The Search for Binaries in Post-AGB Stars: Do Binary Companions Shape the Nebulae?

Bruce J. Hrivnak (Valparaiso University)

- Motivation for question
- How to detect
- Photometric study
- Radial velocity study
- Results & Implications

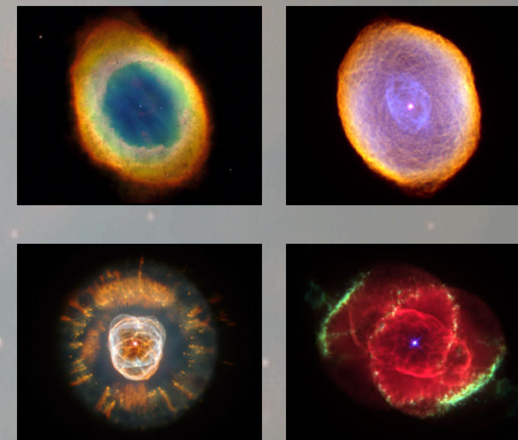
(PhD thesis advisor: Robert H. Koch - binary stars)

Koch Memorial Conference (Villanova University, August 10-12 2011)

1. MOTIVATION: Why search for binaries in post-AGBs?

Shapes of planetary nebulae (PNs):

- Basic classification of round, elliptical, butterfly (Balick)
- Commonly show an axial or point symmetry

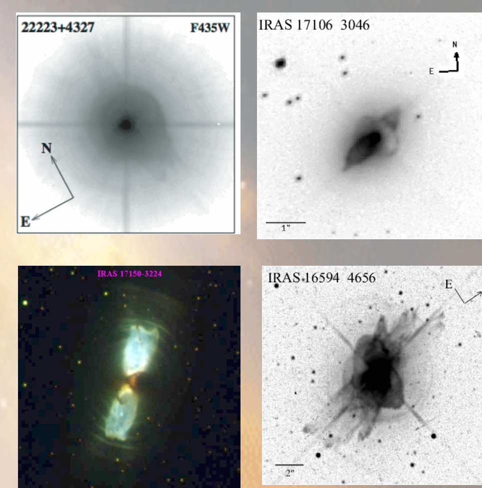


Shapes of proto-planetary nebulae (or pre-PNs, PPNs):

- Preceeding stage of evolution
- Star making transition from AGB to PN
- Images show the axial structure already formed
- Many are bipolar
- Some show an obscured equatorial region
- How is this formed? → binary?

- PPNs are focus of this talk

HST images



1. MOTIVATION: Why search for binaries in post-AGBs?

What are possible mechanisms to produce axial and point symmetry?

1. Binary companion
   - Focusing mass loss into orbital plane --> disk (collimating outflow)
2. Rapid rotation
   - Spinning up star to increase mass loss at equator --> disk (This might be enhanced or sustained by a binary companion)
3. Magnetic field
   - Magnetically confined ionized mass outflow to bipolar lobes (Probably need a binary companion to sustain the magnetic field through transfer of angular momentum)

➢ Thus all 3 mechanisms appear to require or are sustained by a binary companion

Thus common to hear it stated that bipolar PNs and PPNs are due to or even imply a binary companion --> Let's examine this claim

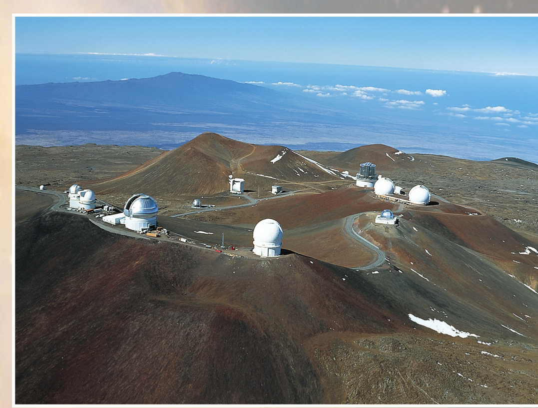
1. MOTIVATION: Why search for binaries in post-AGBs?

Identification of PPNs: What are the difficulties?

- Short lifetime: few thousand years (10^3yr/10^9yr ~ 15 min/75 yr)
- Partial obscuration by circumstellar gas, dust
- Prior to 1983, only a few known (ex., Egg Nebula)

Key to Discovery of PPNs: (led by Sun Kwok)

- Surrounding dust is cool, radiates in infrared
- IRAS satellite, all-sky survey (1983)
  - 4 wavelengths: 12, 25, 60 100 μm
  - ~250,000 objects
  - **We selected candidates based on IR brightness and color**

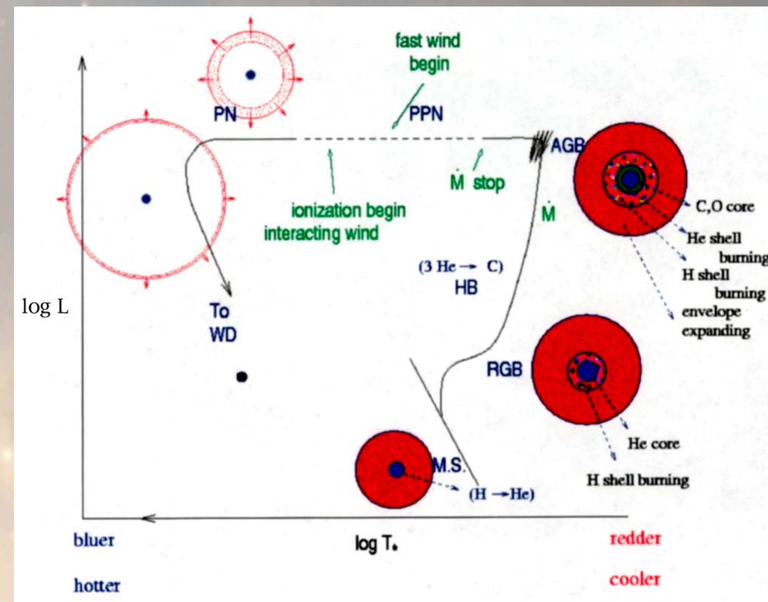


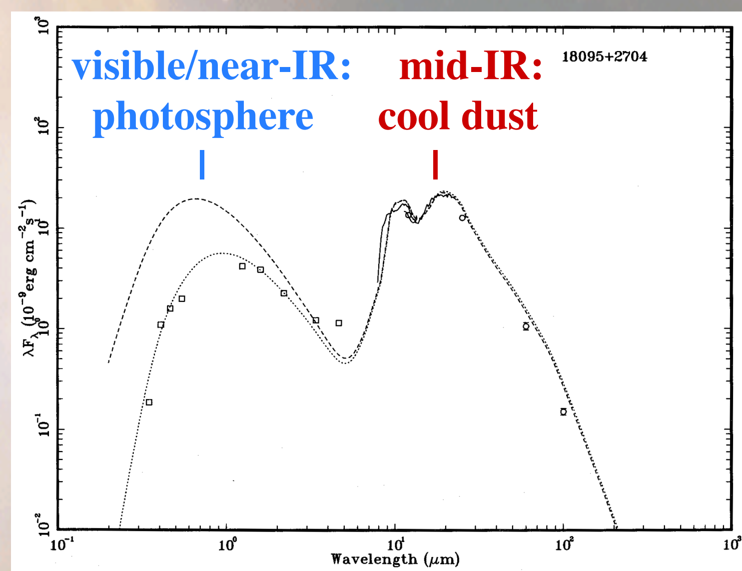
- Visible counterparts found by matching the positions of IRAS objects with stars in catalogs
- **or (ideally) searches at telescope with IR detector**

1. MOTIVATION: Why search for binaries in post-AGBs?

Properties of PPNs

- Objects evolving at constant L (AGB → PPN → PN), increasing T
- SpT: G - B Iab central star
- Evidence of mass loss on AGB
  - Circumstellar envelope, seen in faint scattered visible light
  - CO gas, seen in sub-mm,
  - Dust, seen in mid-IR
  - M(CSE)=0.1-0.5 $M_\odot$
- Evidence of nucleosynthesis
  - Enhanced C, s-process elements
- Physical properties of star (ranges)
  - T: 5000 – 30,000 K
    L: 5000 – 10,000 $L_\odot$ (assumed)
  - R: 100 – 4 $R_\odot$
    M: 0.5 - 0.8 $M_\odot$ (assumed)
- ~100 PPNs & candidates





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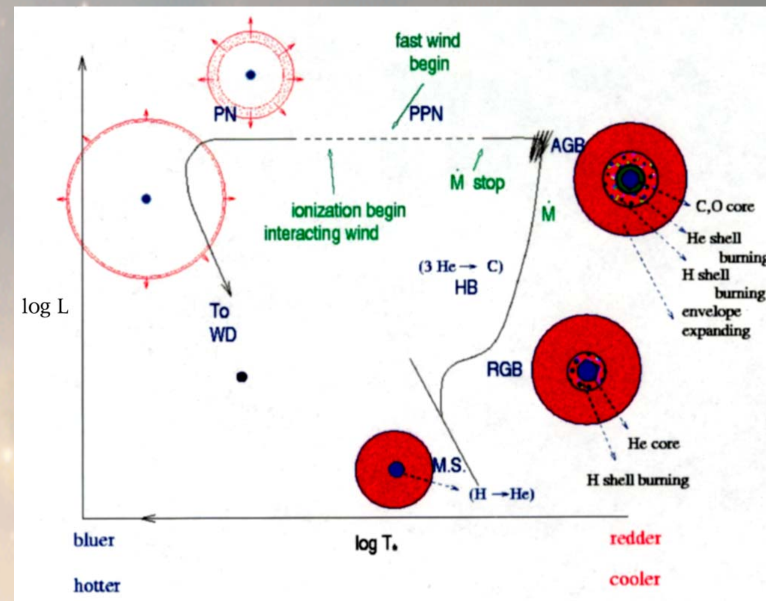
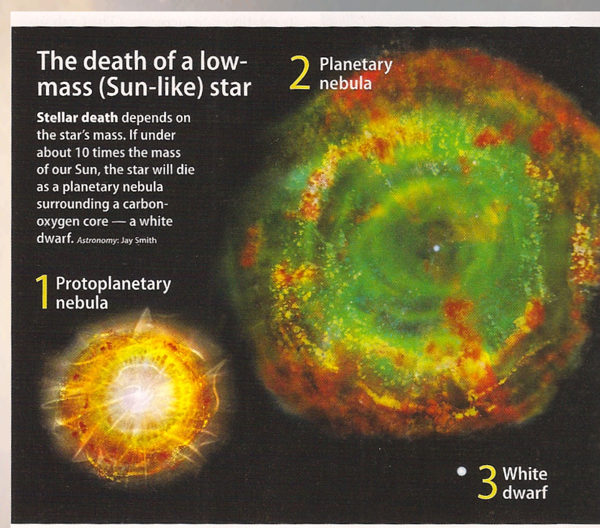




(Astronomy, July 2011)

2. HOW TO DETECT BINARIES IN PPNs?

1. **Photometric variations**
   - Eclipse - unlikely unless very short P
   - Irradiation effect: by a hot companion ($P_{ptm} = P_{orbit}$)
   - Ellipsoidal effect: tidal distortion ($2P_{ptm} = P_{orbit}$)

   Methods used by Bond (2000), Miszalski et al. (2009), Hillwig & others to identify binary companions to central stars of PNs (CSPNs)
     - Results: #=40, P = 1-8 d --> 10-20% of PNe have close binaries

   - Periodic obscuration by circumbinary dust of binaries in longer-P orbits
     - Observed in some post-AGB or post-RG binaries (e.g., Red Rectangle)
     - Note, however, that evolved binaries in this class typically do not possess a nebula and will not evolve into PNs

