Proto-Planetary Nebulae: A Multi-Wavelength Study

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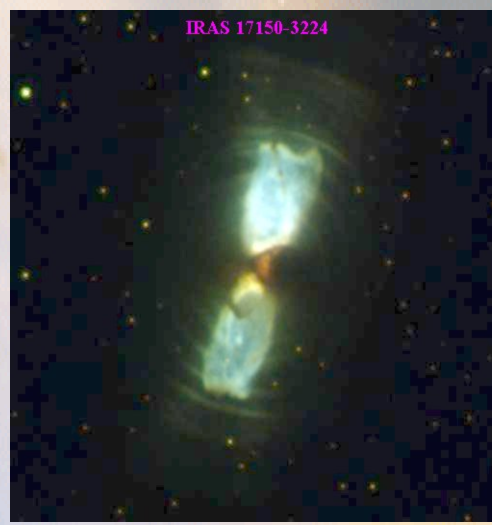
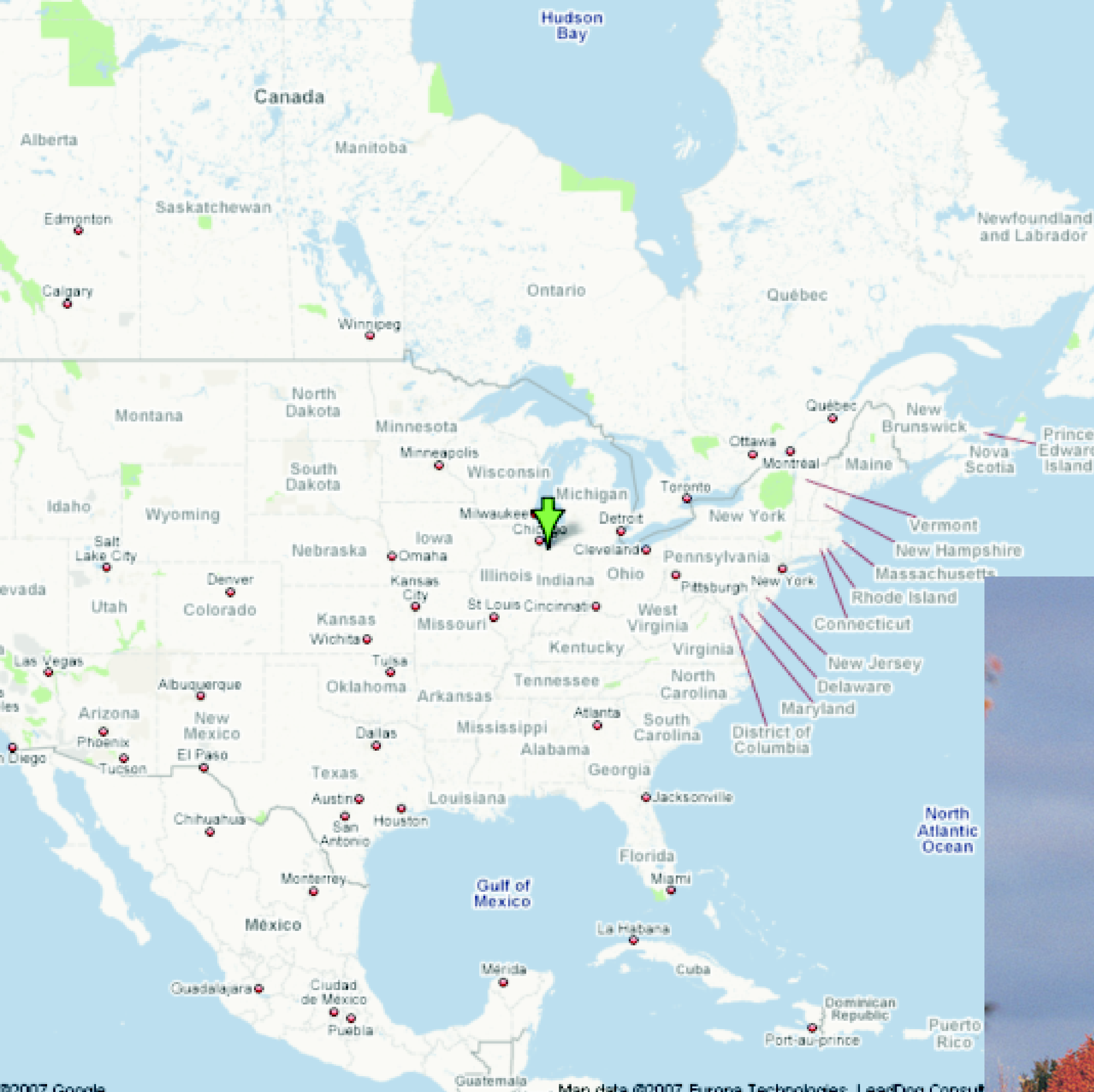


“Cotton Candy” Nebula

“Silkworm” Nebula

VALPARAISO UNIVERSITY

(IIA, Bangalore 2008-01-31)



Valparaiso University

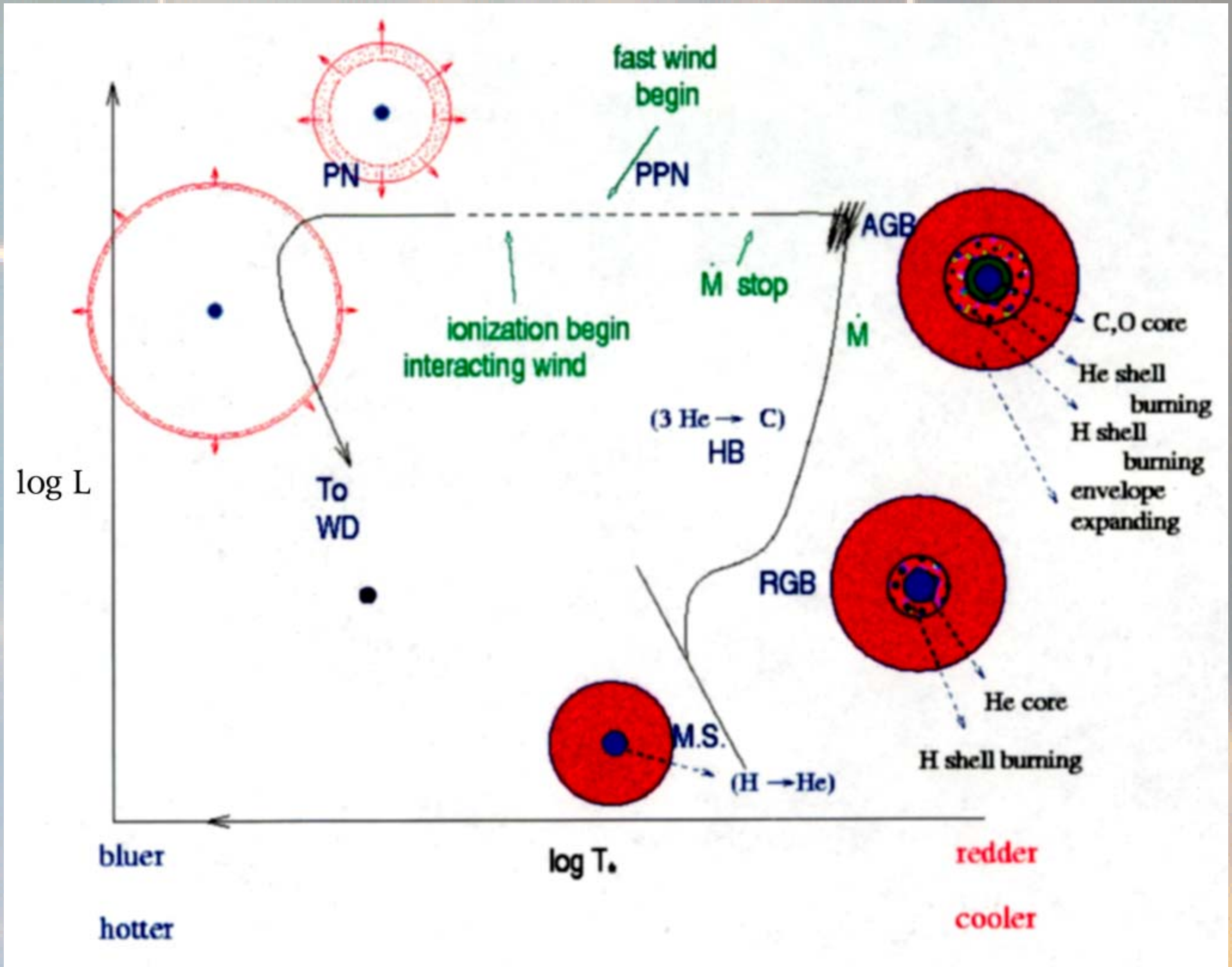
Proto-Planetary Nebulae: Multi-Wavelength Study

Outline:

- Introduction, basic properties — -What are they?
- Circumstellar Envelope (CSE)
    - Nebular shape, shaping — -What are their properties?
- Central star
    - Binarity, variability
    - Abundance studies
- Circumstellar Envelope
    - Chemistry — -What do we learn from them?
- Summary, Questions, Future Studies

Requires observations at a range of wavelengths

Proto-Planetary Nebula: the transitional link in the evolution from AGB star to Planetary Nebula



PPN: mass loss ended but photoionization not started ($T_* > 30{,}000$ K)

Proto-Planetary Nebulae: Finding Them

Expected Properties: **What are we looking for?**

- Properties between AGB and PN
- Luminous star, supergiant spectrum (low surface gravity)
- T(surface) = 5,000 - 30,000 K (photo-ionization begins → PN)
- Expanding CSE (from AGB mass loss), detached but close to star
- Cool dust: T_d = 300 → 150 K
- Chemical signature of post-AGB nucleosynthesis

Discovery: What are the difficulties?

- Short lifetime: few thousand years (10^3yr/10^9yr ~ 15 min/75 yr)
- Partial obscuration by circumstellar gas, dust

Key to Discovery:

- Circumstellar dust is cool, radiates in infrared
- IRAS satellite, all-sky survey (1983)

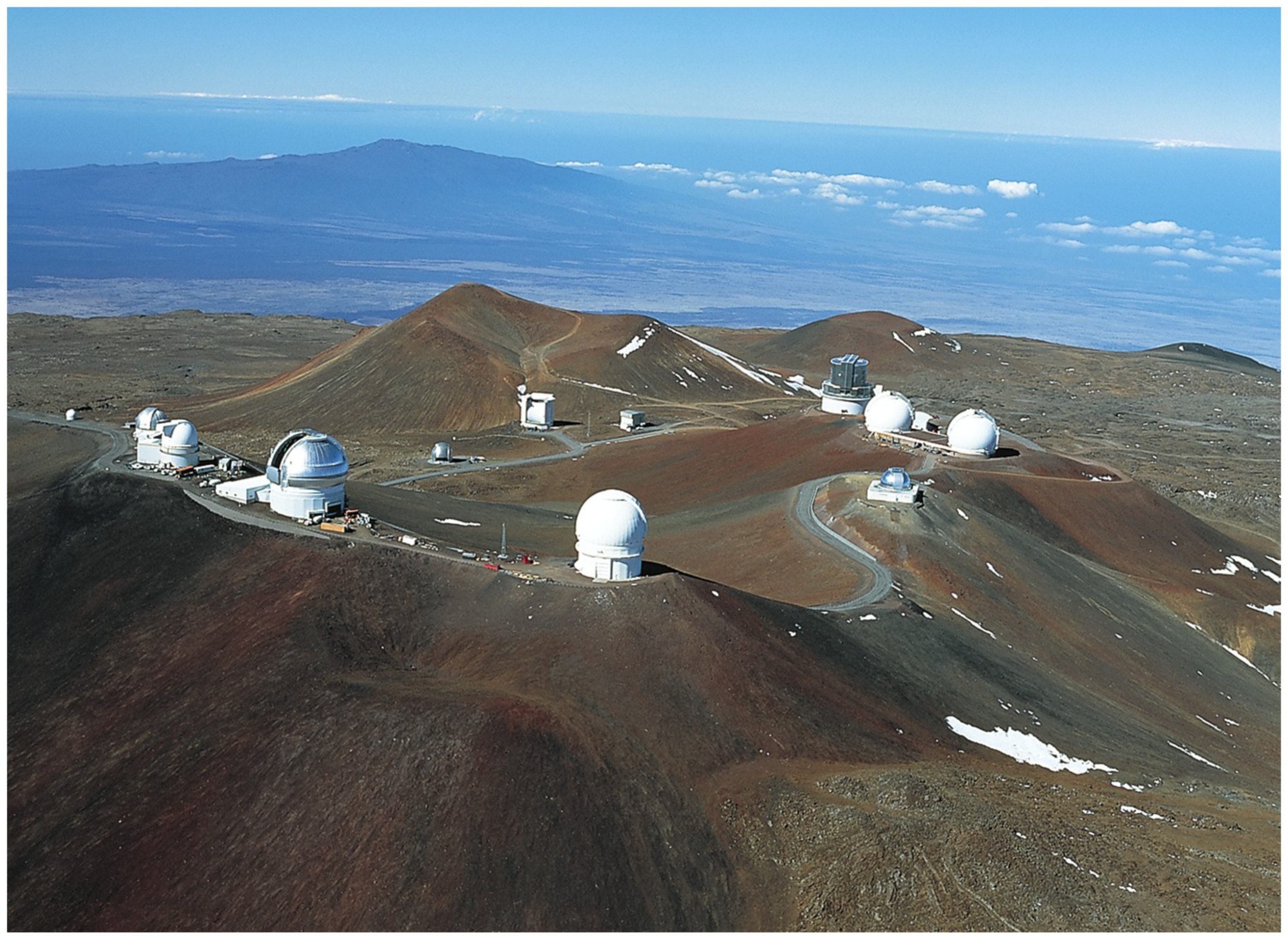
  →**We could select candidates based on IR colors**

- Counterparts found by searches around IRAS position in sky surveys **or searches at telescope with 10 μm detector (ideal)**

Beginning the Search: Identifying Candidates

Identifying the optical counterparts:

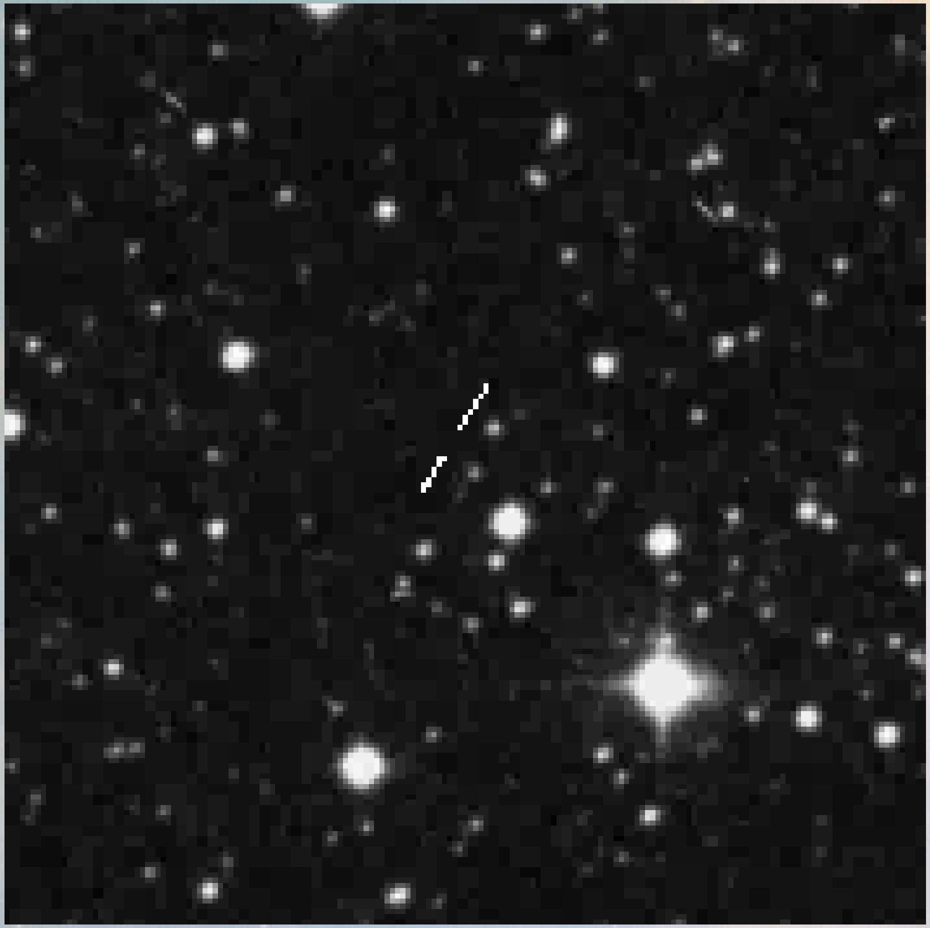
- Observations in Hawaii with infrared detectors on large telescopes



Beginning the Search: Identifying Candidates

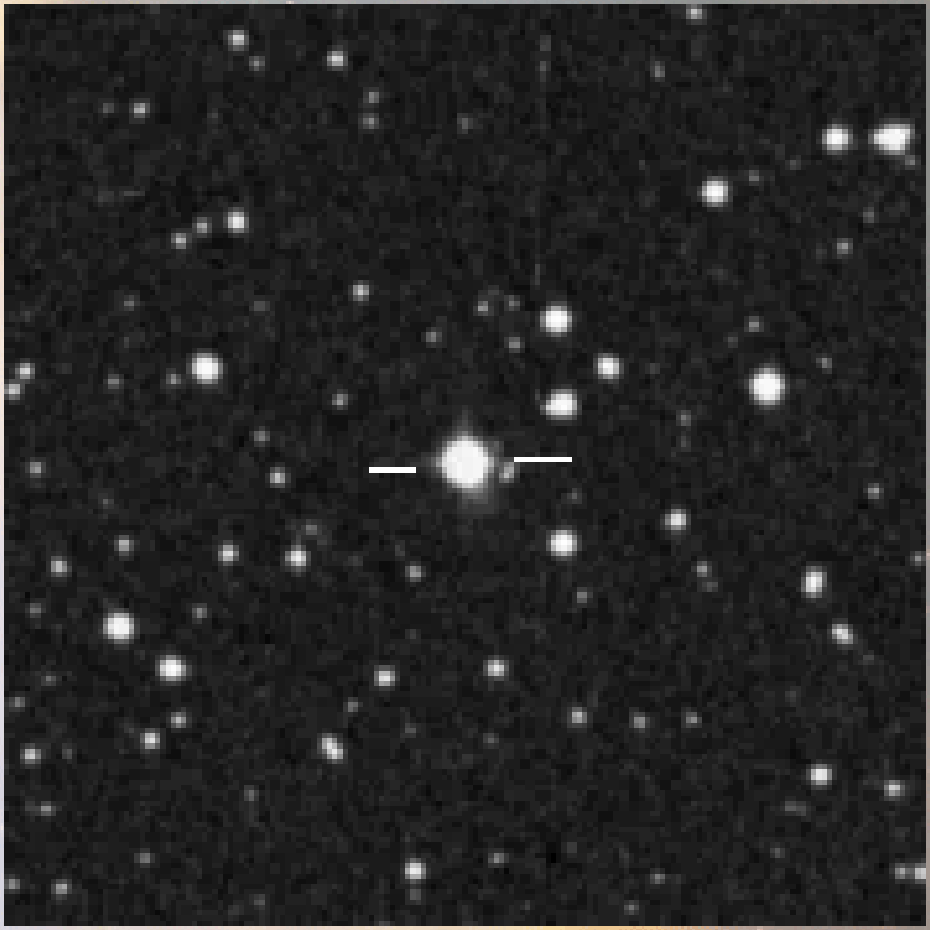
Image of IRAS 19477+2401

- no visible star



Discovery of IRAS 18095+2704

- bright star!

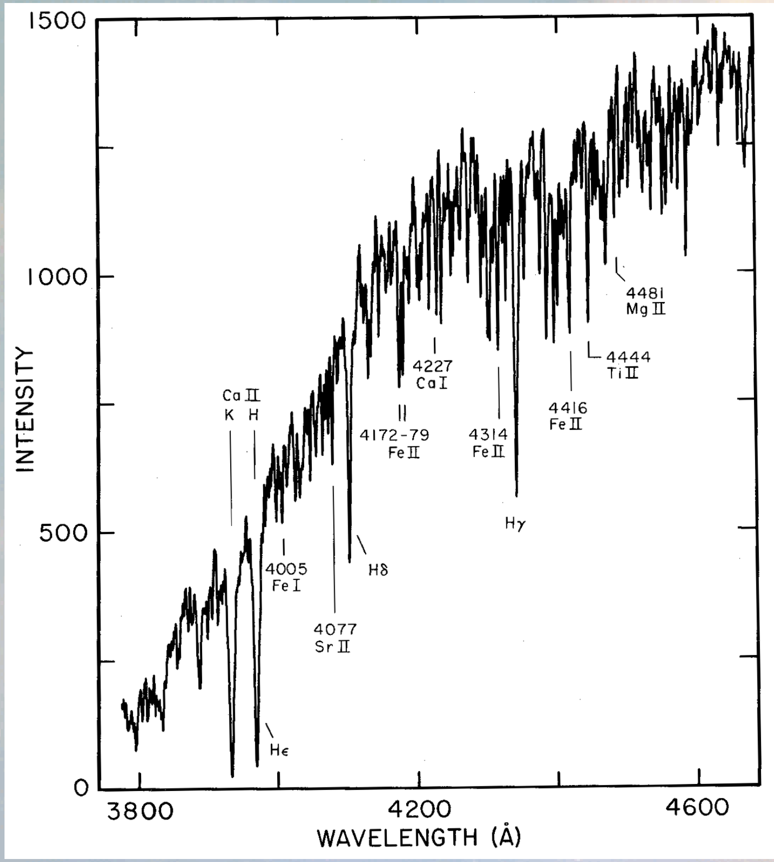


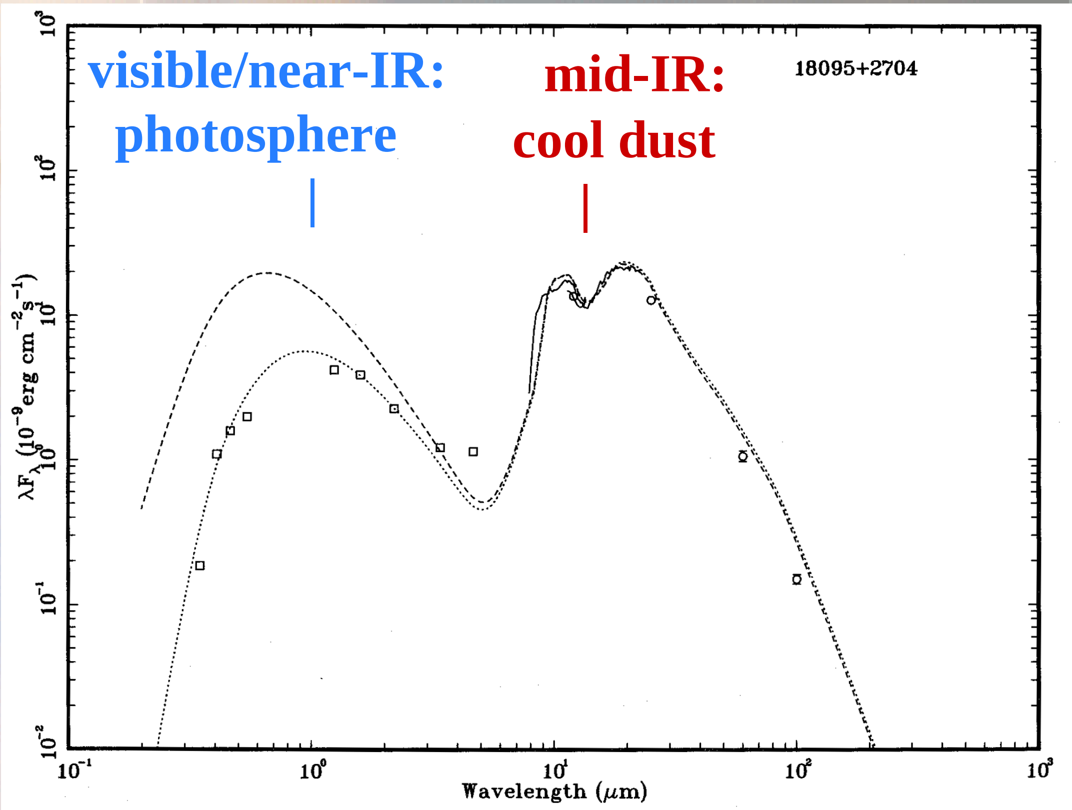
Beginning the Search: Identifying Candidates

Properties of IRAS 18095+2704

- Temperature = 6500 K - F3 I
- Luminosity = supergiant

- Spectral Energy Distribution: double peaked





Beginning the Search: Finding Candidates

Properties: **Did we find what are we expected?**

- Luminous star, supergiant spectra? **Yes**
- T(surface) = 5,000 - 30,000 K?

