The Extraordinary Deaths of Ordinary Stars: Probing the 3-D Structure of Planetary Nebulae with GREAT/SOFIA

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Outline

- **The formation of Aspherical Structure in Planetary Nebulae** (form from ~1-8 Msun stars)

A) Nascent Pre-Planetary Nebulae (nPPNe)

B) Pre-Planetary Nebulae (PPNe)

C) Young and Evolved Planetary Nebulae (PNe)

- Overview (selective) of mid- and far-infrared studies (IRAS, MSX, ISO, Spitzer) of AGB stars, PPNe & PNe

- **Using GREAT to study the 3D Structure of PNe**

The Ring Nebula NGC6720

Understanding AGB => PPN => PN Evolution

- ✓ AGB circumstellar envelopes are generally round
- ✓ Round PNe are rare; show a dazzling variety of aspherical shapes *(bipolar, multipolar, elliptical; often with point-symmetry)*

In order to understand this evolution

a) Systematic Characterization of the Formation of Asphericity in PNe

using HST Surveys of nPPNe, PPNe, and Young PNe

b) Determination of the 3-D Spatio-Kinematical Structure of PNe => *Clues to Formation and Shaping Mechanisms*

since the full structure of a PN covers a very wide range of physical conditions - from X-ray emitting very hot gas in the interior of the PN shell, to cool, dense, molecular gas on the outside, a multiwavelength approach is necessary for above

c) Building hydrodynamic models of interacting stellar winds which can produce the 3-D structures

Imaging Surveys: nPPNe, PPNe, and PNe

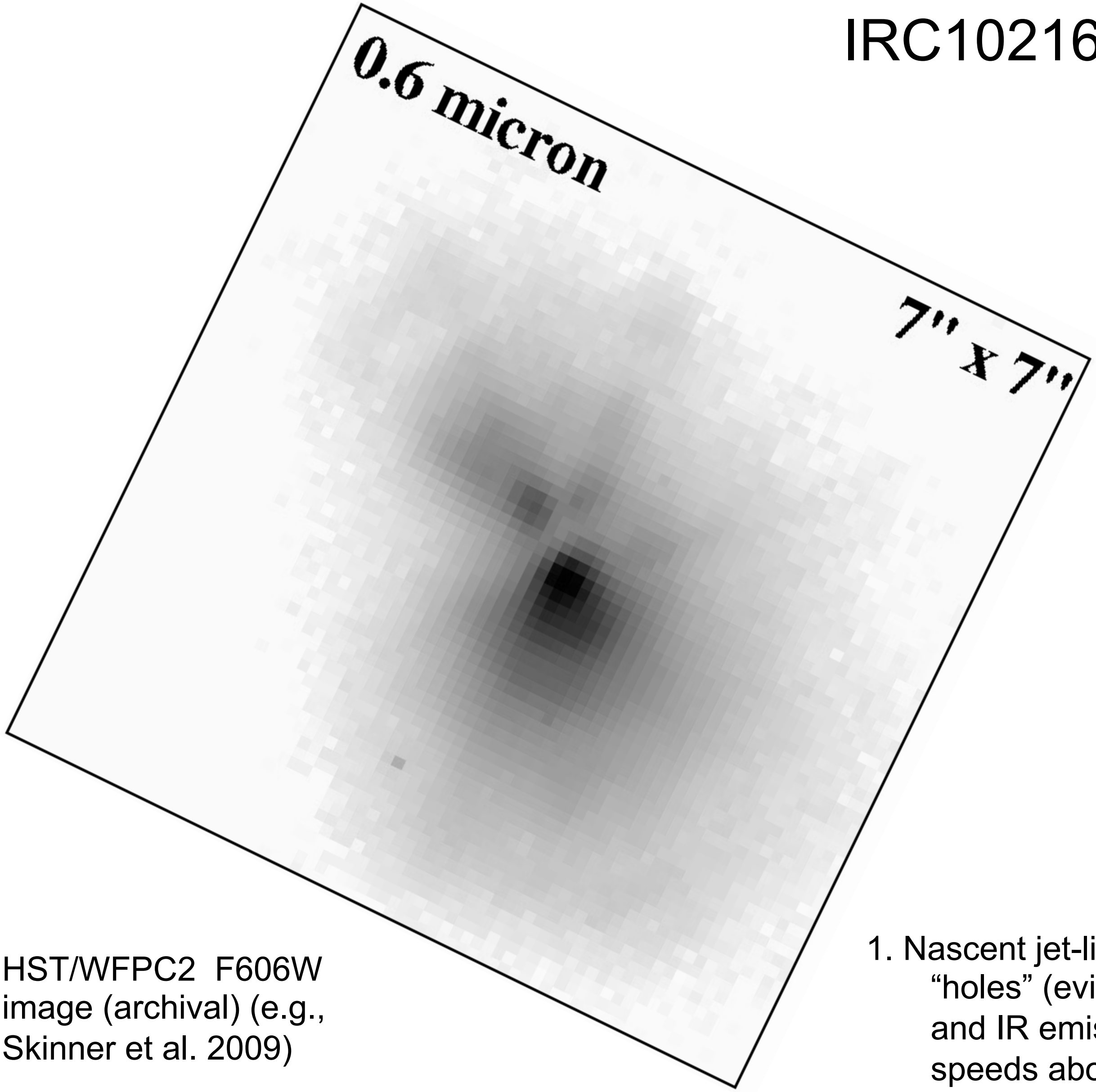
Three morphologically-unbiased HST surveys (*using rather simple selection criteria*) have observationally bracketed the evolutionary phase over which the transition from spherical symmetry to asphericity occurs:

1. Young PN survey(s) (compact, [OIII]/H$\alpha < \sim 1$) (*e.g., Sahai & Trauger 1998; Sahai 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]

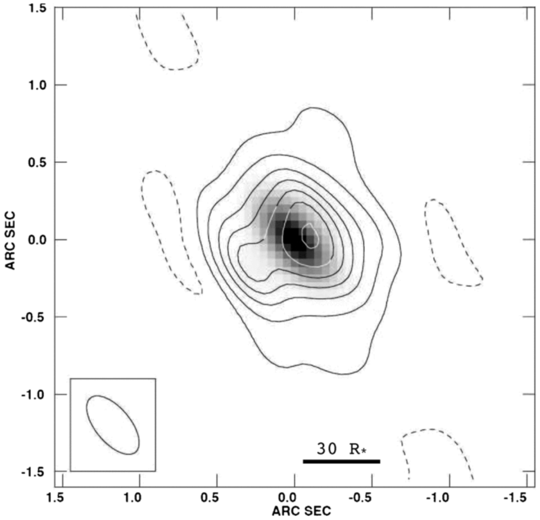
3. Nascent PPN survey [same as in (2), but 1 < F25/F12 < 1.4: earliest phase in PPN evolution] (*Sahai et al. 2010*)

IRC10216 – central region



HST/WFPC2 F606W image (archival) (e.g., Skinner et al. 2009)

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

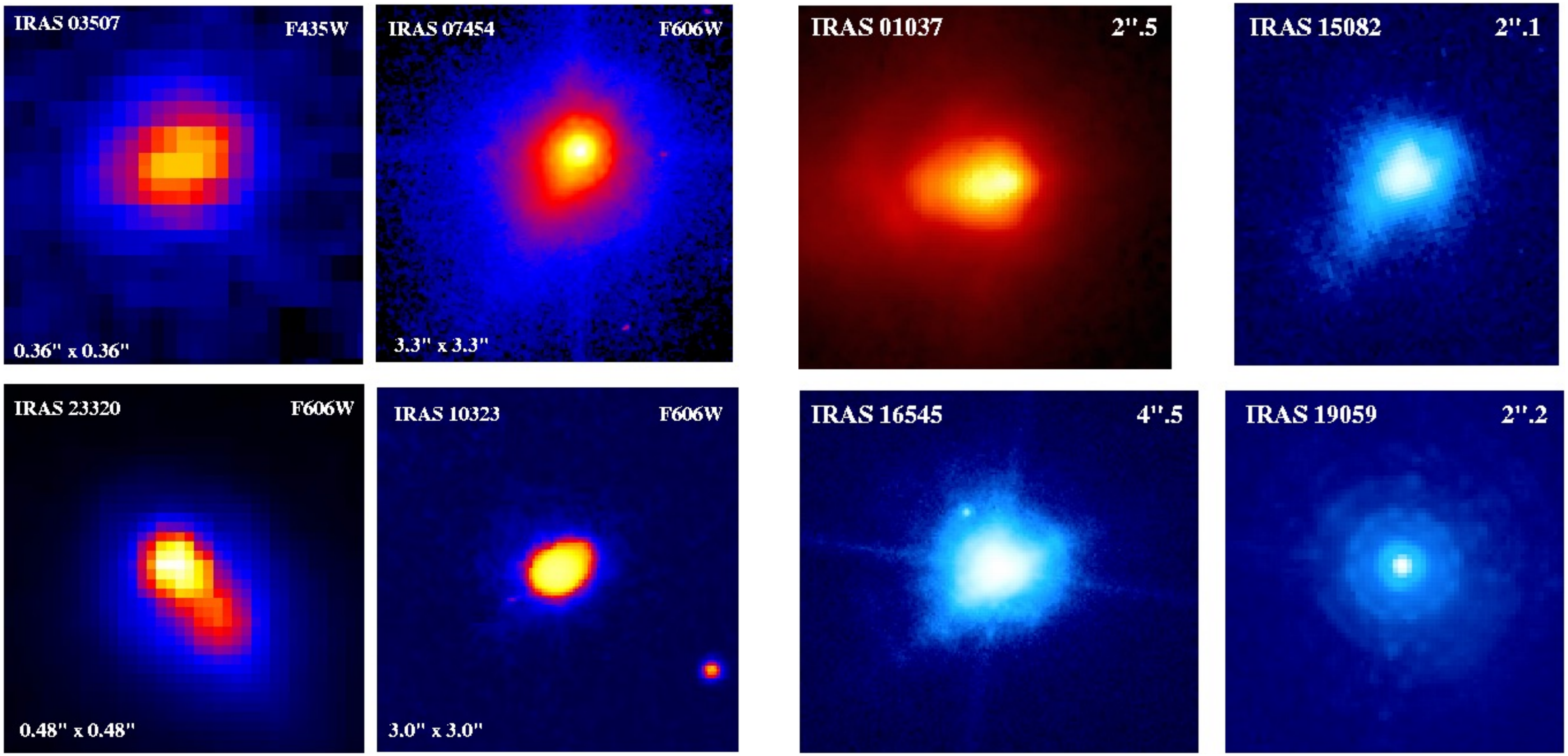


eSMA observations at 1 mm: 4 hr integration, baselines 25-782 m, beam 0.4"x0.22" (Shinnaga et al. 2009)

