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

Raghvendra Sahai

JPL, California Institute of Technology

Main Collaborators: M. Morris (UCLA), C. S’anchez Contreras (IEM-CSIS, Spain),

M. Claussen (AOC/NRAO), C-F. Lee (ASIAA, Taiwan), N. Patel (CfA), Rolf Guesten (MPIfR/Bonn)

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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

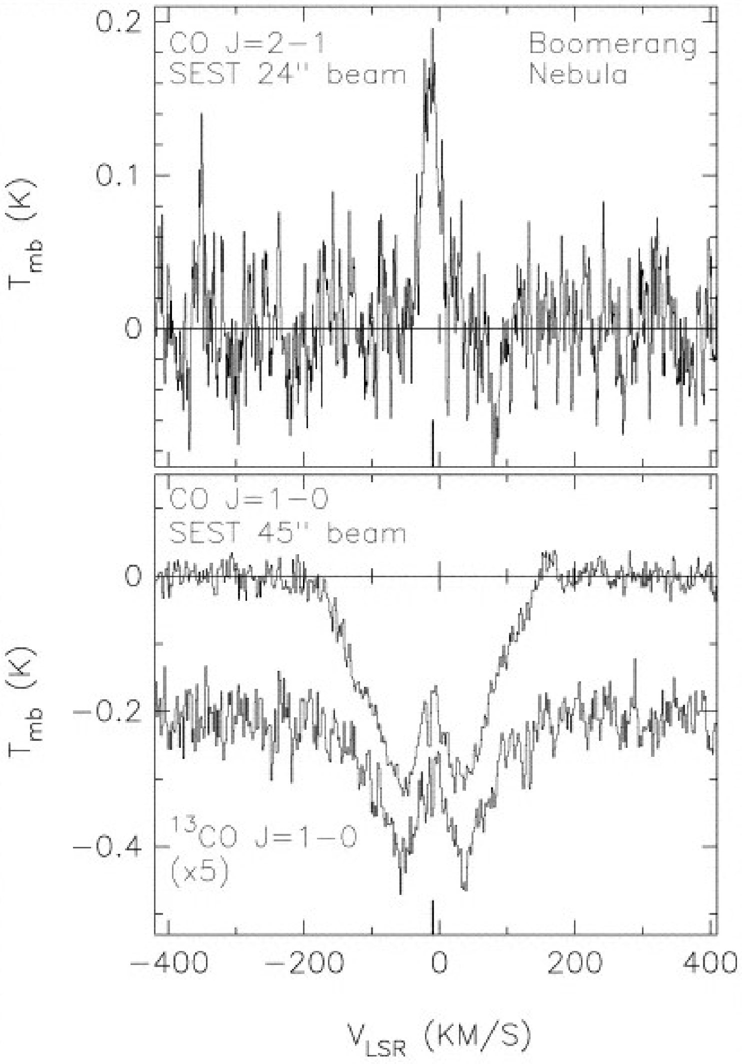
7) detailed far-IR studies of PNe - Herschel (HERPLANS*, NGC6781)

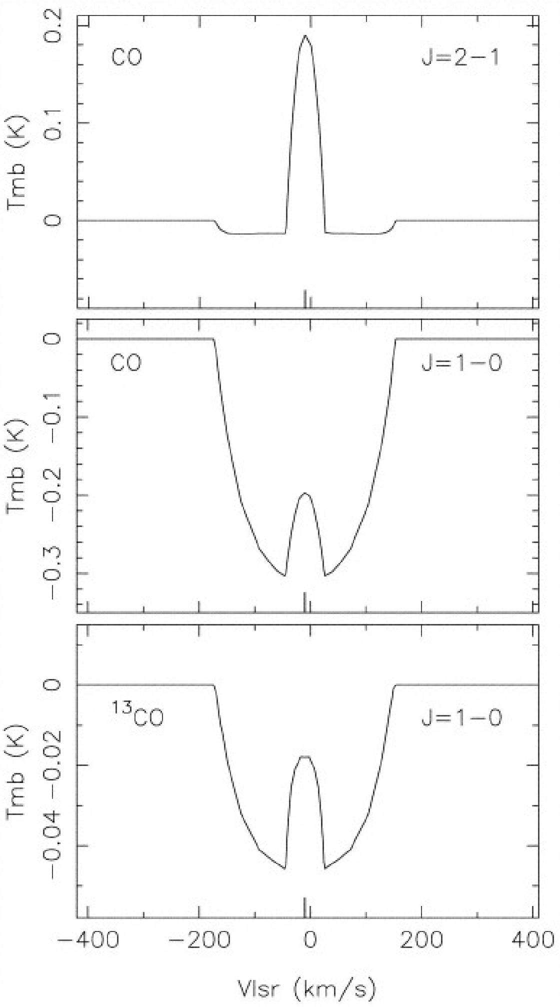
8) SOFIA/GREAT study of the 3D Structure of PNe: "Ring Nebula" NGC6720

*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 ouflow***

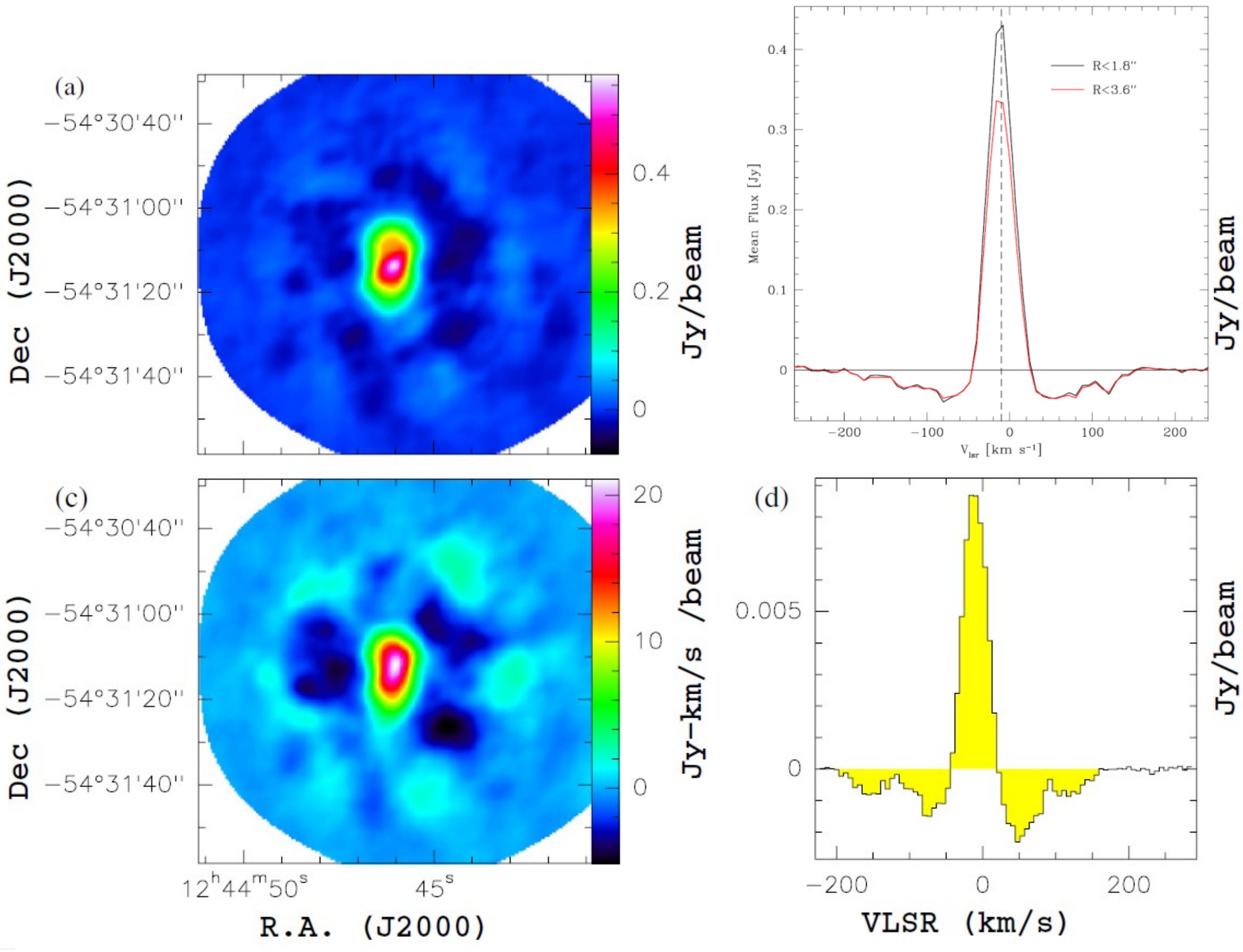
(~10^{-3} Msun/yr)

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

Radiative momentum completely inadequate to drive outflow

Model shows T_{kin} < 2K

Boomerang Nebula: CO 1-0 (ALMA)



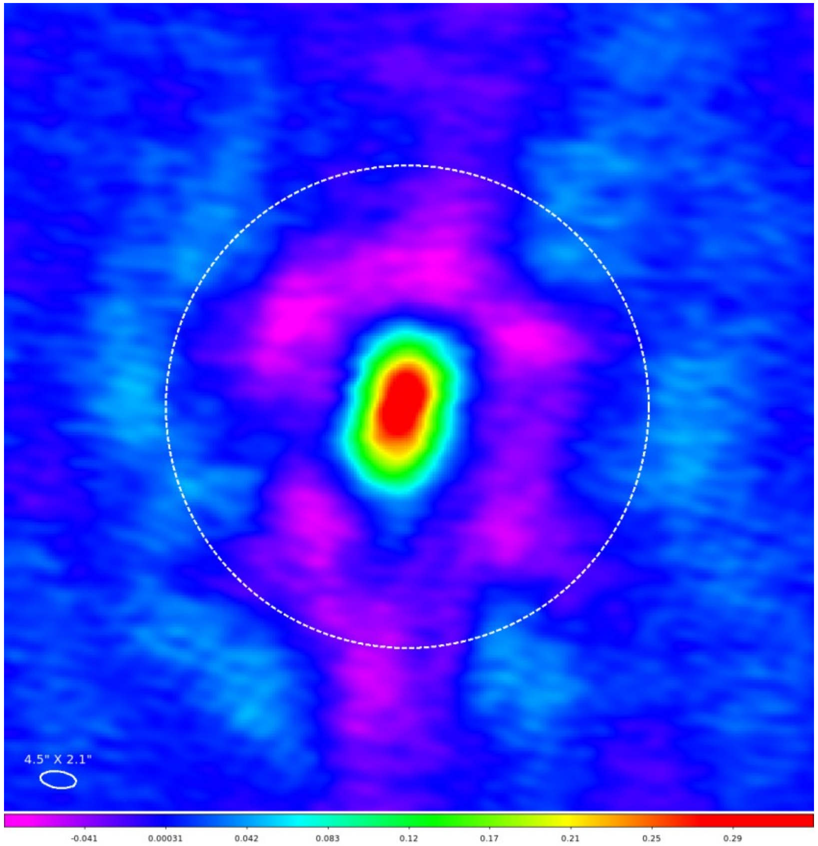
- Absorption over a large range of radial-velocity along line-of-sight to center
- ultra-cool shell has radially-increasing expansion velocity