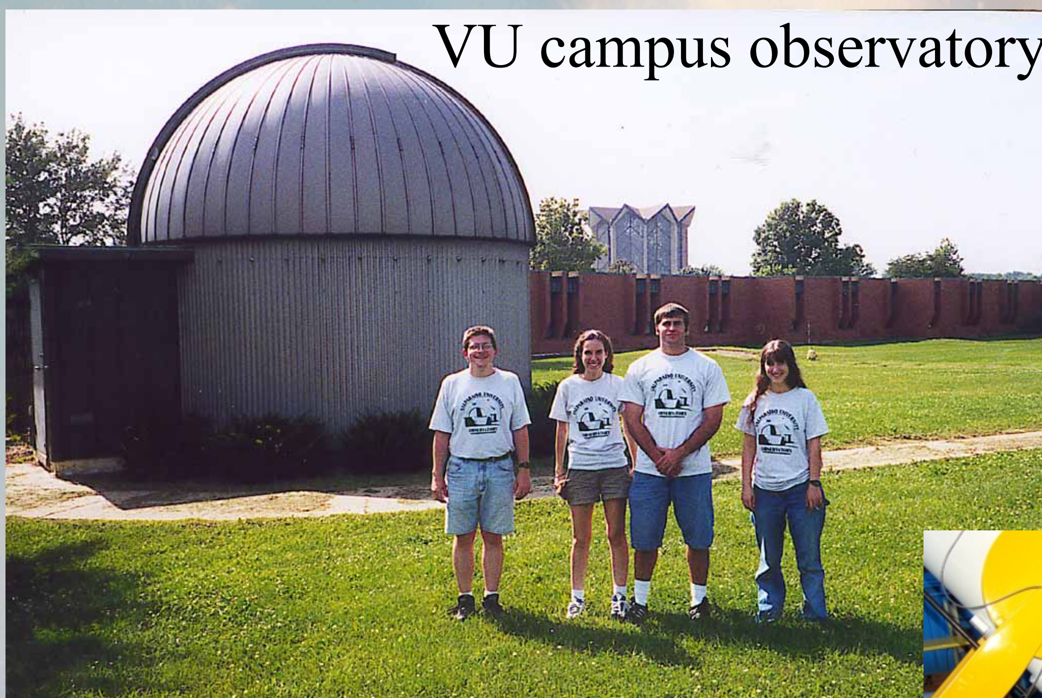
3. PHOTOMETRIC VARIATIONS IN PPNs

Light studies of the central star:

Photometric monitoring program at Valparaiso University,

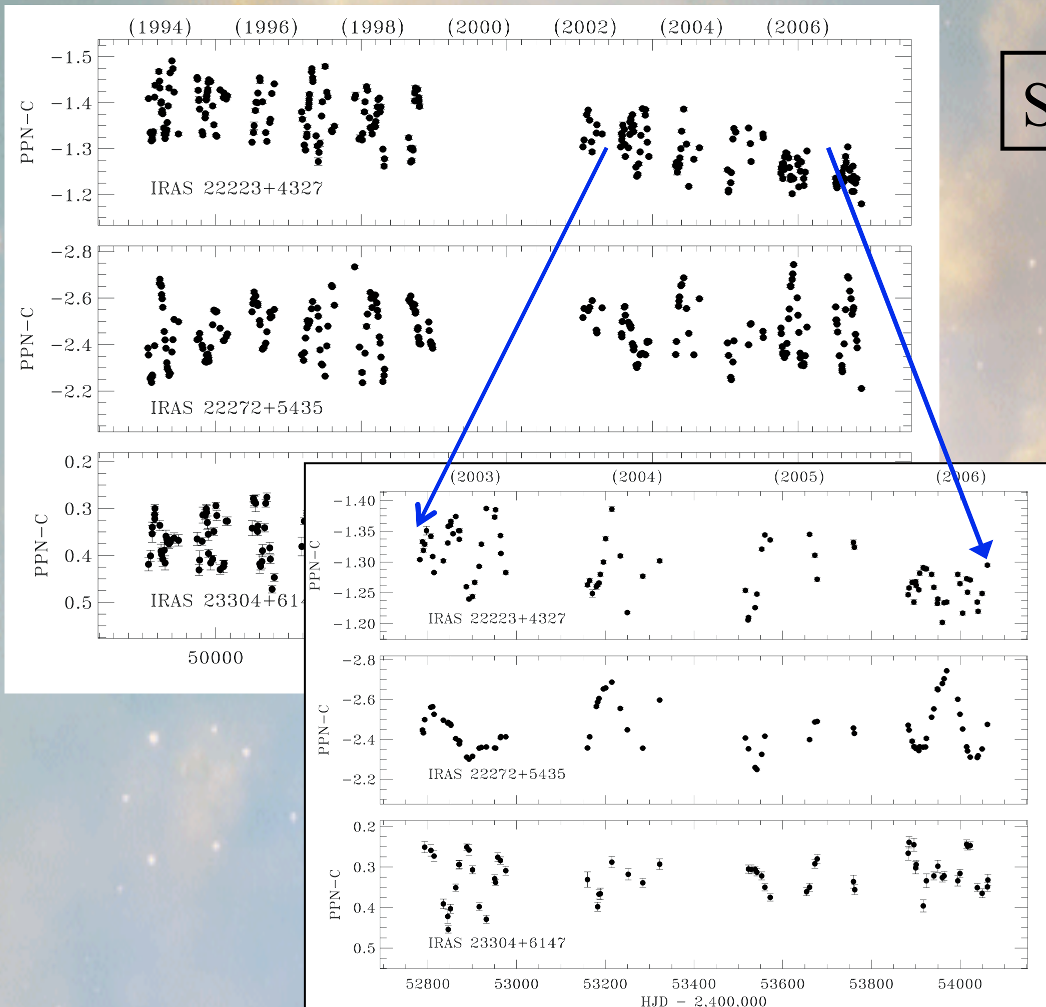
1994 - present (>17 yrs), 30 PPNs, V=8-14 mag,

0.4-m campus telescope with CCD, undergraduate students

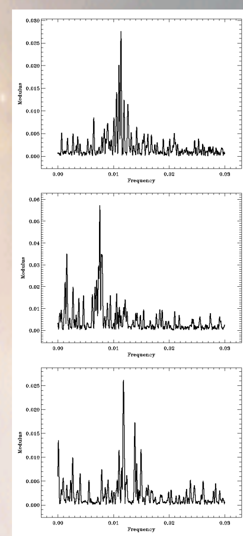

VU campus observatory

Only 1 other group doing LC studies of PPNs (Arkhipova et al. $\Delta T \sim 6$yrs)

3. OUR LONG-TERM LIGHT CURVE STUDY OF PPNs



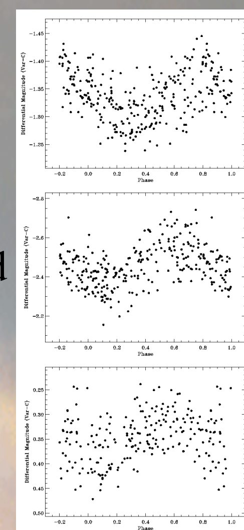
Some typical examples



P = 88 d
G0

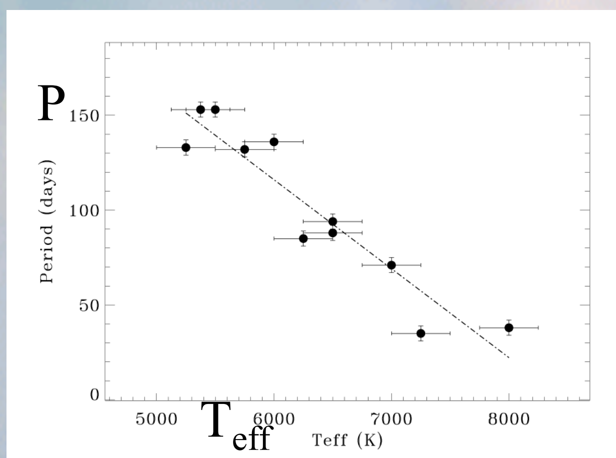
P = 127 d
G5

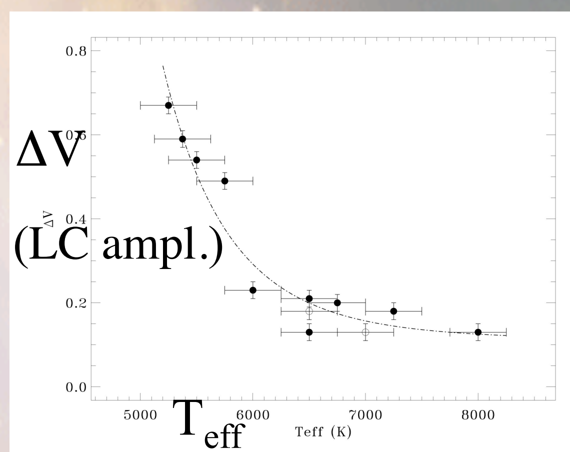
P = 85 d
G2



3. OUR LONG-TERM LIGHT CURVE STUDY - RESULTS

- All vary in brightness; range 0.15 – 0.6 mag
- P = 150 – 35 d (G8 – F3) for sample of 12 C-rich
- Trend of shorter P with higher T_{eff}
- Hotter ones (SpT=B) vary on even shorter timescale (days)
- Multi-P or variable amplitude → pulsation
- Photometric variability due to pulsation; **no evidence for binarity**
- What constraints does this set? What would we expect?





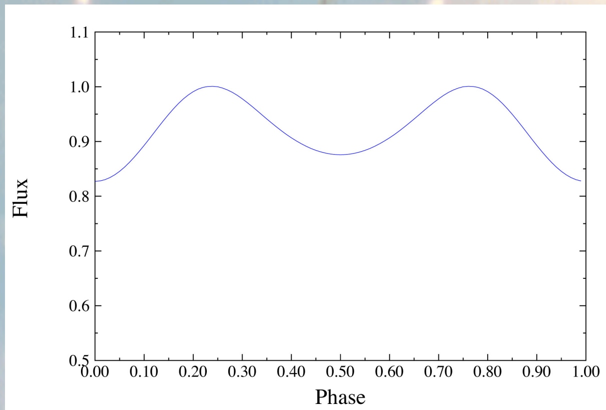
(see Hrivnak et al. 2009, ApJ, 709, 1042)

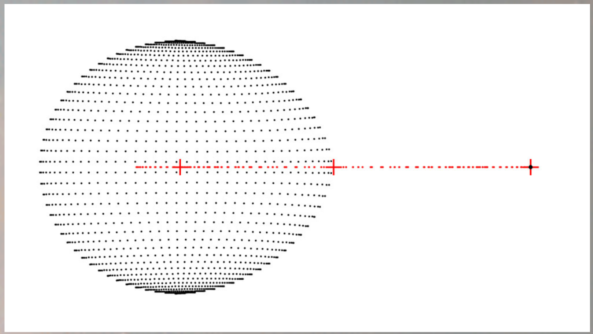
3. PHOTOMETRIC VARIATIONS IN PPNs

What would these look like? - Ellipsoidal

- PPN: $M_{PPN} = 0.62\ M_\odot$ Companion: Main Seq, $M_2 = 0.5\ M_\odot$
- PPN just within Roche lobe
- SpT=G, $R = 90\ R_\odot$, → $P_{orbit} = 1.0$ yr

Light curve ($i = 90^o$)





(BinaryMaker)

$i = 90^o$: $\Delta V = 0.18$ mag
$i = 60^o$: $\Delta V = 0.12$
$i = 30^o$: $\Delta V = 0.04$

However,

- If PPN avoided Roche lobe overflow at **tip of AGB**,
  when $R \sim 400\ R_\odot$ → $P_{orbit} = 11$ yr
- Then at SpT=G, $R = 90\ R_\odot << R(\mathrm{Roche})$ → $i = 90^o$: $\Delta V = 0.002$ mag

Binary photometric variations would require special condition (edge-on, orbital decay, …) → non-detection not a strong constraint