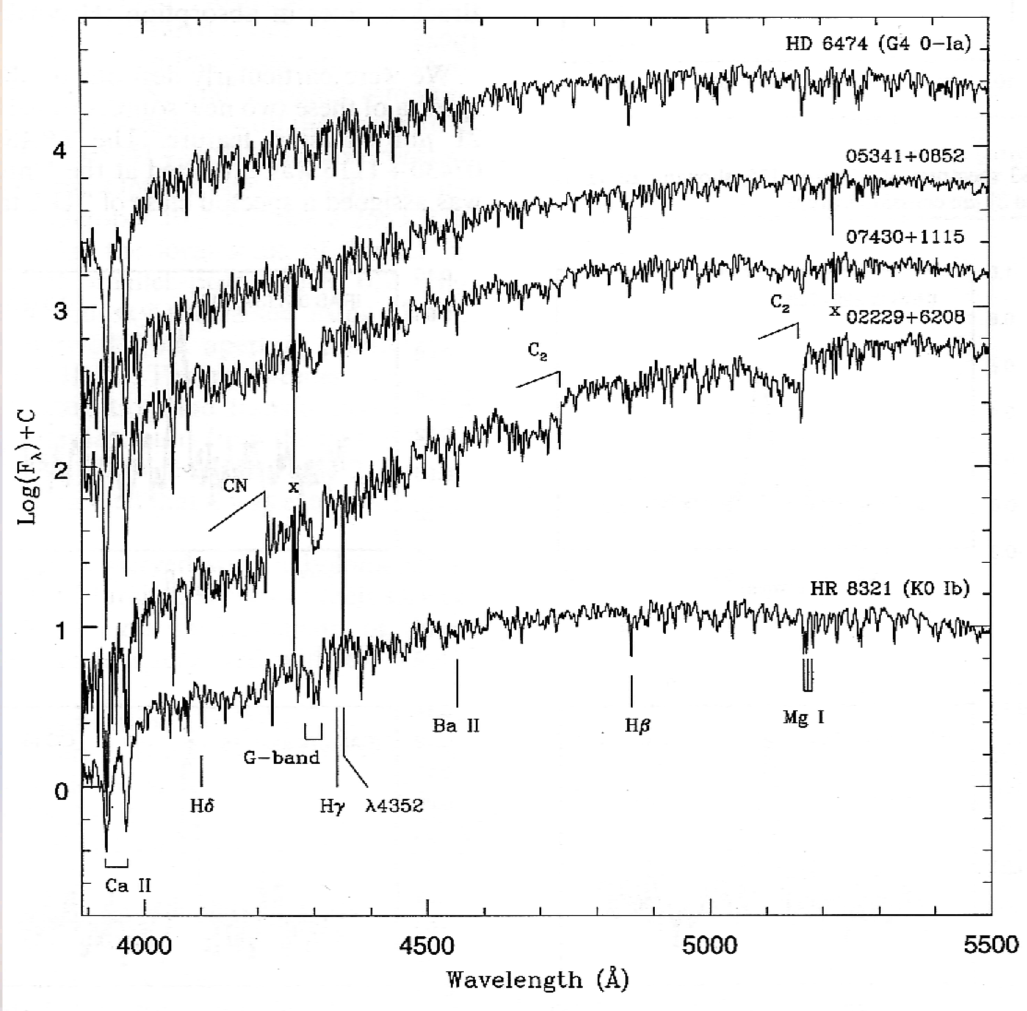
  Yes (SpT= G, F -> B)
- Chemical signature of post-RG nucleosynthesis?

  Yes (C_2,C_3, Ba)
- Expanding circumstellar envelope of gas?

  Yes (radio studies)
- Double-peaked spectral energy distribution? **Yes (IR studies)**

Numbers of PPNs:

- 60 firm candidates (Partha)
- 60 possible candidates
- possible confusion



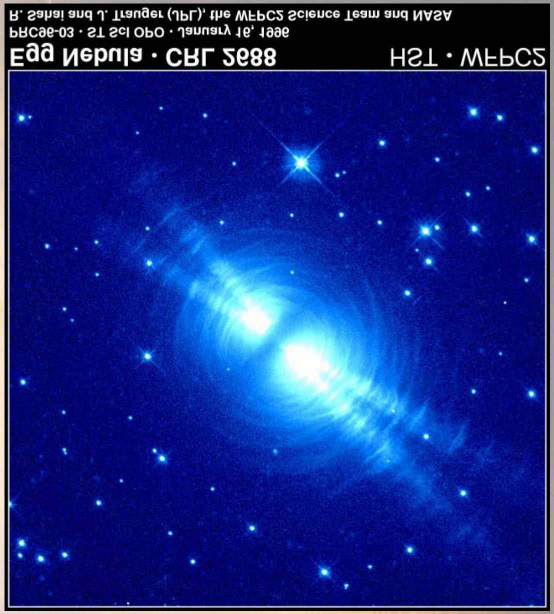
Circumstellar Envelope: (looking forward to the PN phase)

Nebular shapes

Context: AGB: approx. spherical envelope (although …)
PN: elliptical, bipolar, point-symmetric
→ PPN: development of shapes??

What shapes to PPNs have and how did these form?

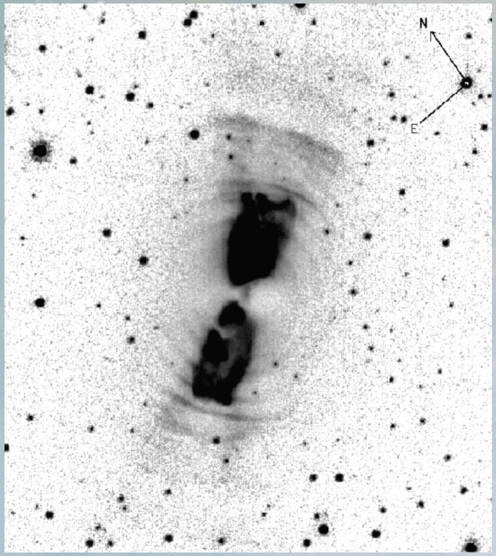
HST-WFPC2: R~0.1”

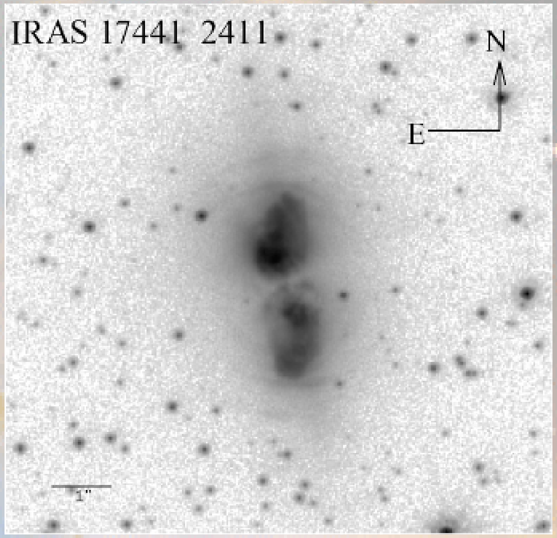


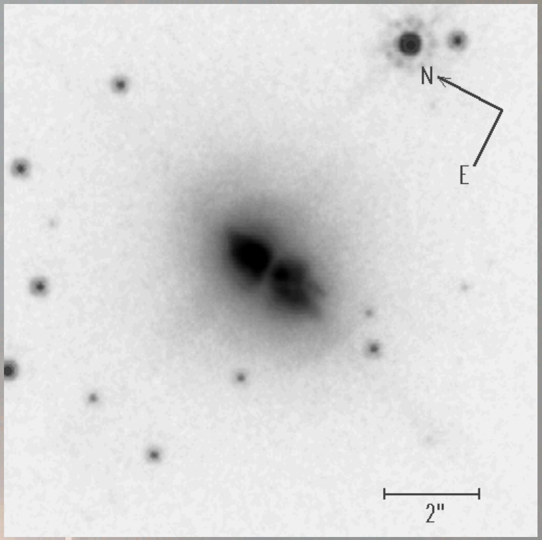
Egg Nebula: typical or unique?

Circumstellar Envelopes: Shapes?

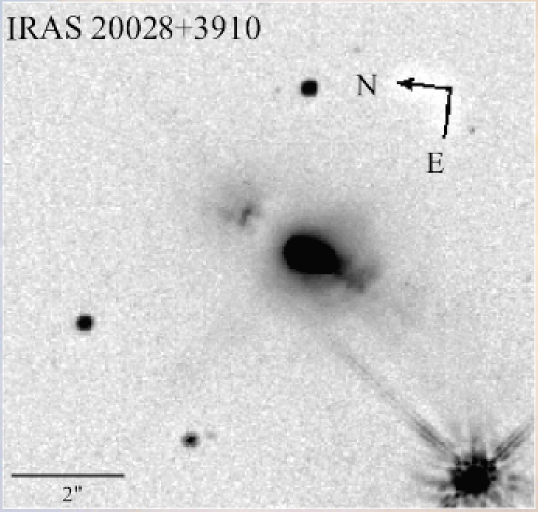
Our HST studies: - Bipolar shape is common

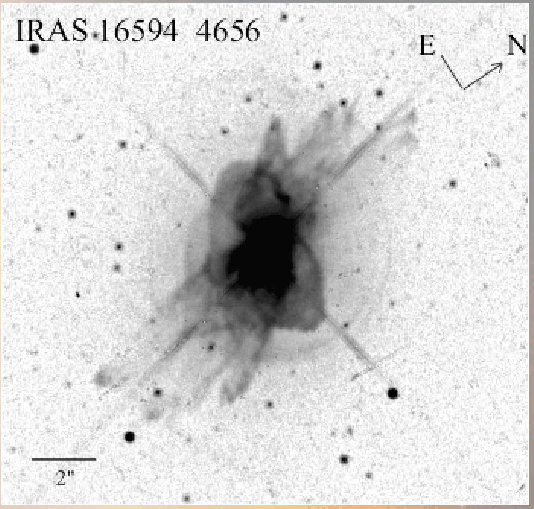






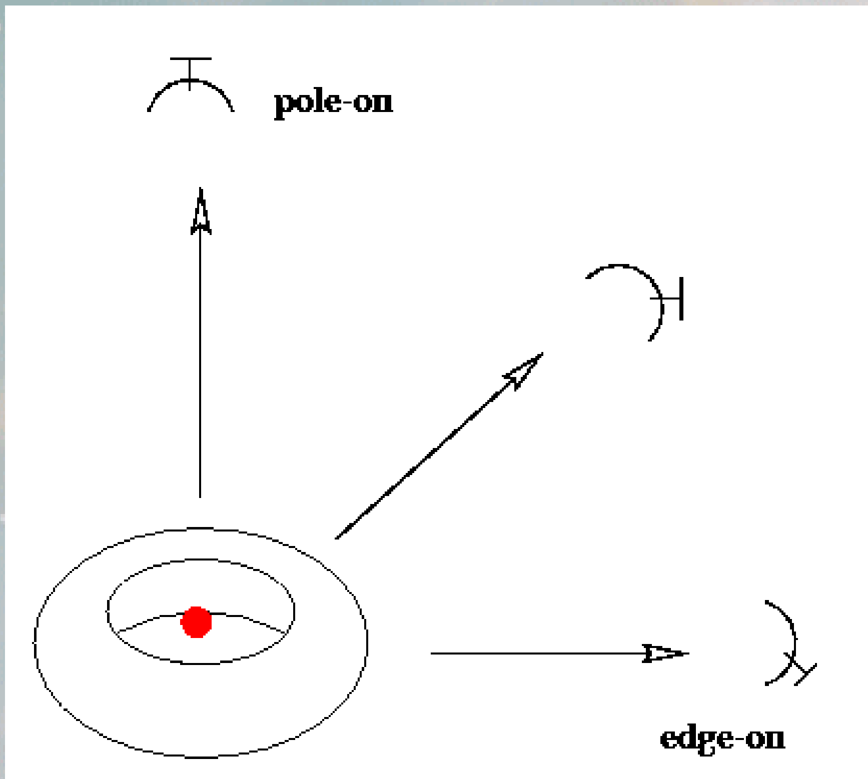
PPNs in scattered light



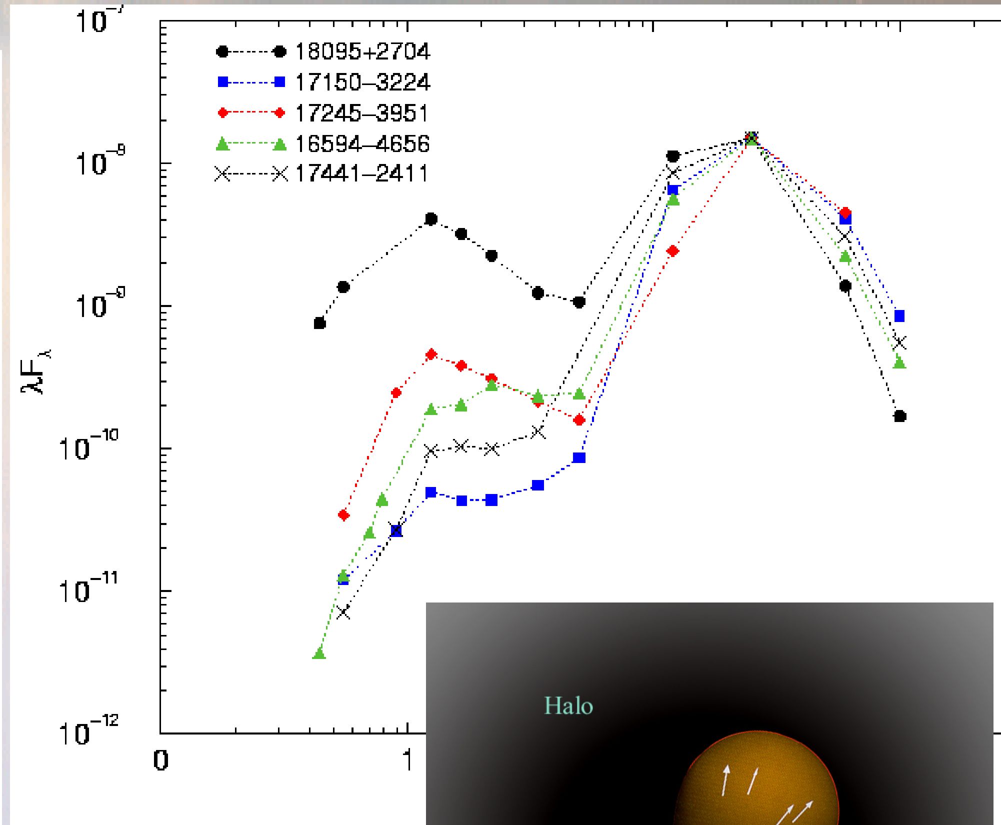


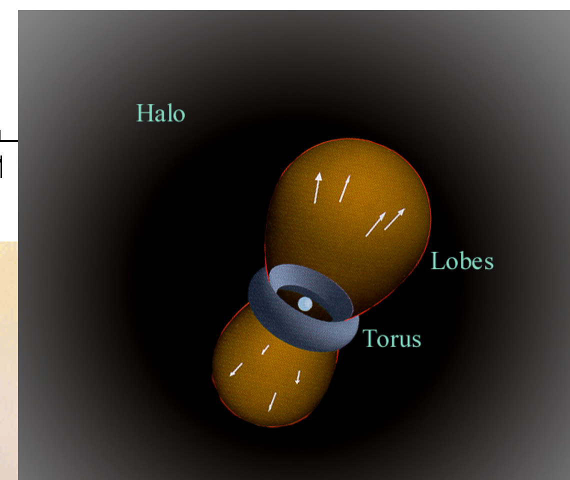
Other studies by
Ueta et al. (2000),
Sahai et a. (2007)

Is there a basic model to explain the shapes?



Spectral Energy Distribution (SED)
(normalized at 25 m)

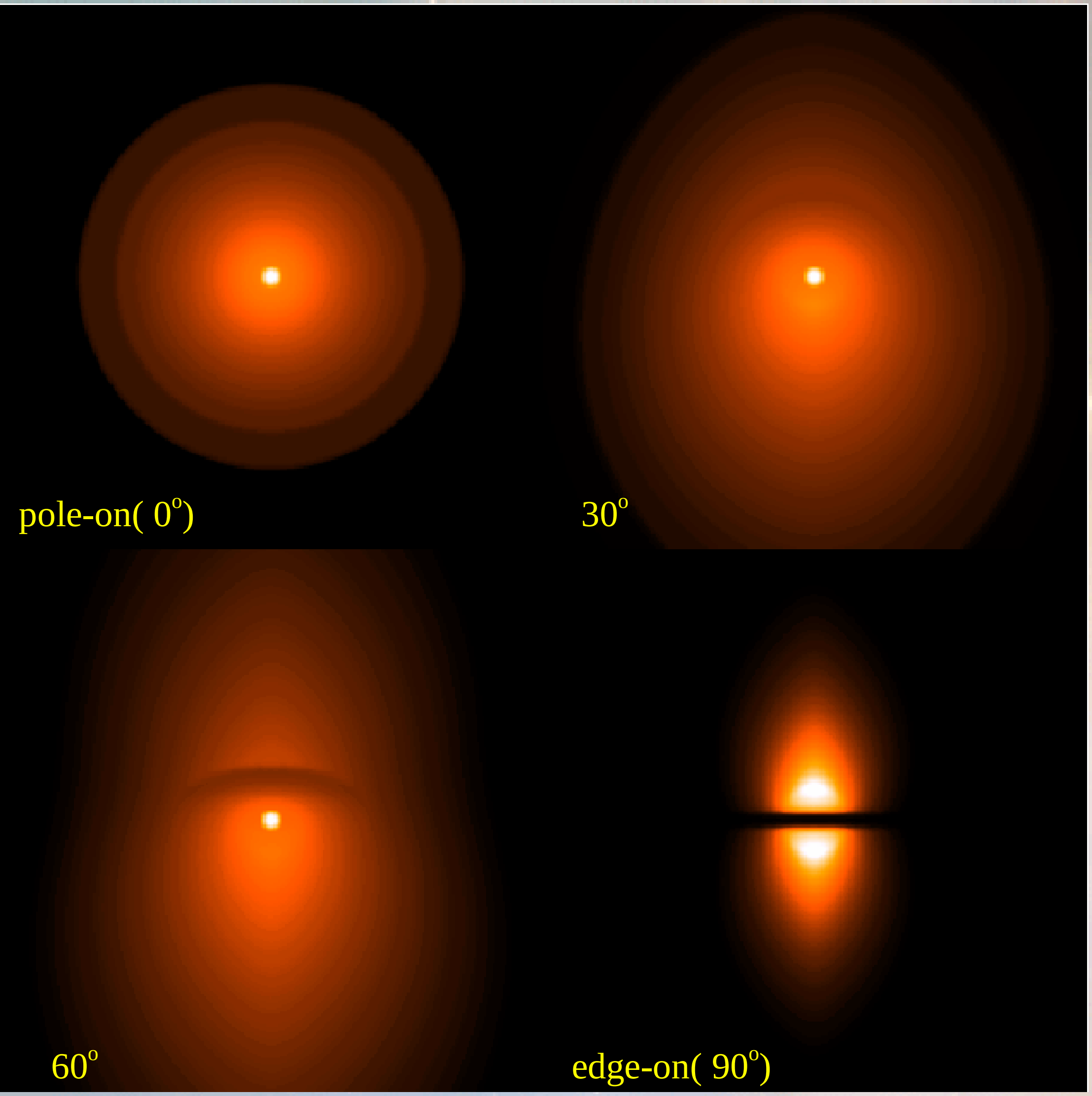


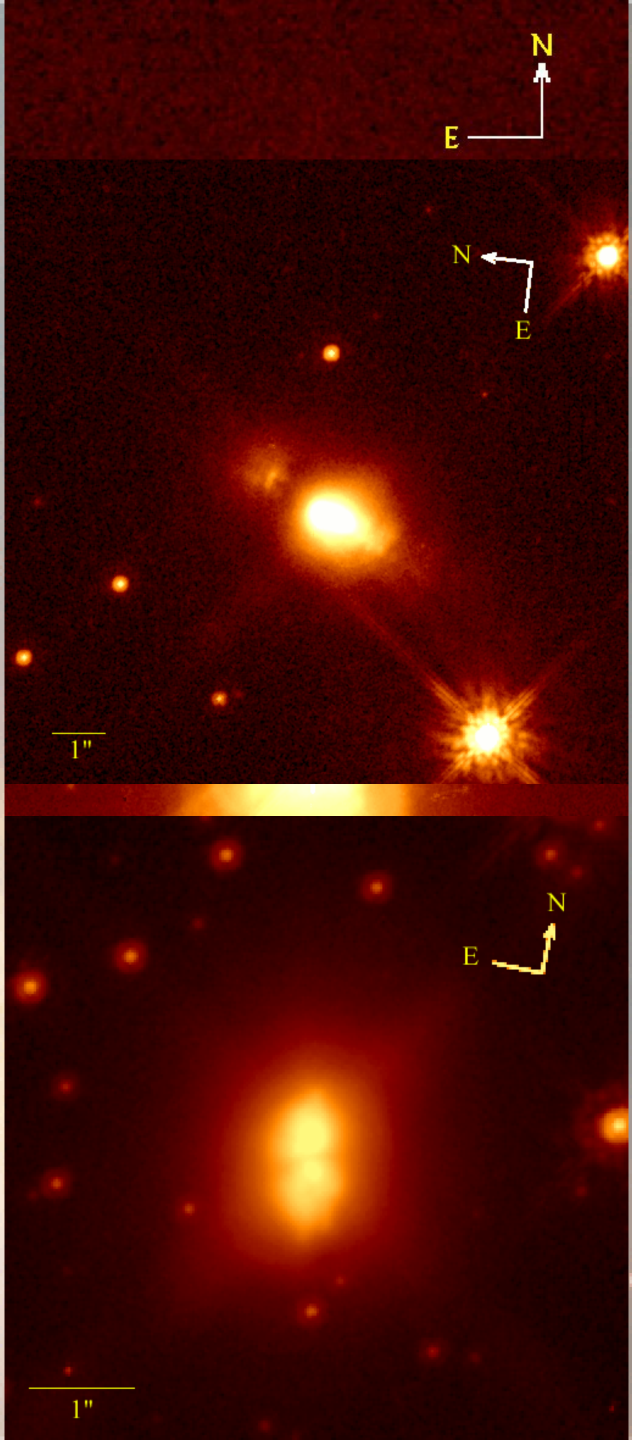


Picture adopted from the paper by Balick, in American Scientist 1996

Obscuring torus and bipolar lobes, as seen from differing orientations.