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)

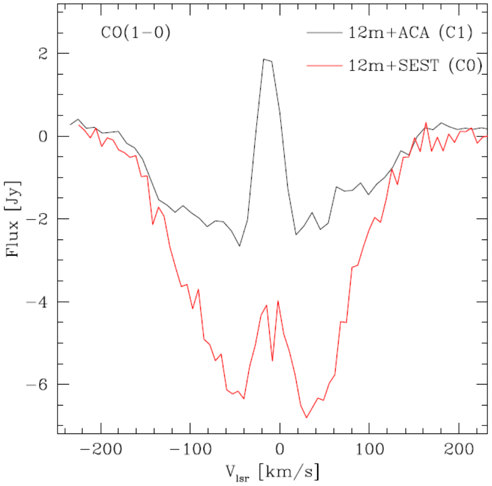
Note weak patchy emission on the periphery of the ultra-cold shell: **first direct evidence of grain photo-electric heating in an AGB CSE**

CO 1-0 ACA+12m (cycle 1, band 3)



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



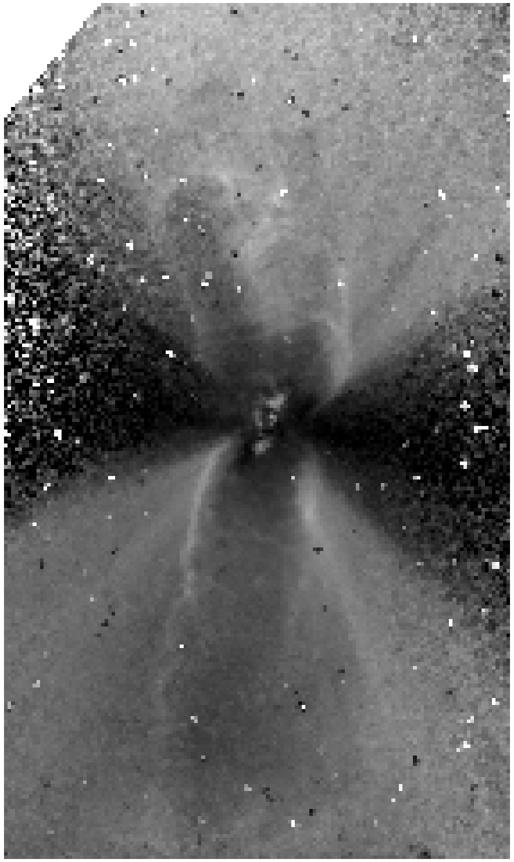
~2/3 of absorption signal seen with single-dish resolved out (i.e., from smooth structures on angular scale > 35")

- > ~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)

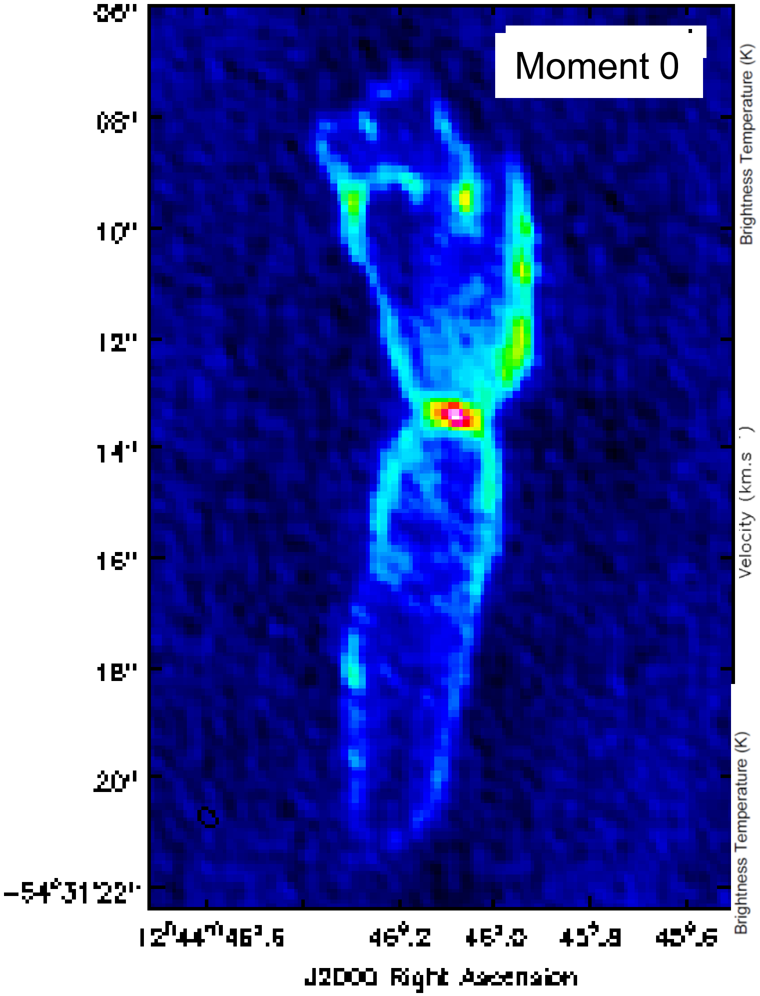
CO 3-2 (cycle 1, band 7)

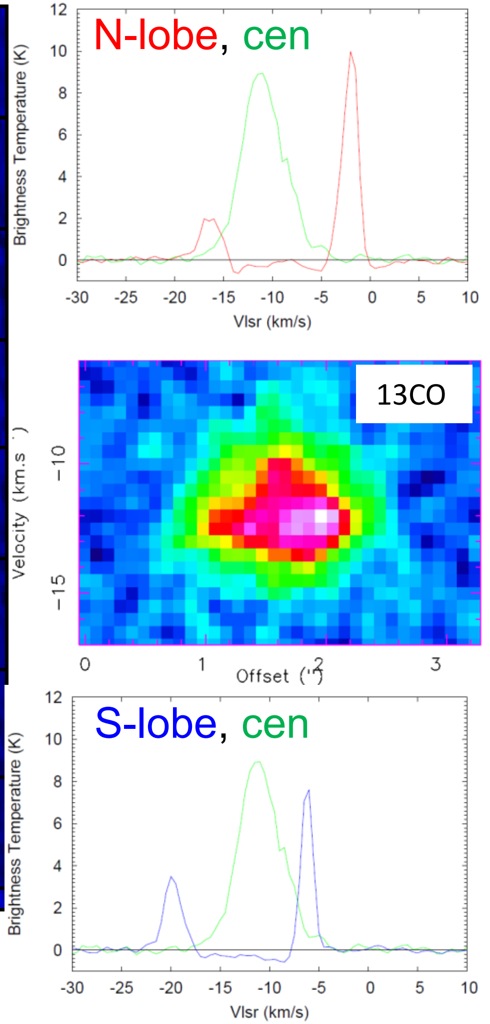
Resolution ~0".1



HST/ACS (*Cracraft & Sparks '07*)
Polarized intensity 0.6 µm

Beam 0".37 x 0".25





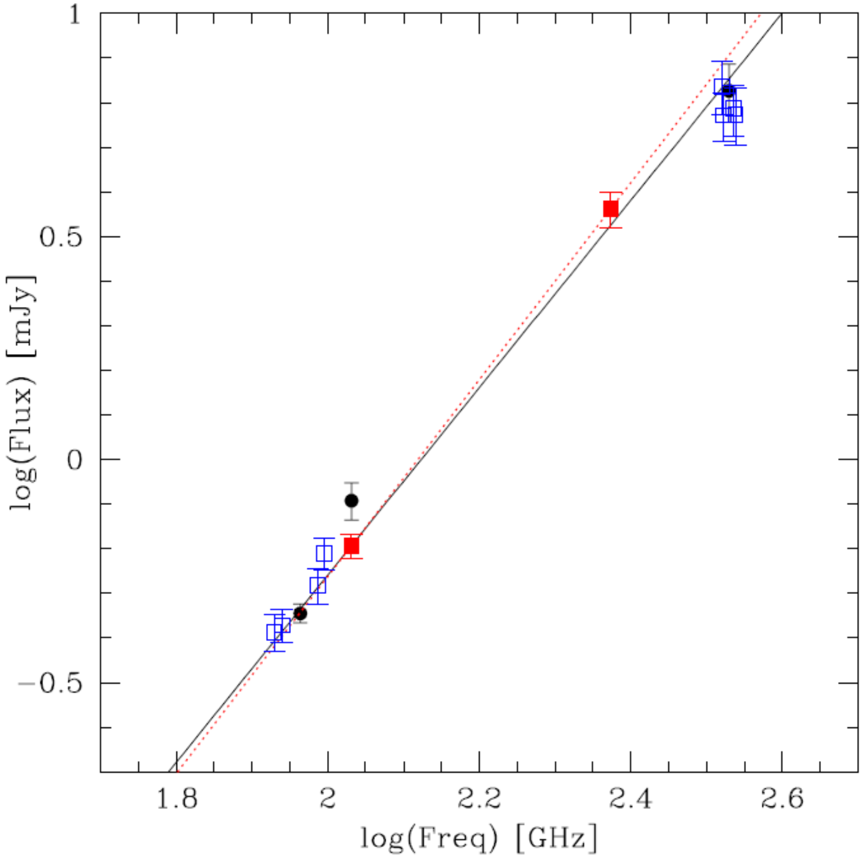
- *Complex spatio-kinematic structure at center , small line width - rotating disk?*

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

- *Central dense, dusty waist, likely expanding torus structure*

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

pAGB mass-loss: Boomerang (continuum)



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

(black curve is fit with spectral-index=2)

(Rayleigh-Jeans limit) if dust-absorption coefficient, k ~ n^p

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

(without R-J): p ~ 0.3, T_d~ 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 ~ 0 for sizes >~10 cm

M_d~ 5 x 10^{-4} M**sun**, or M~ 0.1 M**sun** assume gas-to-dust ratio=200, opacity k(1.3mm) ~ 1.5 cm^2/g

Planetary Nebulae: Herschel & SOFIA

Large Herschel studies

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

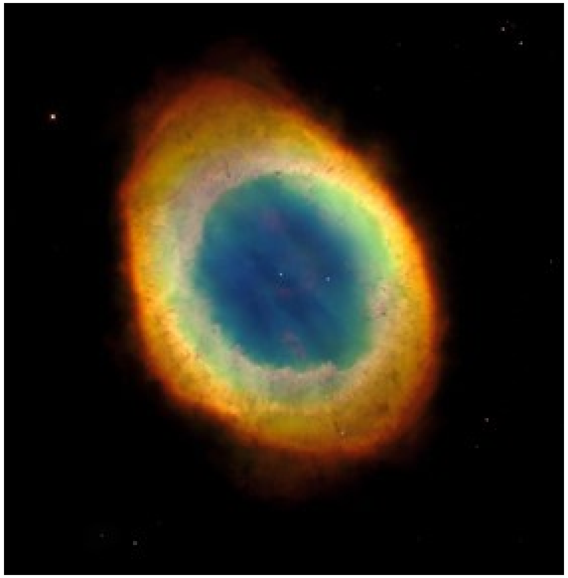
HERPLANS (*Ueta+2014* PACS/SPIRE mapping, spectroscopy of 11 high-exc PNe from CHANPLAN sample: OT1 Large Prog.,197 hr)