2. HOW TO DETECT BINARIES IN PPNs?

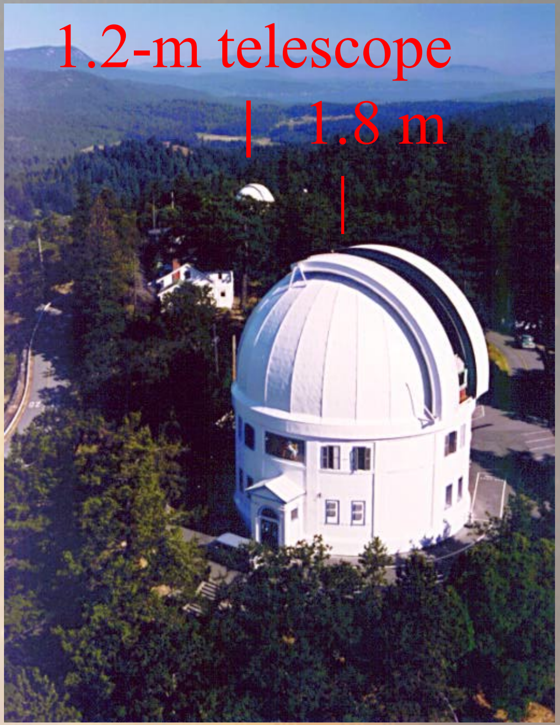
1. **Photometric variations**

2. **Radial velocity variations**
   - Orbital motion
   - Used in some searches for binary central stars of PNs; complicated by intrinsic variations, winds – unsuccessful
   - Can sample companions of intermediate separations, 1 mo < P < few x 10 years
   - Illustration:
     - PPN: $M_{PPN} = 0.62\ M_\odot$ Companion: Main Seq, $M_2 = 0.5\ M_\odot$
     - PPN just within Roche lobe at SpT=G $P_{orbit} = 1.0$ yr
     - → $V_{PPN} = 13$ km/s (measure K = Vsin*i* but sin 30° = 0.5)
     - If P_{orbit}=11 yr → $V_{PPN} = 6.3$ km/s (just detached at tip of AGB)
     - If P_{orbit}=30 yr → $V_{PPN} = 4.5$ km/s

4. OUR RADIAL VELOCITY STUDY OF PPNs

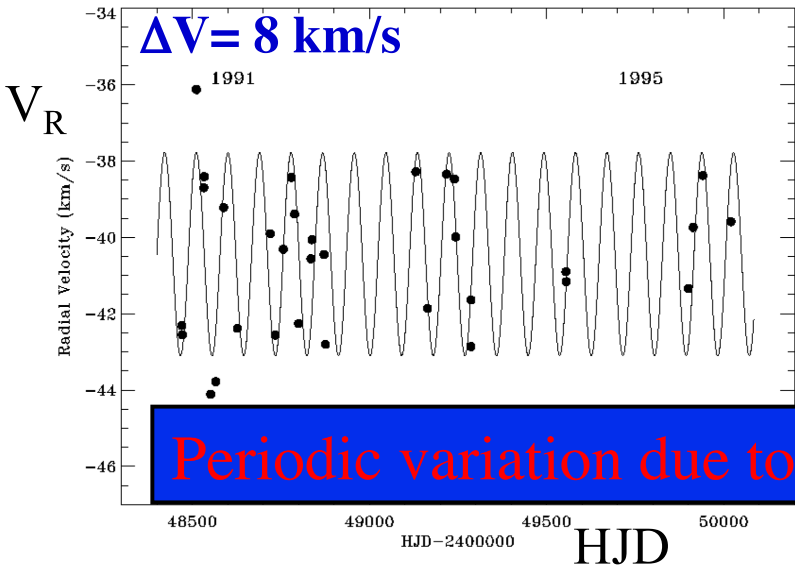
- **Targets: 7 bright PPNs, SpT = F-G Iab**
  - Many, sharp lines (advantage over hot central stars of PNs)
  - V = 7 – 11 mag
  - **Goal - to find binaries** (or at least set limits on them)

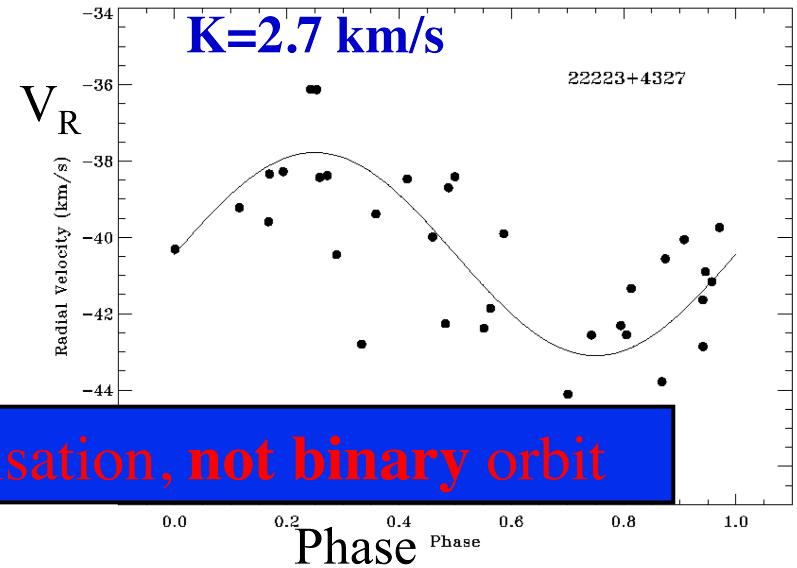
- Observations at the Dominion Astrophysical Obs (Victoria, Canada)
  - 1991 – 1995 (initial study)
  - 2007 – present (new study)
  - No. obs. each = 40 – 100
  - Precision ~ 0.7 km/s
  - Collaborators: D. Bohlender, A. Woodworth, S. Morris, (DAO), C. Scarfe (U. Vic)



4. RESULTS OF INITIAL 1991-1995 RV STUDY

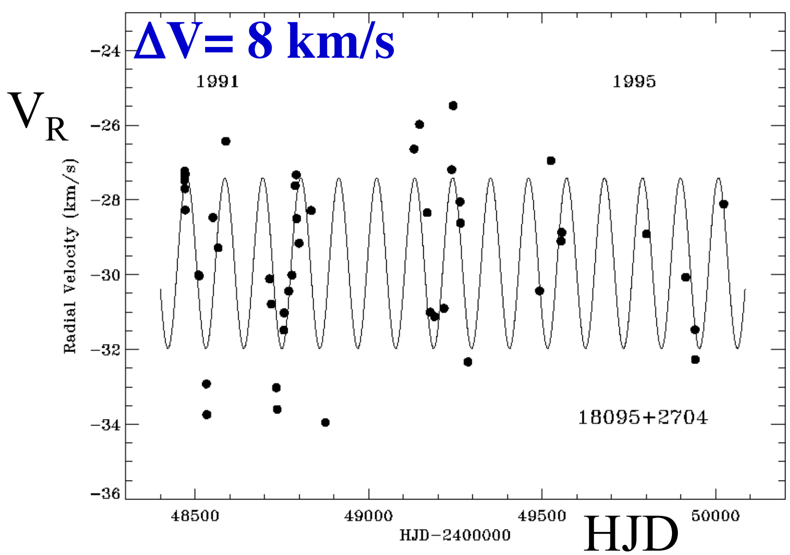
- **IRAS 22223+4327** **P(RV) = 89 d ~ P(LC) = 89 d**

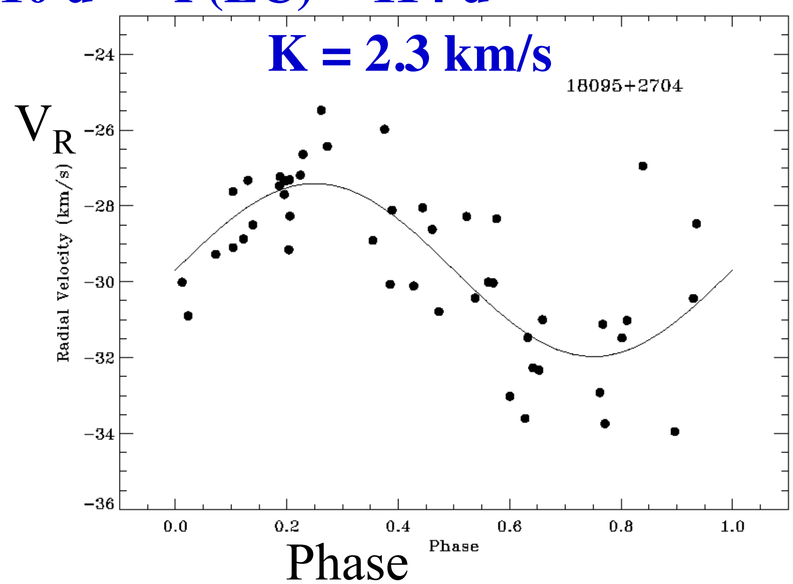




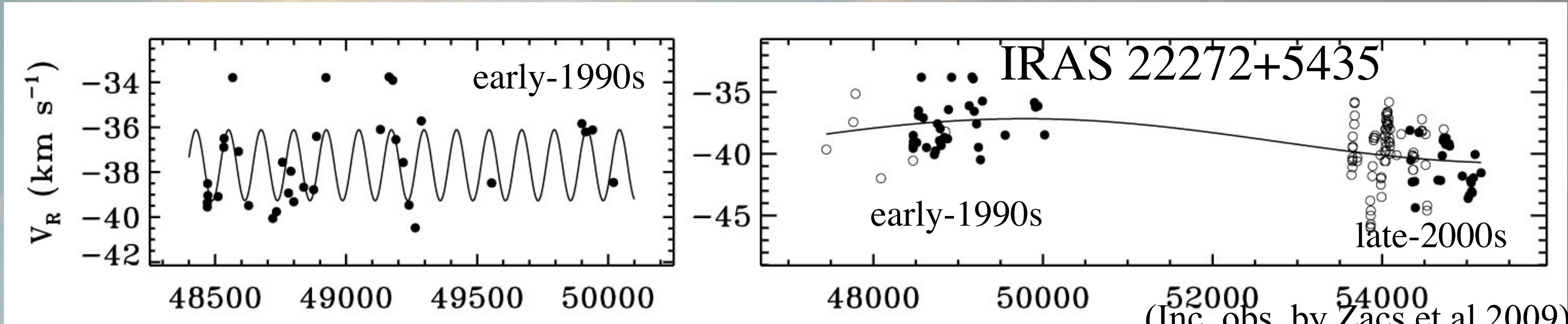
Periodic variation due to pulsation, **not binary** orbit

- **IRAS 18095+2704** **P(RV) = 110 d ~ P(LC) = 114 d**





4. RADIAL VELOCITIES IN PPNs: Long-term Results



(Inc. obs. by Zacs et al 2009)

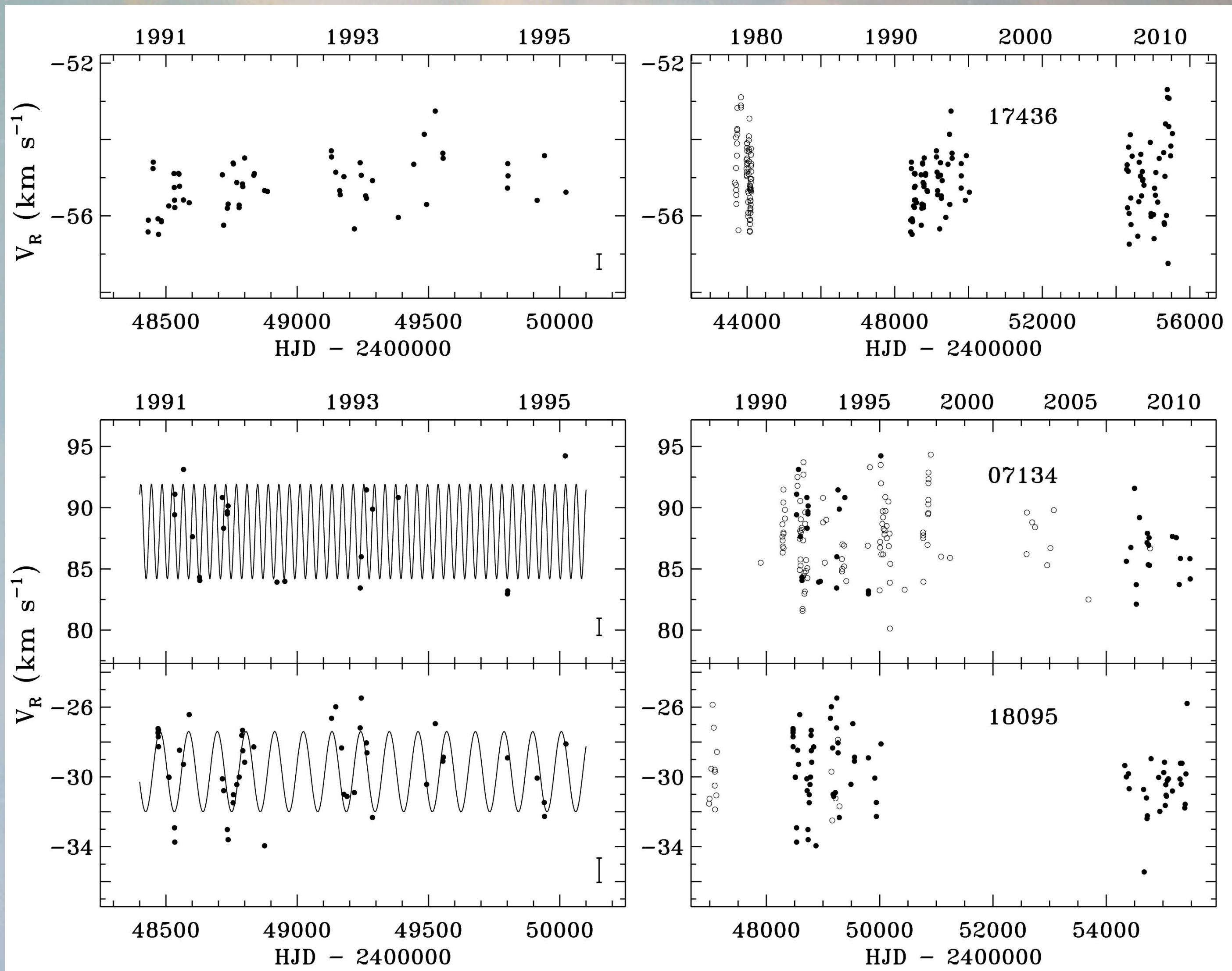
One case of clear velocity change beyond pulsation