1. Nascent jet-like outflows may be carving out these "holes" (evidence from single-dish mm-wave and IR emission lines for outflowing gas at speeds about 5-10 km/s beyond expansion of AGB envelope)

- Torus(?) in eSMA HCN map

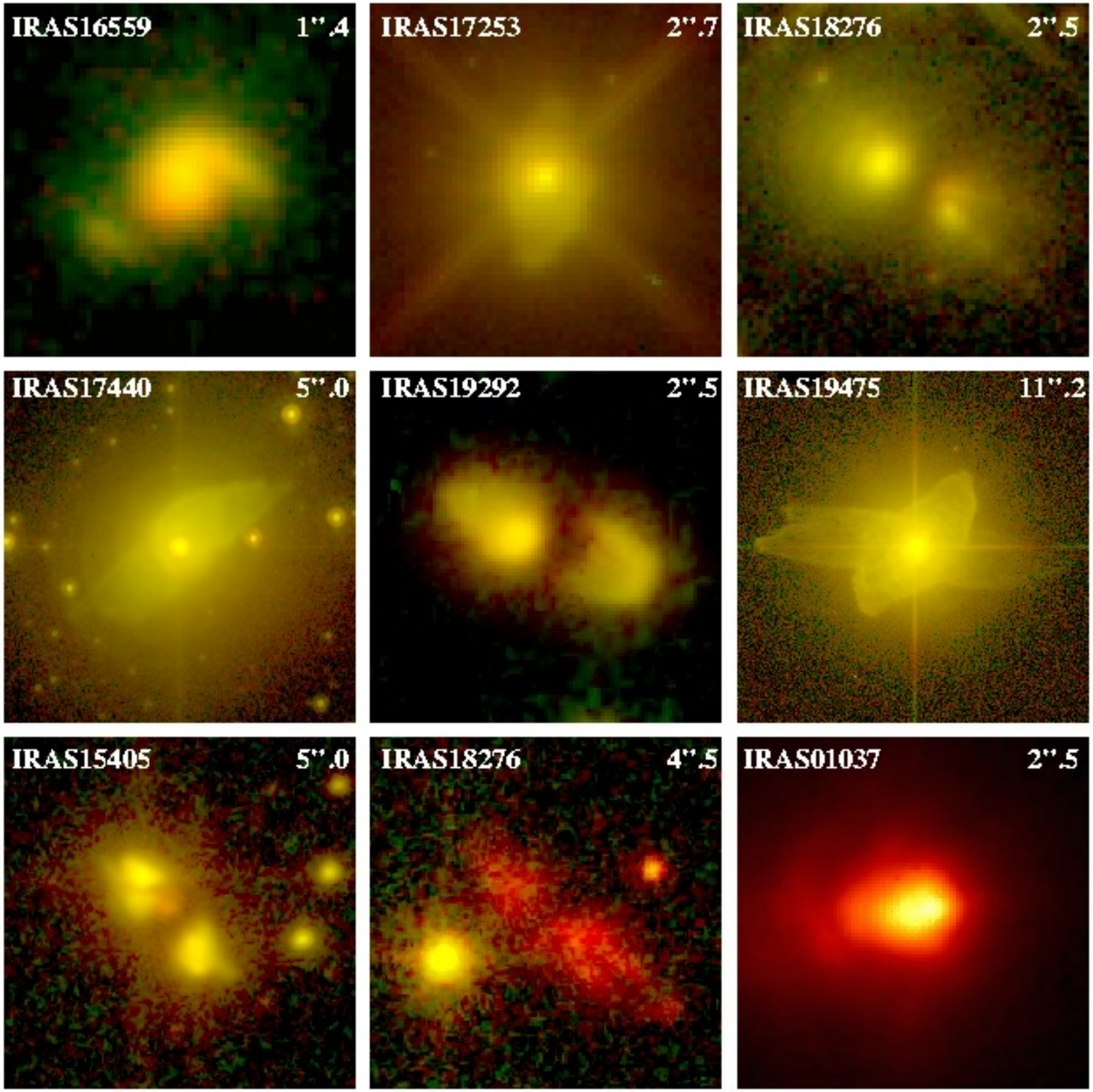
Nascent PPNs (nPPNs)



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, **M**ultipolar

Elongated, **I**rregular

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

Important Point-Symmetric objects are NOT A PRIMARY CLASS

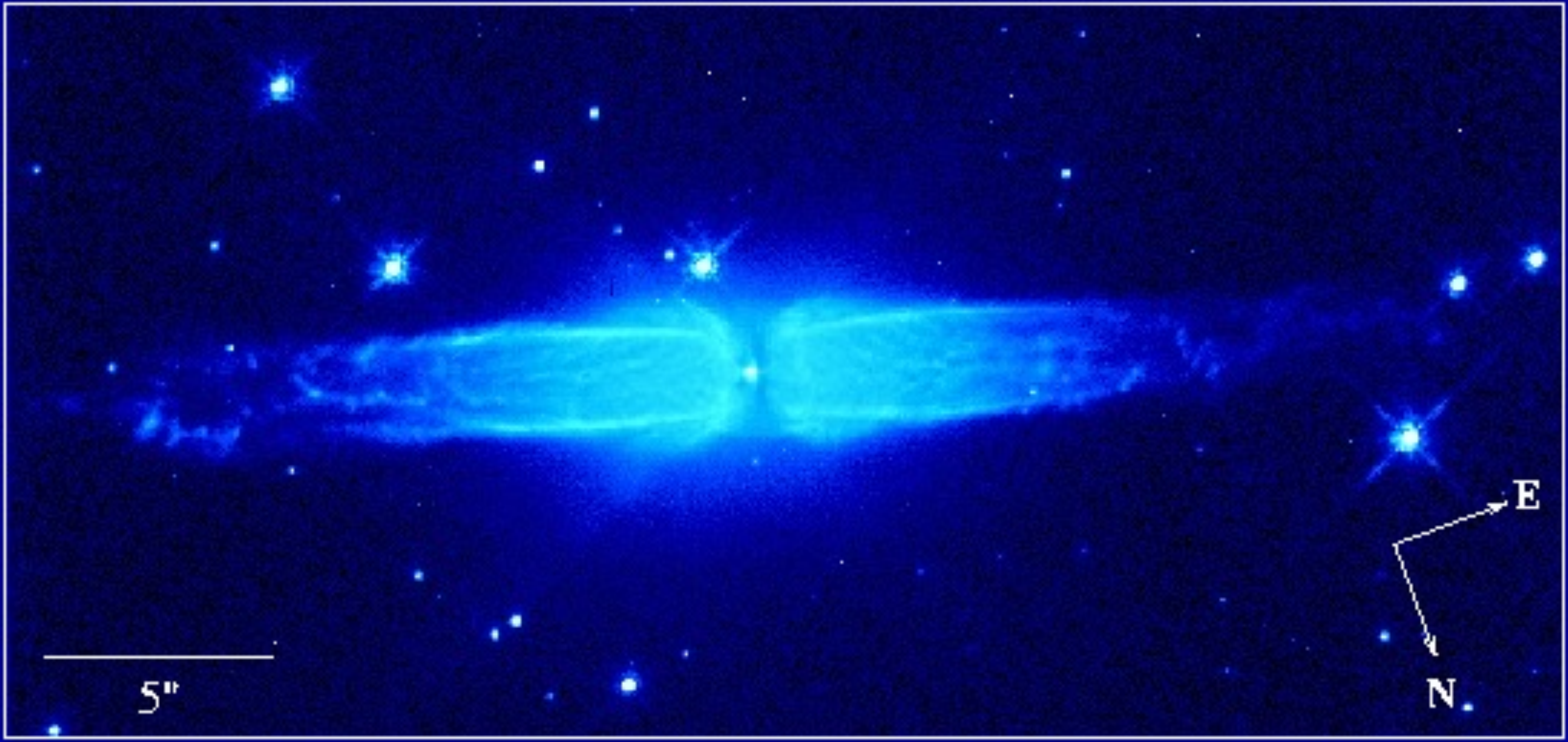
Point-symmetry found in all classes, except I(rregular)

Multipolar PPN IRAS19024

- R/J/H 3-color HST image (5”x5”)
- Multiple elongated lobes
- Double-torus dusty waist
- High-vel compact outflow

(seen via P-Cygni Hα profile with broad wings)