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

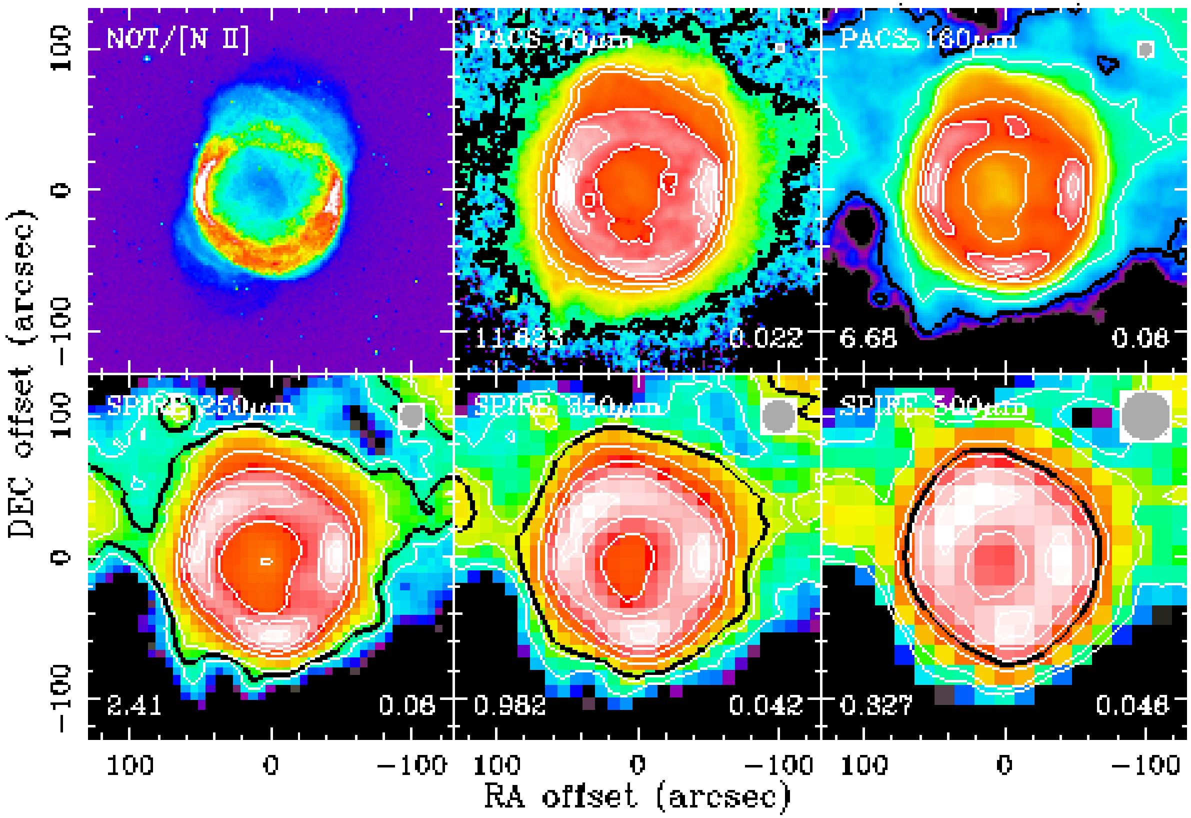


Selected NGC6720 for Cycle 0+1

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

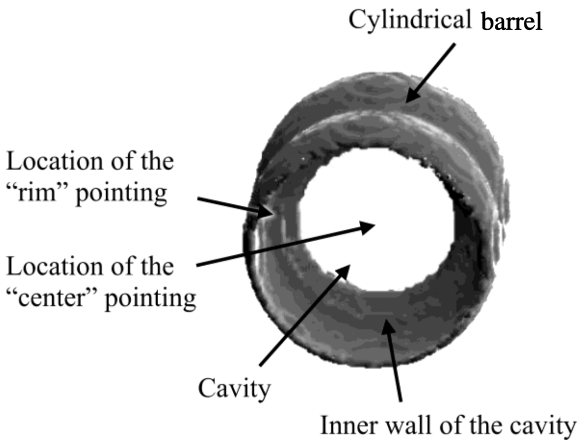
(props: 81-0065, 01-0138: Sahai, Morris, Werner)

NGC6781 (PACS/SPIRE continuum)



(Ueta+2014)

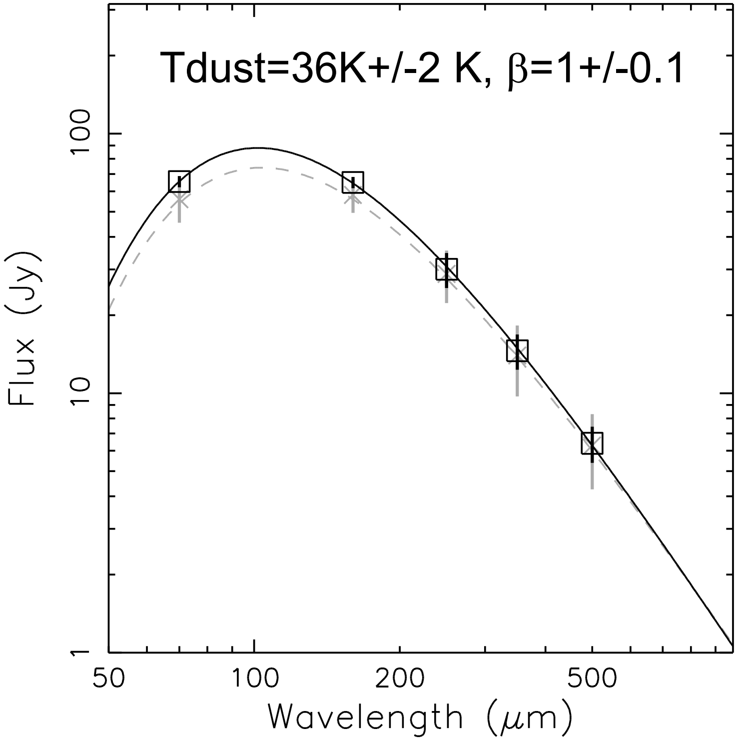
(Schwarz & Monteiro 2006)



(D=0.95 kpc)

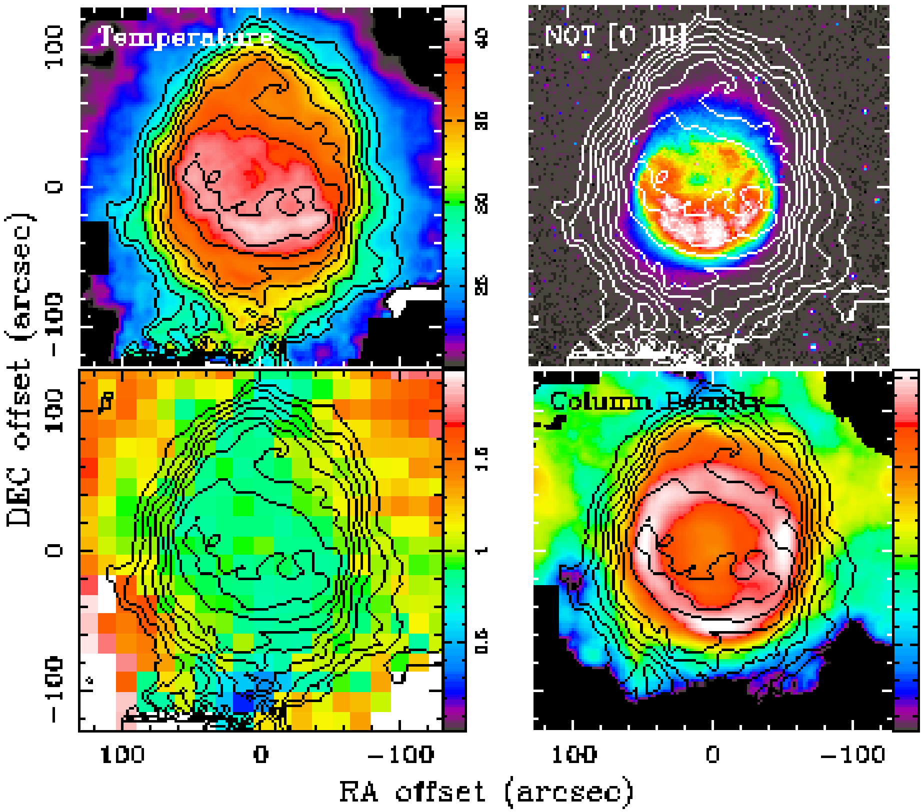
- 10' x 10' broadband maps at 5 wavelengths 70-500 µm (beam 5.6"-36"), 0.02 mJy/arcsec^2 rms
- PACS IFU spectroscopy (5 x 5 grid covering 47" x 47", beam 9.6"-13")
- SPIRE FTS spectroscopy (SSW: 194-342 µm, SLW: 316-672 µm)