- IRAS 22272+5435 ΔVr (early-1990s – late-2000s) = 2.6 km/s
- P > 22 years, K = 1.3 km/s
- Limiting case: If we assume P = 22 yr, K = 1.3 km/s, $M_{PPN} = 0.62\ M_{\odot}$, and $e = 0$, then M_2 = depends on inclination i:
- $i = 25^o$ from model (Ueta et al. 2001, mid-IR) → $M_2 = 0.27$ (+/-0.04)
- If circular orbit, a = 8 AU = 1700 Rs >> R(AGB) >> R(PPN)
- Would survive detached at tip of AGB

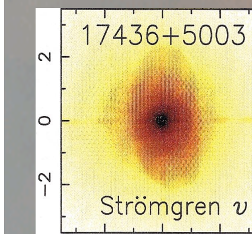
→ **Likely binary**

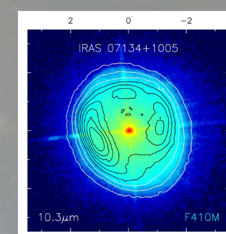
4. RADIAL VELOCITIES IN PPNs: Long-term Results

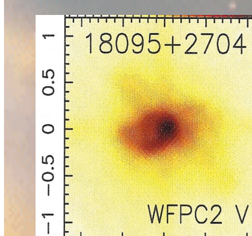
Others show no long-term variations beyond pulsation



HST images



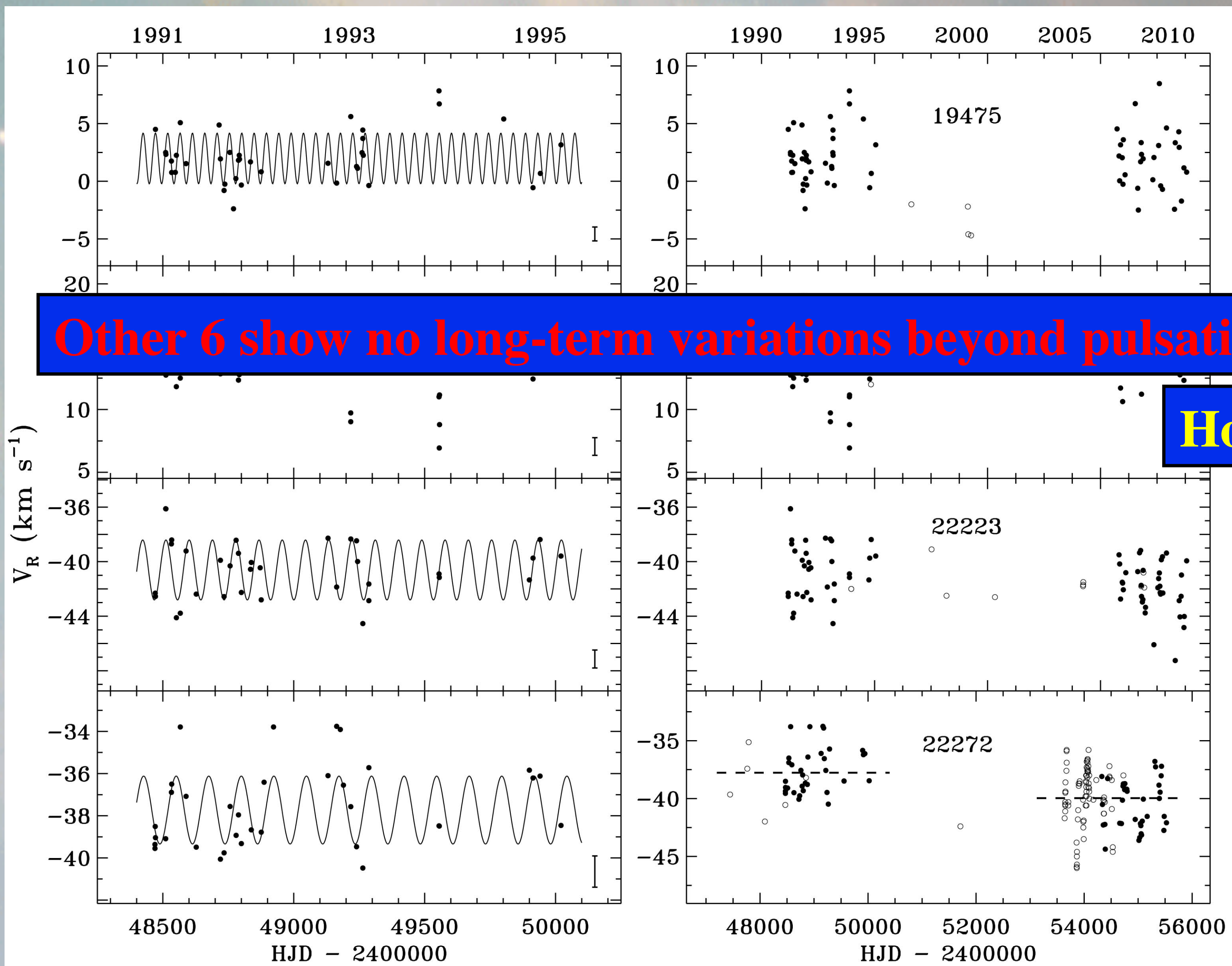




Our observations (filled circles) and others from literature (open circles).

4. RADIAL VELOCITY VARIATIONS IN PPNs

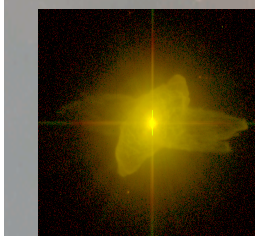
Others show no long-term variations beyond pulsation

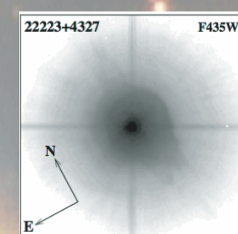


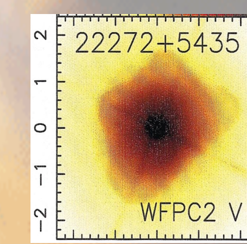
Other 6 show no long-term variations beyond pulsation

However, …

HST images



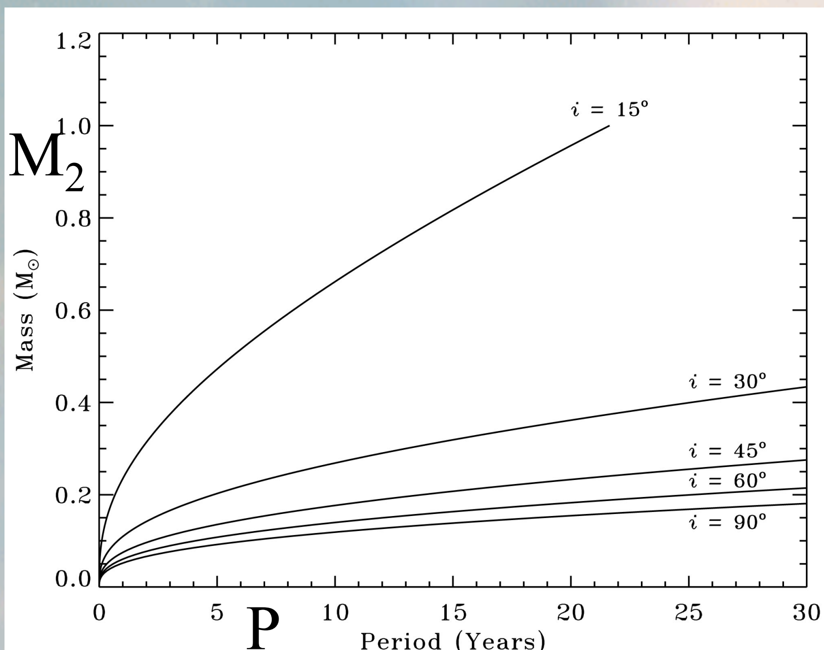




4. RADIAL VELOCITIES IN PPNs: Long-term Results

What about possible bias - selection effects? - Chose brightest, more likely seen at low inclination (less obscuration), more pole-on

Any undetected binaries have low mass or/and long periods



M_2 and P for various inclinations (i)

(Assuming M_{PPN}=0.62 $M_\odot$, K=2.0 km/s, circular orbits)

However, non-detection sets constraints on possible binaries

If M_2 &	$i > 15^o$	$i > 30^o$	$i > 45^o$
0.4 $M_\odot$	P > 3.5 yr	P > 24.5 yr	
0.25 $M_\odot$	P > 1.1yr	P > 8 yr	P > 23 yr

or, for example

- M_2 > 0.3 $M_\odot$ is excluded for P<13 yr at i>30°

(see Hrivnak et al. 2011, ApJ, 734, 25)

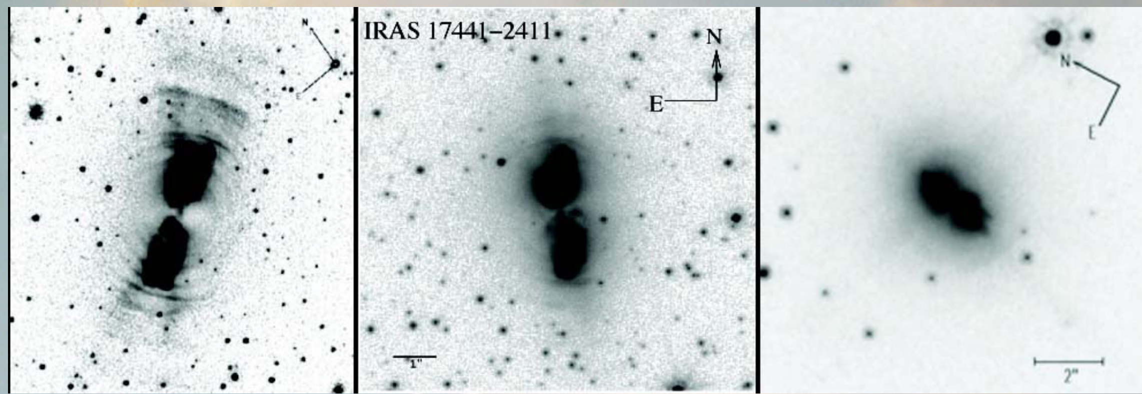
5. RESULTS OF VARIABILTY STUDIES OF PPNs