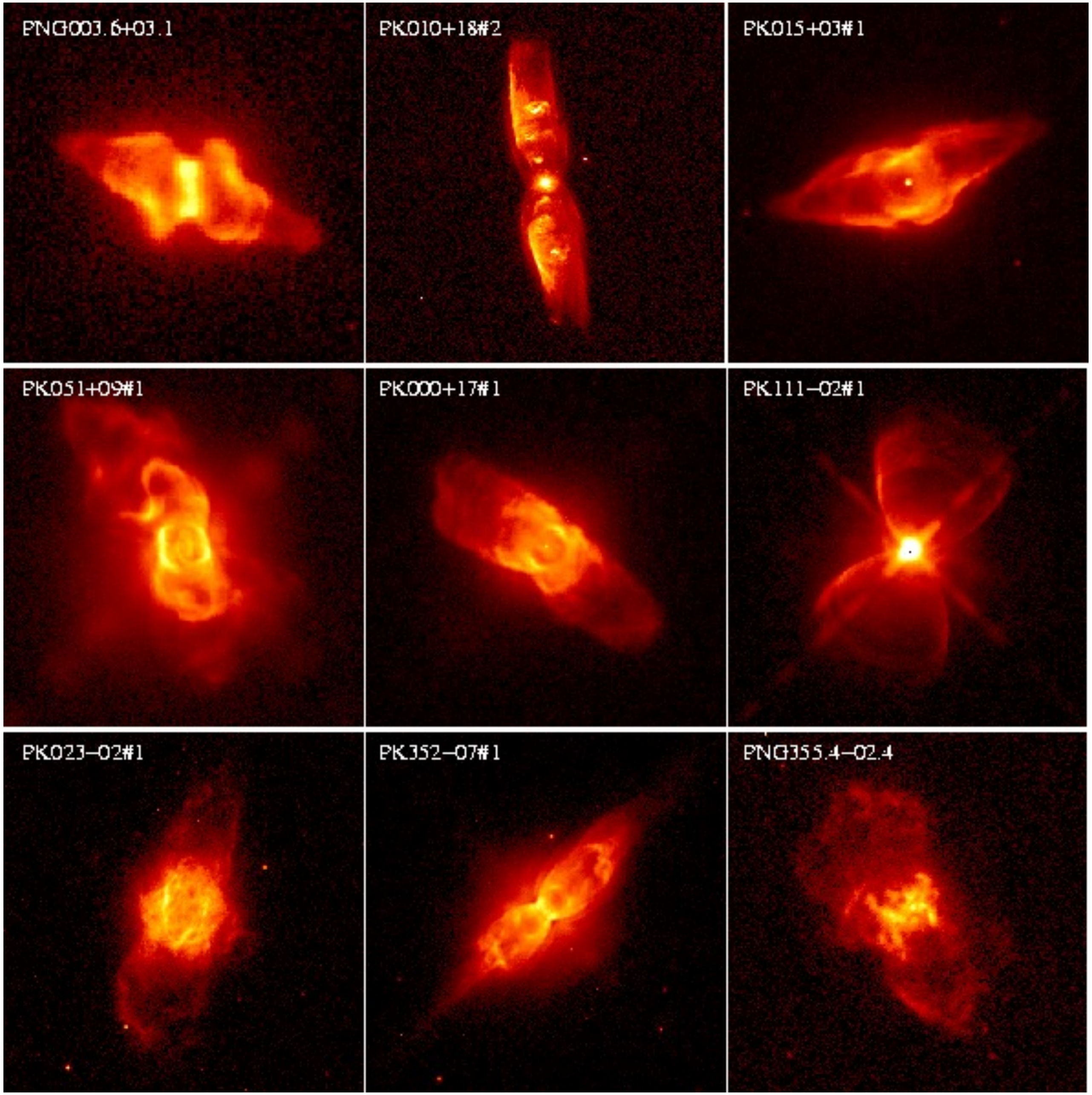
(*Sahai et al. 2005*)



Henize 3-401 (PPN)

(Sahai et al. 1999, ApJ Letters, 518, L115)

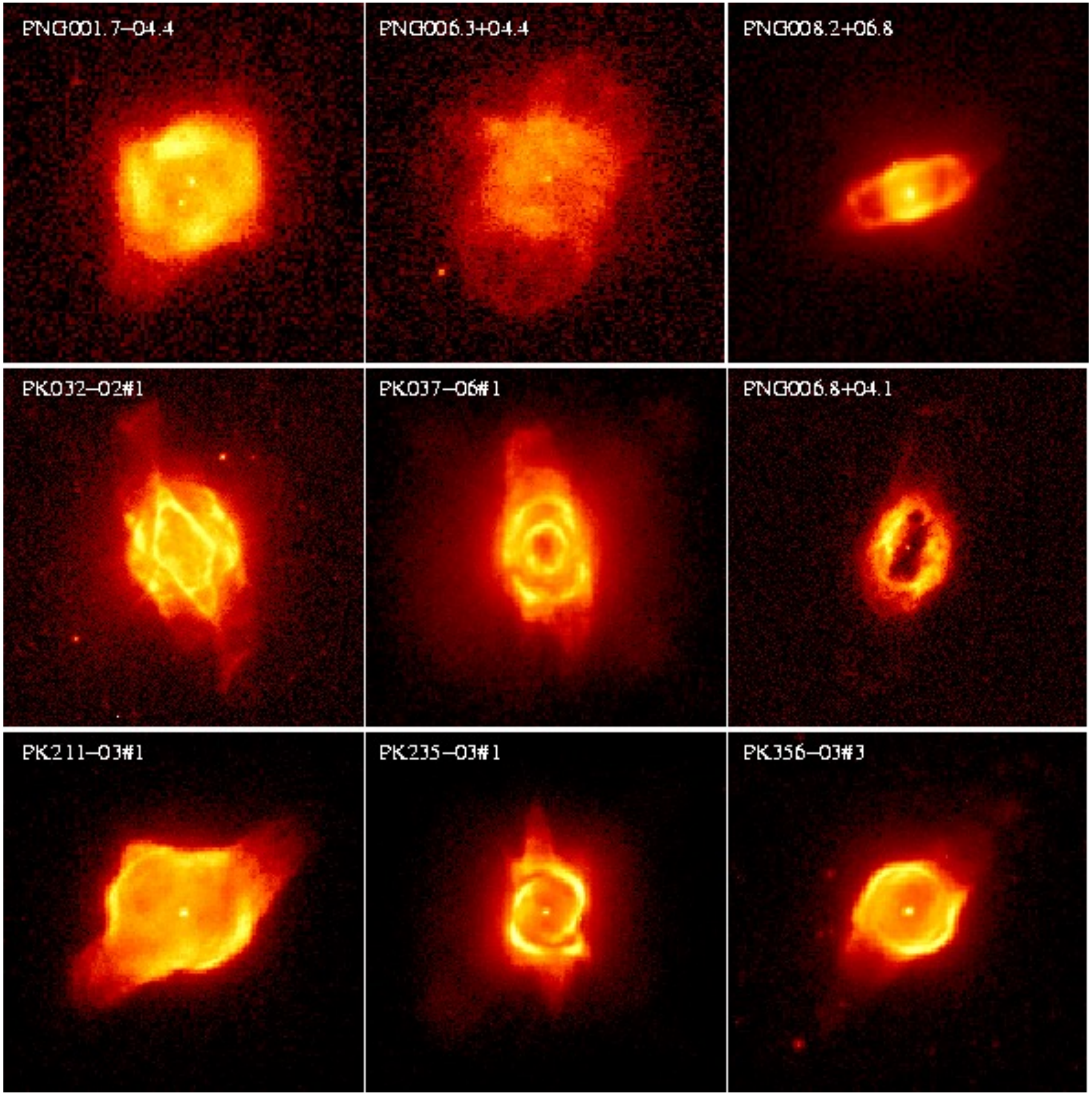
PNs: Primary Class B (bipolar)



27% (32/117 objects)

Adapted from
Sahai, Morris & Villar (2011)

Primary Class L (collimated-lobe pair)

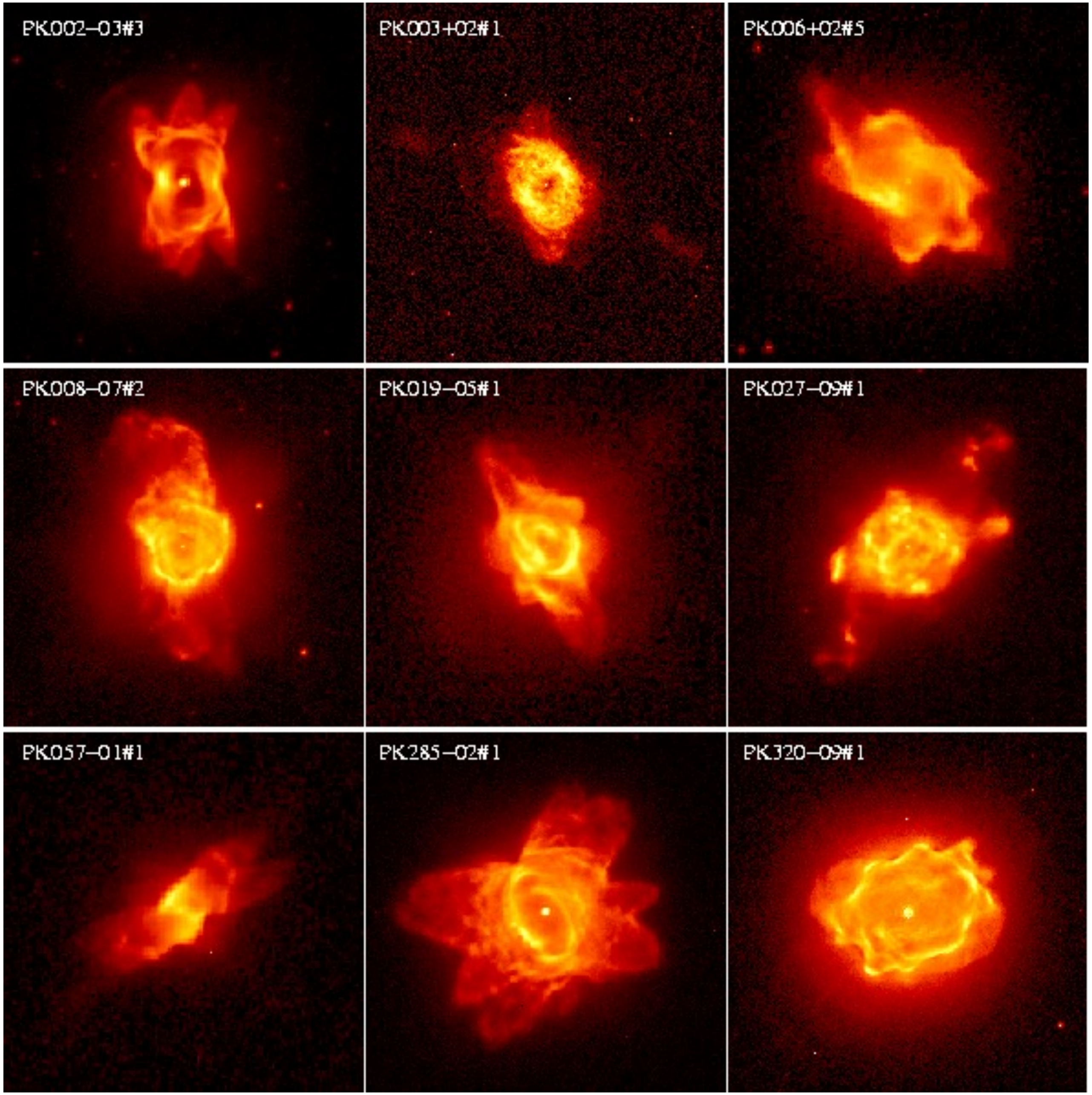


8.5% (10/117 objects)