How does the model compare with the observations?

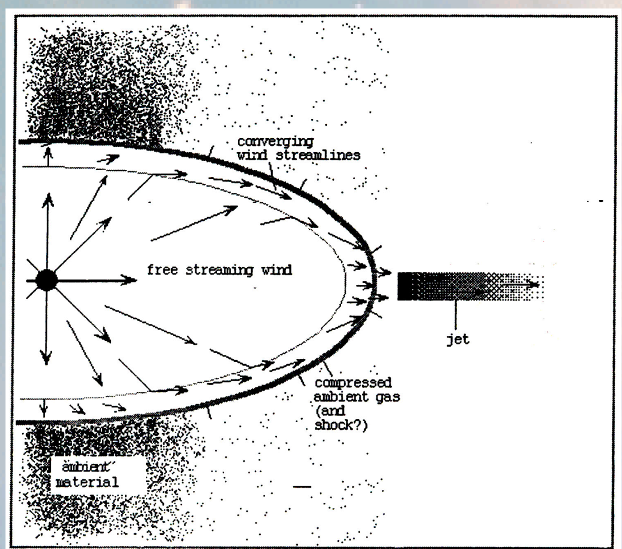


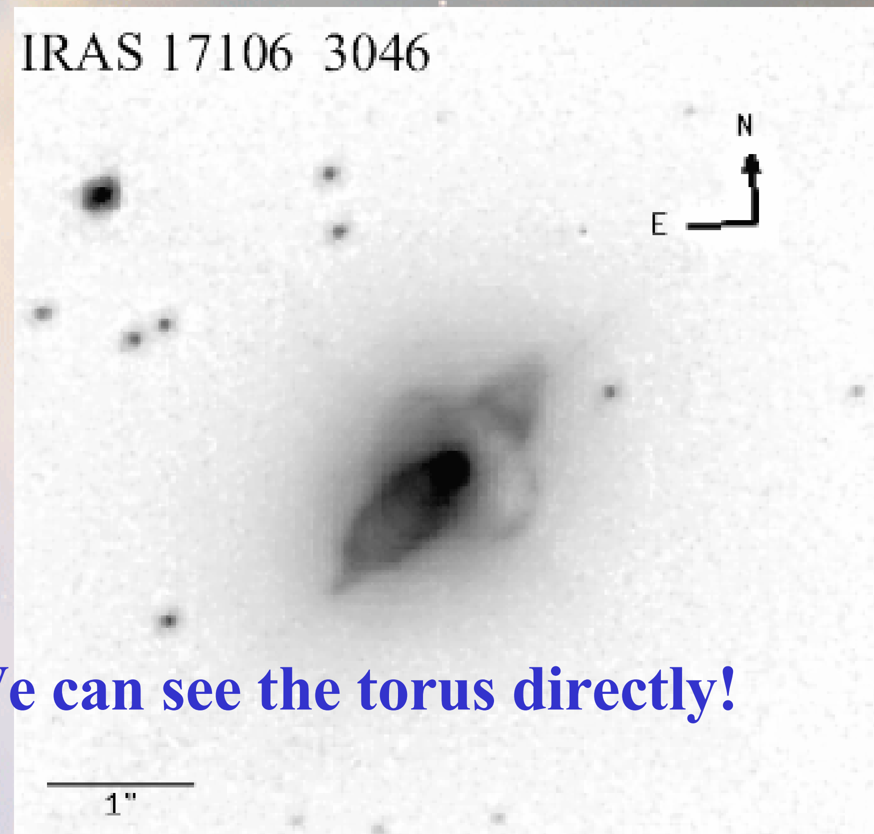


Detailed Studies: Shaping of the Nebula

Cause of bipolar shape?

-Circumstellar torus:
wind expanding into a density gradient leads to bipolar lobes.





We can see the torus directly!

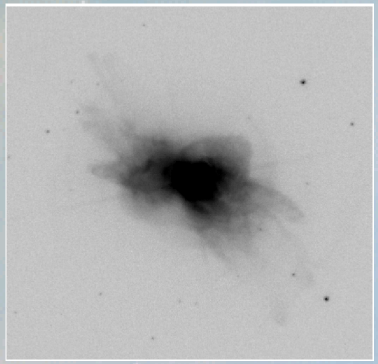
Detailed Studies: Shaping of the Nebula

Can we directly see the dust that is collimating the outflow?

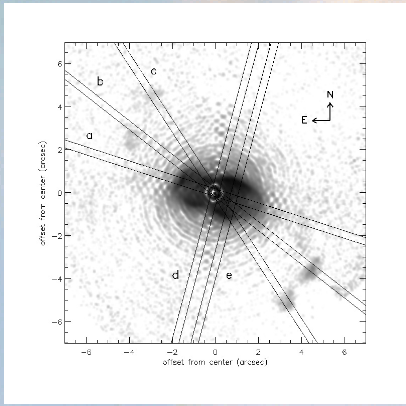
Thermal emission from circumstellar dust radiates in mid-IR

PPNs are small: sizes ~1-2” diffraction limit of ~0.9” with 3-4 m telescope

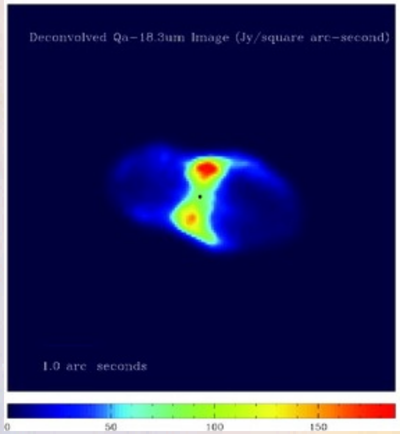
Opportunities: New, larger telescopes: Keck, Gemini (IR optimized, R~0.4” at 10 m) - beginning to see some interesting results for PPNs.



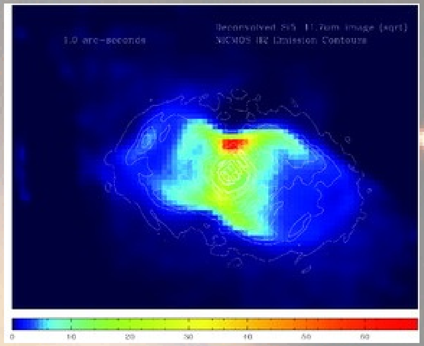
visible



H_2 (near-IR)



10 m (mid-IR)

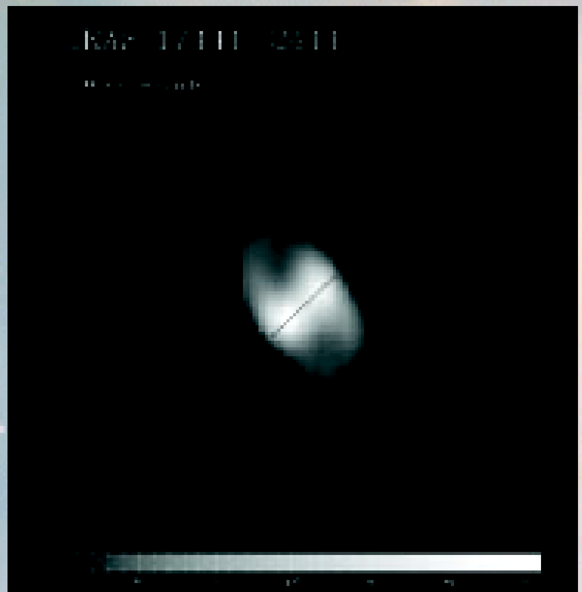


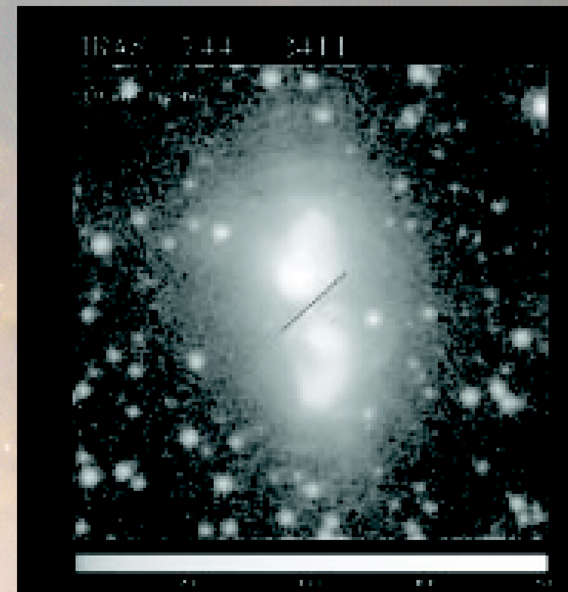
H_2 and 10 m

IRAS 16594-4656: see dust disk directly (Gemini 8-m)

Circumstellar Envelopes: Shaping

IRAS 17441-2411





10 m

V image with orientation of torus drawn

Apparent precession of torus! (or of small disk)

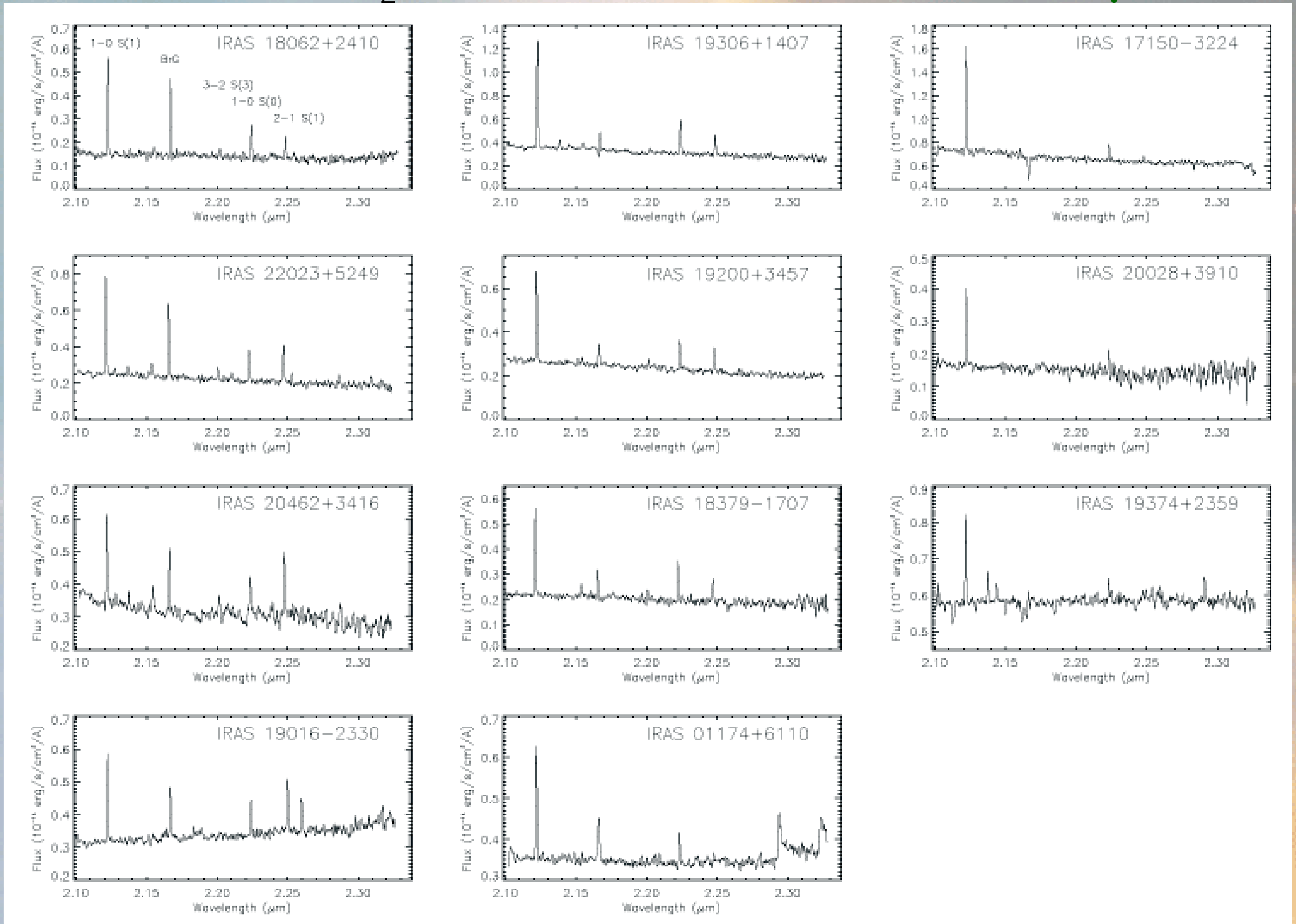
Cause of the torus?

-enhanced mass loss in equatorial region - **why?** **(return to this Q momentarily)**

Circumstellar Envelopes: Shaping

Can we see the shaping of the cavity by the (fast) wind?

Observations of the H_2 vibrational line at 2.12 m → **yes**



Circumstellar Envelopes: Shaping

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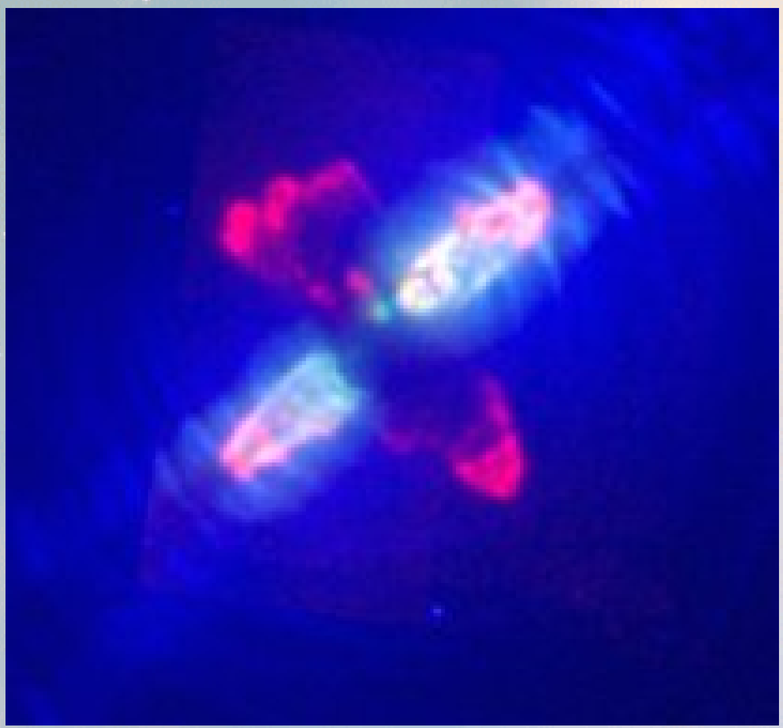
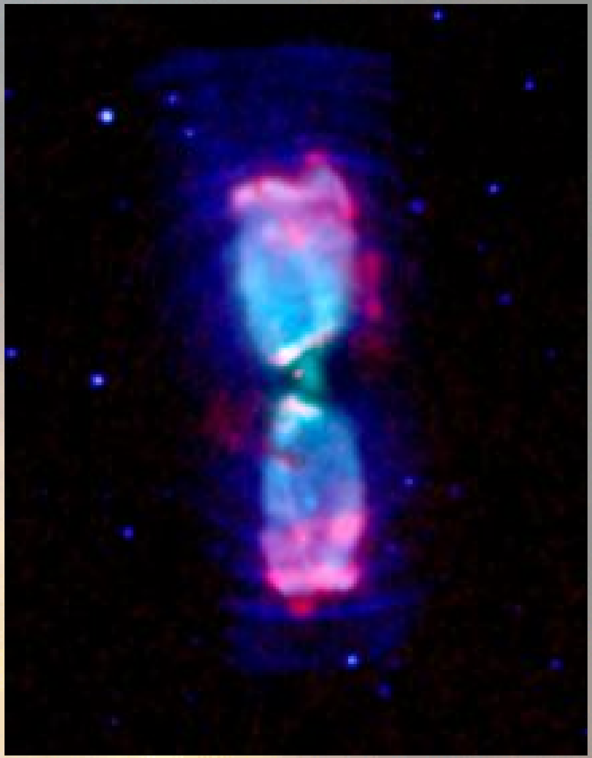


Egg Nebula (Sahai et al. 1998)

HST-NICMOS

H_2(red),
1.6 m (green),
0.6 m (blue)



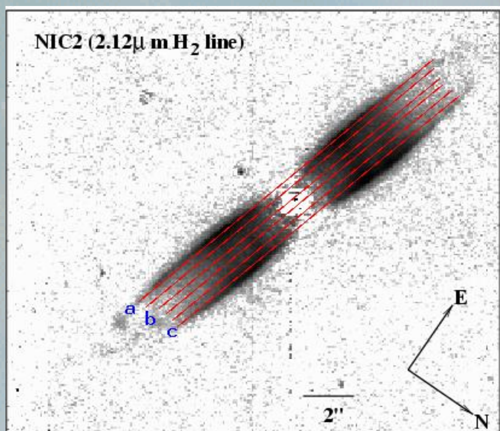
IRAS 17150-3224 (Hrivnak et al. 2006)

Collisionally excited H_2 at ends, edges of lobes & equatorial skirt

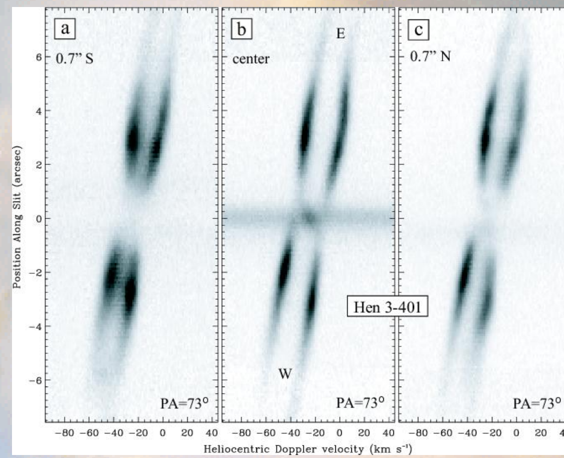
Circumstellar Envelopes: Shaping

Can we see the shaping of the cavity by the (fast) wind?

Observations of the H_2 vibrational line at 2.12 m → kinematics



slit positions

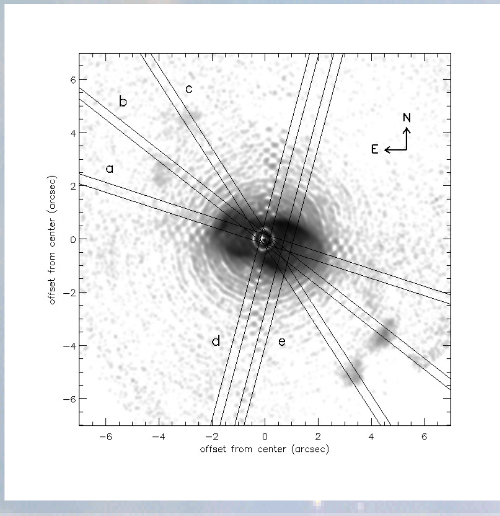


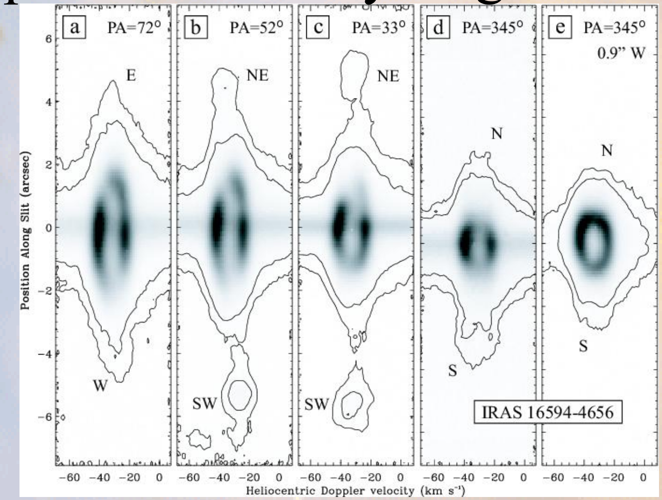
position-velocity diagrams

Collisionally excited H_2 at edges, ends of lobes

Hen 3-401

Expanding lobes with opened ends





IRAS 16594-4656

Expanding shell with closed ends +ejected blobs

Phoenix (R~70,000) on Gemini-S

IMPLICATIONS OF OUR NON-DETECTION OF BINARY PPNe

- Comparison with results of **PNe binary** studies
  - % short-period photometric binaries ~ 10-15% (Bond)
  - short P --> **Common envelope** evolution
  - RV studies: many (most) variable, but that does not mean binary (DeMarco 2006)

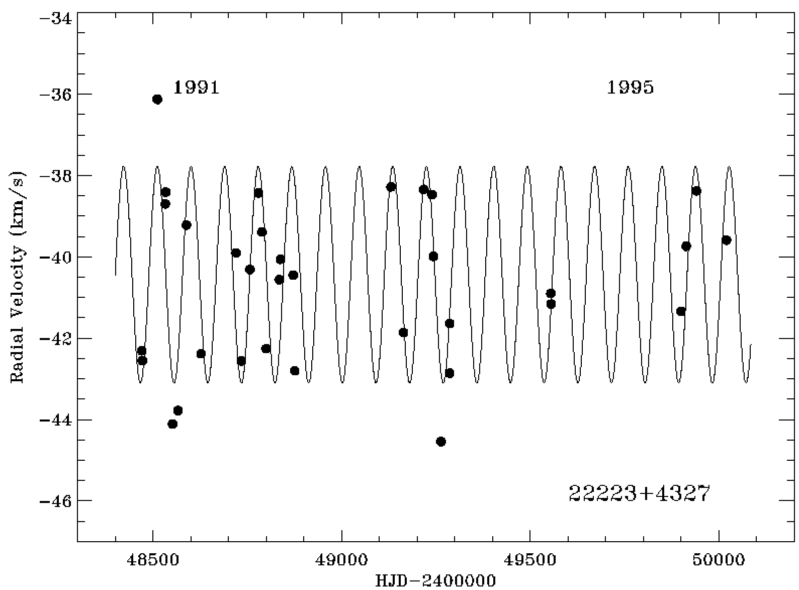
- **Q - Might the PPNe be binaries, but …**
  - In common envelope
    - But this lasts only a short time, unlikely
  - Long P (P>10-100 years) - but then effect on shaping may be small
  - Secondary is not a MS star but brown dwarf or a planet; this would not be detected.