NGC6781: Dust Model



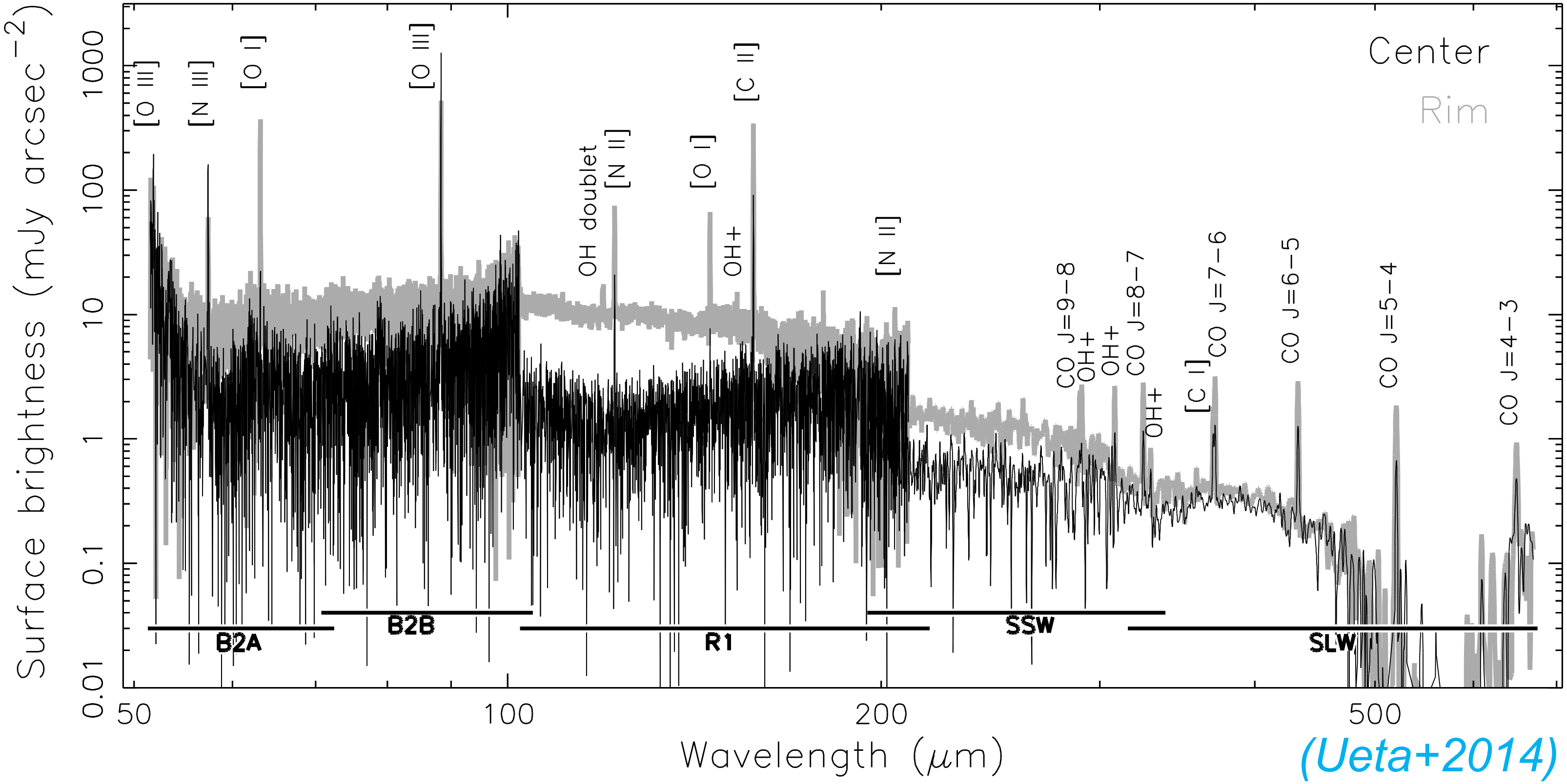
Far-IR SED based on HERPLAN data

(Ueta+2014)



Dust Temperature, Column Density (Msun/pix), β

NGC6781: Far-IR Spectrum

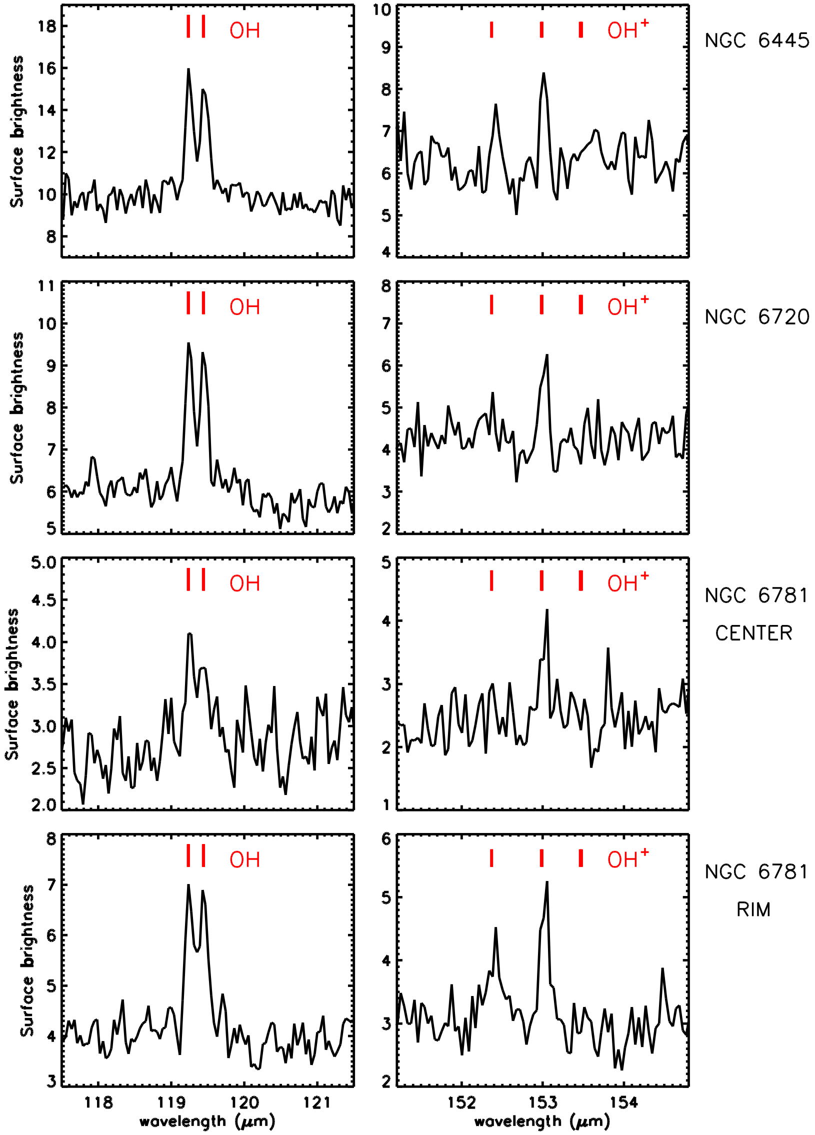


(Ueta+2014)

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.

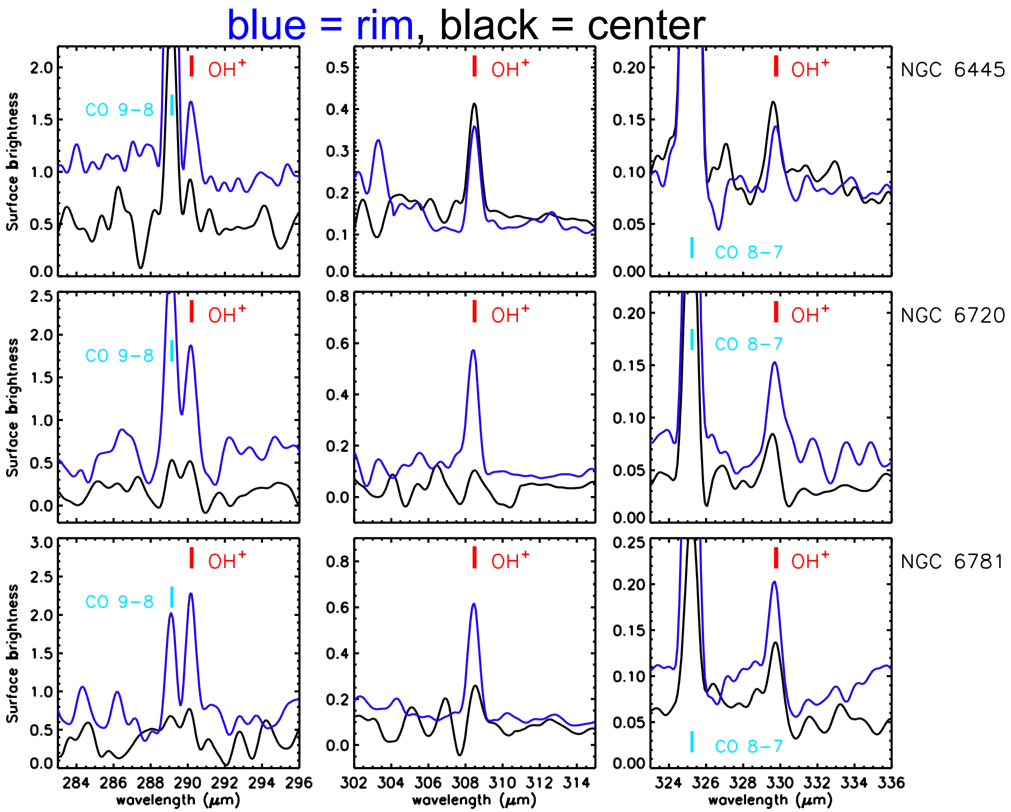
- Gas/Dust 195 +/- 110; Shell Mass 0.86 Msun (0.54 ionized, 0.12 atomic, 0.2 mol)
- Spatially resolved abundances, ratios (C/O, N/O) from far-IR lines
- Progenitor star mass >~1.5 Msun

First detection of OH+ in PNe



OH+, OH lines (PACS & SPIRE)

Aleman+2014 (also Etxaluz+2014)


blue = rim, black = center

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)

GREAT mapping of [CII]158 μm in PNe

- Obtain spatially and velocity-resolved spectra of the [CII]158 μm line (*detected by ISO with 70" beam*) to probe 3-D structure

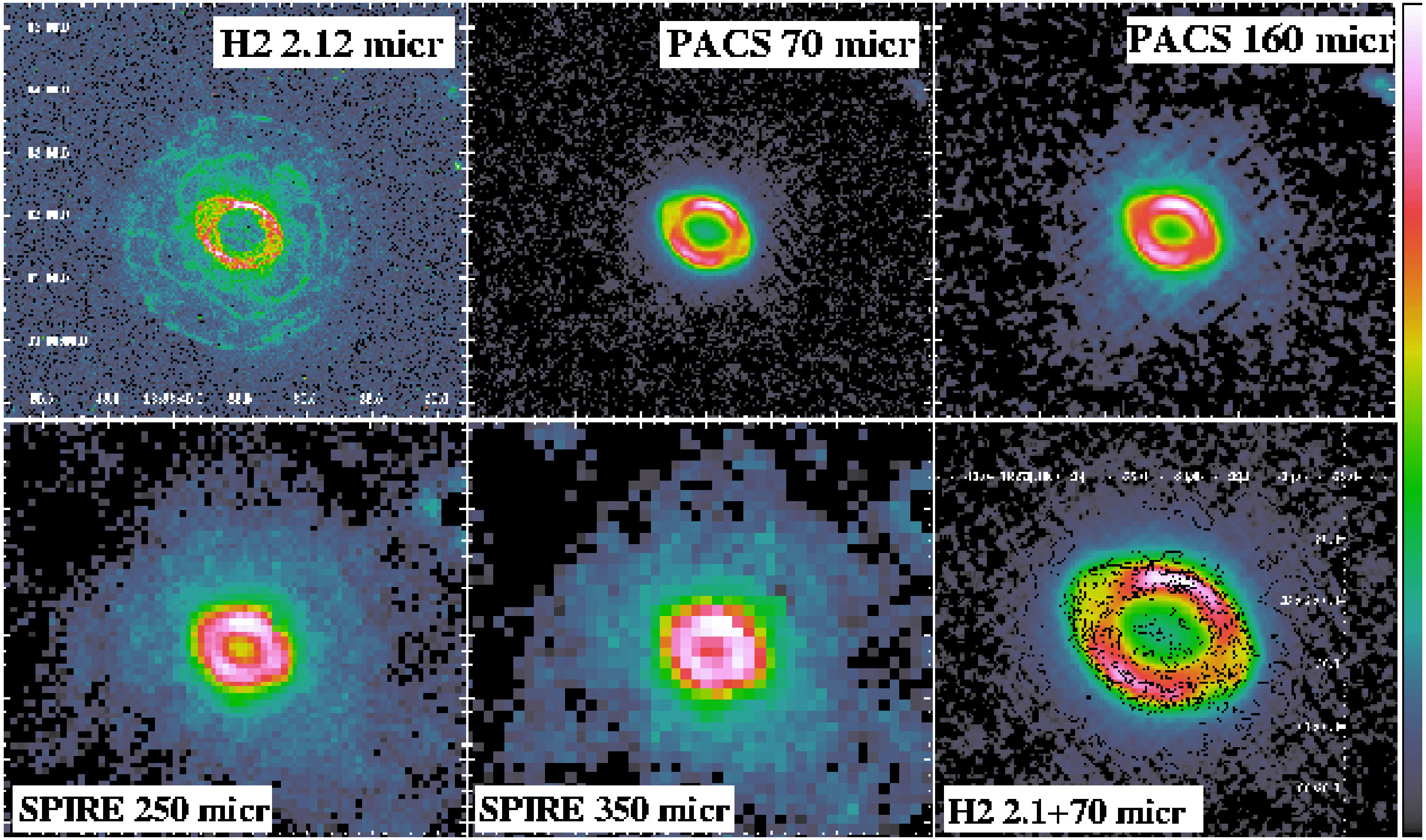
Why [CII]158 μm?