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)

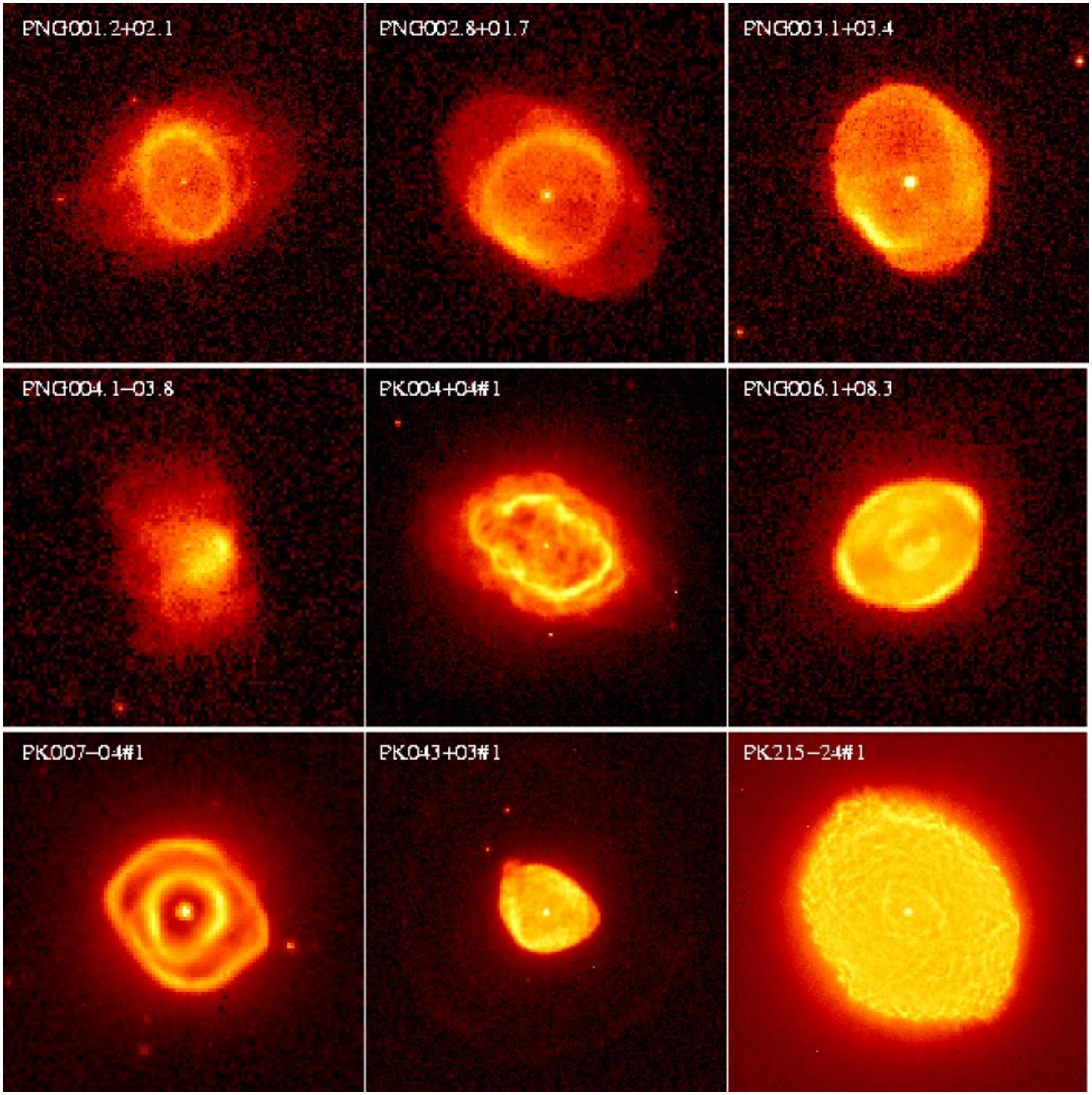
Primary Class M (multipolar)



20% (23/117 objects)

Adapted from
Sahai, Morris & Villar (2011)

Primary Class E (elongated)

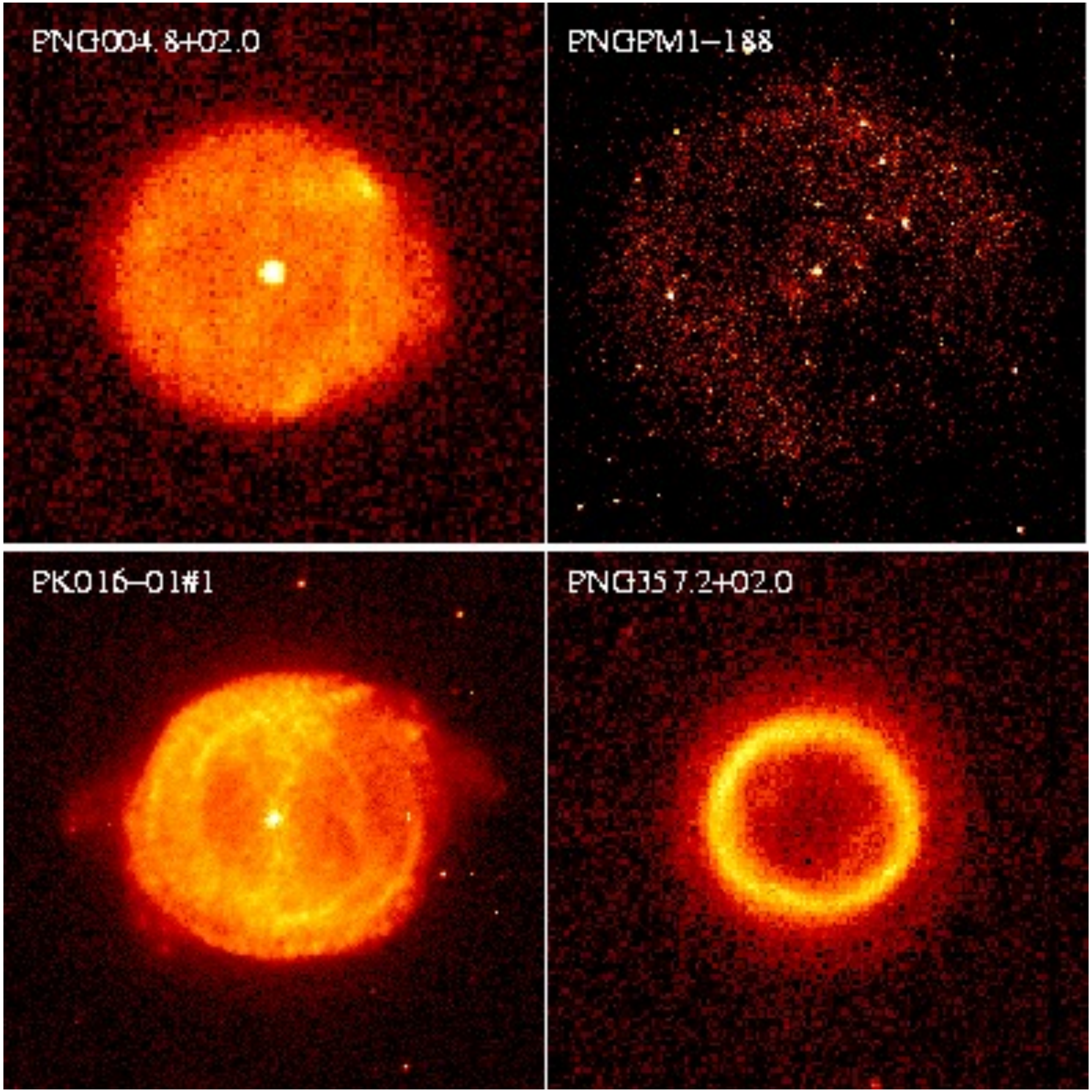


31% (36/117 objects)

Adapted from
Sahai, Morris & Villar (2011)