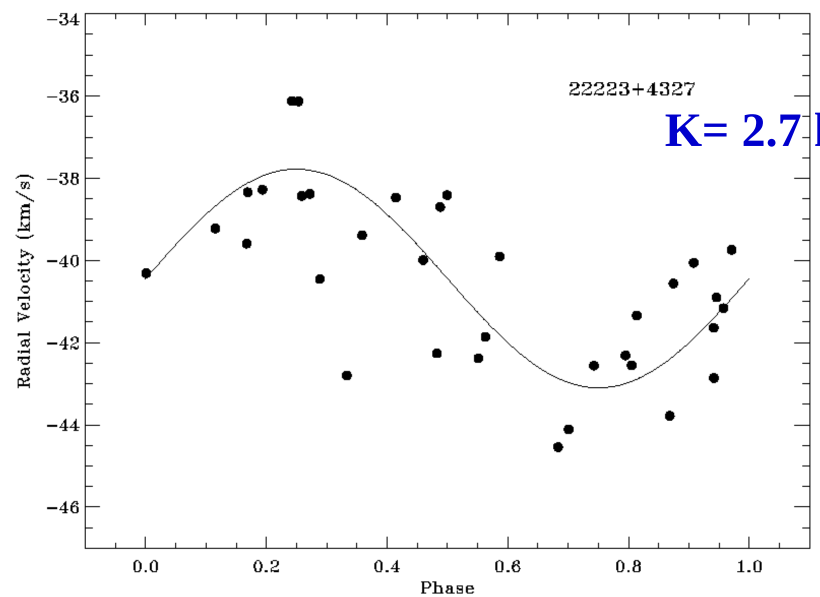
- **Speculation**: Since it appears that these 7 objects are PPNe and shaping has started, then this suggests two ways to form PNe,
  - Common envelope evolution (binary PNNe)
  - Non-common envelope process (occurring in these PPNe)
    - Distant, low-mass companions?
    - Single, pulsating PPNe?

RESULTS OF OUR RADIAL VELOCITY PROGRAM OF PPNe

What are we finding?

- **IRAS 22223+4327** **(G0 Ia, C-rich)**
- **ΔV= 8 km/s** **P(RV) = 89 d ~ P(LC) = 90 d**
  K=2.7 km/s **ΔLC=0.2 mag**





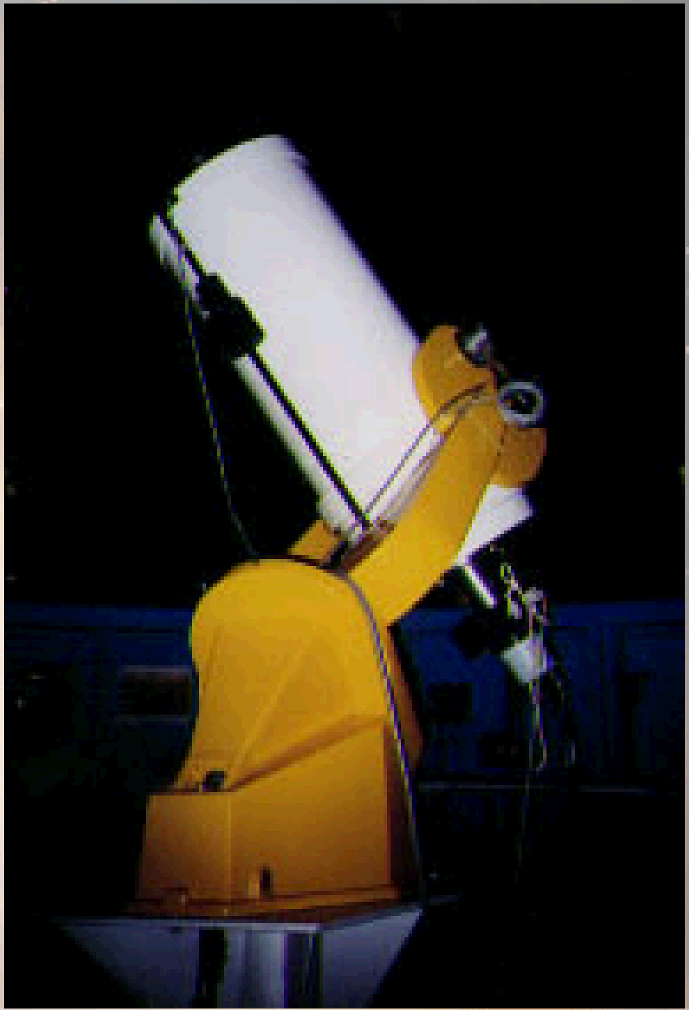
- Periodic, with reasonably consistent pattern;
  ---> Pulsation, not binary orbit

Central Star: (looking back to the AGB phase)

Light variations of the central star: (we know that AGB stars vary)

Do PPNe vary in light and what can we learn from this?

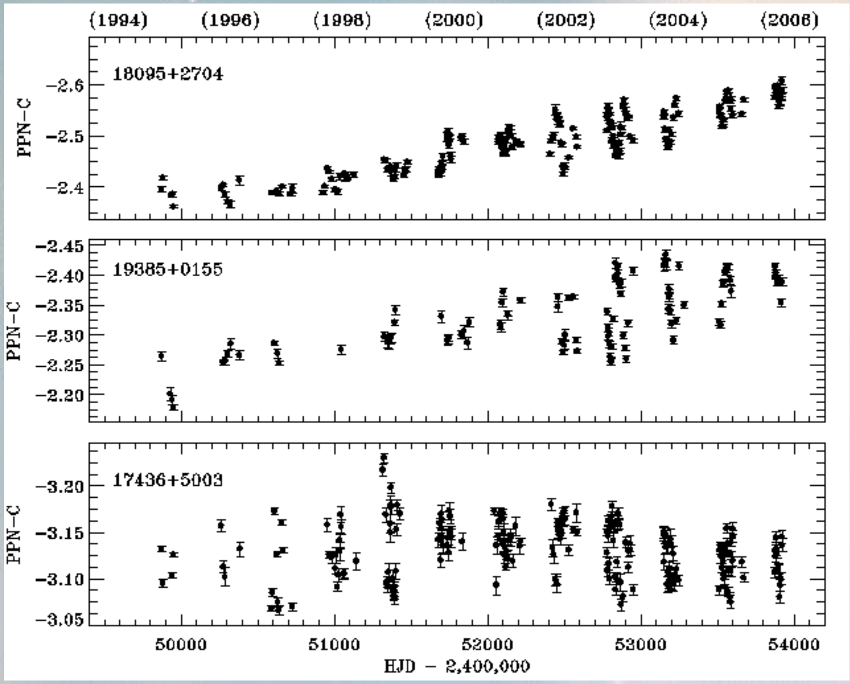
→ Photometric monitoring program at Valparaiso Univ., undergrad students, 14 yrs, 40 PPN candidates → **Results**



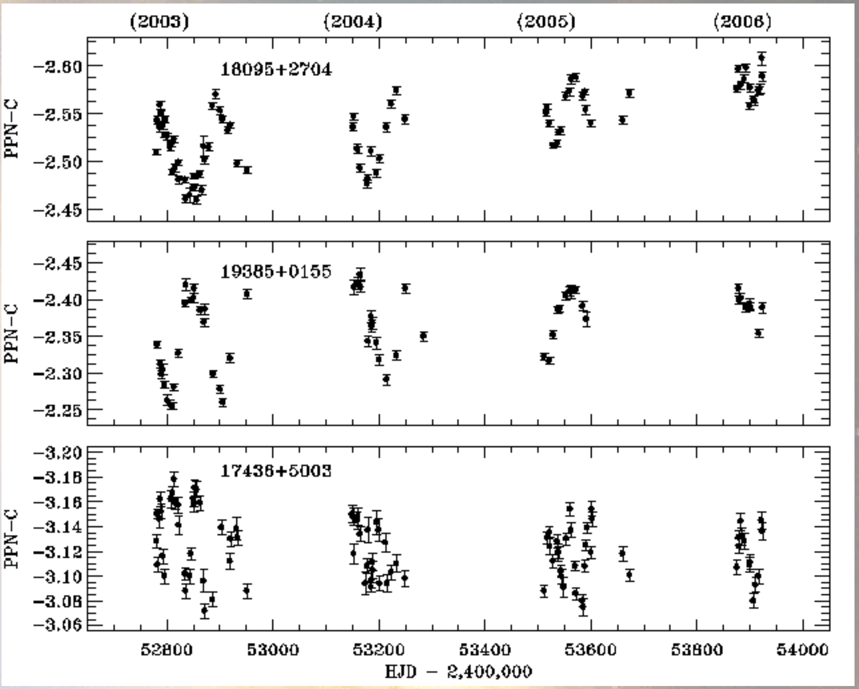
Central Star: (looking back to the AGB phase)

Yes they all vary in light

13 years



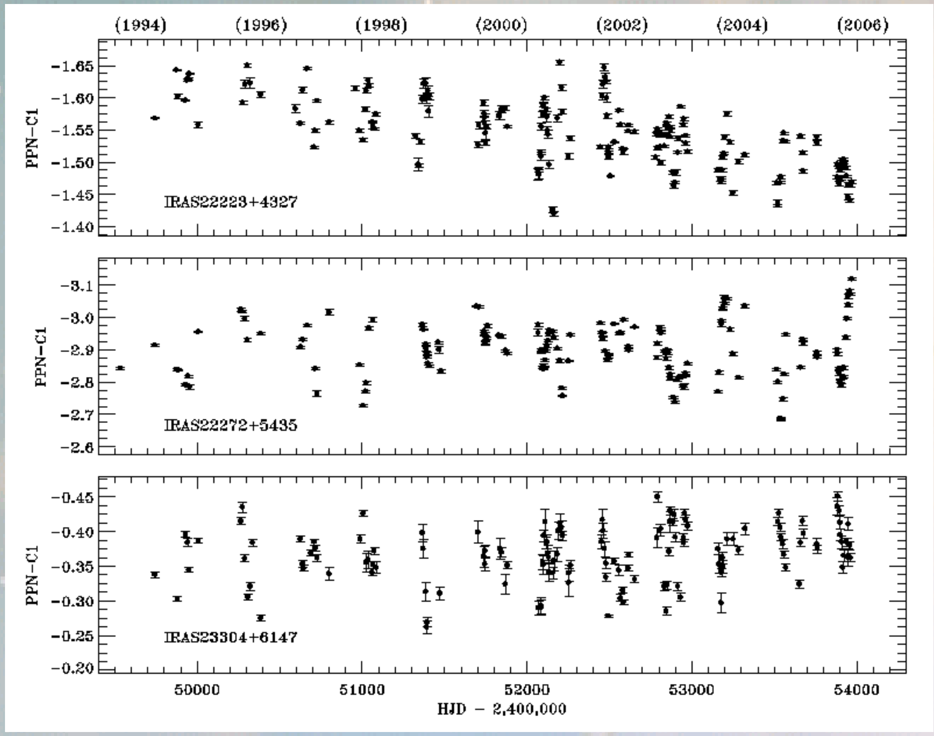
Last 4 years



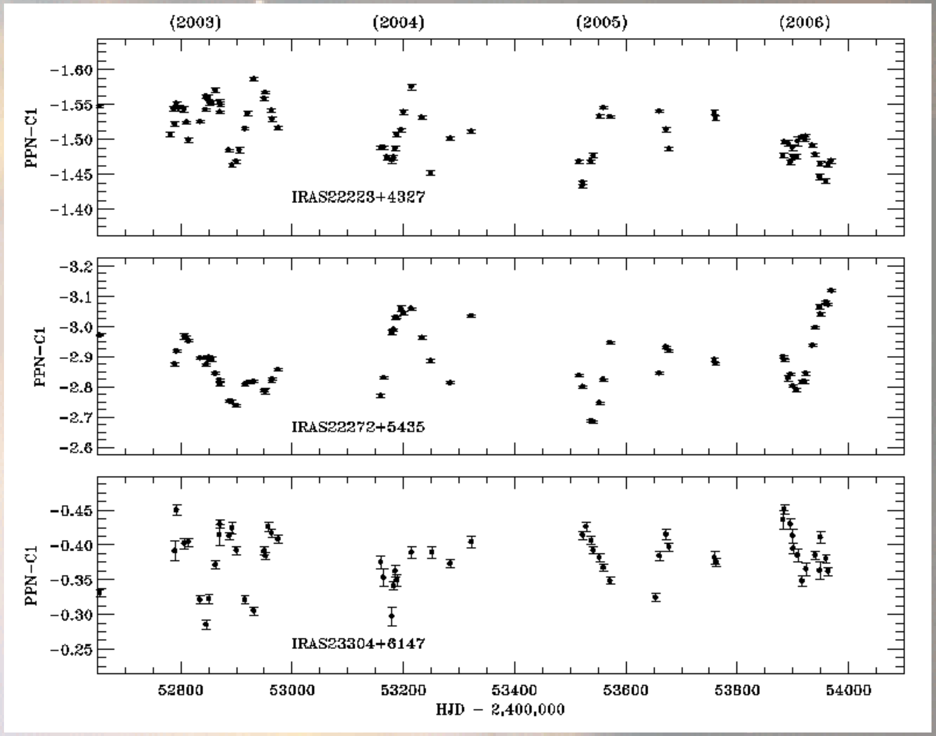
P = 115,103, 44 d

Central Star: (looking back to the AGB phase)

13 years



Last 4 years



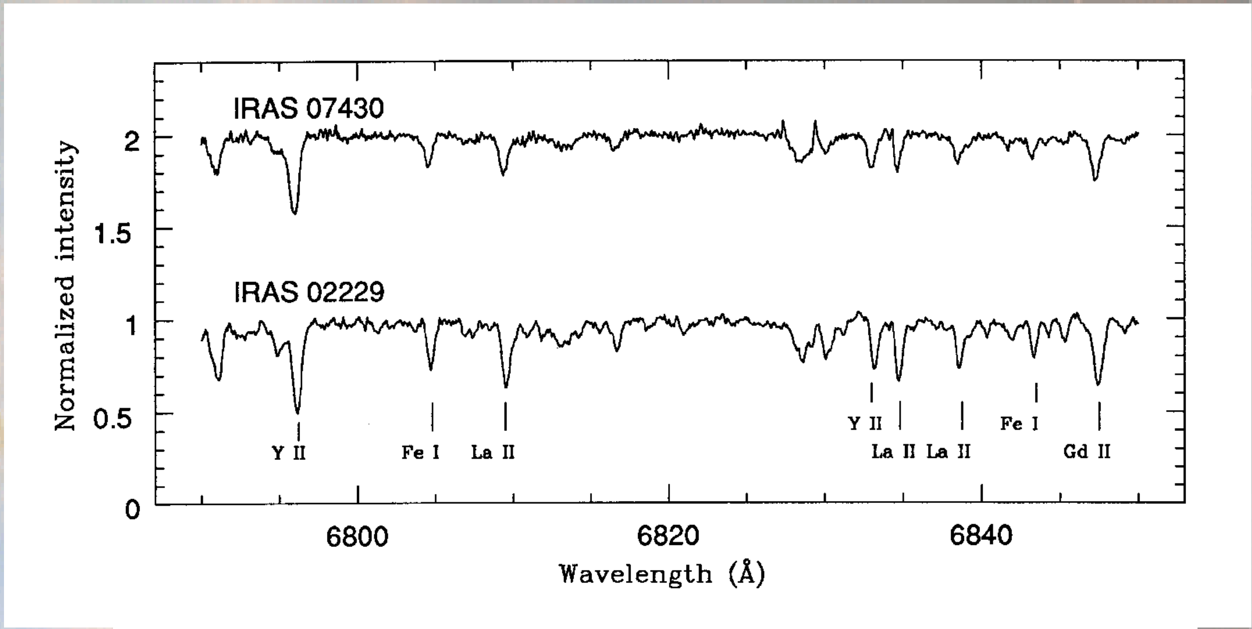
P = 90, 127, 84 d

What are we learning?

- Quasi-periodic variation, P=45-135 d, with variation or multiple P
- Variation due to pulsation (supported by radial velocity observations)
- Period, amplitude of light and velocity variations will be compared with models to give info on internal structure (M, L) of the stars.

Central Star: (looking back to AGB phase)

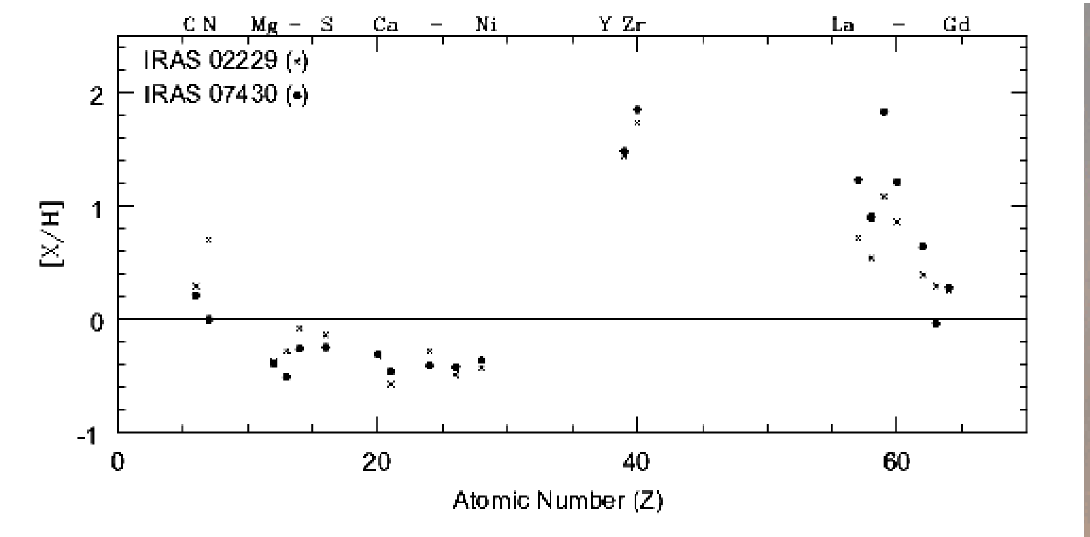
Chemistry of the star: What is the detailed elemental abundance?



- High-resl'n spectra (R~50,000) at McDonald Obs.
- Less Fe, more rare-earths than Sun

What do we learn?

- Low Fe
- More C, N, O & s-process elements
- Agrees with AGB nucleosynthesis



(Reddy et al. 1999)

Central Star: (looking back to AGB phase)

Chemistry of the star: **What have we learned?**

- Fe-poor → older stars

- **C-rich**: [Fe/H] = -0.7, [C/Fe] = +0.9, [s-process/Fe] = +1.5 (N=10)
  clear evidence of third dredge-up on AGB
  [(1) van Winckel, Reyniers et al., (2) Reddy et al., (3) Klochkova et al.]

- **O-rich:** [Fe/H] = -0.5, [C/Fe] =+0.4 , [s-process/Fe] =0.0 (N=4)

Why don't the O-rich show the expected post-AGB abundance patterns?

- lower mass (< 1.4 M_{sun}), no third dredge up (?)

Problem Reddy and I are presently working on.

Central Star: (looking back to AGB phase)

Chemistry of the star: **What have we learned?**

- Fe-poor → older stars

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  clear evidence of third dredge-up on AGB
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- **O-rich:** [Fe/H] = -0.5, [C/Fe] =+0.4 , [s-process/Fe] =0.0 (N=4)

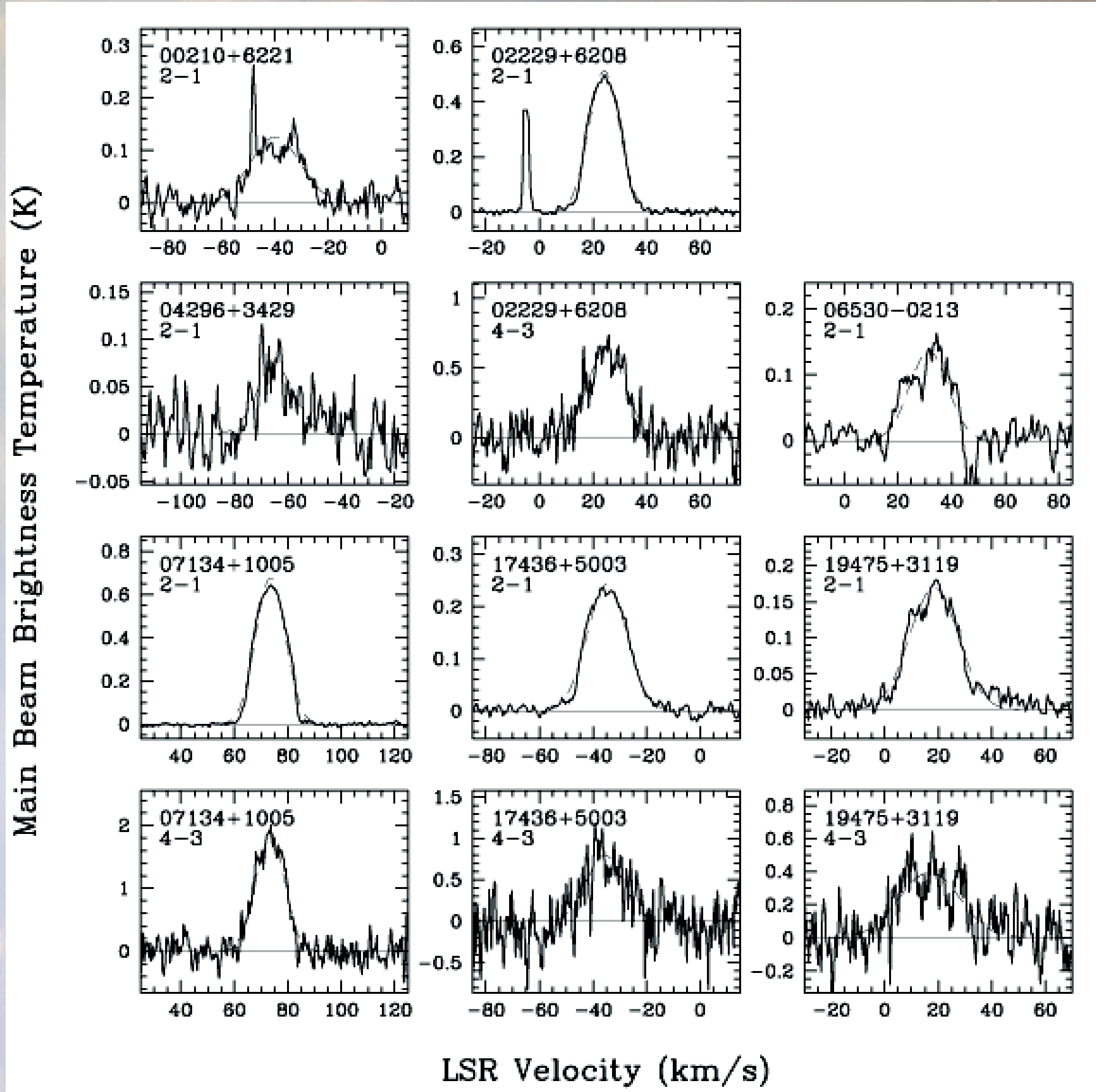
Note that there are other post-AGB stars that have abundance anomalies
- very low [Fe/H], high [CNO, S, Zi/Fe] (van Winckel et al.)
- explained as chemical fractionation of non-volatiles on dust, formation of disk, then re-accretion of gas
- show broad IR excess (broad SED) --> hot + cool dust
- these all appear to be in binary systems, which may stabilize disk
- these are different objects, likely low mass and not proto-PNs

Circumstellar Envelopes: Chemistry

What can we learn of/from the chemistry of the CSE of PPNs?

mm, submm:
molecular component observed in
CO, OH, HCH, …

CO: 2-1 and 4-3
12-m HHT in Arizona



Circumstellar Envelopes: Chemistry

What can we learn of/from the chemistry of the CSE of PPNs?