- 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 μm 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 μm, together with [OI]63 and 146 μm, 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



adapted from van Hoof+2010

- 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

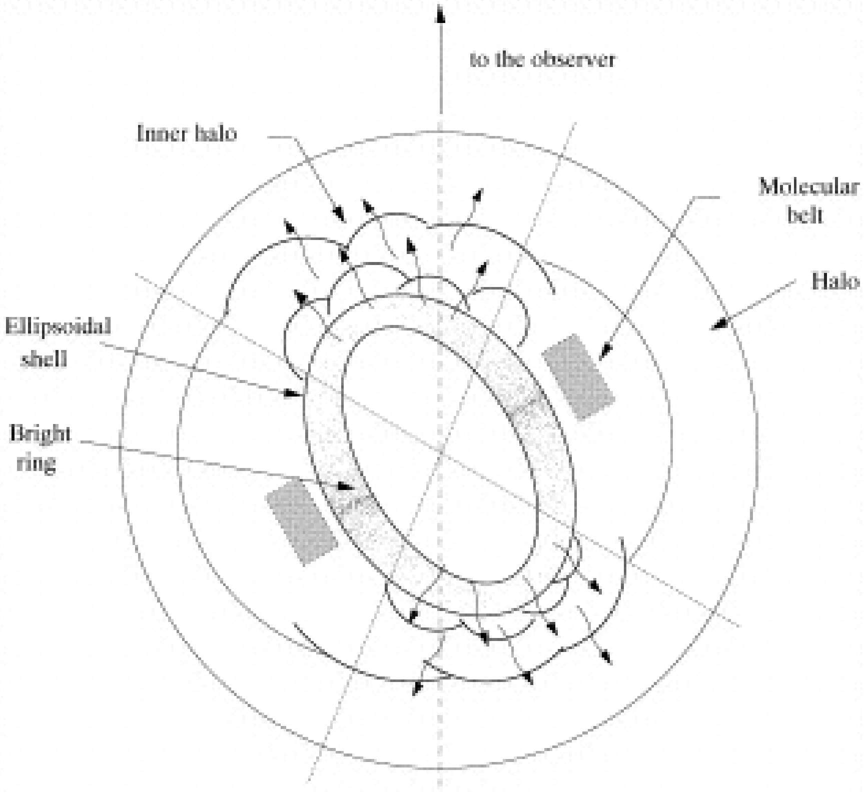
- Torus (1960)
- Flat Ring (1970)
- Cylinder (1974-75)
- Spheroid (1983)
- Bipolar (1992-1994)
- Ellipsoid (1997)

also

Two halos surround bright ring

Inner halo: structured

Outer halo: smooth, circular



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

Most modern models based on velocity-resolved multi-slit optical spectroscopy

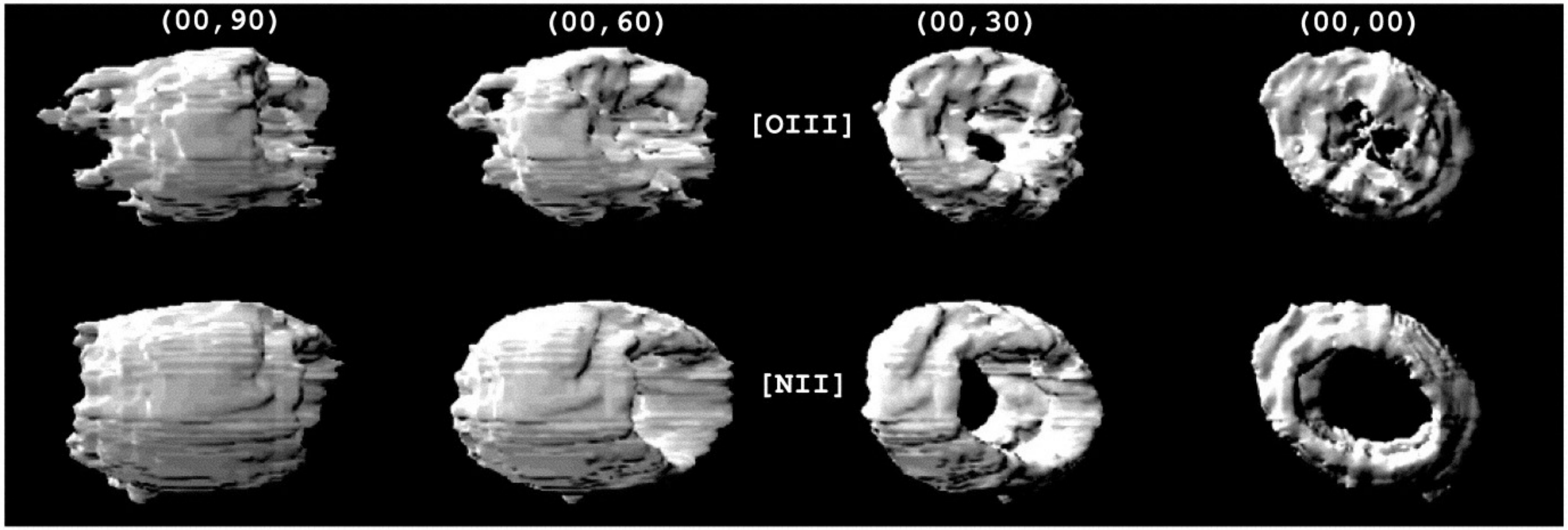
Models: Two Broad Classes

(1) Prolate Ellipsoid

(2) Bipolar, seen nearly pole-on

Molecular Line Studies (CO, H_2) lead to models with elements of both classes

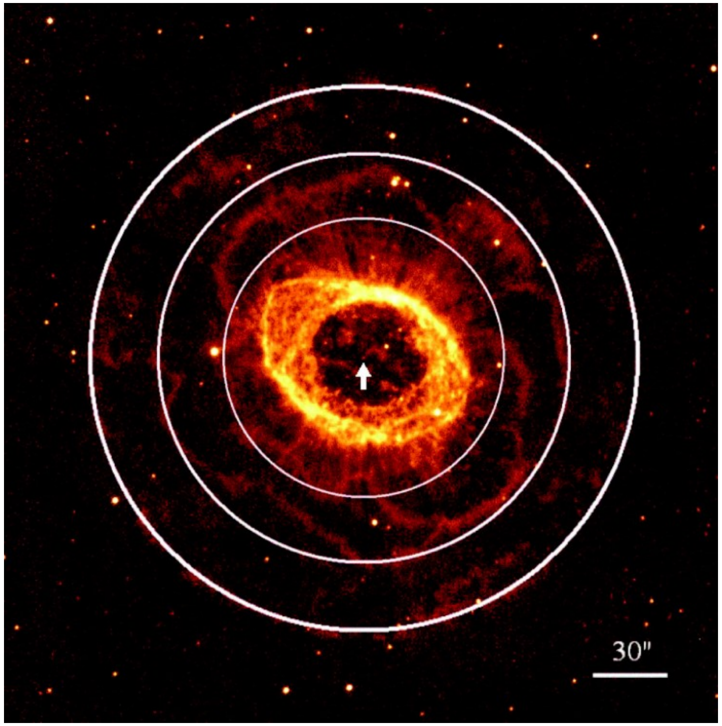
3D Structure: Class 1 model

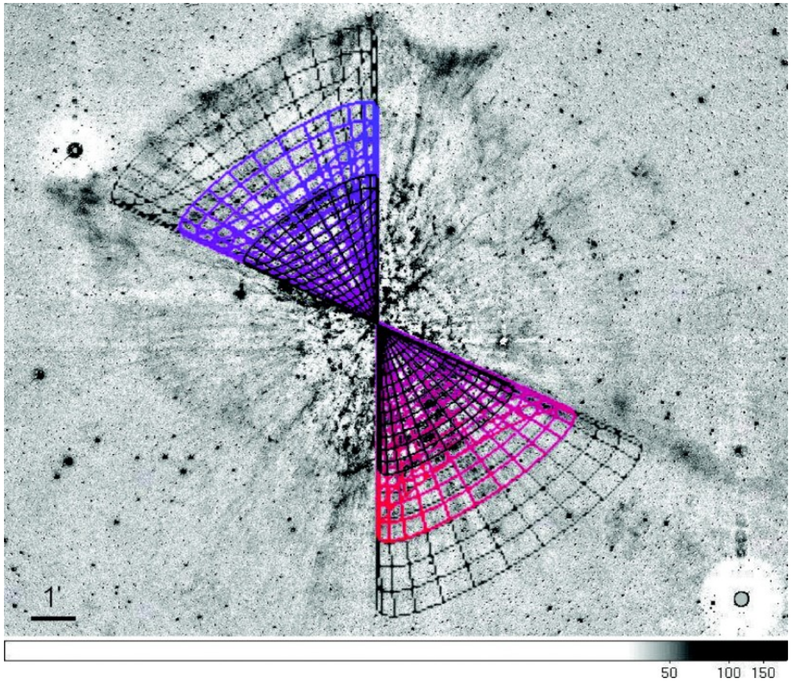


Opaque reconstruction in [OIII] and [NII] at mean flux levels (*O'Dell et al. (2007*)