- **Photometric (#=30):** All vary due to pulsation; **no evidence of binaries**

- **Radial Velocity (#=7):** All vary due to pulsation; **1 tentative binary**
  - **Likely binary (P > 22 yrs, $M_2 > 0.27\ M_\odot$)**
  - Possible selection effects, but
  - **Results set constraints** on possible binary companions
    - Must have low mass (< $0.25\ M_\odot$) or long period (P > 30 yrs)
    - Could be brown dwarfs or super Jupiters
    - Will not evolve into short-P binary central stars of PNe

  - **Ideally observe edge-on bipolar PPNe with obscuring torus**

5. NEW PROGRAM: Edge-on PPNs in Near-IR Spectroscopy

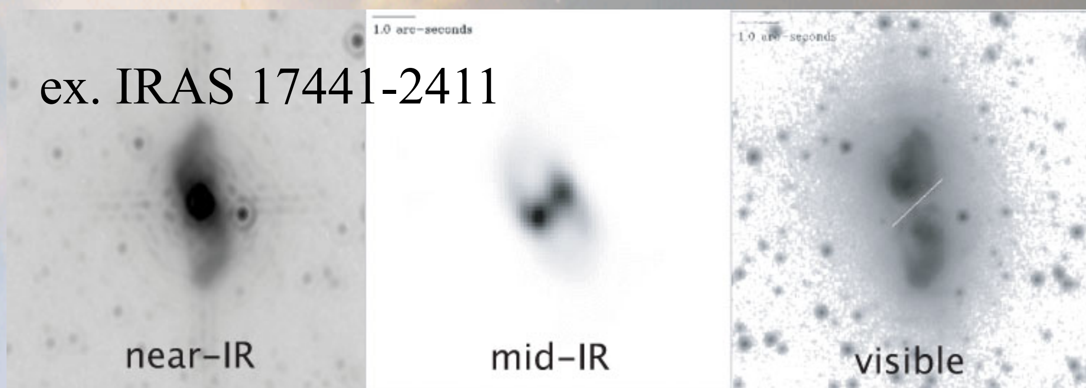


Bipolar, equatorial enhancement obscuring star

3 edge-on PPNs, but each of which has a visible star in near-IR

New observing program:

ex. IRAS 17441-2411



- Began this last year – Near-IR, high-resolution spec, 8-m telescopes
- Gemini-S (Ken Hinkle – NOAO) Phoenix (R=70,000) - discontinued
- ESO (Florian Kerber – ESO) CRIRES (R=100,000)
- Data reduction in process
- If ΔV_R > 10-15 km/s (larger than pulsation) → (possible/likely) binary

5. RESULTS OF VARIABILTY STUDIES OF PPNs

- **Implications of non-detections**
  - Comparison with results of **PNs binary** studies
    - 10-20 % CSPN have short-period (P~1 day) photometric binaries
    - Short P --> **Common envelope** evolution
  - Q – Might **PPNs** be binaries, but
    - In common envelope - but this lasts only a short time (~1 yr), unlikely
    - Long P (P>30-100 years) - but then effect on shaping may be small
    - Secondary is not a MS star but brown dwarf or a massive planet - would not be detected.

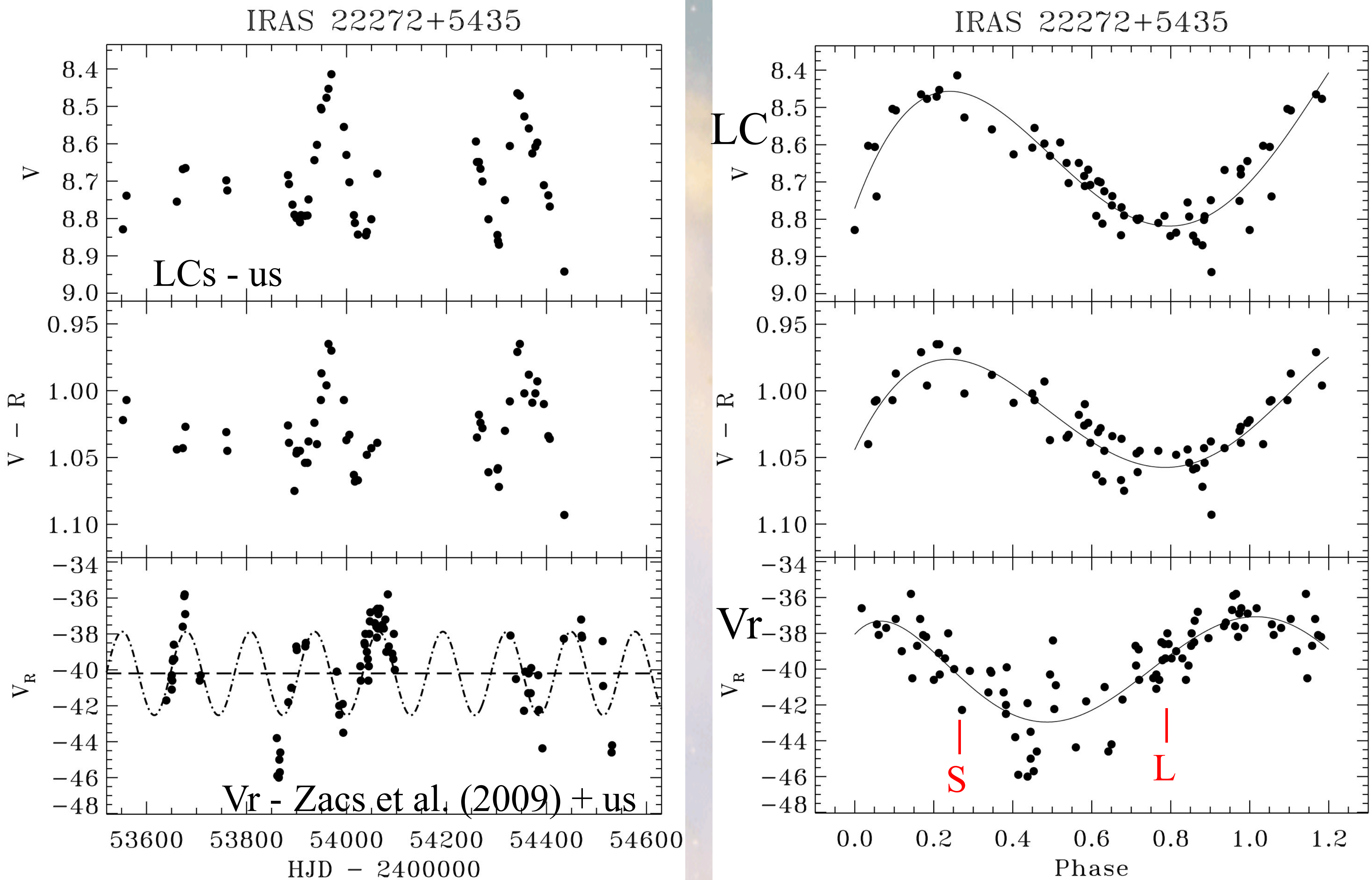
- **If 50% stars are binaries, why not more detected?**
  - Binary fraction of Duquennoy & Mayor (F-G) - 33% SB, but
  - **14% of small sample (1/7) not discrepant**

5. RESULTS OF VARIABILTY STUDIES OF PPNs

- **What does cause PN & shape the nebula?**
  - Since it appears that these 7 objects are PPNs and shaping has started, then this suggests two ways to form PNs & shape the nebulae:
    1. Common envelope (CE) evolution with ejection and shaping of the envelope → short-period binary central star of PNs
    2. Non-CE – Since CE spiral-in and ejection timescale on order of 1 yr and we find PPNs still retaining their envelopes, thus CE ruled out by statistics and time scale. So …
       - Binary, with companion of low mass (< 0.25 $M_{\odot}$) or long period (P > 30 yrs), or
       - Non-binary (pulsational induced?)

- **Studies continuing**
  - Continuing to monitor
    - V_R: to further constrain possible binary properties
    - LC: study pulsation
      - To investigate ΔP (decades) → rate of evolution of post-AGB
      - New PPNs in SH (with Henson, Hillwig, Kaitchuck – SARA)

Pulsation - New contemporaneous light, color, and velocity curves



Star is brightest, hottest when ~ smallest

Results: Pulsational Variability in PPNs

1. All vary in light:
   - $\Delta V \sim 0.15 - 0.60$ mag
   - not simple periodic var.: varying ampl., varying or multiple P
   - P = 153 – 35 d, G-F stars; short-term variability among B stars
   - Trend of decreasing P, Amplitude with increasing T_{eff}
2. All vary in velocity:
   - $\Delta V_r \sim$ 8-12 km/sec
   - P(Vr) ~ P(LC)
3. Contemporaneous Light & Velocity: (in progress)

   - ~ Smallest when brightest, hottest -- only 1 good case thus far, but more in progress

   $\Delta V \rightarrow L_{max}/L_{min}$ $\Delta(V\text{-}R) \rightarrow \Delta T_{eff} \rightarrow R(L_{max})/R(L_{min})$

   $\Delta Vr \rightarrow \Delta R$ (during pulsation cycle) $\rightarrow R_{max}, R_{min}, \langle R \rangle$

   R & T_{eff} $\rightarrow$ L -- first direct determinations for PPNs

   & R with log *g* (model atm) $\rightarrow$ ~M (distance>1 kpc)

Analyses of Pulsational Variability

Models needed

Fokin et al. (2001)
- non-linear radiative models of post-AGB stars
- M: 0.6, 0.8 M_{Sun}
- T_{eff}: 5600 - 6000 K
- L: 5000 - 8000 L_{Sun}
- Results
  P=25-50 d,
  ΔV=0.2-0.4 mag,
  ΔV_r=+/-5 km/s

Models: M = 0.8 M_{Sun}
- X=0.7, Z=0.004

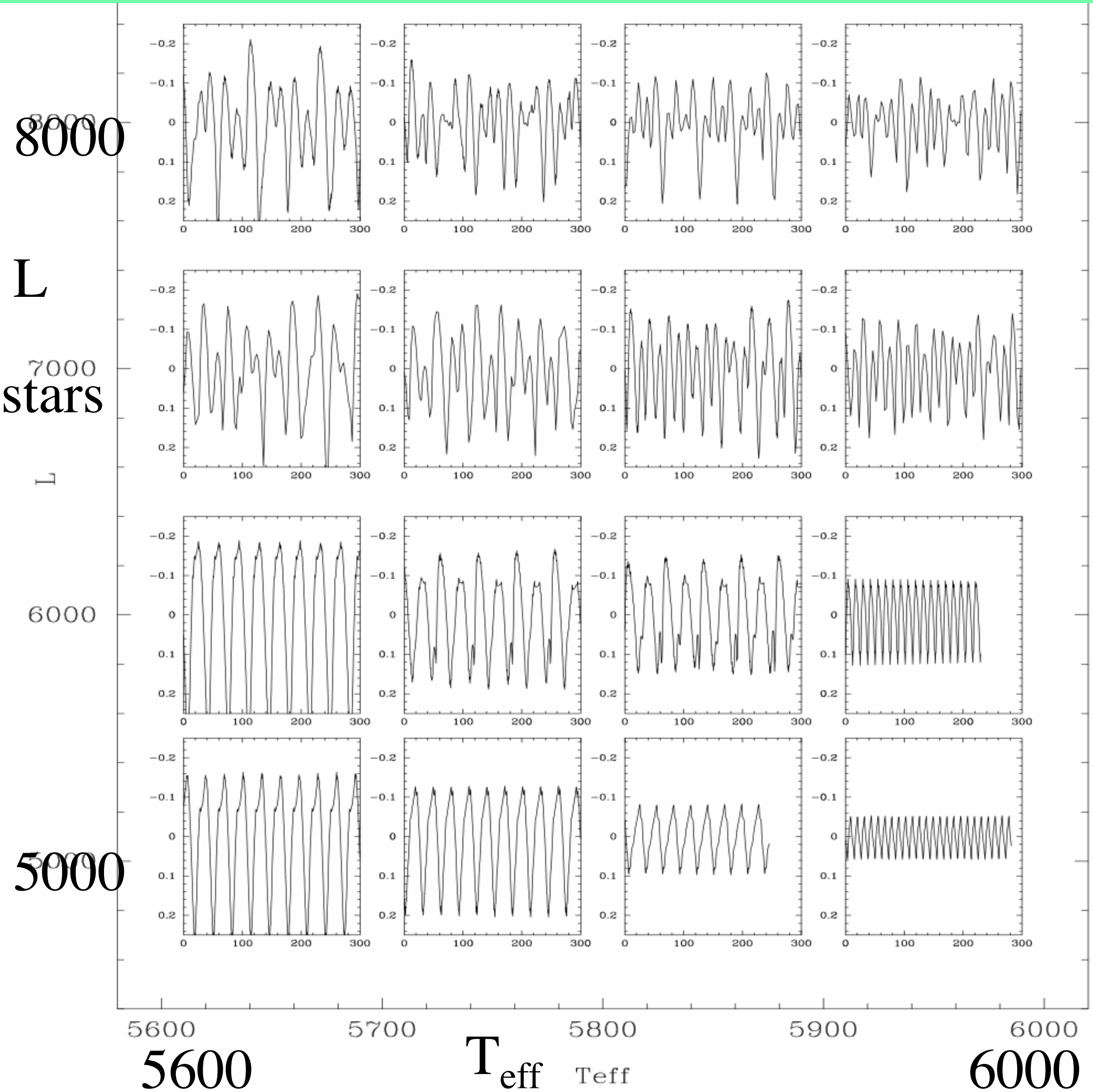


Fig. 1. Grid of computed bolometric light curves ($M = 0.8\,M_\odot$, $X = 0.7$, $Z = 0.004$ and with the OPAL92 opacity table). Model axes are the time (in days) as abscissa, and Δm_{bol} as ordinates.