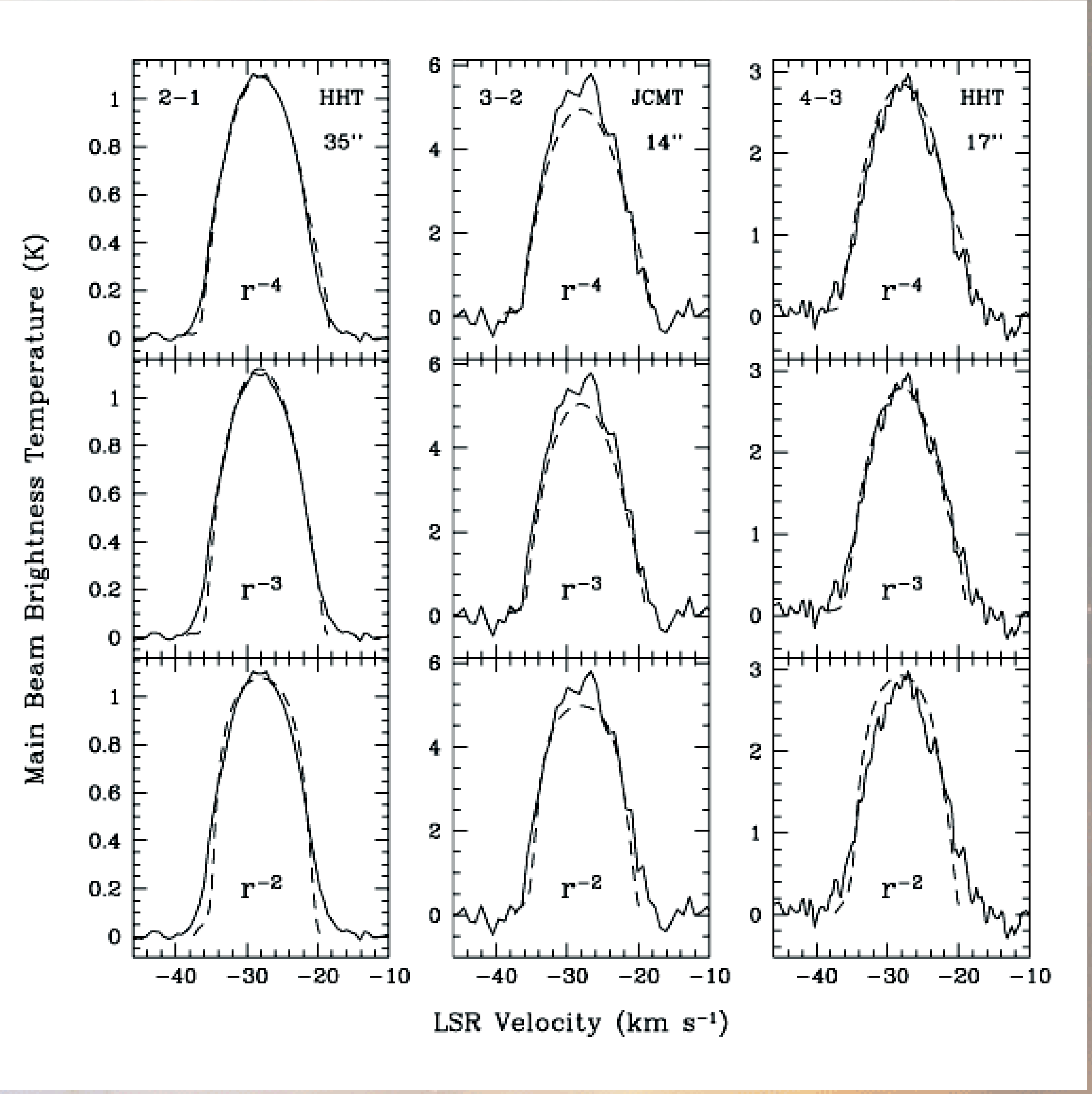
12 PPNs:

V_{exp} = 8-15 km/s

$\dot{M}$ = 0.1-1.4 x 10^{-4} M_s/yr

Mass loss decreasing with t,
r^{-3} or r^{-4}
(constant mass loss: r^{-2})

(Hrivnak & Beiging 2005)

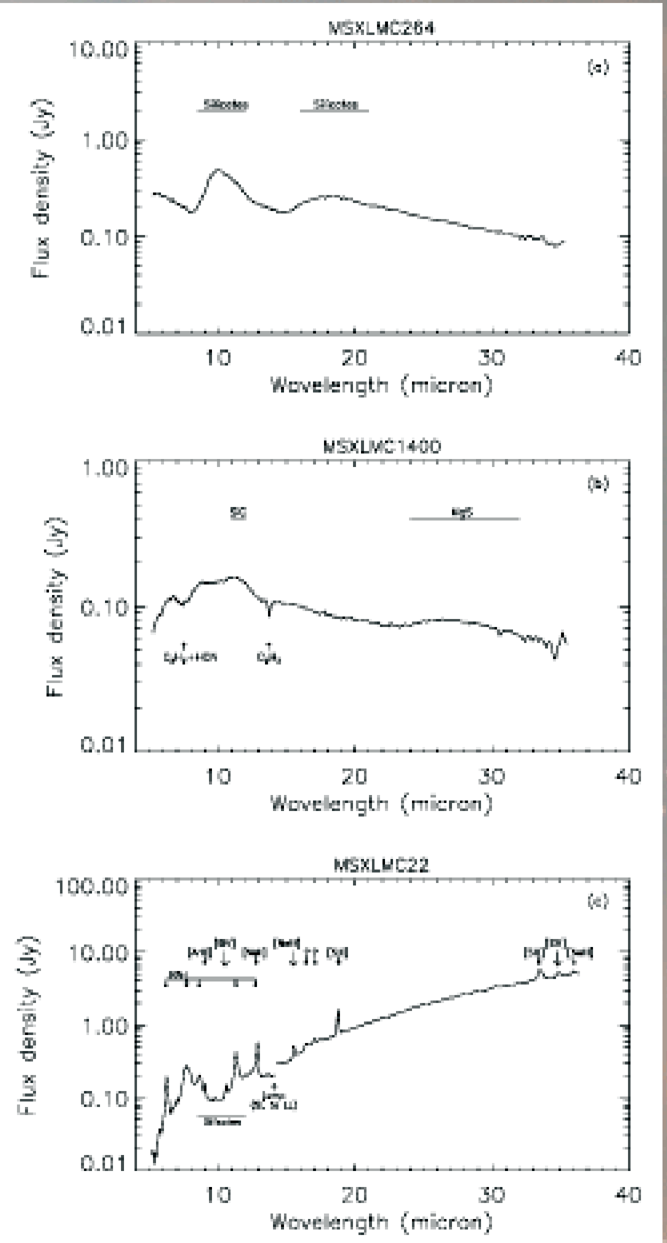


Circumstellar Envelopes: Chemistry

What can we learn of/from the chemistry

IR:

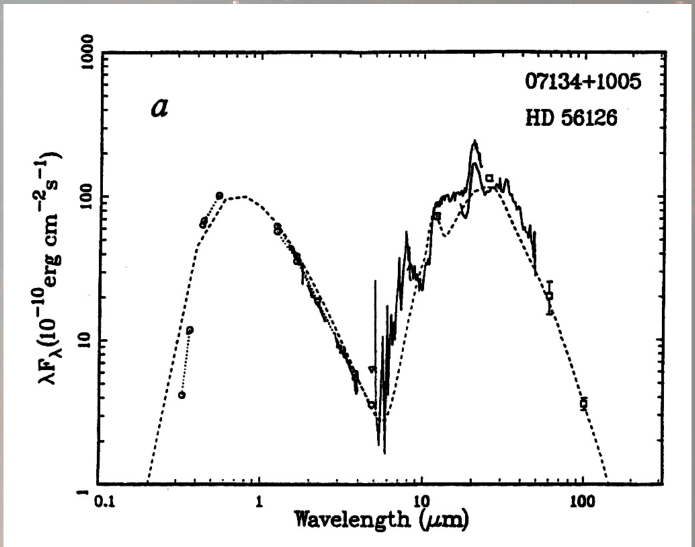
- Silicates: 9.7 m, 18 m
  O-rich AGB stars, some PNs
  (Some show crystalline silicates)



- Silicon-carbide : 11.3 m
- broad emission 30 m feature (MgS)
  C-rich AGB stars, some PNs

- Unidentified IR emission bands (UIR):
  3.3, 6.2, 7.7, 8.6, 11.3 m (PAHs)
  C-rich PNs and other nebulae
  with hot central star

Circumstellar Envelopes:

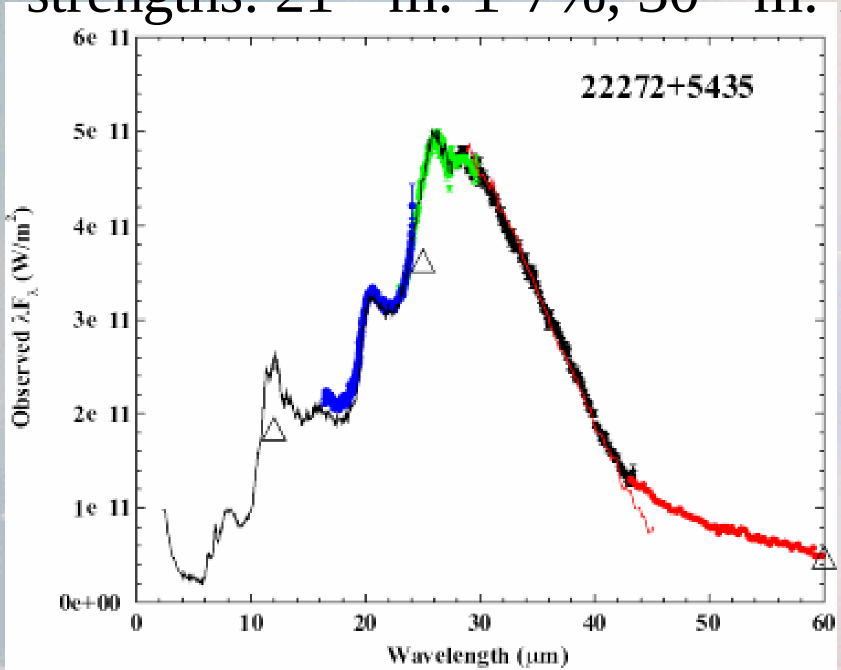


What about PPNs?

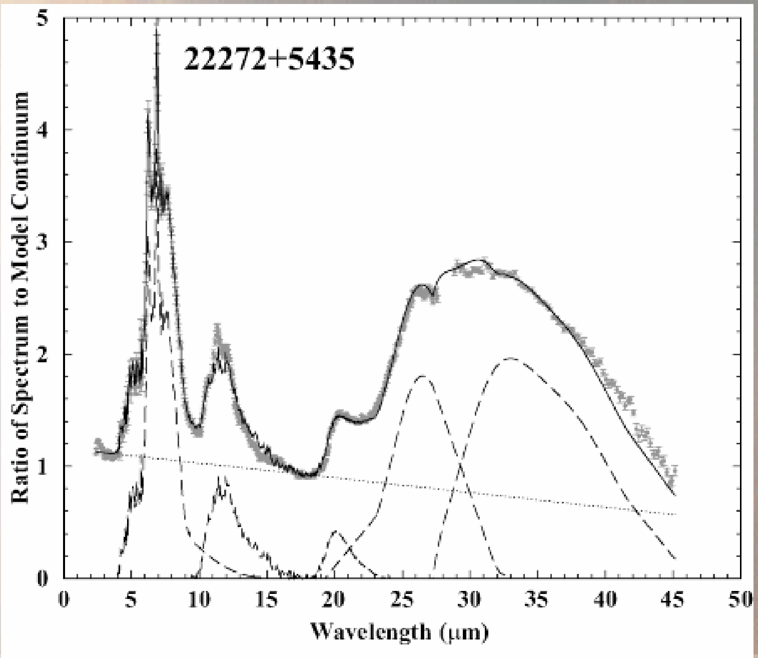
-some interesting surprises; a new emission feature at 20.1 m **("21 μm feature")** seen in 16 PPNs, all C-rich showing post-AGB abundance patterns

- **30 μm feature** prominent

- strengths: 21 m: 1-7%, 30 m: 15-25% of total emission



ISO spectra

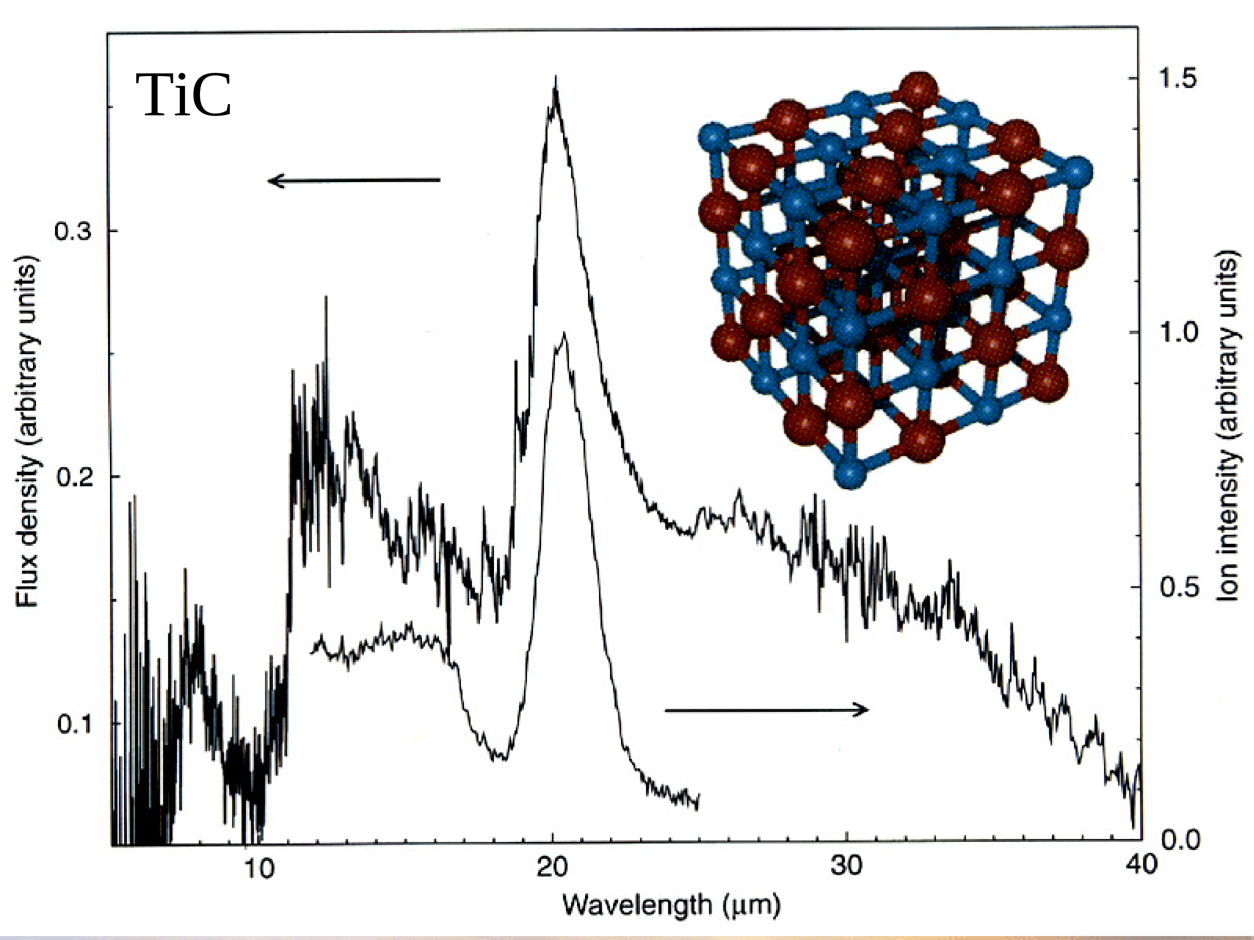


Circumstellar Envelopes:

What dust grains/molecules produce the 21 μm feature?

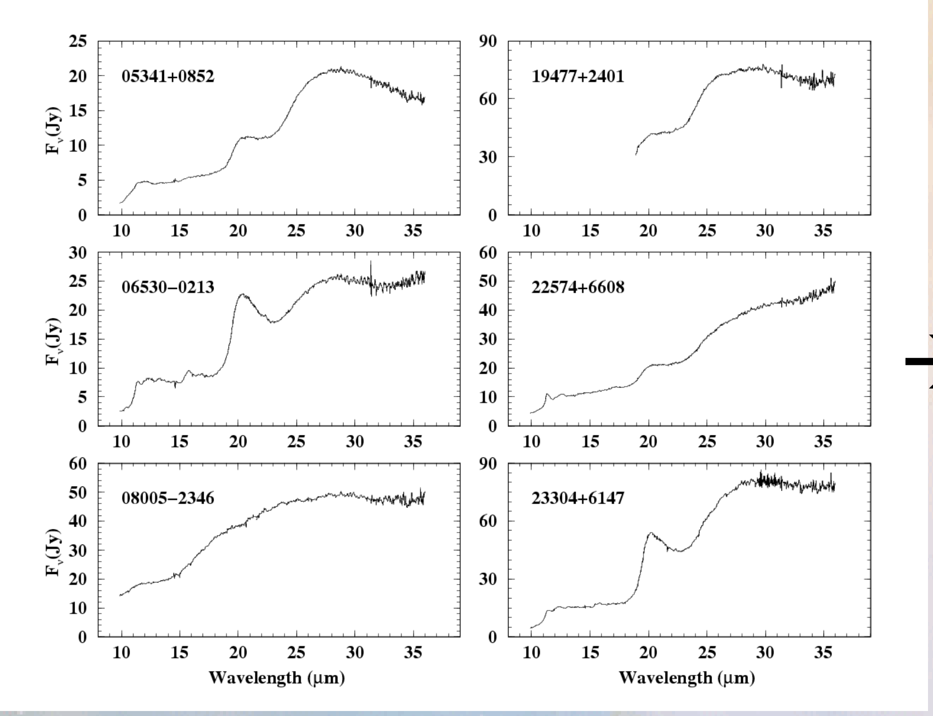
Laboratory studies:
- crystalline nanodiamonds?
- nanocrystalline TiC?
- SiC crystals?
- **still uncertain**

→ Info on physical conditions in the nebula

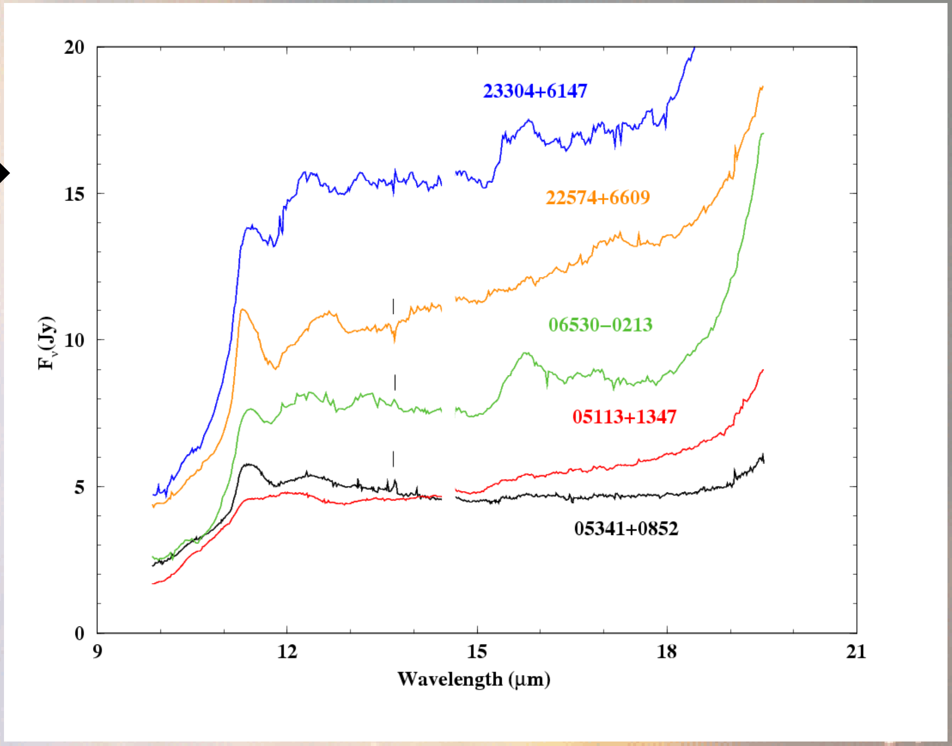


Circumstellar Envelopes:

New Spitzer data on fainter sources



11.3 & 12 m PAH features



21 & 30 m features
(all but lower left)

Also C_2H_2 at 13.7 m; ? at 15.8 m

Conclusions: What we've learned and what we're asking

Study of PPNs is important as a link to the **previous AGB** phase
- AGB nucleosynthesis   carbon, later returned to space

and as a link to the **succeeding PN** phase
- shaping of nebulae
  - however, exact mechanism for shaping not known
  - **Q**: role of binaries vs. magnetic fields vs. other?