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

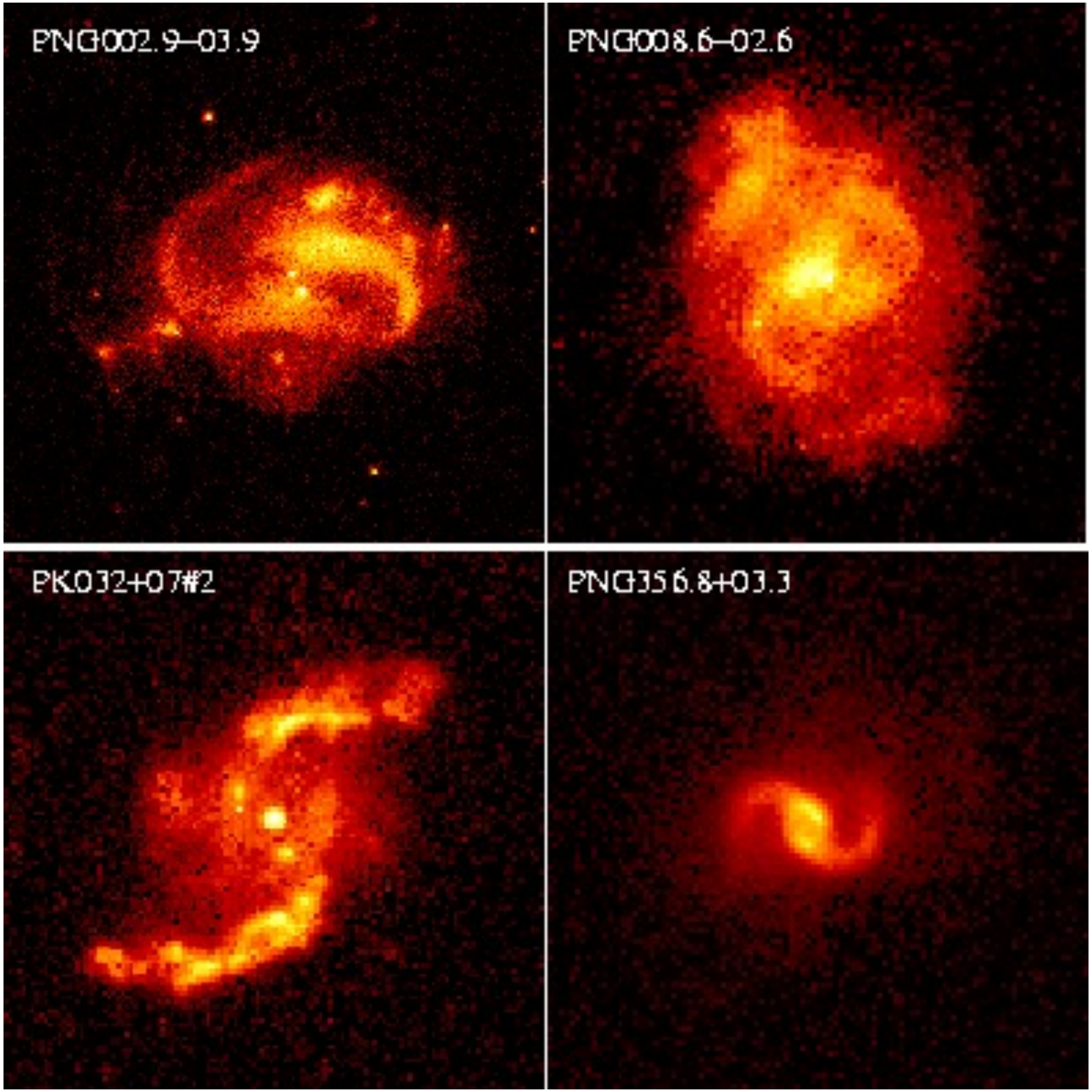
Primary Class R (round)



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)

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

PN shapes/shaping: Primary Physical Processes (1)

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. From a study of a small sample, 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 tend to preserve their shapes/geometries (since main morphological classes same in PPNe and young PNe)

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

Fundamental Questions

- What is the origin and properties of the CFWs (~few x100 km/s) (e.g., scalar momentum, episodicity)?

(understanding these will also help in our general understanding of the astrophysical jet phenomena and launching mechanisms -- rotation/ magnetic fields, accretion disks, disk instabilities)

- 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]

Hydrodynamical Simulations

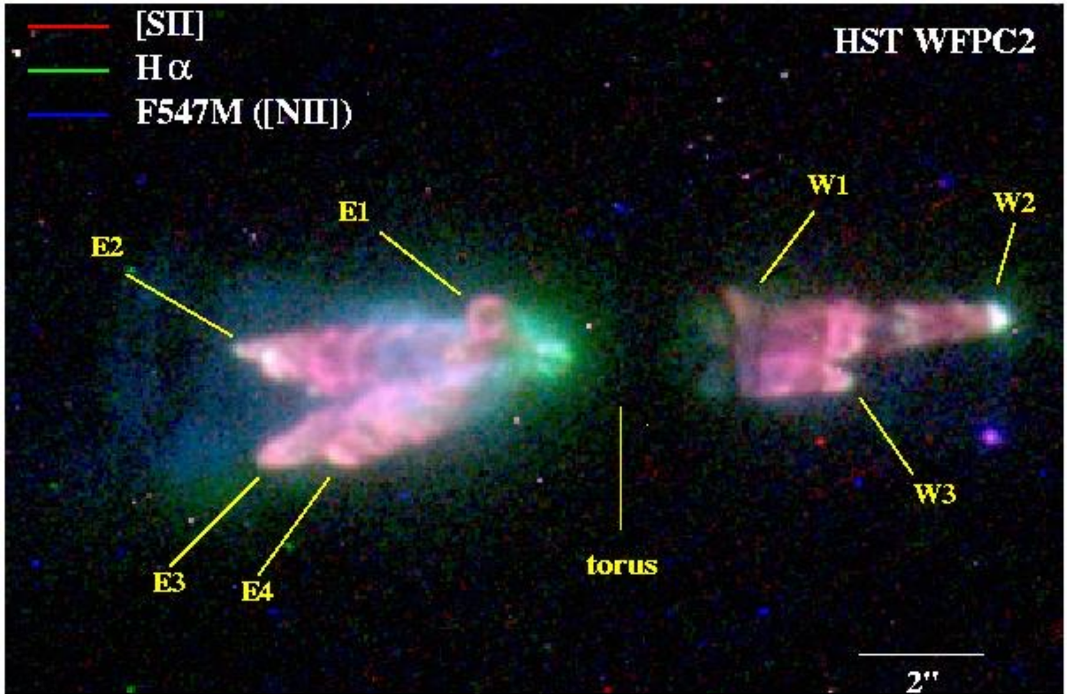
- Numerical simulations of (magneto) hydrodynamic interactions of stellar winds are needed in order to build quantitative models for the formation/shaping of PNe

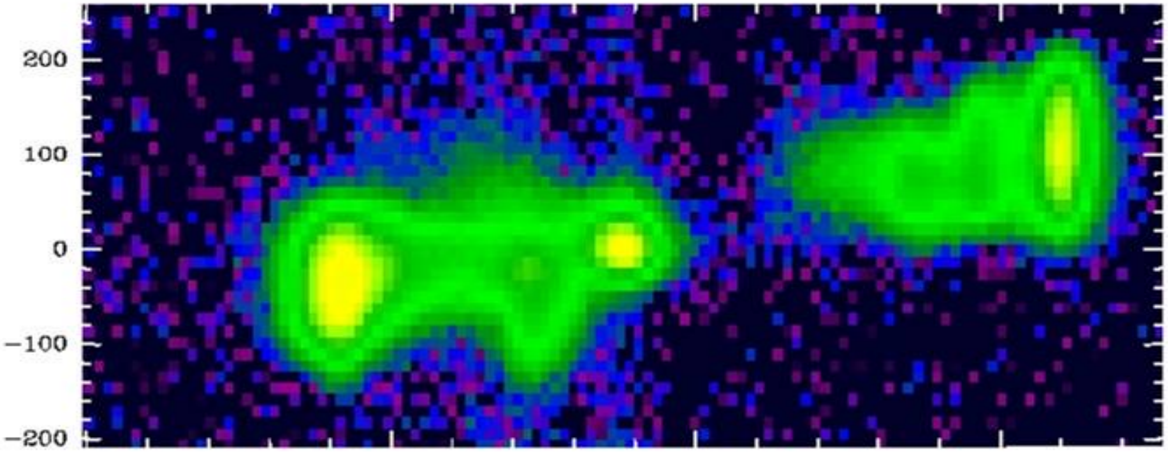
(1) CFW interacting with spherical AGB wind =>

modelling of the spatio-kinematic structures of PPNe => infer the physical properties of the CFWs e.g., mass and momentum flux, opening angle, episodicity, duration

(2) SRFW and ionisation front interacting with structured PPN shape => modelling of the spatio-kinematic structures of PNe => understand the final shaping processes which lead to young and evolved PNe

CFW interacting with spherical AGB wind





Position-Velocity plot of [NII]6584
(unpublished Keck ESI data – Sahai, Morris, Goodrich)

CRL618

-- hot (B sp.type), post-AGB central star (obscured by a dense, dusty torus)

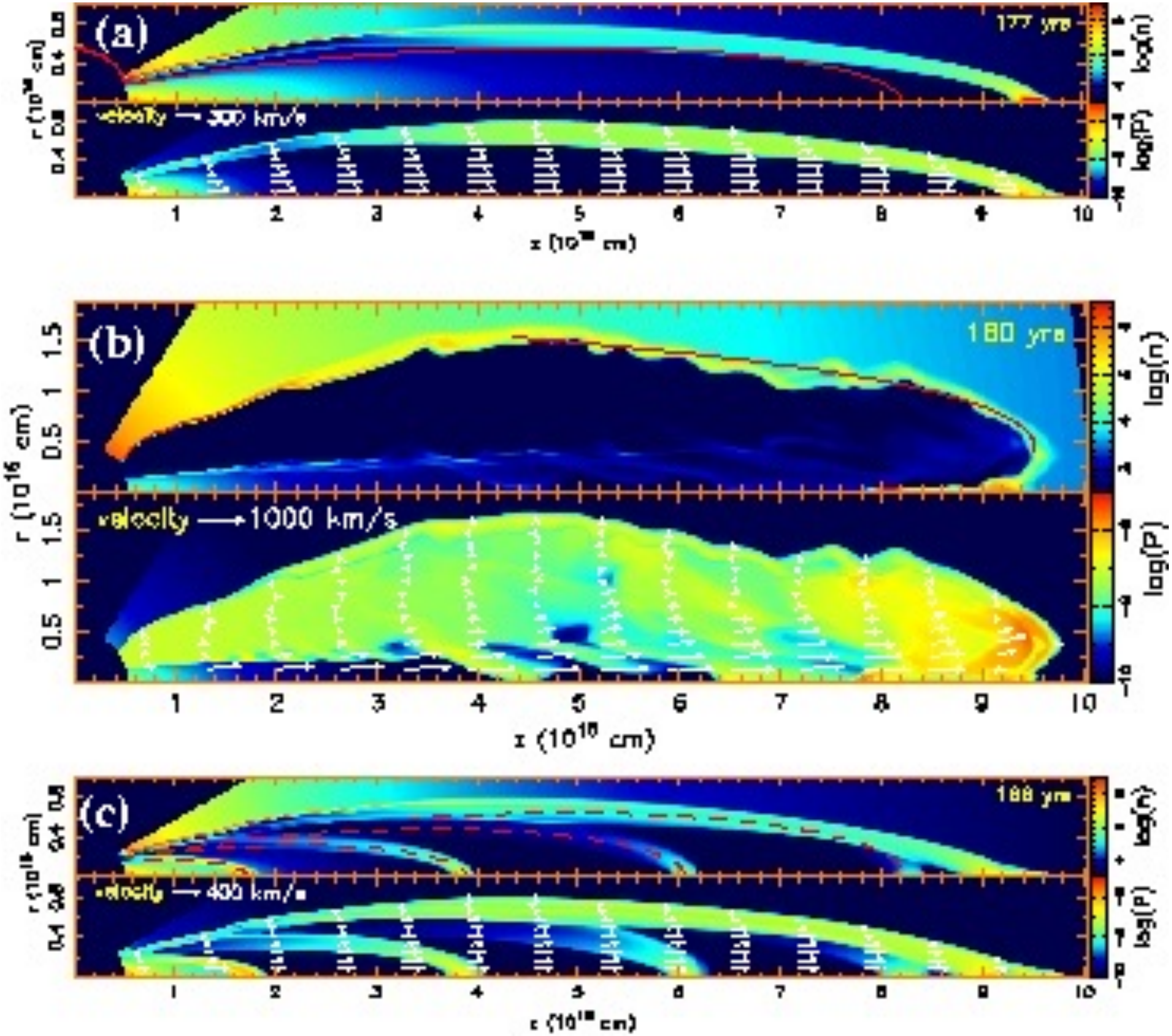
-- extended, C-rich, round, dense molecular envelope, expanding at 20 km/s