6. Acknowledgements

- **Acknowledgements:**
  - Wen Lu (Valparaiso U) & ~ 25 students over past 17 years (LC)
  - Dominion Astrophysical Observatory & collaborators (VC)
  - National Science Foundation
  - Indiana Space Grant Consortium (student funding)

  - **Robert H. Koch**

6. Acknowledgements

- **Robert H. Koch**

  - PhD advisor
    - Diligently
    - Carefully

1980 (following my thesis defense)

  - Collaborator
    - Respect the data
    - Bigger picture
    - 5 papers together

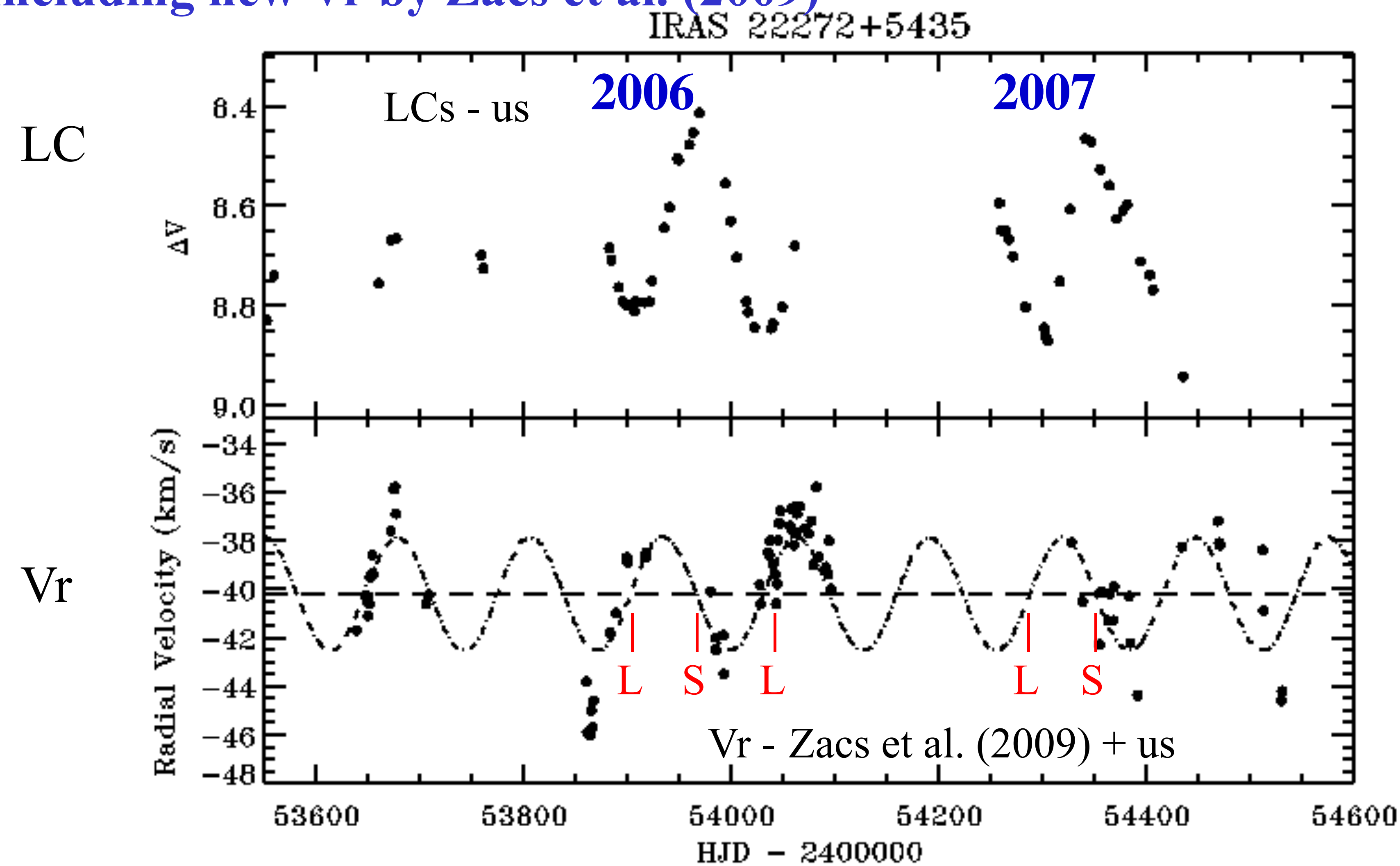
1985 IAU New Delhi, Com 42 - he asked me to serve as secretary)

  - Friend
    - Encouragement

2008 - dinner together with Joanne and my wife Lucy during a Philadelphia visit

Pulsation - New contemporaneous light, color, and velocity curves

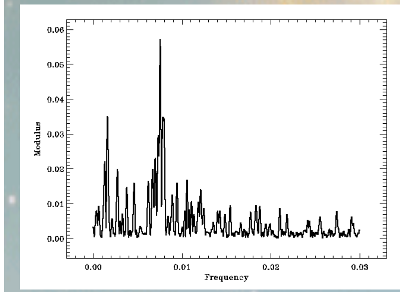
Including new Vr by Zacs et al. (2009)



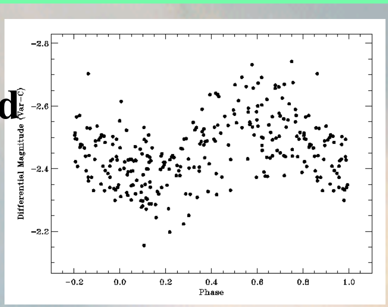
Star is brightest, hottest when smallest (S)

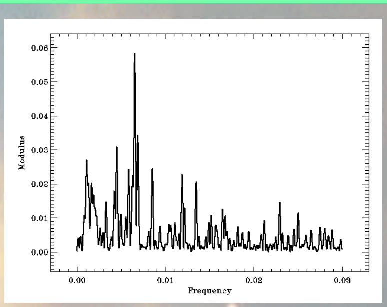
and faintest, coolest when largest (L) or just after.

Light Curves - Period Determination

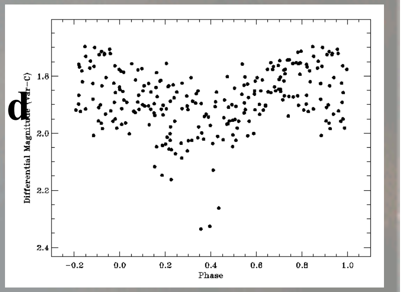


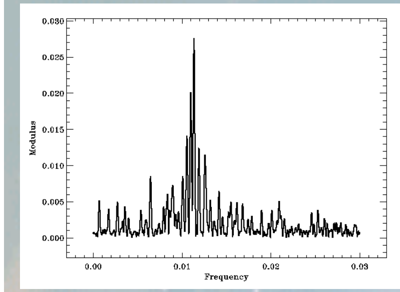
P = 130 d
G0



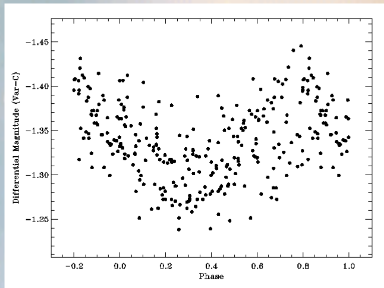


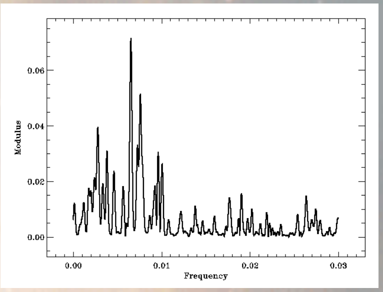
P = 153 d
G8



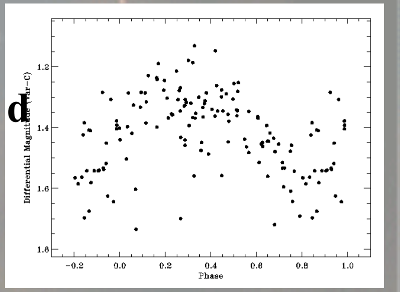


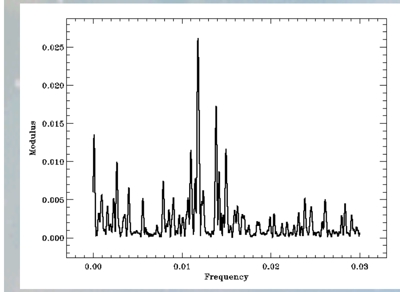
P = 89 d
G5



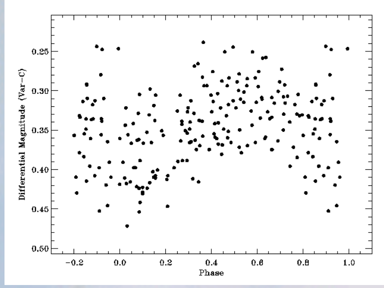


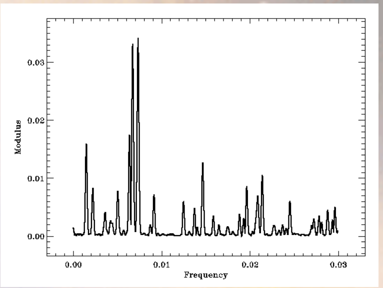
P = 153 d
G8



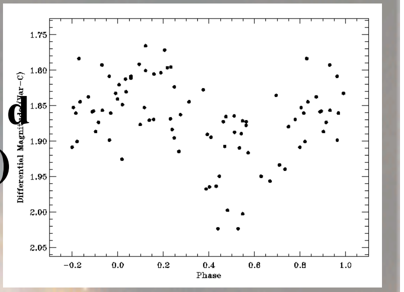


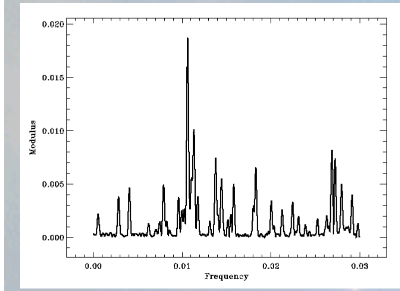
P = 85 d
G2



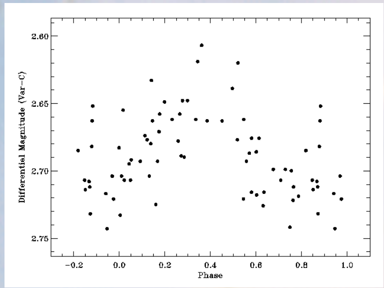


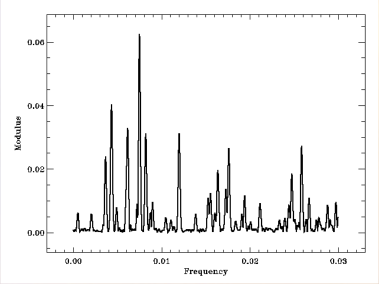
P = 136 d
(148 d)
G5



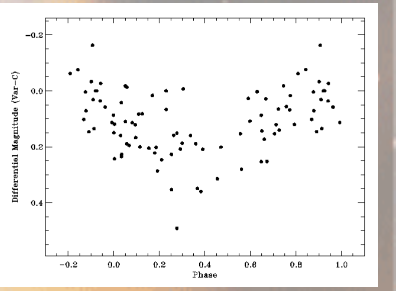


P = 94 d
G2





P = 133
G8



P analysis - Clean & Period04

1. MOTIVATION: Searching for Candidates

Image of IRAS 19477+2401
- no visible star

Discovery of IRAS 18095+2704
- bright star! (V=10.5)