In addition, study of **PPNs** has become important in its own right:
- chemistry of nebulae in changing radiation, density environment

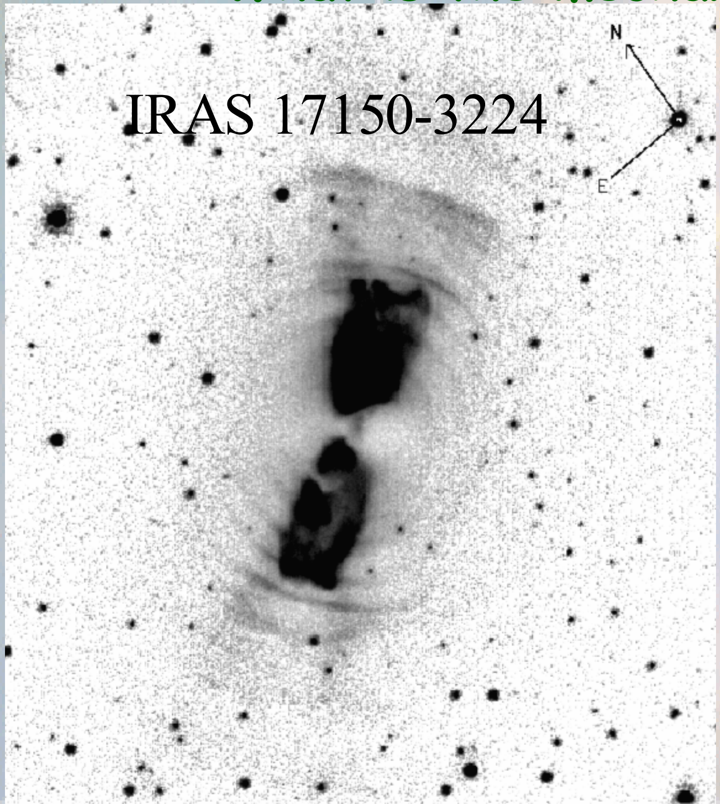
New: Present and near-future studies
- push to higher resolution
- distribution of dust & features (mid-IR imaging, spatially-res spec.)
- radial, azimuthial distribution of molecules (submm interfer.-ALMA)
- PPNs in nearby galaxies (LMC/SMC) - known distances, diff. metal.
  - Spitzer, SOFIA, Herschel

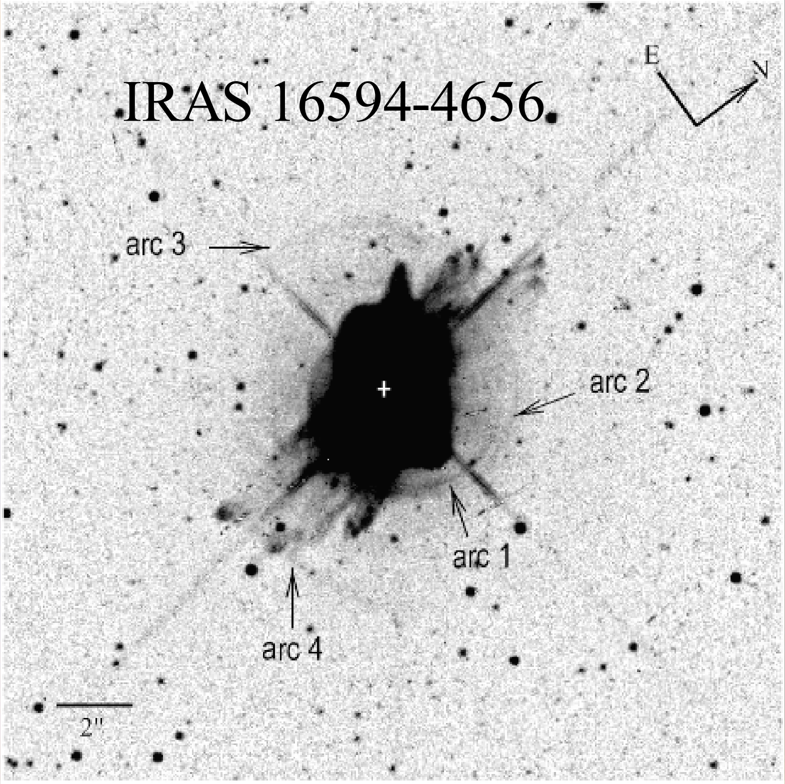
Circumstellar Envelopes: Shaping?

Change from spherical AGB to bipolar PPNe must happen quickly

Record seen in **circumstellar arcs**: 5 PPNs, 4 PNs, 1 AGB Egg (>20), 17150 (8), 17441 (3), 16594 (4), 20028 (3)

- **illuminated shells,** **timescales** 10^2–10^3 yr
- How common are they?
- What is the mechanism?





Circumstellar Envelopes: Shaping?

Change from spherical AGB to bipolar PPNe must happen quickly

Circumstellar Arcs (illuminated shells):

Timescale:

Arcs :	10^2–10^3 yr
Stellar pulsations:	1 yr
Thermal pulses:	10^4–10^5 yr

Suggested explanations:

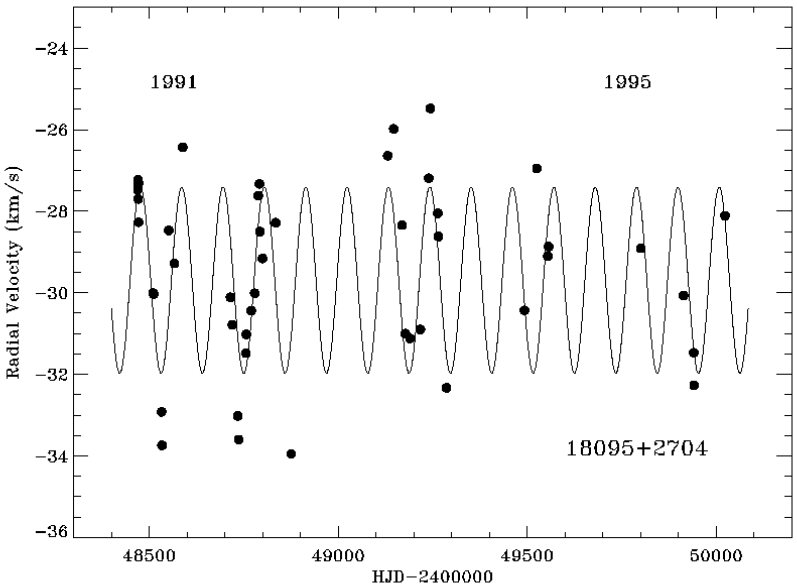
- periodic mass loss
- periodic effect of binary companion
- magnetic cycles on star
- gas-dust hydrodynamics

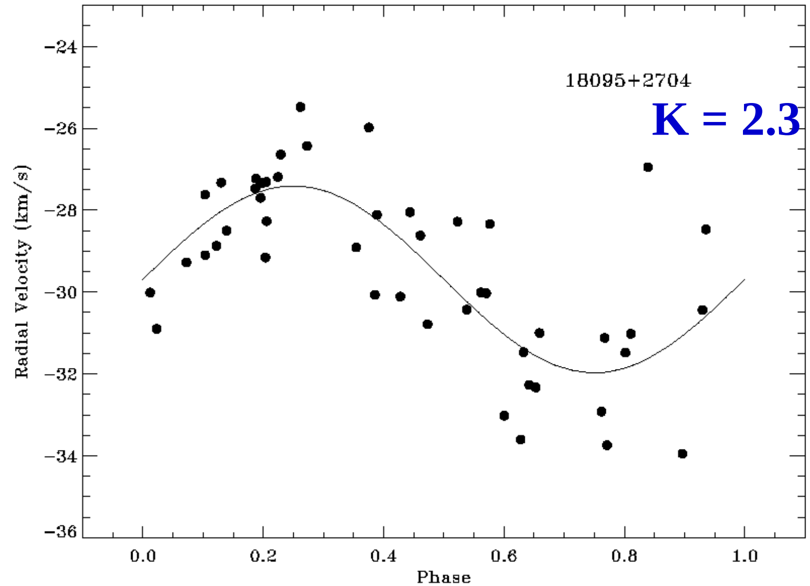
OUR RADIAL VELOCITY PROGRAM OF PPNe

- Observations at the Dominion Astrophysical Observatory (Victoria) with the RVS (mechanical mask, ~300 lines) on the 1.2 m Coude
  (used by McClure to detect binary Ba stars)
- Observed extensively for 3 years (1991-1993), occasionally for 2 more
- **Targets: SpT = F-G Iab**
  - Many, sharp lines (advantage over PNNe)
  - Precision ~ 0.65 km/s
  - **Goal - to find binaries** (or at least set limits on them)
- **Targets: 7 bright PPNe**
  - V = 7 - 11 mag
  - No. Obs. Each = 30 - 60 over T = 1600 d
  - Collaborators: A. Woodworth, S. Morris, D. Bohlender (DAO), W. Lu (Valpo. U.)
- Period study using CLEAN and PDM

RESULTS OF OUR RADIAL VELOCITY PROGRAM OF PPNe

- **IRAS 18095+2704 (F3 Ib, O-rich)**
- **ΔV= 8 km/s P(RV) = 110 d ~ P(LC) = 113 d**
  K = 2.3 km/s ΔLC=0.15 mag --> Pulsation



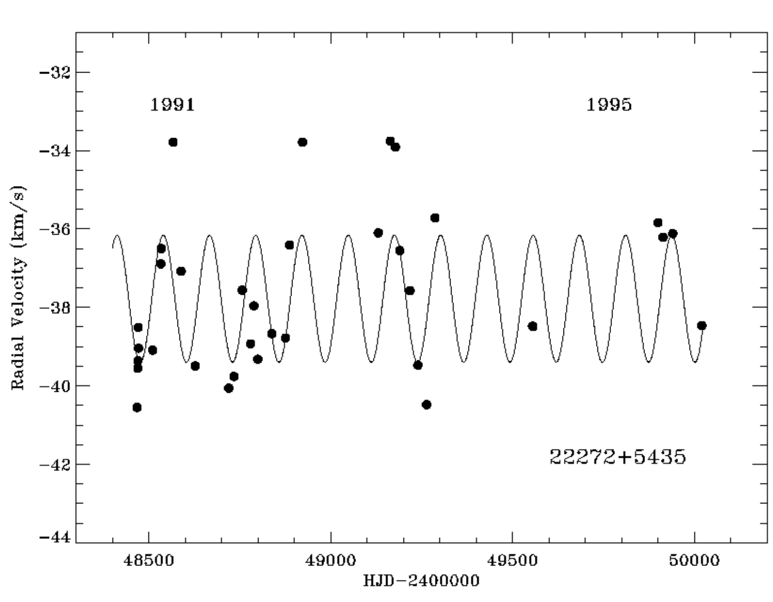


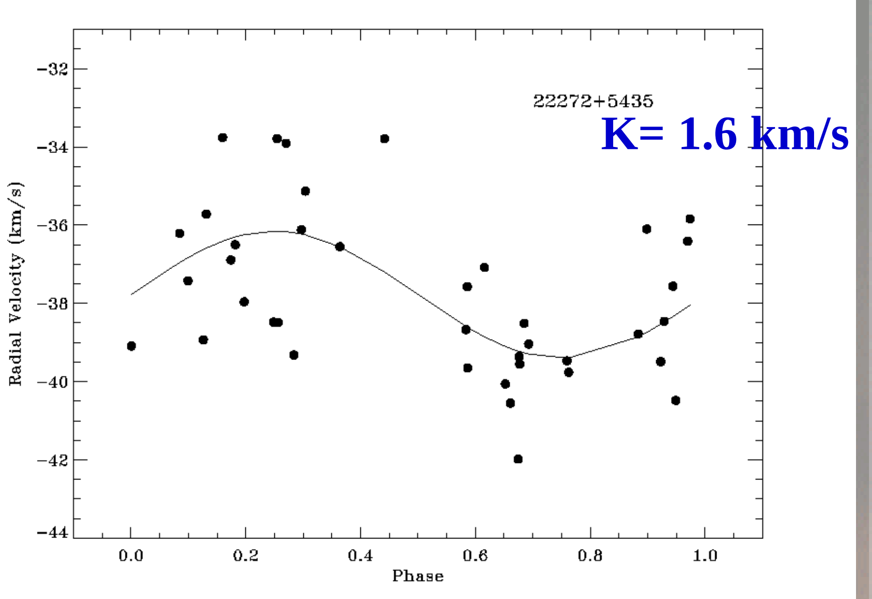
K = 2.3 km/s

- Periodic pulsation, with reasonably consistent pattern

RESULTS OF OUR RADIAL VELOCITY PROGRAM OF PPNe

- **IRAS 22272+5435** **G5 Ia (C-rich)**
- **ΔV= 8 km/s** **P(RV) = 125 d ~ P(LC) = 130 d**
  K = 1.6 km/s **ΔLC=0.3 mag** **--> Pulsation**

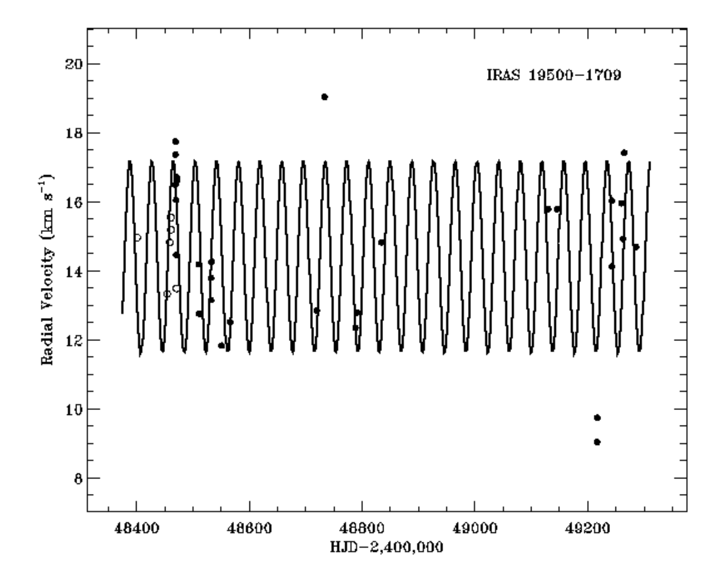


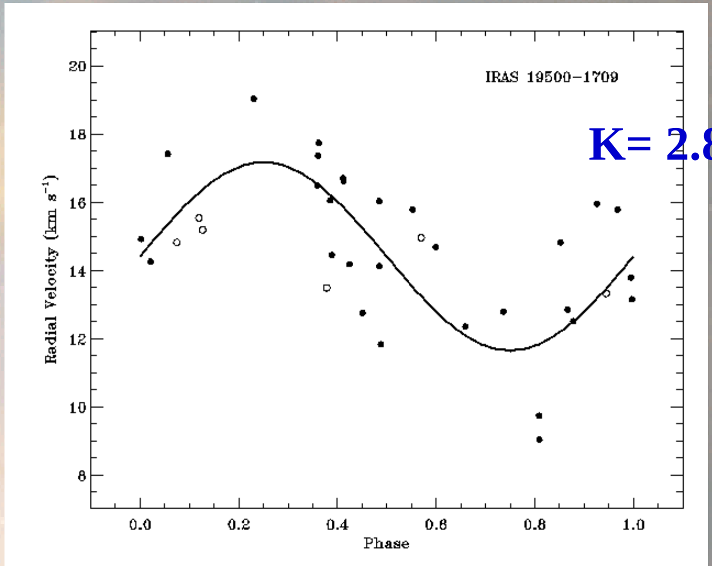


- Periodic pulsation, but with varying amplitude or multiple periods (or other effects)

RESULTS OF OUR RADIAL VELOCITY PROGRAM OF PPNe

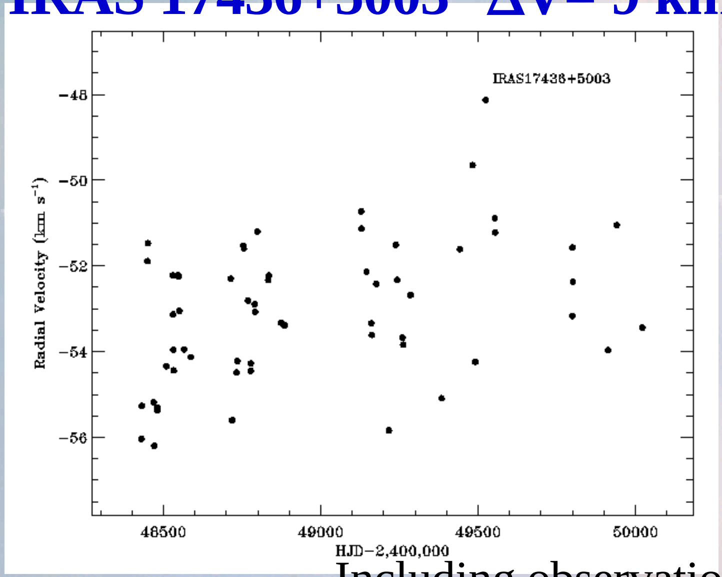
- **IRAS 19500-1709 ΔV= 12 km/s P(RV) = 38.5 d ~ P(LC) = 38, 41 d**

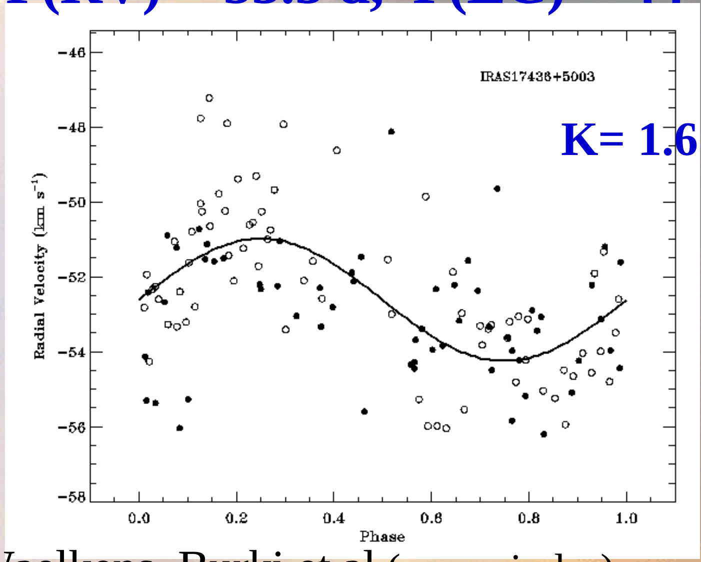




K= 2.8 km/s

- **IRAS 17436+5003 ΔV= 9 km/s P(RV) = 53.5 d, P(LC) = 44 d**



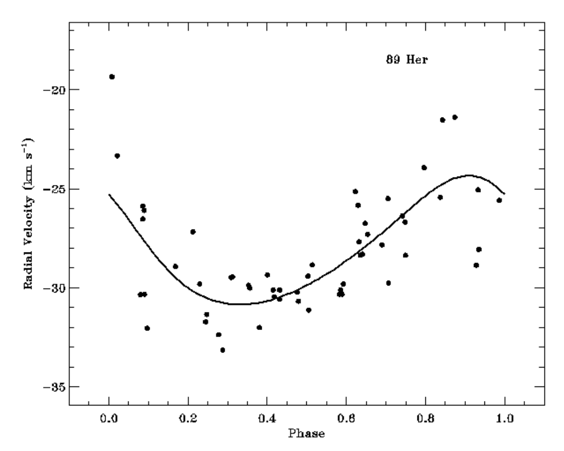


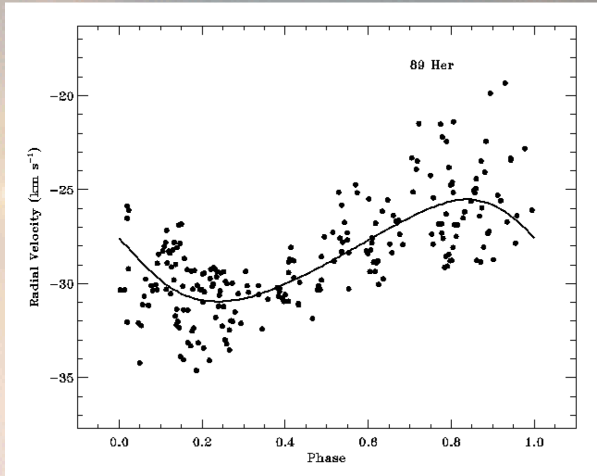
K= 1.6 km/s

Including observations by Waelkens, Burki et al.(open circles)

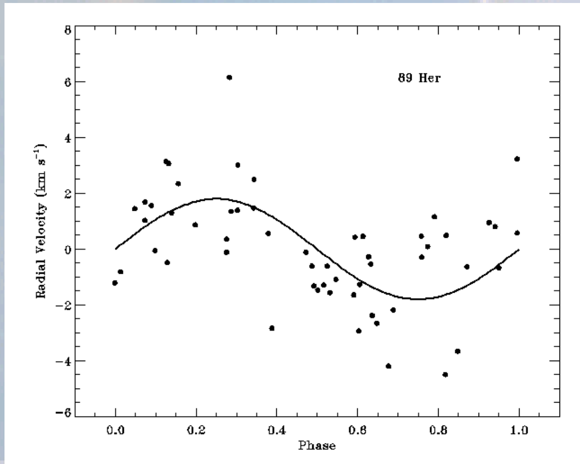
RESULTS OF OUR RADIAL VELOCITY STUDY OF OTHER POST-AGB OBJECTS

- **Are we able to find binaries with pulsators? - Yes**
- **89 Her ΔV = 12 km/s P(RV) = 292 d (our data), 289 d (all data), K = 3.3 km/s, e = 0.18 --> binary**





Including observations by Waters et al. (1993)



89 Her - with binary orbit removed
P(RV) = 66 d ~ P(LC) = 65 d, K= 1.6 km/s
--> pulsator

RESULTS OF OUR RADIAL VELOCITY PROGRAM OF PPNe

- **No** binaries found among our PPNe sample (#=7)
- **Why?** - Selection effect?
  - Brightest PPNe, so less obscuration
    - Perhaps close to pole on
    - What is know about their inclination? (2D models)
      - i ~ 10^o - 80^o, although most likely < 45^o
    - Detection limits from this study (based on 89 Her, i=11^o)
    - P=300 d, K=3.3 km/s --> i > 11^o
    - P=3 yr, K=3.3 km/s --> i > 18^o
    - P=10 yr, K=3.3 km/s --> i > 27^o
  - These are conservative, since in our case $K_{(orbit)}$<2.5 km/s
  - **Thus unlikely that it is primarily a selection effect**

Circumstellar Envelopes: Shaping?

What is the cause of such a torus?

- **Binary** companion – diverting mass loss into plane of orbit
  - could be star or planet (Soker, Livio, others)
- Rapid rotation – preferred plane for mass loss (perhaps **binary**)
- Magnetic field – leading to constraints on mass loss direction

How to detect an unseen binary?

-**Velocity** variations – gravity of unseen companion causes reflex motion of visible star about the center of mass.

- **Light** variations - light varies due to eclipses by unseen companion, ellipsoidal shape (tides), or re-radiation of light from hot comp. (method used to find binary PN CS)

Our studies: (1) radial velocity - 7 PPNs monitored over 5 yrs
(2) light curve - 25 PPNs monitored over 14 yrs

No binaries detected! **How to understand this?** (not time to discuss)

RESULTS OF OUR RADIAL VELOCITY PROGRAM OF PPNe

- **No** binaries found among PPNe sample (#=7) - with K > 2.5 km/s
  - For *i*=30 --> a > 6 AU, P > 14 yr
  - For *i*=60 --> a > 17AU, P > 70 yr

- **Why no binaries detected?**
  - Not primarily selection effect (bright --> low *i*, low V amplitude)
  - Binary, but with very low mass companion (or planet) – however …
  - Long P (P>10-100 years)
  - but in either case the effect on shaping should be small

- **An area that will need to be further explored!**

Follow-up studies

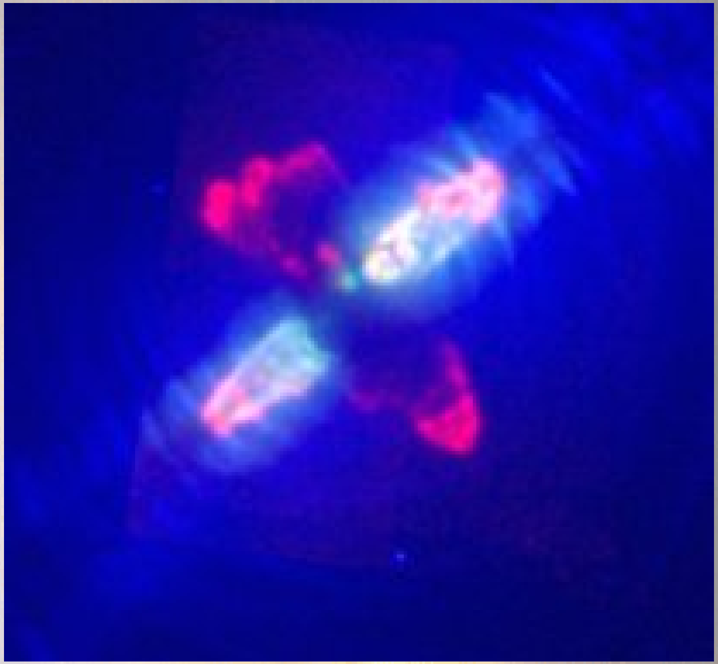
- Re-initiated Vr study of these 7 PPNe to look for long-period SB1
- Try to observe near-IR spectra of edge-on PPNe with torus along line of sight, to see full effect of orbital velocity.