-- high-speed molecular gas (~200 km/s)

-- Multiple, collimated lobes with shocked gas emission (e.g. [OI], [SII], [NII], [OIII], also Hα), shock speeds of ~100-150 km/s

Collimated lobes roughly coeval and shocks currently active – multiply directed CFWs operate simultaneously

HYDRODYNAMIC SIMULATION: Collimated Fast Wind (CFW) simulation of W2 lobe, CRL618



(Lee & Sahai 2003, Lee, Hsiu & Sahai 2009)

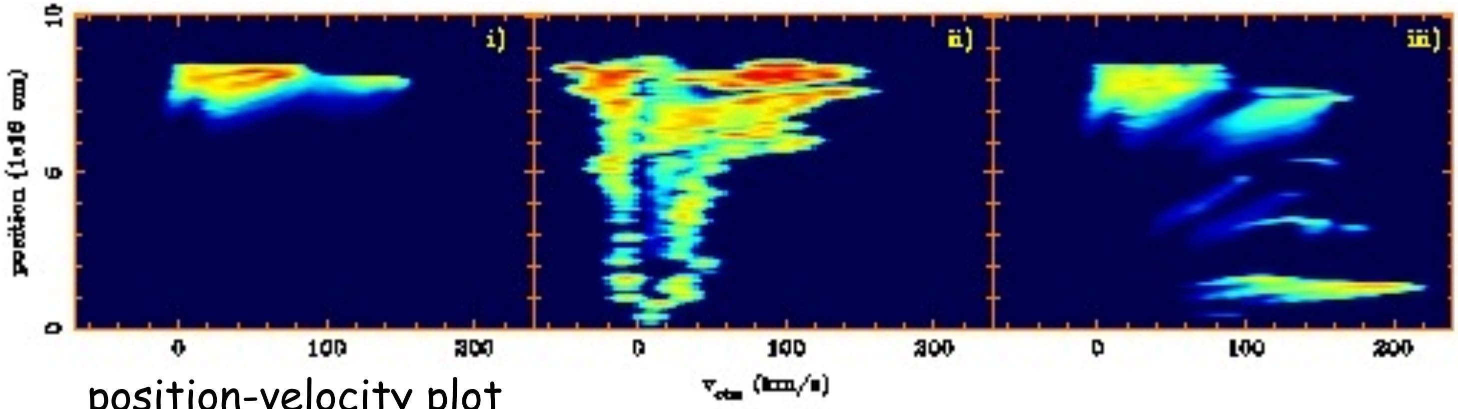
V(CFW)=300 km/s

V(CFW)=1000 km/s

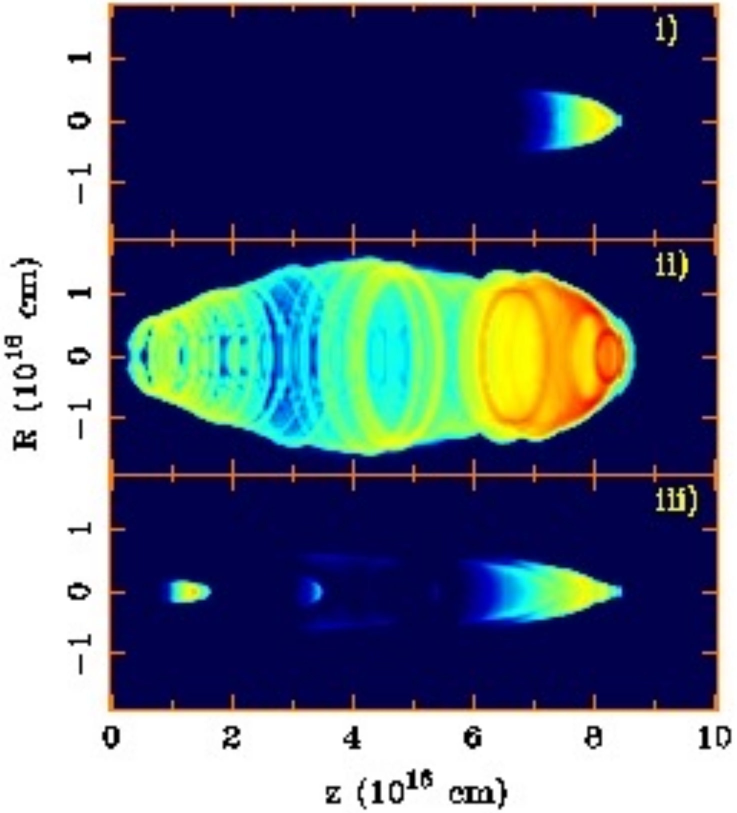
V(CFW)=300 km/s, Pulsed

CFW simulation

[OI] & X-ray emission (*Lee and Sahai 2003*)

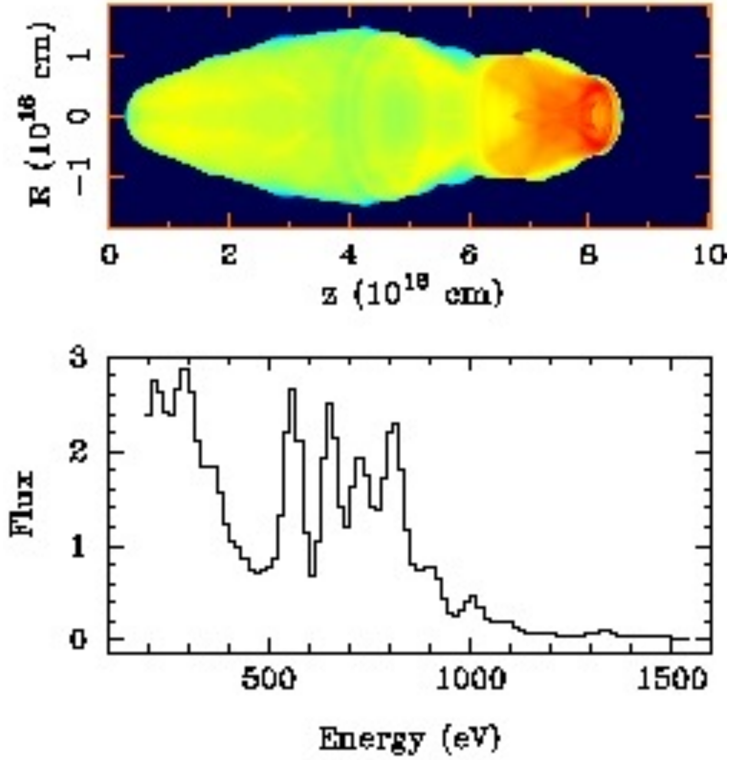


position-velocity plot



[OI]6300 image

X-ray image and spectrum



(not shown) CO (mm-wave lines) & H_2 2.1 μm line (*Lee, Hsu, Sahai 2009*)

Mid- and Far-Infrared Studies of AGB stars, PPNe, and PNe

- IRAS, MSX (whole-sky / galactic plane surveys), and ISO (pointed observations)

(i) ~10 to ~200 μm photometry: thermal dust emission continuum =>

dusty, AGB mass-loss phase: temperature, mass of ejecta & mass-loss rates

(ii) low resolution spectroscopy (IRAS LRS, ISO SWS, LWS):

dust solid-state features (amorphous silicates, crystalline silicates) => dust composition

narrow atomic/ionic lines (in PNe) => excitation, ionization structure, density, temperatures, masses of ionized gas, abundances

Notable Studies (examples)

- surveys of fine structure lines in PNe, PPNe

emission from PDRs or shocks

e.g., Liu et al. 2001, Castro-Carrizo et al. 2001, Fong et al. 2001

- discovery of crystalline silicates (and other solid-state features

grain processing (crystallisation/ growth) in disks/ outflows

e.g., Molster et al. 1999-2002

- mixed chemistry PNe (C- and O-rich features, PAHs and crystalline silicates), carbon stars with silicate features

primordial (e.g., Oort cloud), long-lived O-rich disk, final thermal pulse

e.g., Cohen et al. 2002, Perea-Calderon 2009, Little-Marenin 1986

(IAU symposium #209 on PNe [eds: Kwok, Dopita, Sutherland 2003] good source for ISO studies of planetary nebulae)

Modern Era: Spitzer, SOFIA, Herschel

- Spitzer: (imaging arrays, huge increase in sensitivity)

i) build upon legacy of previous missions by obtaining photometric/spectroscopic data on

large, (equi)distant populations (Bulge, LMC, SMC)

e.g., Blum et al. 2006, Buchanan et al. 2006, Hora et al. 2008

low-mass loss rate objects (e.g., Bulge Red Giants)