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**

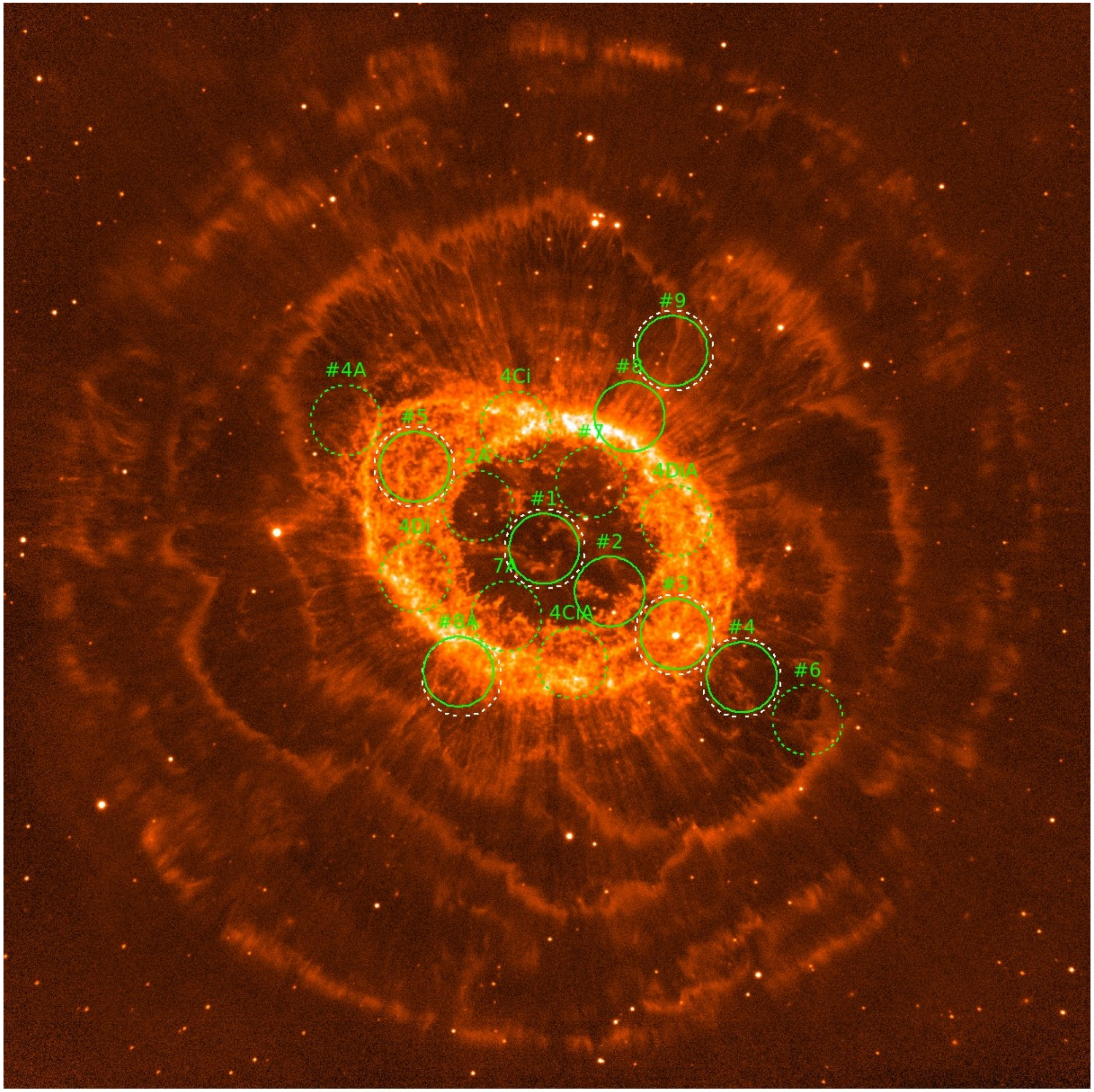
Triple bi-conical shape (seen pole-on) & central torus (bright optical ring)

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*)

NGC6720 (SOFIA)



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

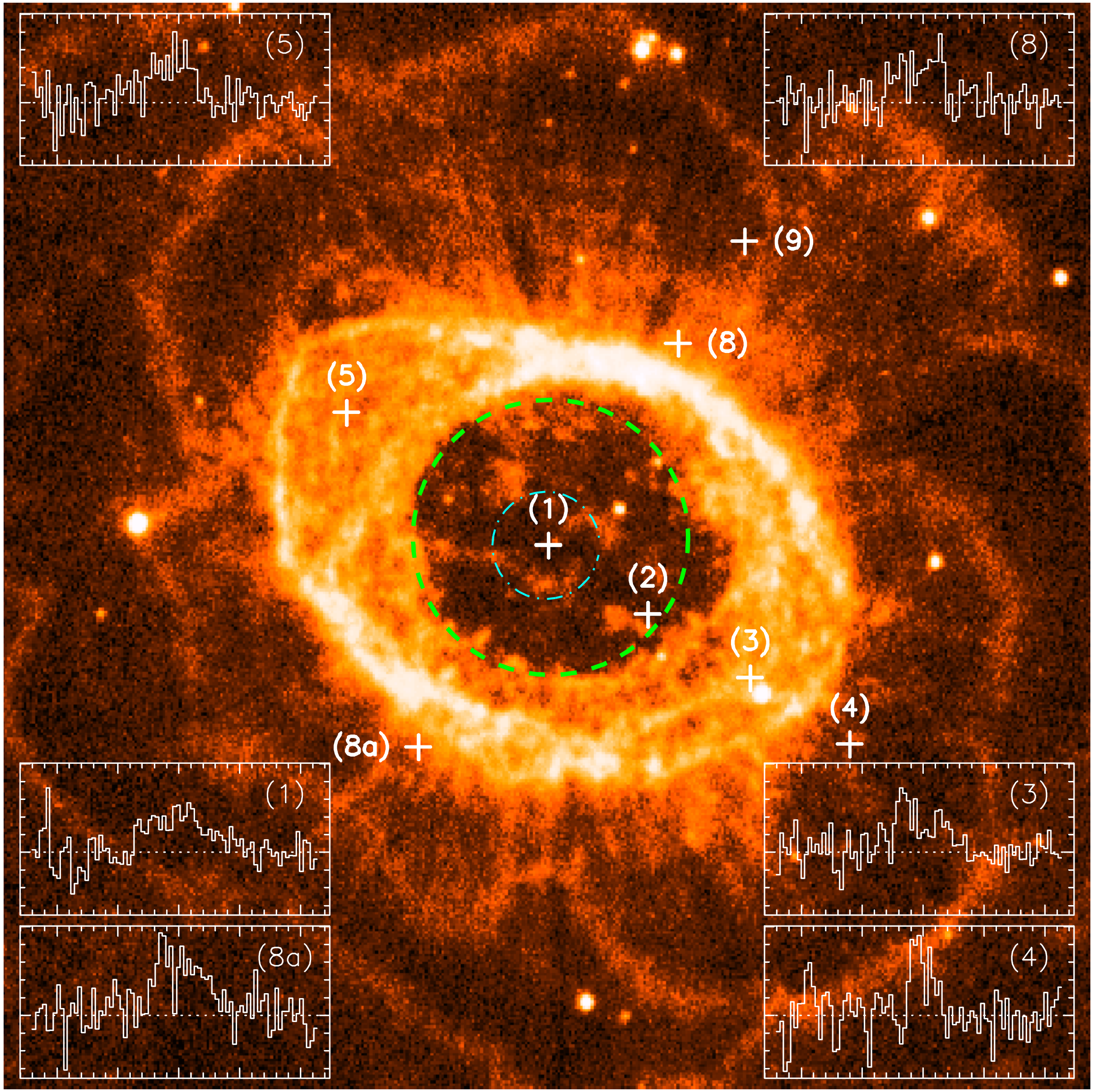
6 min (Cyc 1, Tsys~2600K)

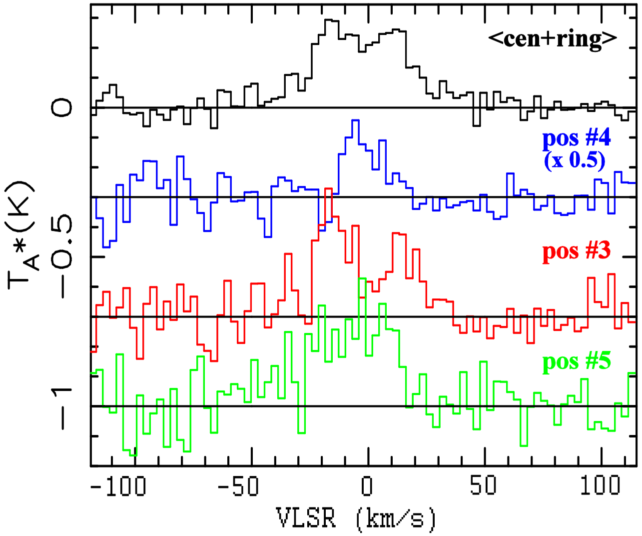
17 min (Cyc 0, Tsys~4500K)

Supplementary APEX data at selected positions for

CO 3-2, 2-1 (white dashed circles) and ^{13}CO 2-1

NGC6720 - SOFIA/GREAT (Cyc 0)





- Mass(PDR)~0.1 Msun (within <88" diameter region)
- Abund Ratio CI/CO > 6.5 in optical shell region

(*using published CO 2-1 data*)

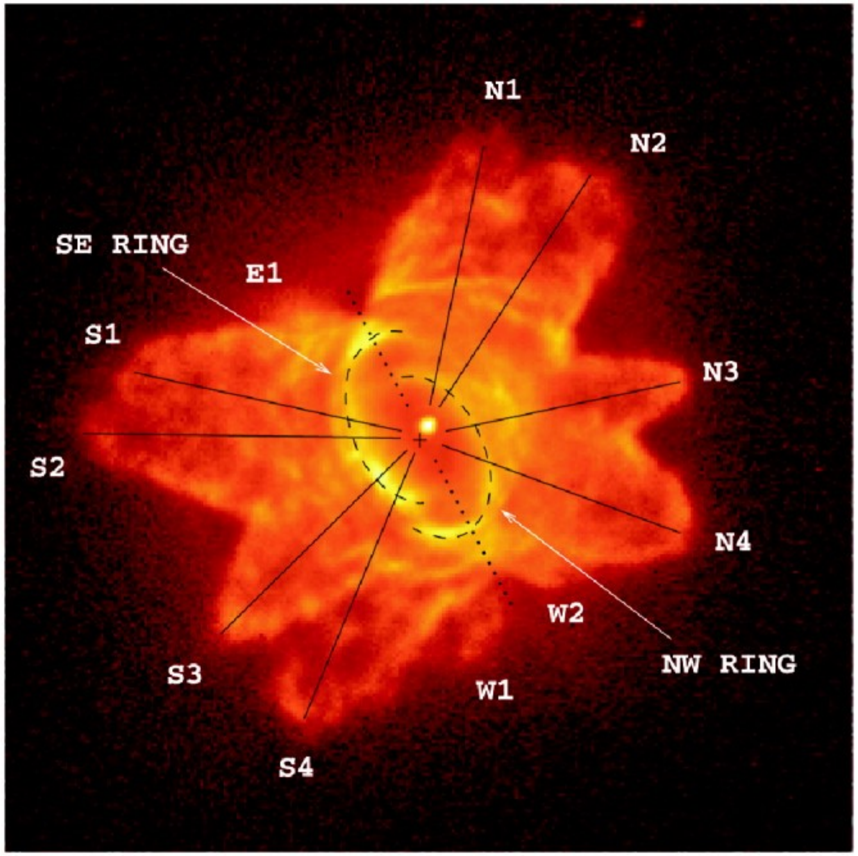
we proposed that best model for NGC6720 is a ***multipolar*** PN **(seen pole-on)** with a **barrel-shaped central region** (a secondary classifier in PN morphological scheme of SMV12)