Proto-Planetary Nebulae: A Multi-Wavelength Study

Bruce J. Hrivnak (Valparaiso University, USA)

Collaborators:

Sun Kwok – U. Hong Kong
Kevin Volk – Gemini-N
Kate Su – U. AZ
B.E. Reddy - IIA



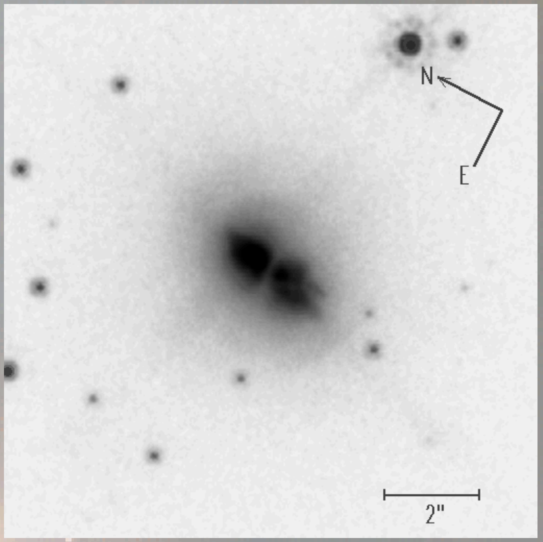
Egg Nebula (Sahai et al. 1998)

H_2(red), 1.6 m(green), 0.6 m(blue)

(IIA, Bangalore 2008-01-31)

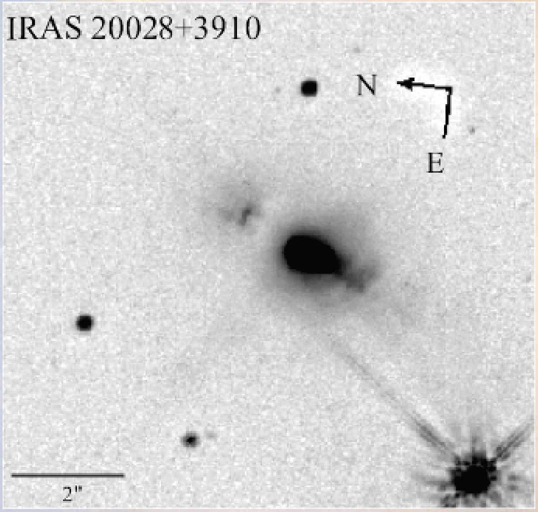
Circumstellar Envelopes: Shapes?

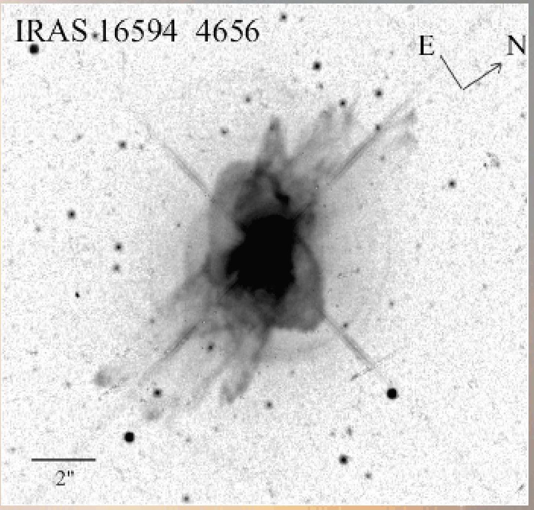
Our HST studies: - Bipolar shape is common



PPNs in scattered light

Other studies by Ueta et al. (2000), Sahai et al. (2007)

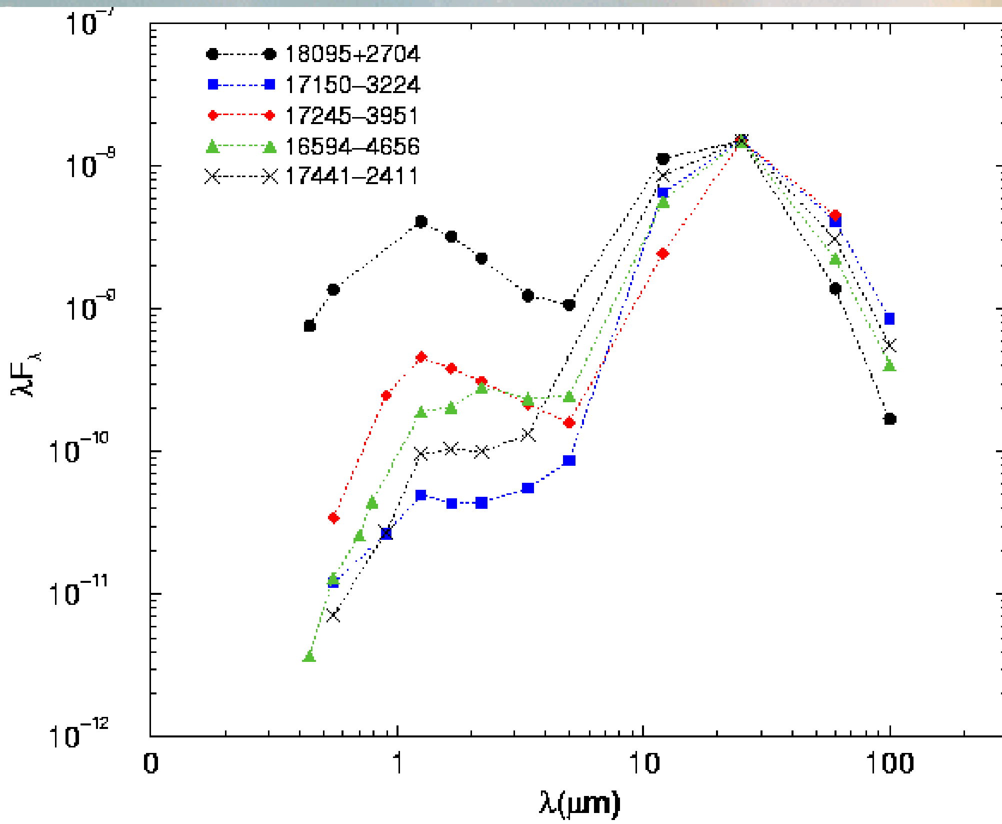


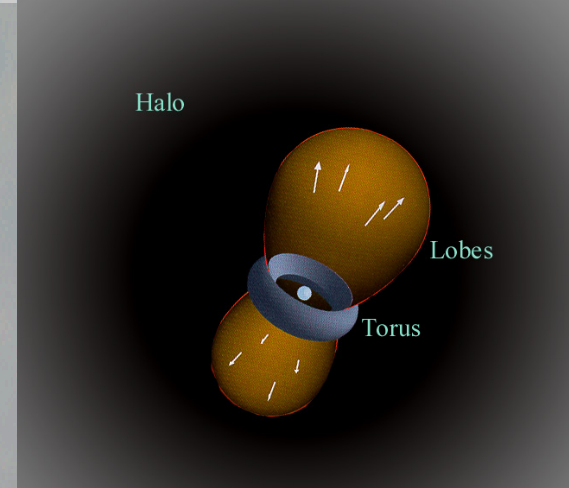


Is there a basic model to explain the shapes?

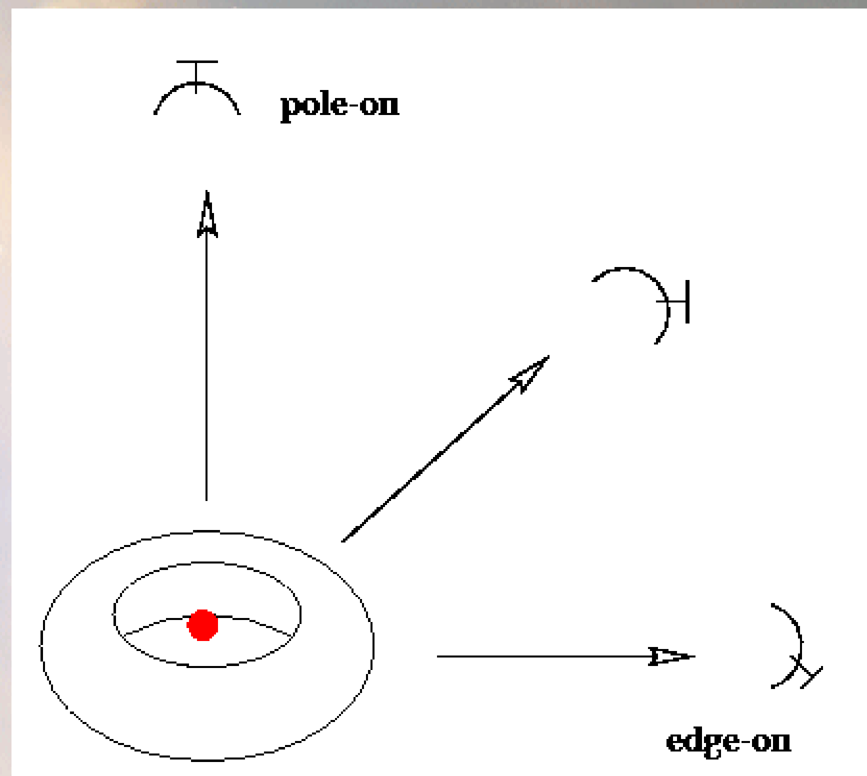
Spectral Energy Distribution (SED)

(normalized at 25 m)





Picture adopted from the paper by Balick, in American Scientist 1996



Obscuring torus and bipolar lobes, as seen from differing orientations.

Circumstellar Envelopes: Chemistry

What can we learn of/from the chemistry of the CSE of PPNs?

Begin with review chemistry of CSE in evolved stars

mm, submm: molecular component observed in CO, OH, HCH, …

IR: Large molecules & solid-state features observed in evolved objects

- Silicates: 9.7 m, 18 m O-rich AGB stars, some PNs
- Silicon-carbide : 11.3 m C-rich AGB stars, some PNs

- Unidentified IR emission bands (UIR):
- 3.3, 6.2, 7.7, 8.6, 11.3 m (PAHs) -- observed in PNs and other nebulae with hot central star (C-rich)

- Very broad emission 30 m feature seen AGB and PN (ISO) -- C-rich attributed to MgS

- Crystalline silicates (ISO): seen in PNs -- O-rich

SUMMARY OF OUR RADIAL VELOCITY PROGRAM OF PPNe

PPNe	V(mag)	SpT	Vr		P(RV)	P(LC)	Results
07134	8.2	F5 I	10	0.65	40 d	35 d	Pulsate
17436	7.1	F3 Ib	8	0.55	53.5	44	Pulsate
18095	10.4	F3 Ib	8	0.80	110	113	Pulsate
19475	9.4	F3 I	10	0.70	47:, 39:	37, 41	Pulsate
19500	8.7	F3 I	11	0.70	38.5	38, 41	Pulsate
22223	9.7	G0 Ia	8	0.65	89	90	Pulsate
22272	9.1	G5 Ia	8	0.65	125	130	Pulsate
Related							
19114	7.9	G5 Ia	30	0.80	---	---	Pulsate
20004	8.9	G7 Ia	14	0.70	---	---	Pulsate
HD 46703	9.1	F8 Ia	32	0.70	606	---	Binary
89 Her	5.5	F2 Ib	12	0.55	289/66	65	Bin + Puls

HOW TO SEARCH FOR BINARIES IN PPNe? - 2

3. **Composite spectra**
   - Unlikely, would require both objects to be AGB, post-AGB
   - Could have any separation, P

4. **Radial velocity variations**
   - Orbital motion
   - Used in more recent searches for binary PNNe (DeMarco et al. 2006)
   - Can sample companions of intermediate separations
     - Assume M_1=0.6, M_2=0.6, e=0 — (i=90°) — (i=30°)
       - K_1 = 20 km/s --> P ~ 0.5 yr — P ~ 20 d
       - K_1 = 10 km/s --> P ~ 4 yr — P ~ 0.5 yr
       - K_1 = 3 km/s --> P ~ 150 yr — P ~ 20 yr
     - Case 2 M_1=0.6, M_2=0.2 — (i=90°) — (i=30°)
       - K_1 = 10 km/s --> P ~ 0.3 yr — P ~ 15 d
       - K_1 = 3 km/s --> P ~ 12 yr — P ~ 1.5 yr
     - Case 3 M_1=0.8, M_2=0.4 — (i=90°) — (i=30°)
       - K_1 = 10 km/s --> P ~ 1.2 yr — P ~ 50 d
       - K_1 = 3 km/s --> P ~ 40 yr — P ~ 4 yr

WHAT ABOUT KNOWN BINARY POST-AGB STARS?

- Aren't Hans Van Winckel & collaborators finding post-AGB binaries?

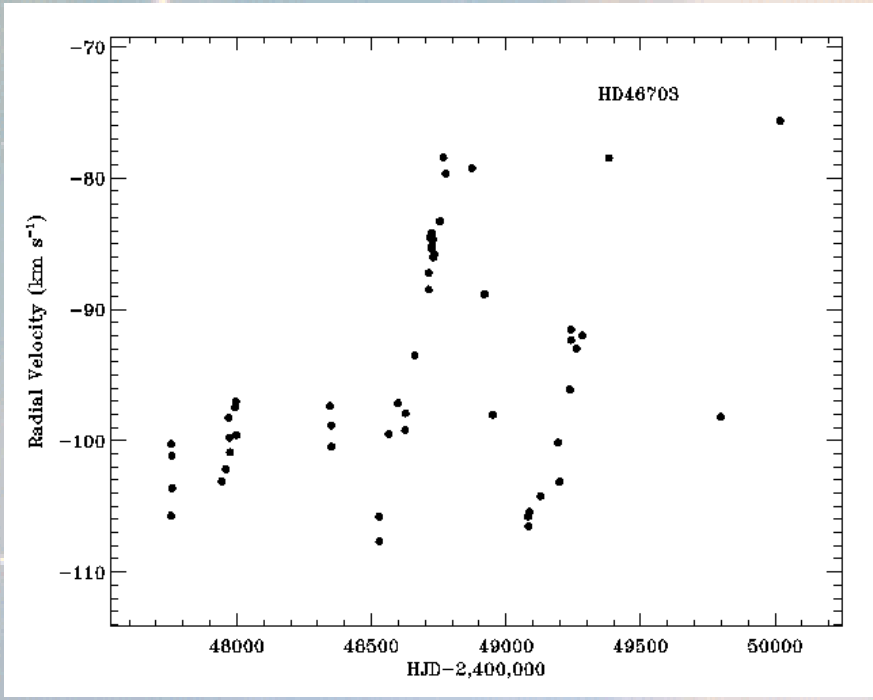
- **Characteristics of their sample**
  - Bright star (not obscured)
  - Broad IR excess (broad SED) --> hot + cool dust
  - Abundance anomalies, attributed to chemical fractionation of non-volatiles on dust, re-accretion of volatiles
  - Attributed to circumbinary disks, stability due to companion
- 10 well-studied cases, F-G star, P = 116 to 2600 d
- With these periods, may not be post-AGB, but post-RGB

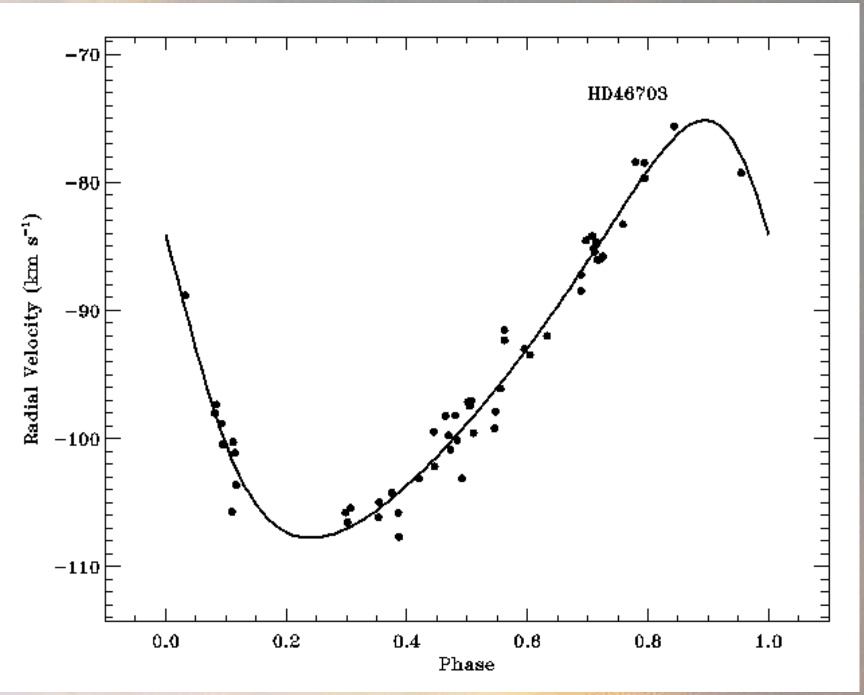
- **Our objects are different**
  - Double-peaked SEDs, no hot dust due to circumbinary disk
  - Chemical evidence of 3rd dredge-up, C-rich, s-process --> post-AGB

RESULTS OF OUR RADIAL VELOCITY STUDY OF OTHER POST-AGB OBJECTS

- **Are we not able to find binaries? - Yes, we can**

- **HD 46703 ΔV = 32 km/s**
  - **P(RV) = 606 d, K = 16.3 km/s, e = 0.27 --> binary**





Including observations by Van Winckel & Waelkens

RESULTS OF OUR RADIAL VELOCITY PROGRAM OF PPNe

Comparison of light and velocity curves - 1994-1995

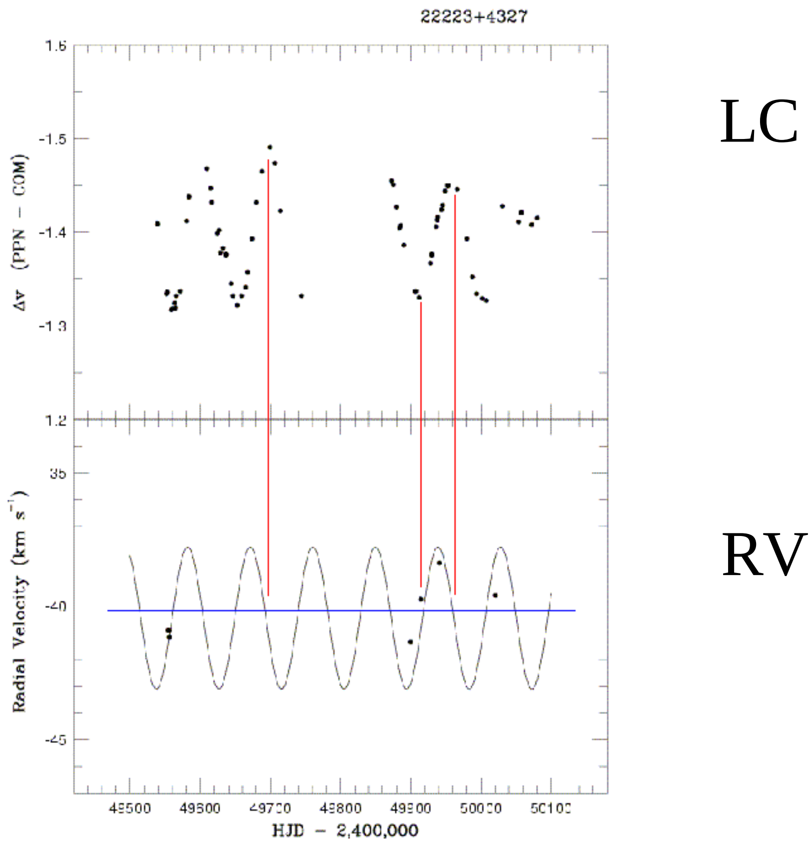
IRAS 22223+4327

P(RV) ~ P(LC) ~ 90 d

Most regular pulsator,
but still varying amplitude
(not reflection or ellipticity)

Brightest when star is smallest
(and hottest - from colors)

Would be very helpful to have contemporaneous RV and LC

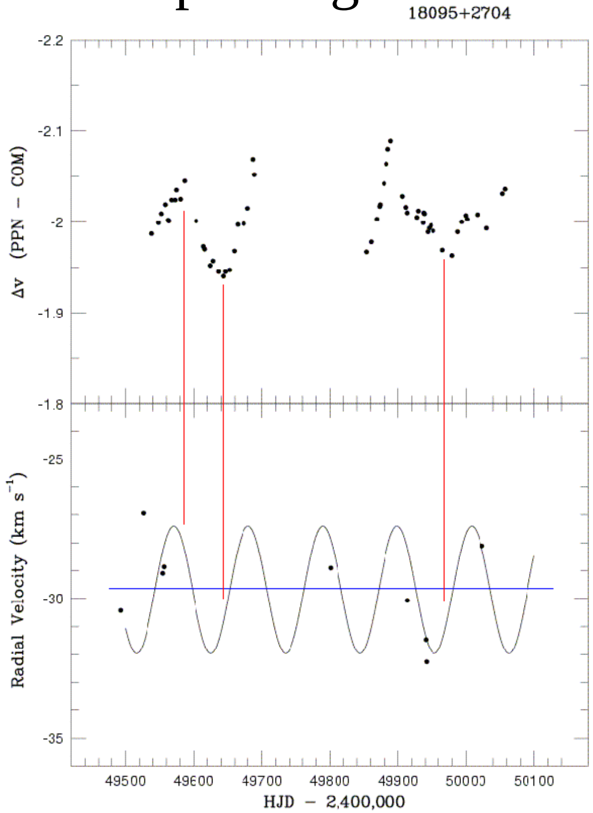


RESULTS OF OUR RADIAL VELOCITY PROGRAM OF PPNe

Comparison of light and velocity curves - 1994-1995

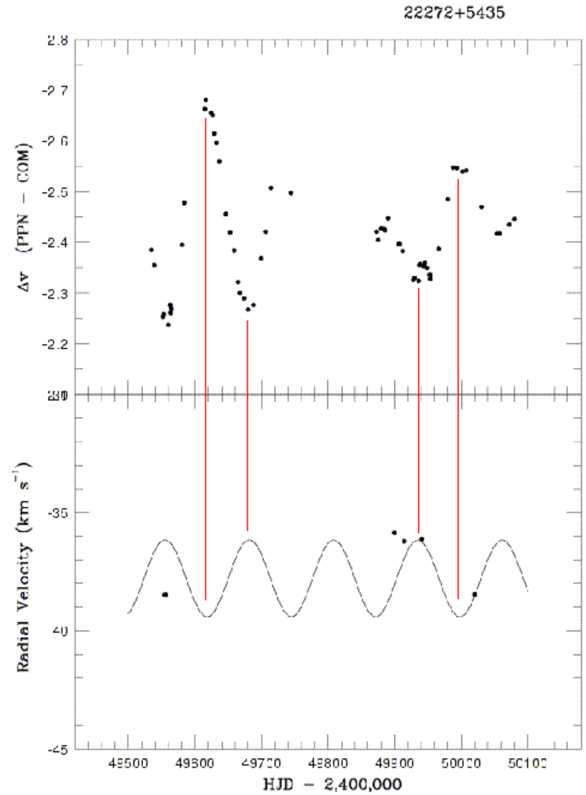
IRAS 18095+2704

Brightest when star is expanding and hottest



IRAS 22272+5435

Brightest when star is contracting and hottest

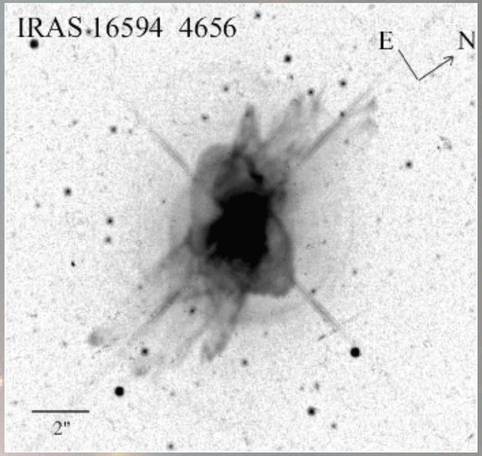


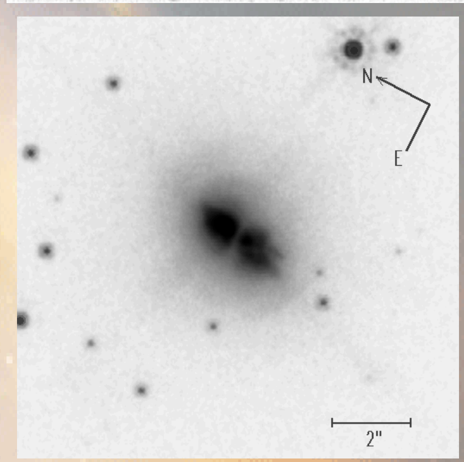
A SEARCH FOR BINARIES IN PROTO-PNe

(LOOKING FOR THE DIRECT EVIDENCE)