Uttenthaler, Stute, Sahai et al. 2009

ii) new discoveries: e.g. dust excesses towards the central stars of PNe, buckminsterfullerene in PNe (C60, C70)

e.g., Su et al. 2007, Cami et al. 2010

Main limitation of previous studies: lack of (simultaneous) adequate angular resolution & spectral resolution => SOFIA (& Herschel)

SOFIA (& Herschel)

Large Herschel studies relevant to PNe/ PPNe (not described here)

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

HERPLAN (*Ueta, Sahai et al.* PACS/SPIRE mapping, spectroscopy of high-exc PNe being studied with Chandra: OT1 Large Prog.,197 hr)

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

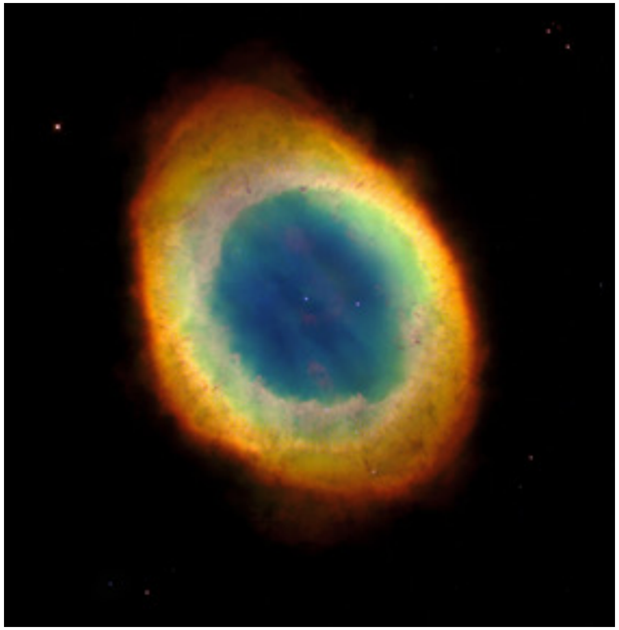
select bright objects from ISO survey by Liu et al (2001) with angular sizes larger than SOFIA beam (17.5” at 158 μm)

Select NGC6720 for Basic Science

flux [CII]158 μm=6.8 x 10^{-12} erg/cm^2/s, optical shell size ~ 90 x 60 arcsec^2

large, but not too large, so can be (strategically) mapped in few hours

(proposal 81-0065: Sahai, Morris, Werner)



GREAT mapping of [CII]158 μm

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

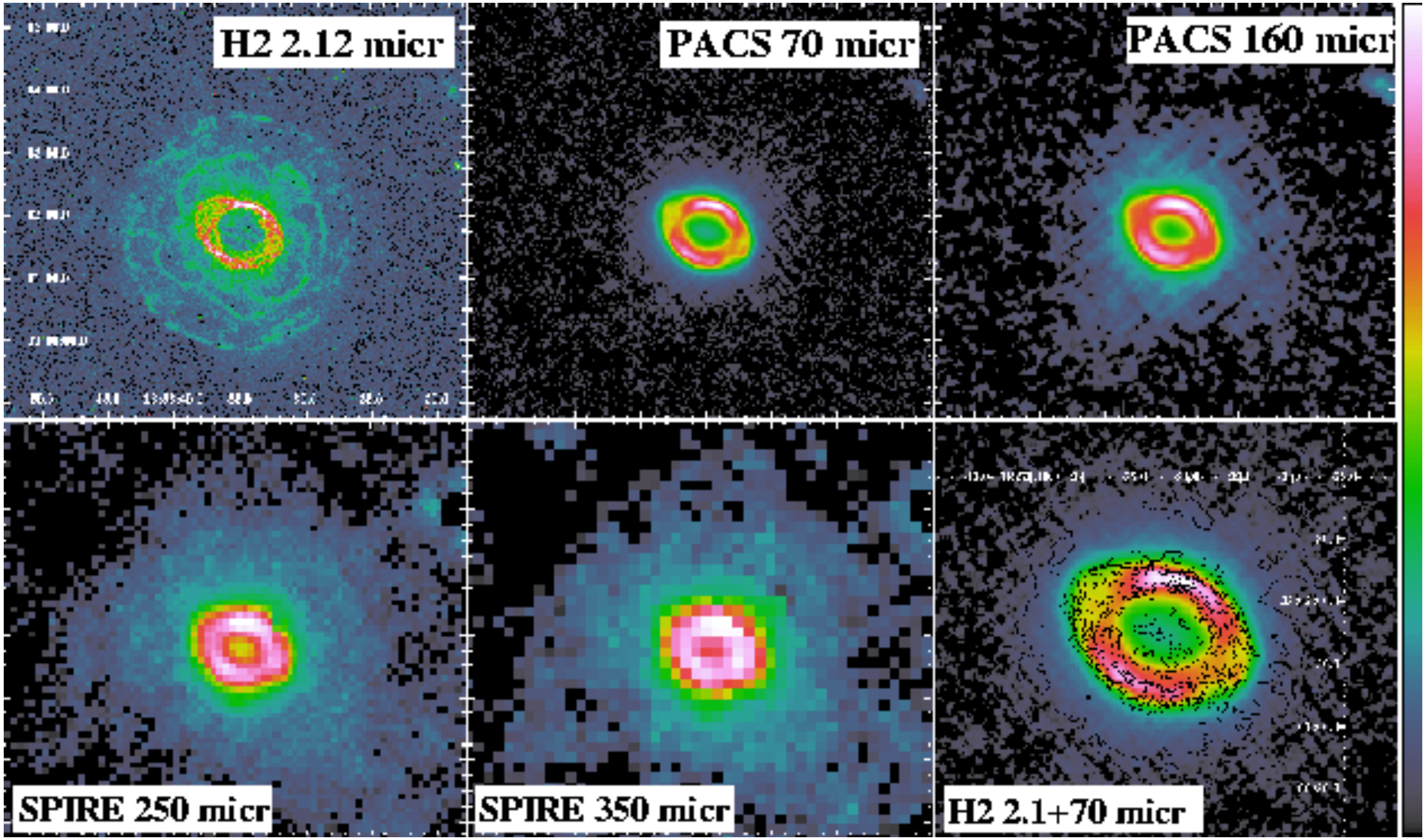
Why [CII]158 μm?

- 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 et al. 2010

- Evolved, oxygen-rich PN
- 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 et al 2010*)

3D Structure: Models

Bright “Ring” seen in optical images: old models

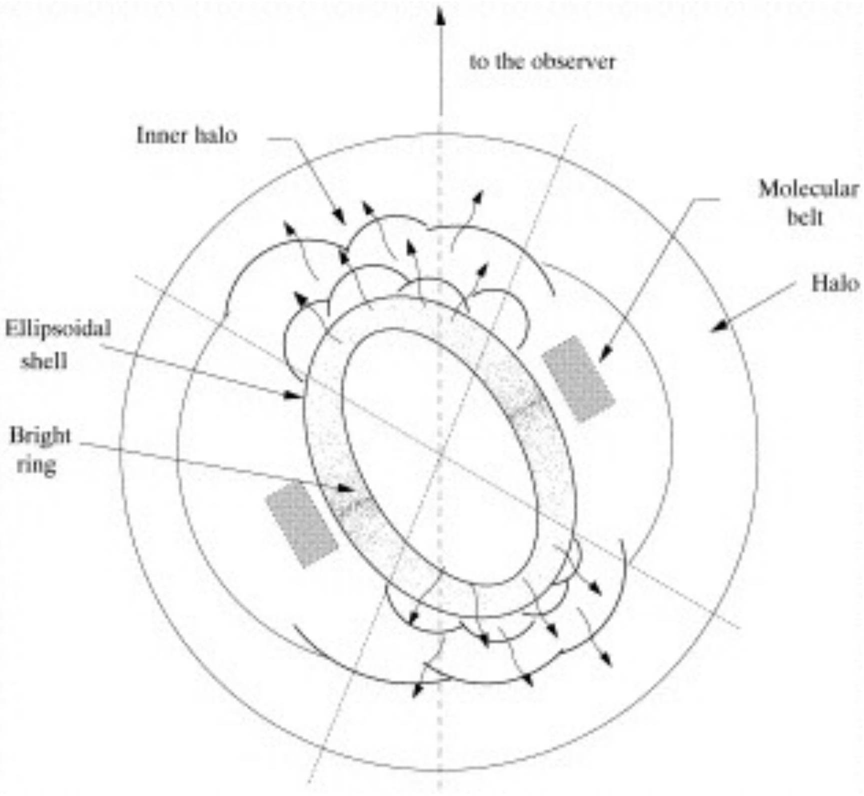
- Torus (1960)
- Flat Ring (1970)
- Cylinder (1974-75)
- Spheroid (1983)
- Bipolar (1992-1994)
- Ellipsoid (1997)