3. PHOTOMETRIC VARIATIONS IN PPNe

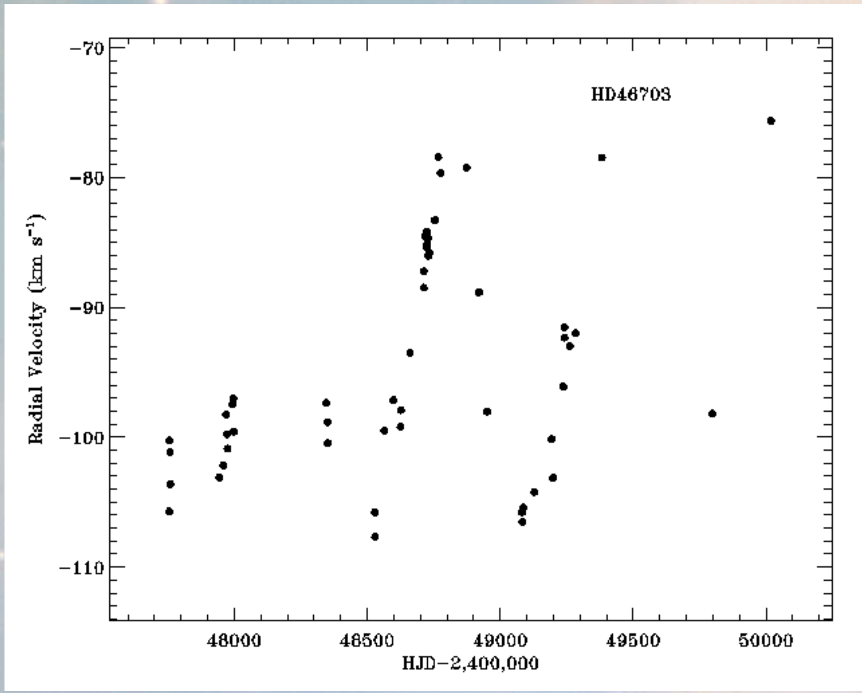
PPNe	P(d)	SpT	T_{eff} *	Δ(V-R)	ΔT_{eff}	ΔV(mag)	
05113	133	G8 Ia	5250	0.12	520	0.67	
02229	153	G8 Ia	5500	0.08	500	0.54	
20000	153	G8 Ia	5350	0.10	400	0.59	
22272	130	G5 Ia	5750	0.09	590	0.49	
07430	136:	G5 Ia	6000	0.05	310	0.23	
05341	94	G2 Ia	6500	0.07	510	0.13	
22223	89	G0 Ia	6500	0.06	440	0.21	
23304	85	G2 Ia	6750	0.08	590	0.20	
AFGL2688	…	F5 Iae	6500	0.05	370	0.18	
04296	71:	G0 Ia	7000	0.06	470	0.13:	
07134	35:	F5 I	7250	0.04	340	0.18	
19500	38:	F3 I	8000	0.05	640	0.13	

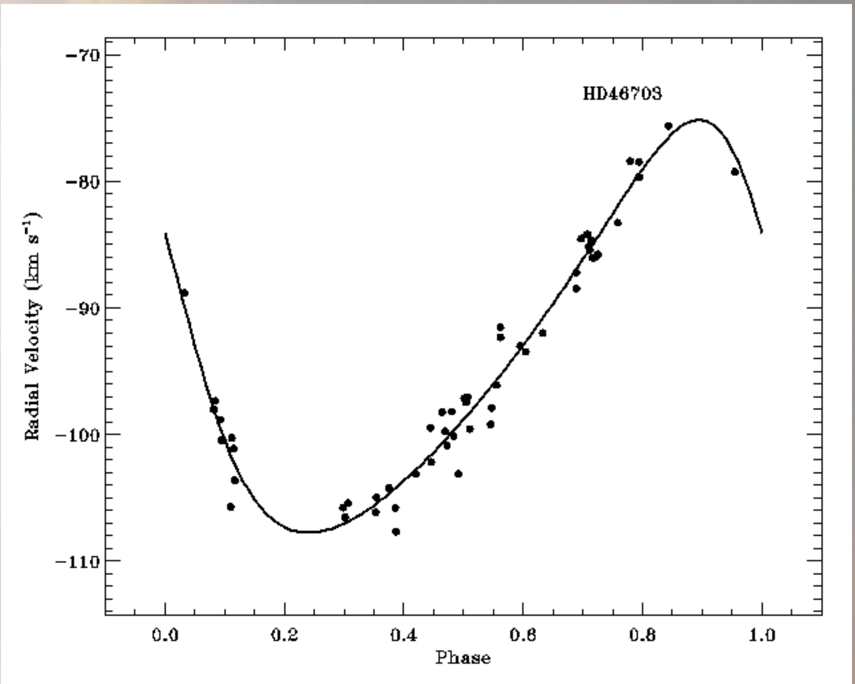
* T_{eff} from model atmosphere analysis

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**

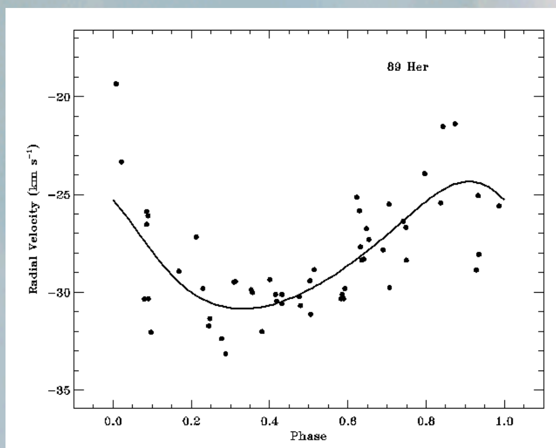


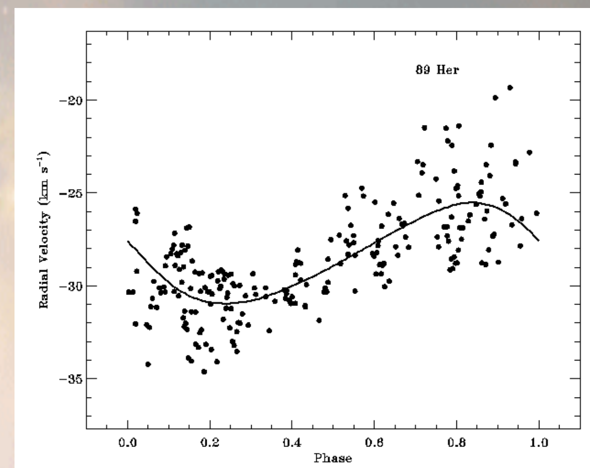


Including observations by Van Winckel & Waelkens

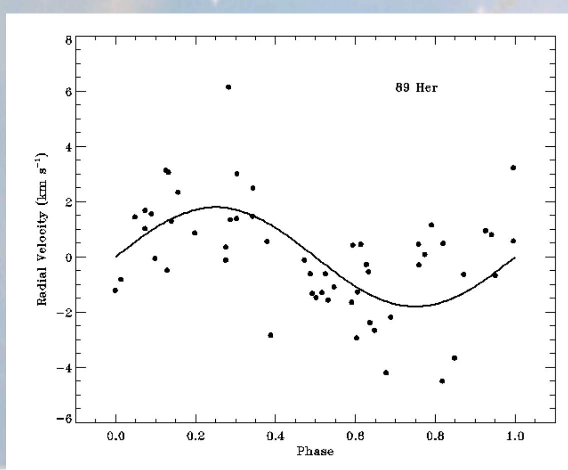
RESULTS OF OUR RADIAL VELOCITY STUDY OF OTHER POST-AGB OBJECTS

- **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

2. HOW TO DETECT BINARIES IN PPNe?

1. **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)
   - 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
  - 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

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

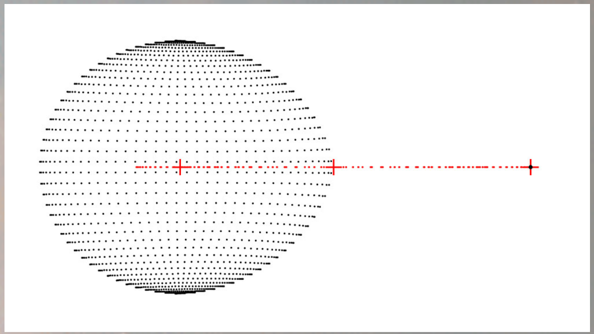
- **No** binaries found among PPNe sample (#=7) - with K > 2.5 km/s
  - For i=30 --> a > 6 AU, P > 14 yr
  - For i=60 --> a > 17AU, P > 70 yr

- **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

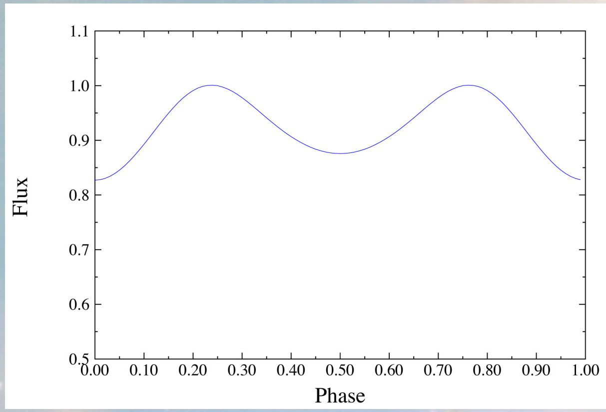
3. PHOTOMETRIC VARIATIONS IN PPNs

What would these look like? - Ellipsoidal

- PPN: $M_{PPN} = 0.62\ M_\odot$ Companion: Main Seq, $M_2 = 0.5\ M_\odot$
- PPN just within Roche lobe
- SpT=G, $R = 90\ R_\odot$, → $P_{orbit} = 1.0$ yr



$i = 90^o$



$i = 90^o$: $\Delta V = 0.18$ mag
$i = 60^o$: $\Delta V = 0.12$
$i = 30^o$: $\Delta V = 0.04$

- If PPN avoided Roche lobe overflow at **tip of AGB**, when $R \sim 400\ R_\odot$ → $P_{orbit} = 11$ yr
- Then at SpT=G, $R = 90\ R_\odot << R(\text{Roche})$ → $i = 90^o$: $\Delta V = 0.002$ mag

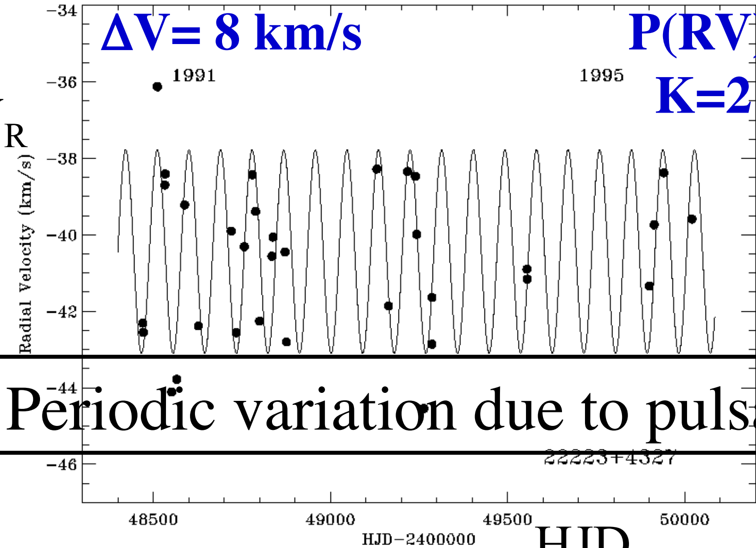
Binary photometric variations would require special conditions