Bruce J. Hrivnak (Valparaiso University, USA)

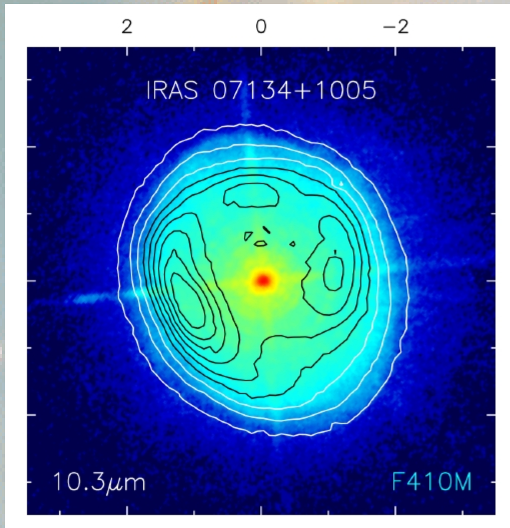
- Motivation
- How to detect
- Radial velocity study
- Results
- Implications



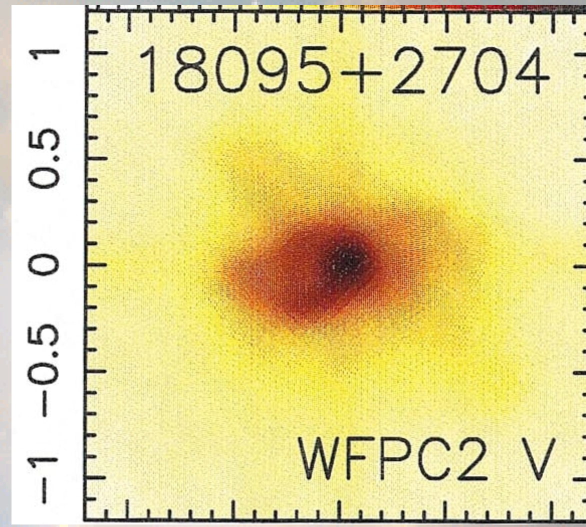


APN4: (La Palma June 2007)

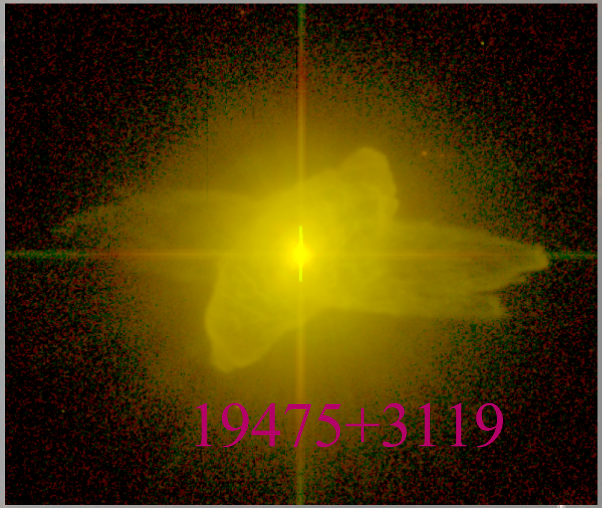
HST IMAGES OF PROGRAM OF PPNe - ORIENTATIONS



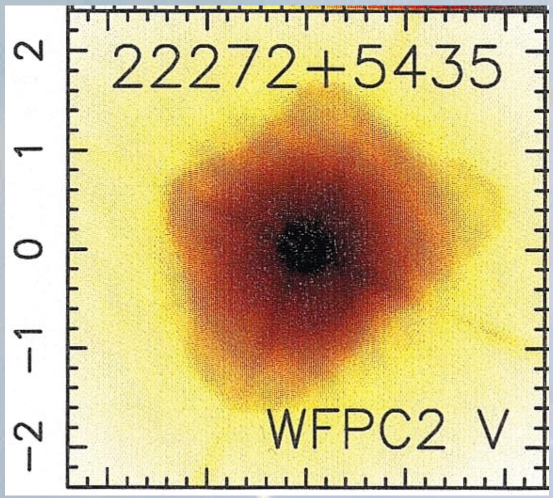
Limb-brightened disk at 10 um

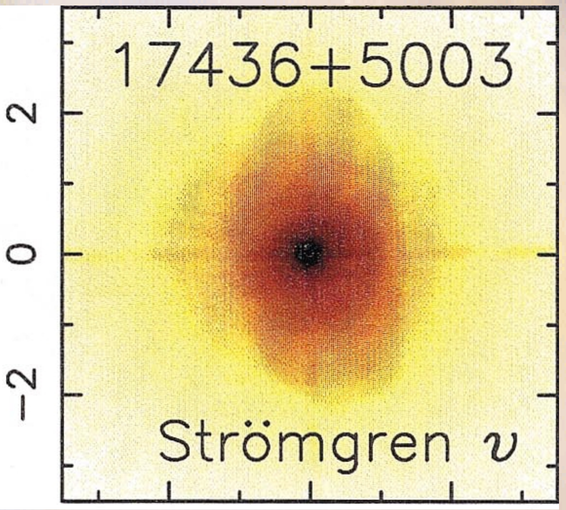


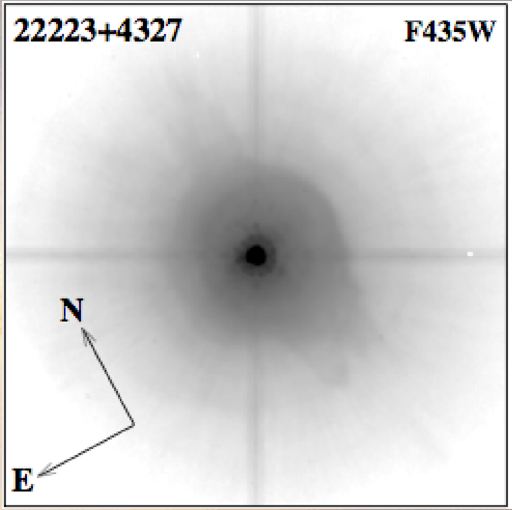
Bipolar morphology



Quadra-polar morphology







RESULTS OF OUR RADIAL VELOCITY PROGRAM OF PPNe

- **No** binaries found among PPNe sample (#=7) - with K > 2.5 km/s
  - For *i*=30 --> a > 6 AU, P > 14 yr
  - For *i*=60 --> a > 17AU, P > 70 yr

- **Why no binaries detected?**
  - Not primarily selection effect (bright --> low *i*, low V amplitude)
  - Binary, but in common envelope
    - But this lasts only a short time, unlikely
  - Long P (P>10-100 years) - but then effect on shaping may be small

Central Star: (looking back to AGB phase)

Nucleosynthesis:

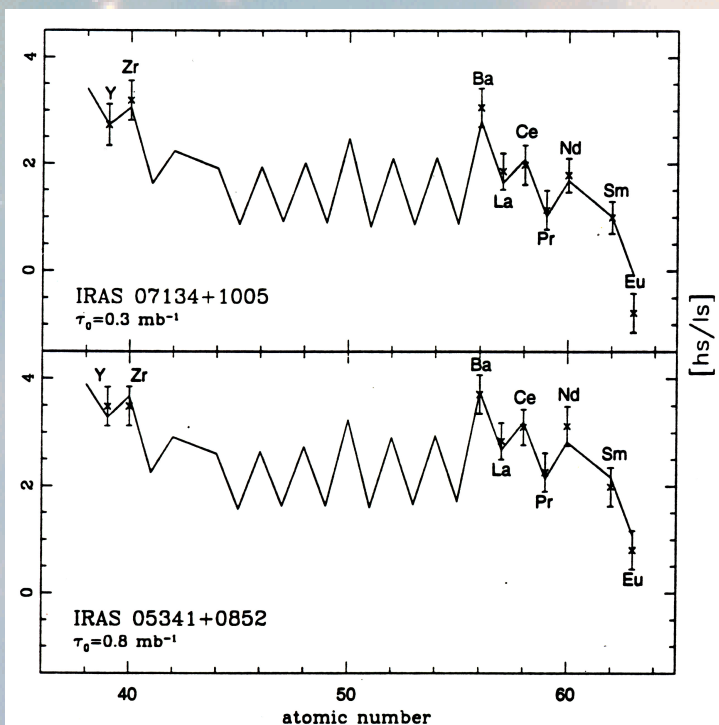
- s-process elements
- Neutron source: $^{13}C($ $,n)^{16}O$

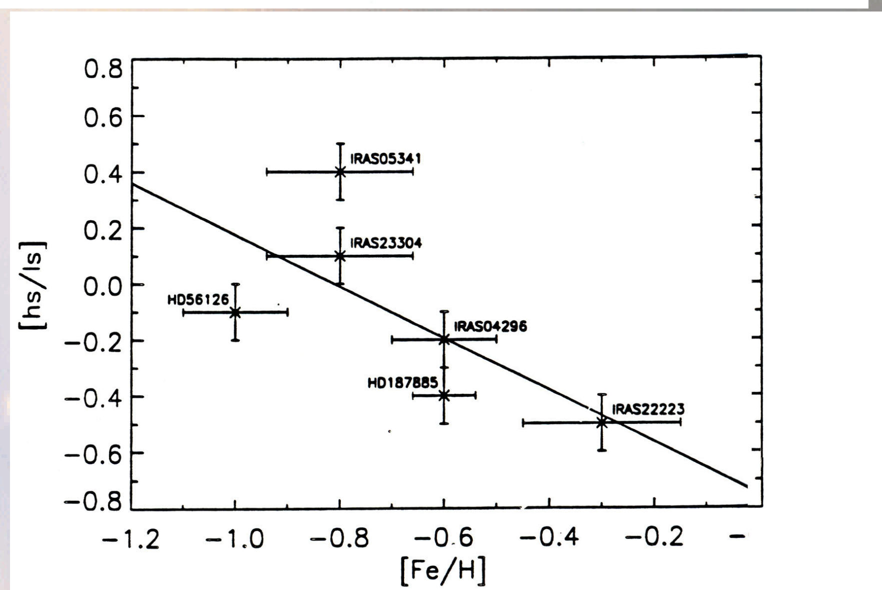
→ Neutron exposure

Ratios of Heavy to Light *s*-Process Elements ([*hs*/*ls*]) and Mean Neutron Exposure (τ_0) for Carbon-rich PPNs

Object	[Fe/H]	[*hs*/*ls*]	τ_0 (mbarn^{-1})	References
IRAS Z02229+6208	−0.49	−0.7	∼0.2	1
IRAS 04296+3429	−0.70	−0.3	∼0.2	2
IRAS 05431+0852	−0.90	+0.5	∼1.0	3
IRAS 07134+1005	−1.20	−0.1	∼0.4	4
IRAS 07430+1115	−0.42	−0.4	∼0.2	1
IRAS 22223+4327	−0.40	−0.6	∼0.2	2
IRAS 22272+5435	−0.49	−0.0	∼0.4	5

References.—(1) This study; (2) Decin et al. 1998; (3) Reddy et al. 1997; (4) Hrivnak et al. 1999; (5) Začs et al. 1995.





Circumstellar Envelopes: Shaping?

What is the cause of such a torus?

- **Binary** companion – diverting mass loss into plane of orbit
  - could be star or planet (Soker, Livio, others)
- Rapid rotation – preferred plane for mass loss (perhaps **binary**)
- Magnetic field – leading to constraints on mass loss direction

How to detect an unseen binary?

-**Light** variations - light varies due to eclipses by unseen companion, ellipsoidal shape (tides), or re-radiation of light from hot comp

-**Velocity** variations – gravity of unseen companion causes reflex motion of visible star about the center of mass.
(method used to find planets around other stars!)

Increasing common to hear it stated that bipolar PNe and PPNe are due to effect of binary companion --> examine this claim

OUR RADIAL VELOCITY PROGRAM OF PPNe

- Observations at the Dominion Astrophysical Observatory (Victoria) with the 1.2 m Coude telescope
- Observed extensively for 3 years (1991-1993), occasionally for 2 more
- **Goal - to find binaries** (or at least set limits on them)

- **Targets: 7 bright PPNe**
    - V = 7 - 11 mag
    - No. Obs. Each = 30 - 60 over T = 1600 d
    - Collaborators: A. Woodworth, S. Morris, D. Bohlender (DAO), W. Lu (Valpo. U.)

- Period study

CENTRAL STAR: (looking back to AGB phase)

Variability:

Photometric monitoring program now for 13 yrs at Valparaiso Univ.

40 PPN candidates **Results**

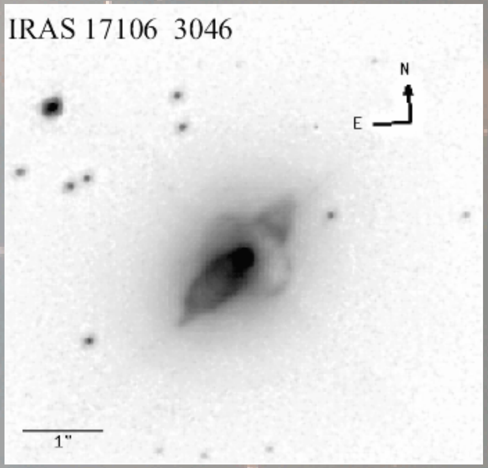
Results:

- almost all vary, V ~ 0.15 – 0.40 mag
- not simple periodic var.: varying ampl., varying or multiple P
- 10 quasi-periodic, P = 45 – 140 d, F-G stars,
  short-term variability among B stars, some cool stars - Irr
- due to **pulsation** (also Vr)
- general trend of shorter-term variability with hotter star;
  expected since smaller atmosphere

Potential to learn about the structure of the star

Could bear on post-AGB mass loss

1. INTRODUCTION: Why search for binaries in PPNe?



Shaping of PNe and PPNe:

- PPNe show a basic bipolar structure with axial and point symmetry
- Some show an obscured equatorial region
- How is this formed?

Mechanisms to produce lobes

- Binary companion
  - Focusing mass loss into orbital plane --> disk
  - Spinning up star to increase mass loss at equator --> disk
- Magnetic field
  - but even this might be enhanced or sustained by a binary companion spinning up star to strengthen magnetic field, which produces bipolar outflows
- Other?

Increasing common to hear it stated that bipolar PNe and PPNe are due to effect of binary companion --> examine this claim

2. HOW TO DETECT BINARIES IN PPNe?

- **Visible companions**
  - Distant companions: 0.5” at 1 kpc => a = 500 AU => P~10^4 yrs
  - Results:
    - HST - WFPC2: # objects~66, # binaries = 0 (Ueta; Sahai; #48)
    - HST - NICMOS: # obj.~20, # binaries = 0 (Su; Hrivnak; Sahai)
    - Ground-based NIR AO: # obj.~9, # binaries=1: (Sanchez Contraras)
    - (These studies were NOT optimized to find faint companions)
  - If too distant, effect on shaping is likely small

2. **Photometric variations**
   - Eclipse - unlikely unless very short P
   - “Reflection” (re-radiation) effect: hot + cool stars ($P_{ptm} = P_{orbit}$)
   - Ellipsoidal effect: tidal distortion ($2P_{ptm} = P_{orbit}$)
   - Methods used by Bond to identify binary companions to PNNe
     - Results: Reflection or Ellipsoidal - #=10, Eclipsing - #=6: P = 1-16 d --> 10-15% of PNe are binaries.

       (Bond 2000 (APN2); DeMarco 2006; Hillwig et al. 2006)
   - Close companions: P < 20 d

HOW TO SEARCH FOR BINARIES IN PPNe? - 2

3. Composite spectra

- Unlikely, would require both objects to be AGB, post-AGB
- Could have any separation, P

4. Radial velocity variations

- Orbital motion
- Used in more recent searches for binary PNNe (DeMarco et al. 2006)
- Can sample companions of intermediate separations

	(i=90°)	(i=30°)
Assume M_1=0.6, M_2=0.6, e=0		
K_1 = 20 km/s -->	P ~ 0.5 yr	P ~ 20 d
K_1 = 10 km/s -->	P ~ 4 yr	P ~ 0.5 yr
K_1 = 3 km/s -->	P ~ 150 yr	P ~ 20 yr
Case 2 M_1=0.6, M_2=0.2	(i=90°)	(i=30°)
K_1 = 10 km/s -->	P ~ 0.3 yr	P ~ 15 d
K_1 = 3 km/s -->	P ~ 12 yr	P ~ 1.5 yr
Case 3 M_1=0.8, M_2=0.4	(i=90°)	(i=30°)
K_1 = 10 km/s -->	P ~ 1.2 yr	P ~ 50 d
K_1 = 3 km/s -->	P ~ 40 yr	P ~ 4 yr

IMPLICATIONS OF OUR NON-DETECTION OF BINARY PPNe

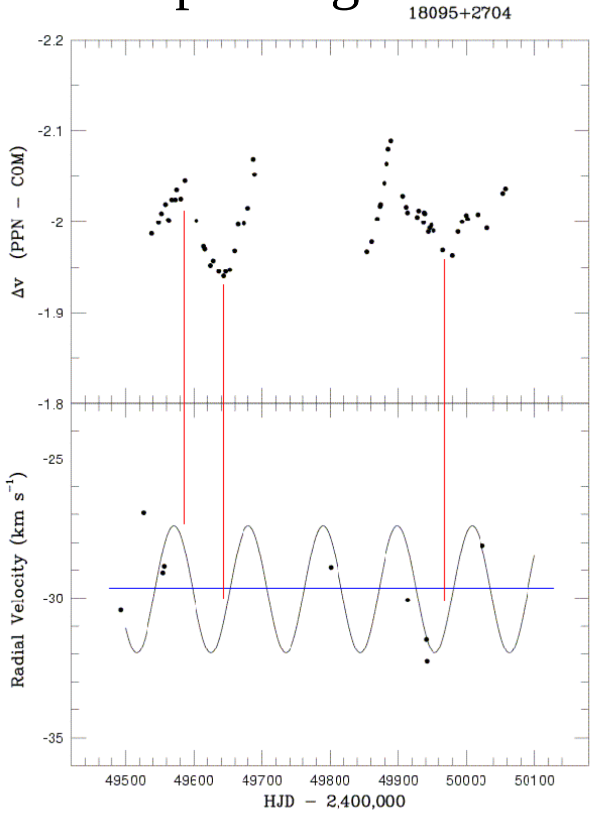
- Comparison with results of **PNe binary** studies
  - % short-period photometric binaries ~ 10-15% (Bond)
  - short P --> **Common envelope** evolution
  - RV studies: many (most) variable, but that does not mean binary (DeMarco 2006)
- ? Might **PPNe** be binaries, but
  - In common envelope
    - But this lasts only a short time, unlikely
  - Long P (P>10-100 years) - but then effect on shaping may be small
  - Secondary is not a MS star but brown dwarf or a planet - would not be detected.
- Since it appears that these 7 objects are PPNe and shaping has started
  - then this suggests two ways to form PNe,
    - Common envelope evolution (binary PNNe)
    - Non-common envelope process (occurring in these PPNe)
      - Distant, low-mass companions?
      - Single, pulsating PPNe?

RESULTS OF OUR RADIAL VELOCITY PROGRAM OF PPNe

Comparison of light and velocity curves - 1994-1995

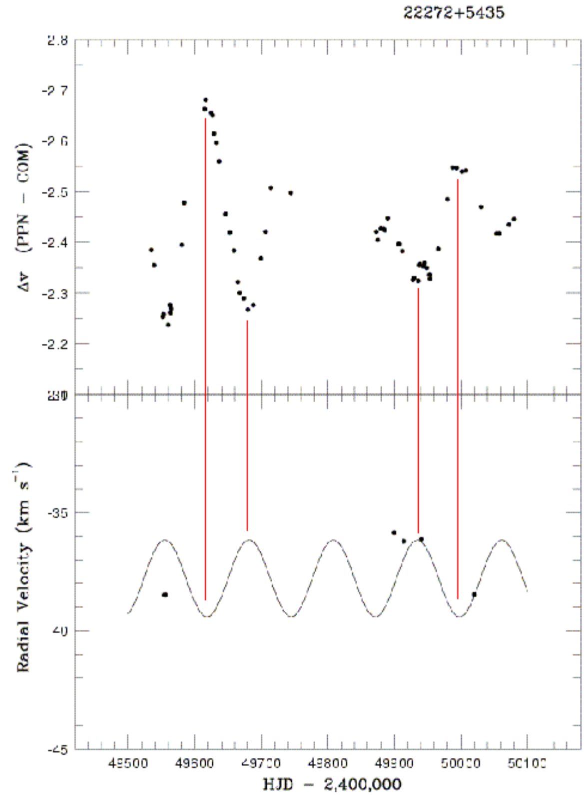
IRAS 18095+2704

Brightest when star is
expanding and hottest



IRAS 22272+5435

Brightest when star is
contracting and hottest



RED GIANTS TO PLANETARY NEBULAE:

STUDYING THE TRANSITIONAL OBJECTS

(PROTO-PLANETARY NEBULAE)

Bruce J. Hrivnak (Valparaiso University)

Outline:

Introduction: stellar evolution
Studies I: 1984-1994 -- finding PPN basic properties (low resolution)
Studies II: 1994-present -- detailed studies properties (higher res'ln)
Present/future studies: what we look forward to

Western Michigan U.: 23 October 2006

Detail: Shaping of the Nebula

What is the cause of such a torus?

- **Binary** companion – diverting mass loss into plane of orbit
  - could be star or planet
- Rapid rotation – preferred plane for mass loss (perhaps **binary**)
- (Magnetic field – leading to constraints on mass loss direction)

How to detect an unseen binary?

- **Velocity** variations – gravity of unseen companion causes motion of visible star about the center of mass.
- **Light** variations - light varies due to eclipses by unseen companion.

Results of velocity study: 7 PPNs monitored over 5 yrs

- All vary, Vr ~ 10 km/s, **pulsation not binarity**

no close binaries (P < 1 yr) observed

--> still **no direct evidence** for close (shaping by) binaries in PPNs

Observe objects in these stages: Planetary Nebulae