

- The transition from sphericity (AGB) to asphericity (PN) on "large-scales" is observationally/phenomenologically reasonably well-characterized (action of collimated fast wind (late-AGB/ early post-AGB), followed by spherical, radiative, fast wind from CSPN

(*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 (IRAS19374, IRAS22036)

Directions for Future Observational Progress

(focus on) Central Star and its Vicinity

1) (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)

2) Mid-IR Interferometry (e.g., VLTI) and imaging (e.g., JWST in the future)

3) UV Studies: 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) Binarity: investigate central stars of Round and Elliptical/Elongated PNe (*since the fraction of PNe with bipolar/multipolar morphologies, and/or point-symmetry is quite high, finding binaries central stars at the centers of a sample of such PNe is not strong evidence of binarity* ***causing*** *asphericity*)