Sahai, Morris,Werner et al. 2012

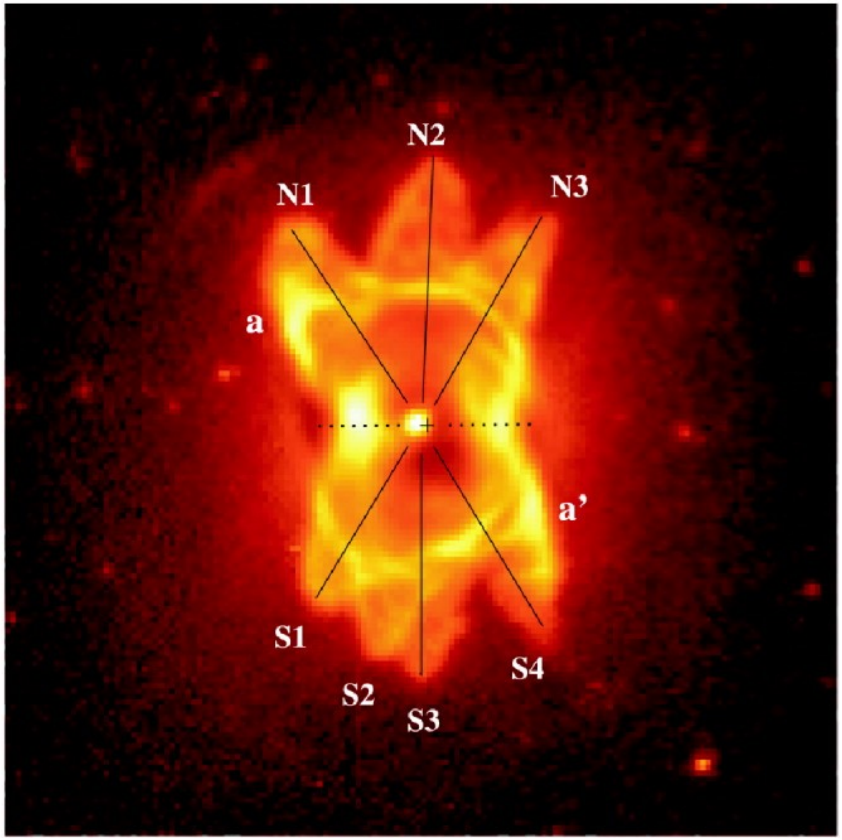
"Starfish Twins"

HST Hα images

He 2-47

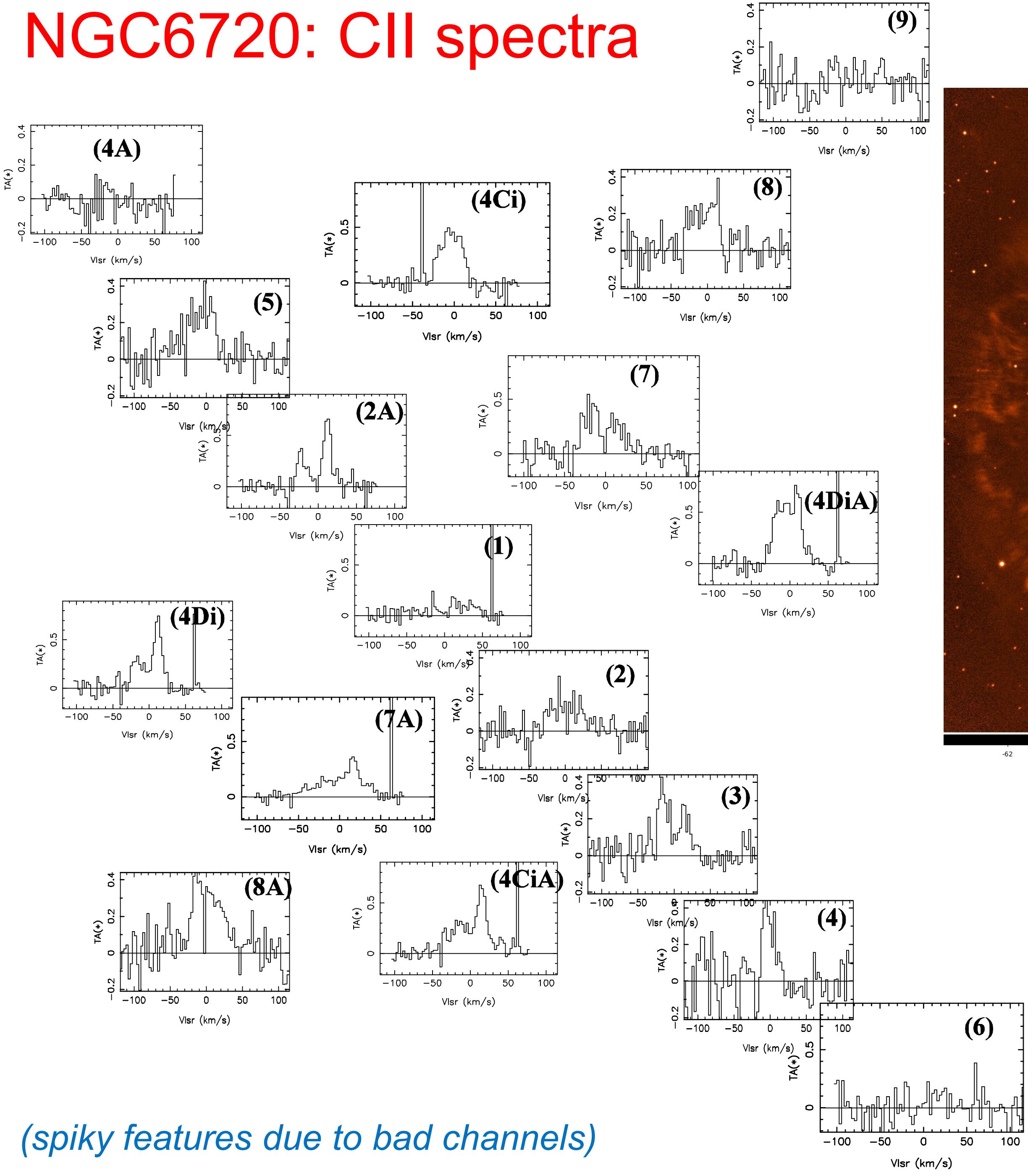


M1-37

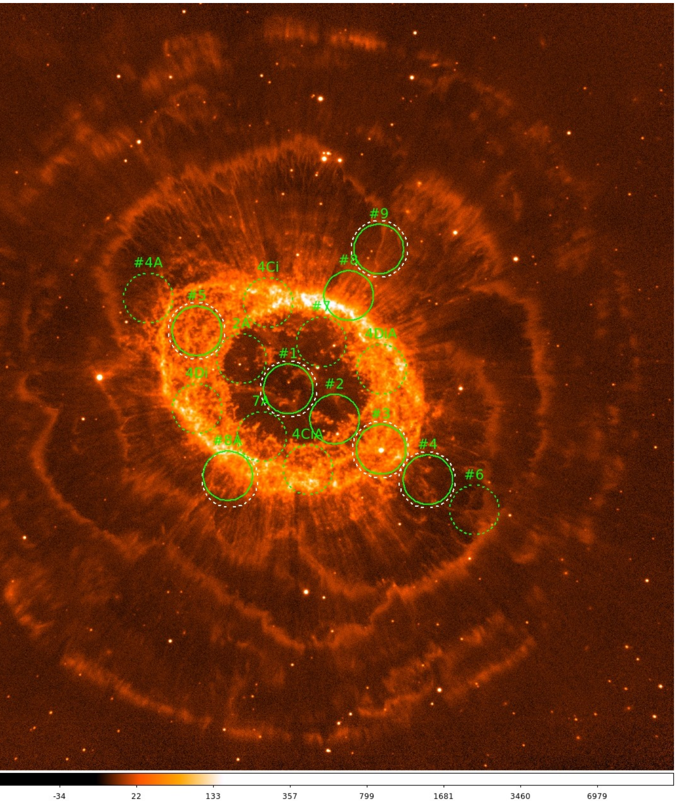


These multipolar PNe give an idea of what NGC6720 might look like at more edge-on orientations

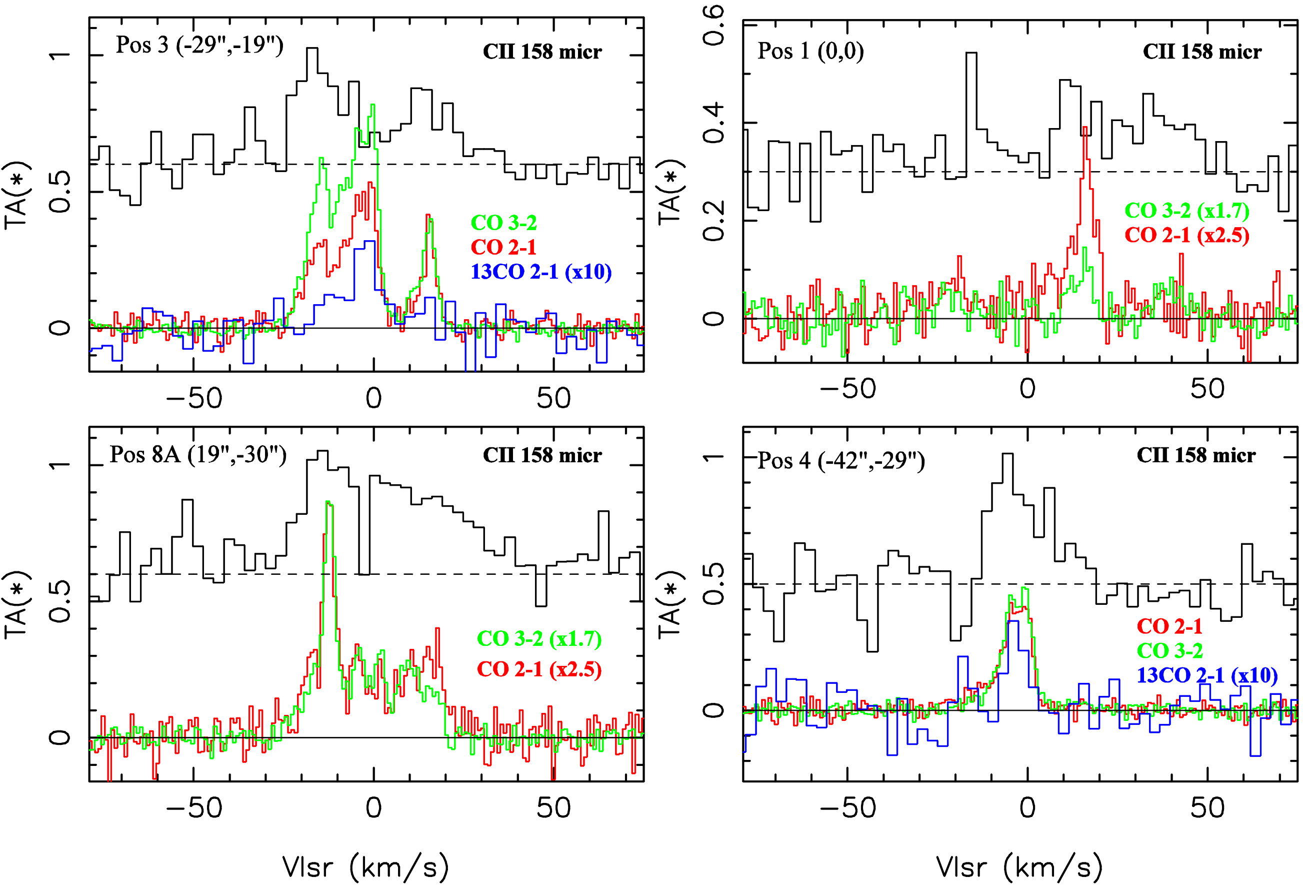
NGC6720: CII spectra



(spiky features due to bad channels)