also

Two halos surround bright ring

Inner halo: structured

Outer halo: smooth, circular



Models: Two Broad Classes

(1) Prolate Ellipsoid

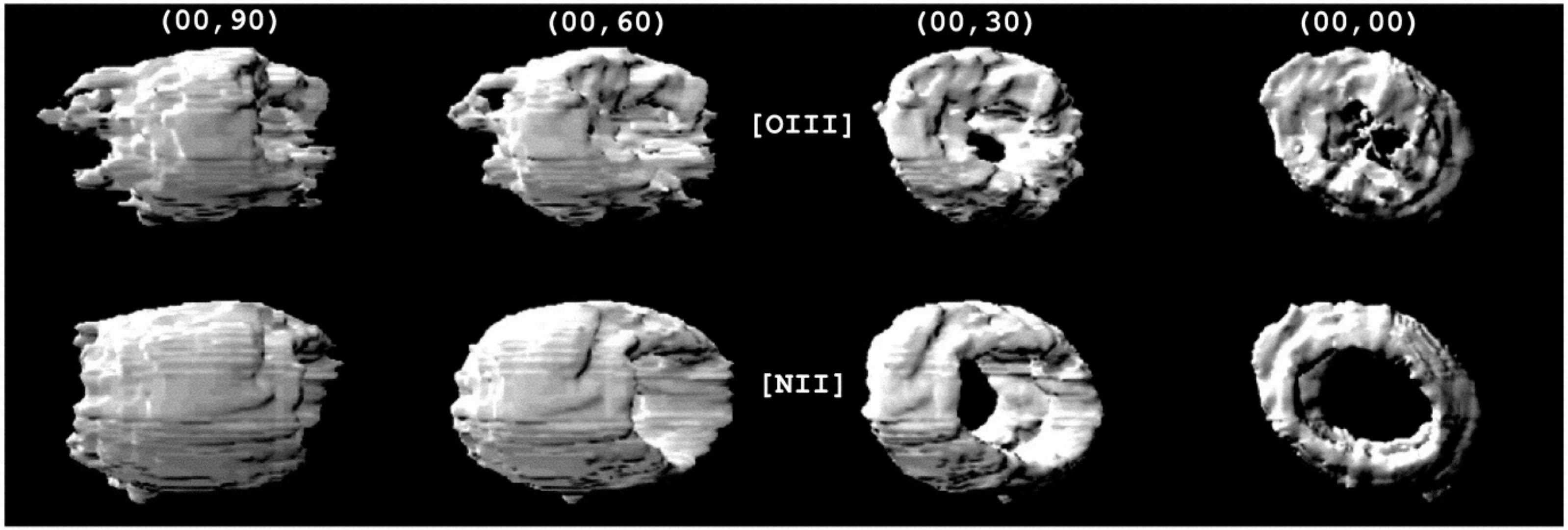
(2) Bipolar, seen nearly pole-on

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

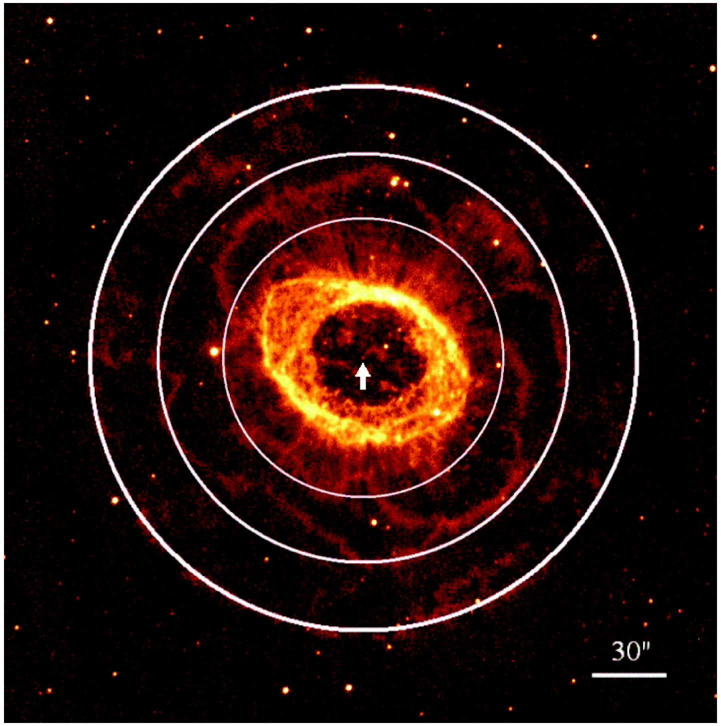
3D Structure: Class 1 model

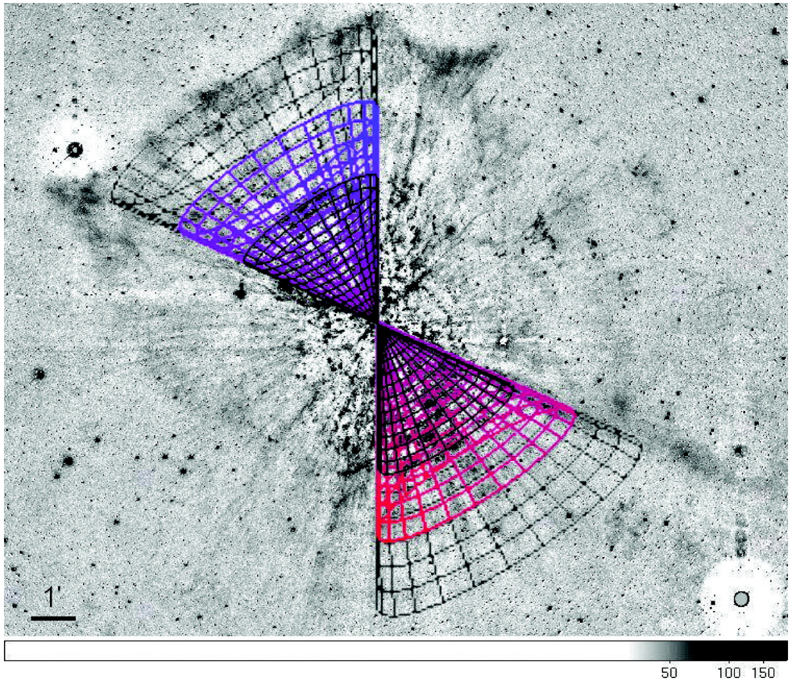


Opaque reconstruction in [OIII] and [NII] at mean flux levels (*O'Dell et al. (2007*)

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 propose

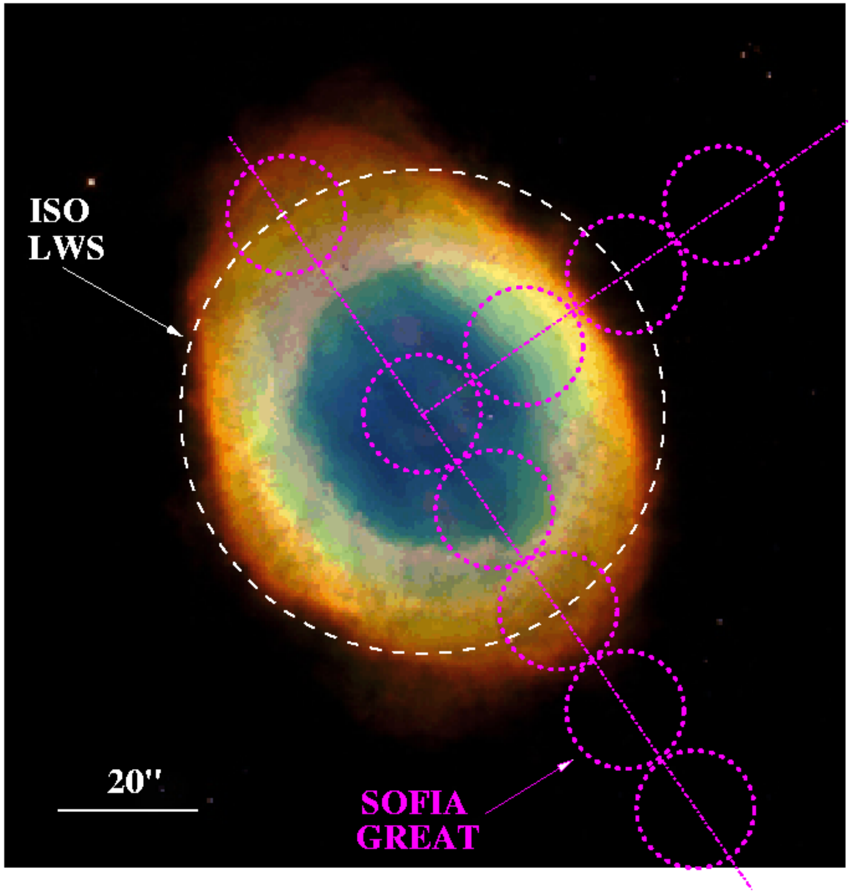
Triple bi-conical shape (seen pole-on) & central torus (bright optical ring)

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*)

GREAT Observations of NGC6720



We have (intentionally) devised a modest observational program for the SOFIA Basic Science Proposal Cycle

We will obtain spectra at 9 locations along major and minor axis, including positions on and away from the bright optical shell

We use an L-shaped pattern which takes advantage of the nebular symmetry to keep the time request to a minimum (using beam-switching against reference positions offset 5 arcmin from center on opposite sides of the nebula)

Total integration time per position is 17 min to get a S/N~10 at 3 km/s resolution (line profiles expected to be ~ 20 km/s wide)

[NII] 205 μm line will be observed simultaneously in Band L1. Both this and the [CII] line have nearly identical critical excitation densities, and observations of both lines can help in better characterization of the cooling (Oberst et al. 2006)

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

<u>Major difference in expected line-profiles for above models</u>:

- 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

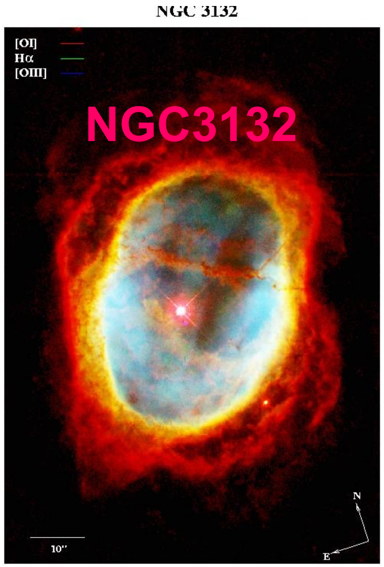
line profiles outside the optical shell should show double-peaked profiles with blue- and red-shifted peaks due to emission from the approaching and receding bicones, respectively.

Future PNe Studies with GREAT

- Additional PNe to explore a variety

of 3-D morphologies (and thus different formation mechanisms)

(e.g., NGC3132, NGC6302, NGC6572, NGC6781, NGC40)



- More extensive mapping per object

=> stronger constraints on 3-D structure, especially for multipolar objects

- Additional Lines for PDR studies

(e.g., [OI]63, 146 μm: together with [CII]158 μm are major coolants; simultaneous observations provide density, temperature and gas masses)

CO 2-1 mapping (23" beam) shows (i) high-velocity outflow (upto ~90 km/s), (ii) massive inclined torus (*Sahai, Wootten & Clegg 1990*)