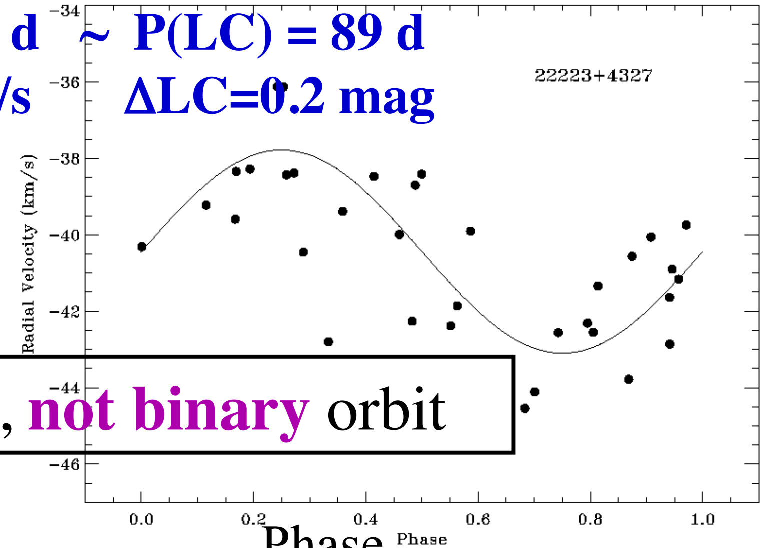
4. RESULTS OF INITIAL 1991-1995 RV STUDY

- **IRAS 22223+4327** **(G0 Ia)**

ΔV= 8 km/s **P(RV) = 89 d ~ P(LC) = 89 d**

K=2.7 km/s **ΔLC=0.2 mag**



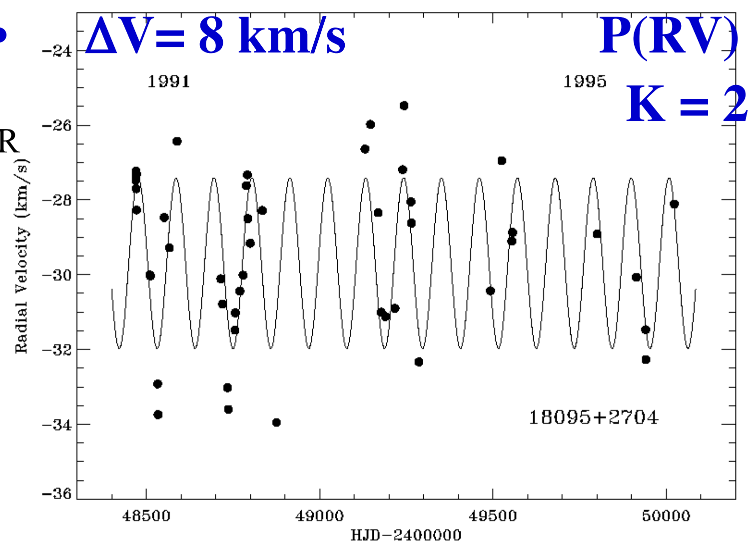


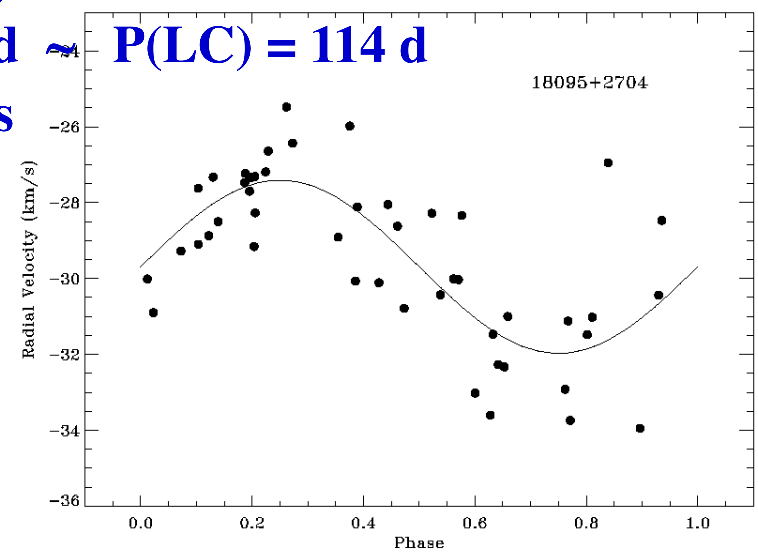
V_R HJD Phase

Periodic variation due to pulsation, **not binary** orbit

- **IRAS 18095+2704** **(F3 Ib)**
- **ΔV= 8 km/s** **P(RV) = 110 d ~ P(LC) = 114 d**

K = 2.3 km/s



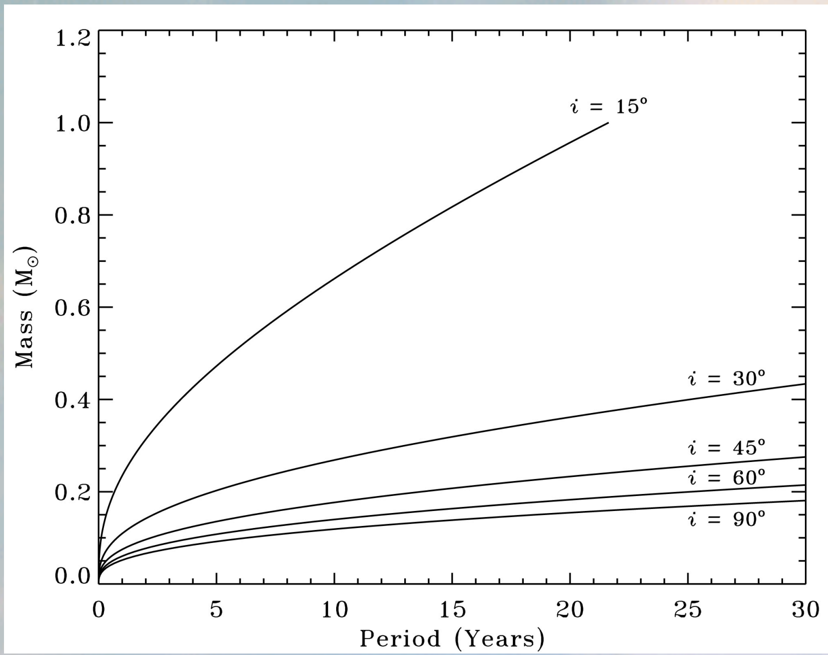


V_R

4. RADIAL VELOCITIES IN PPNe: Long-term Results

Bias - Selection effects: Chose brightest – more likely seen at low inclination, more pole-on

Any **undetected binaries** have low mass or/and long periods



M_2 and P for various inclinations (i)

(Assuming M_{PPN}=0.62 $M_\odot$, K=2.0 km/s, circular orbits)

However, non-detection sets constraints on possible binaries:

- If M_2 = 0.4 $M_\odot$, then P>3.5 yr if i>15°, P>24.5 yr if i>30°
- If M_2 = 0.25 $M_\odot$, then P>1.1yr if i>15°, P>8 yr if i>30°, P>23 yr if i>45°

or

- M_2 > 0.3 $M_\odot$ is excluded for P<13 yr at i>30°

(see Hrivnak et al. 2011, ApJ, 734, 25)

5. RESULTS OF VARIABILTY STUDIES OF PPNs

- 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
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    - But this lasts only a short time, unlikely
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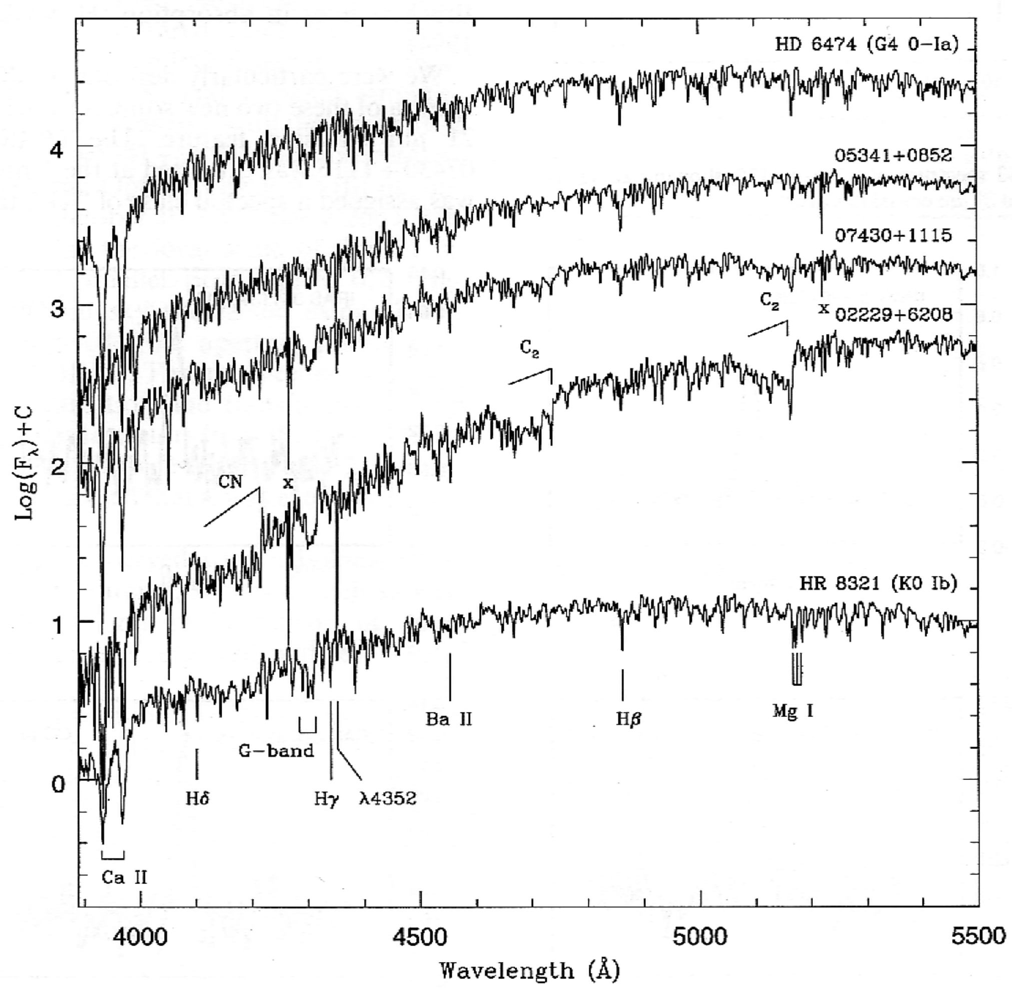
  - then this suggests two ways to form PNe,
    - Common envelope evolution (binary PNNe)
    - Non-common envelope process (occurring in these PPNe)
      - Distant, low-mass companions?
      - Single, pulsating PPNe?

Beginning the Search: Finding Candidates (1st decade)

Properties: **Did we find what 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-OH,CO)
- Double-peaked spectral energy distribution? **Yes (IR studies)**



Numbers of PPNs:

- 60 firm candidates
- 60 possible candidates
- possible confusion

5. RESULTS OF VARIABILTY STUDIES OF PPNs

- **What does cause PN & shape the nebula?**
  - Two paths to form & shape PN?
    1. Common envelope (CE) evolution with ejection and shaping of the envelope → short-period binary central star of PNs
    2. Non-CE – since CE spiral-in and ejection timescale on order of 1 yr and we find PPNs still retaining their envelopes, thus non-CE
       - Binary, with companion of low mass ($< 0.25\ M_{\odot}$) or long period ($P > 30$ yrs), or
       - Non-binary (pulsational induced?)