- 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)



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*

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 (Vlsr ~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 (Vlsr ~ 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 μm line often much stronger than [CII] 158 μm 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

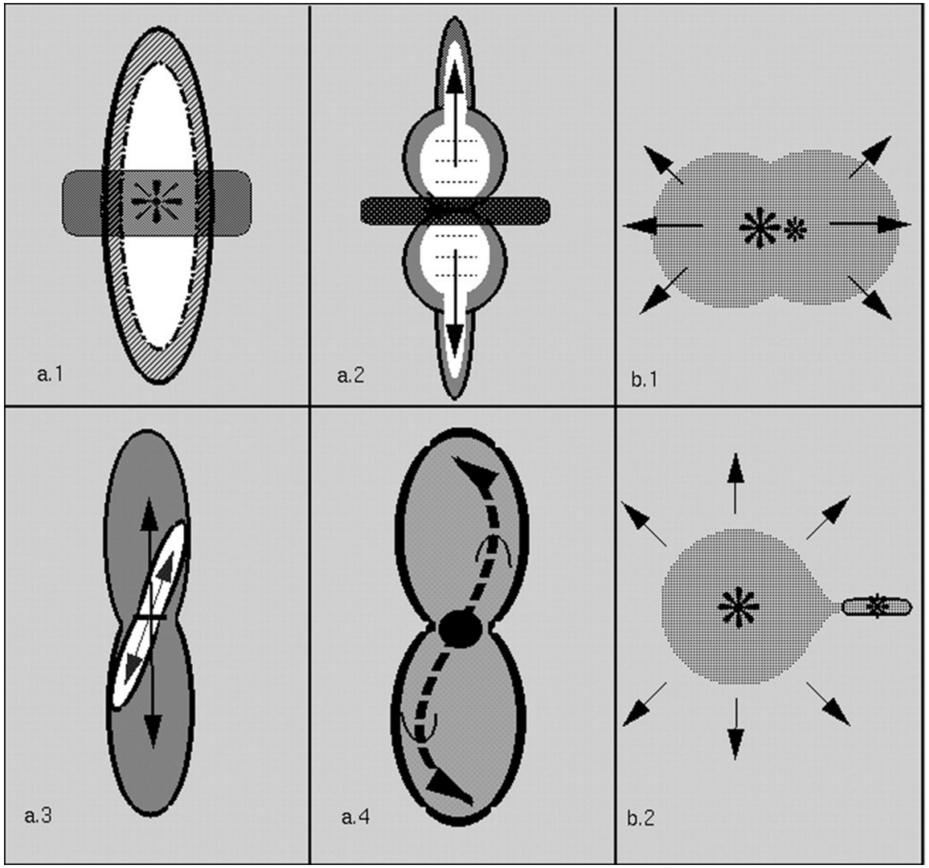
line profiles outside the optical shell should be centrally-peaked at systemic velocity

- 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

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)

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

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

Central Star:

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

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

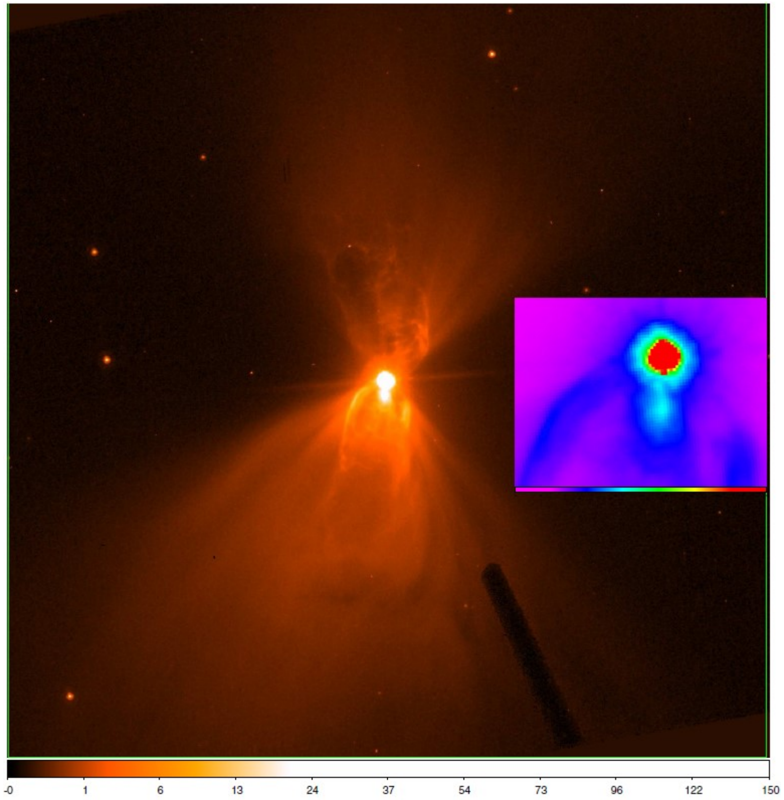
Halo:

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

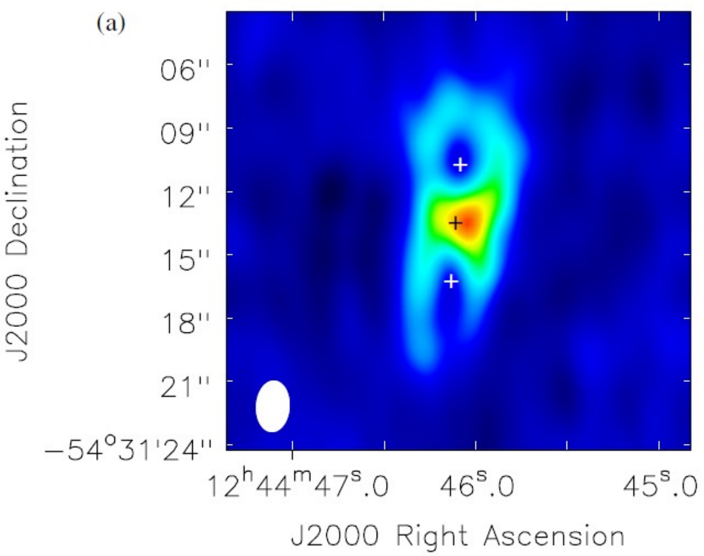
h(d): ionisation front outside main nebula, in progenitor AGB envelope

pAGB mass-loss: Boomerang Nebula

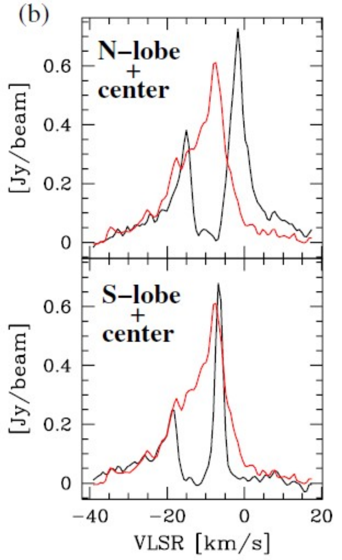
(Sahai, Vlemmings, Nyman, Huggins: Cycle 0 ALMA project: *Sahai+2013*)



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



CO 2-1 image (systemic velocity)



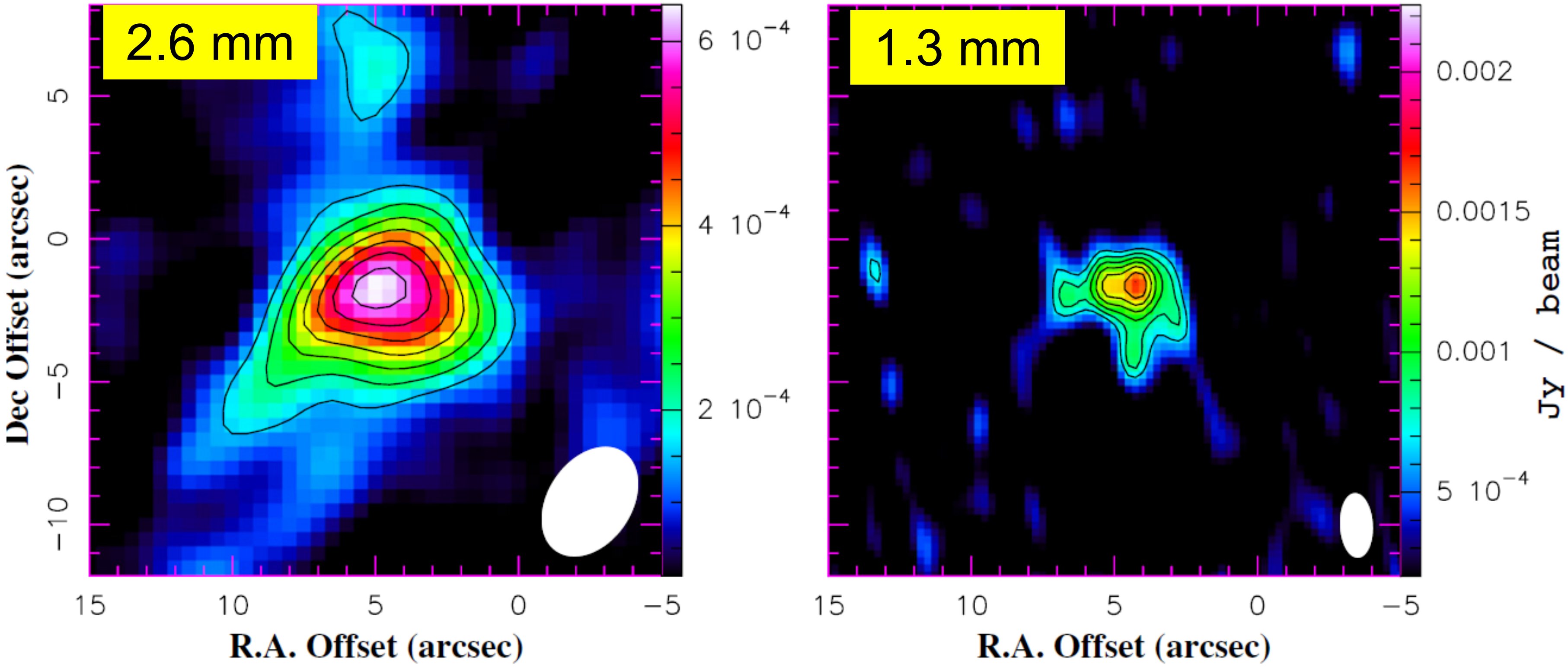
spectra

- 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: 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 $\kappa(1.3mm) \sim 1.5\ cm^2/g$

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

expansion time scale for dust region ~ 420 yr => Mass-loss rate $\sim 1.7 \times 10^{-4}\ M_{sun}/yr$