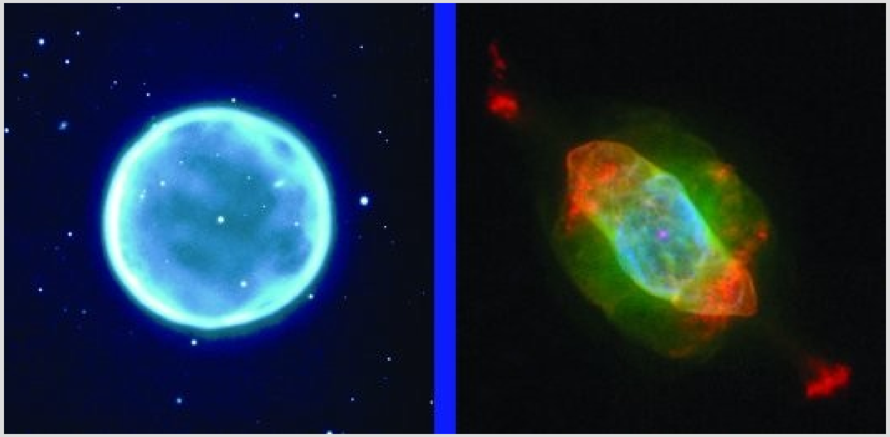
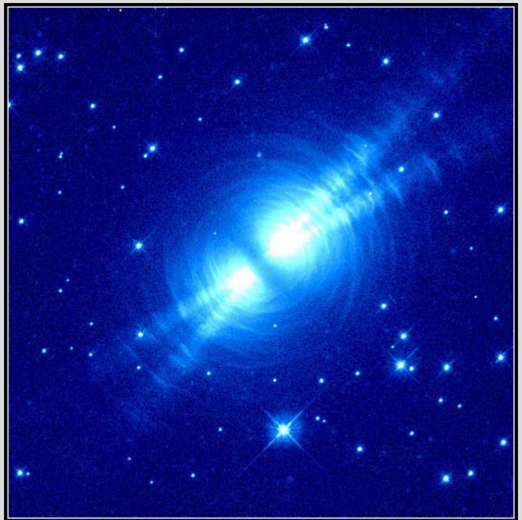
Planetary nebula formation and evolution

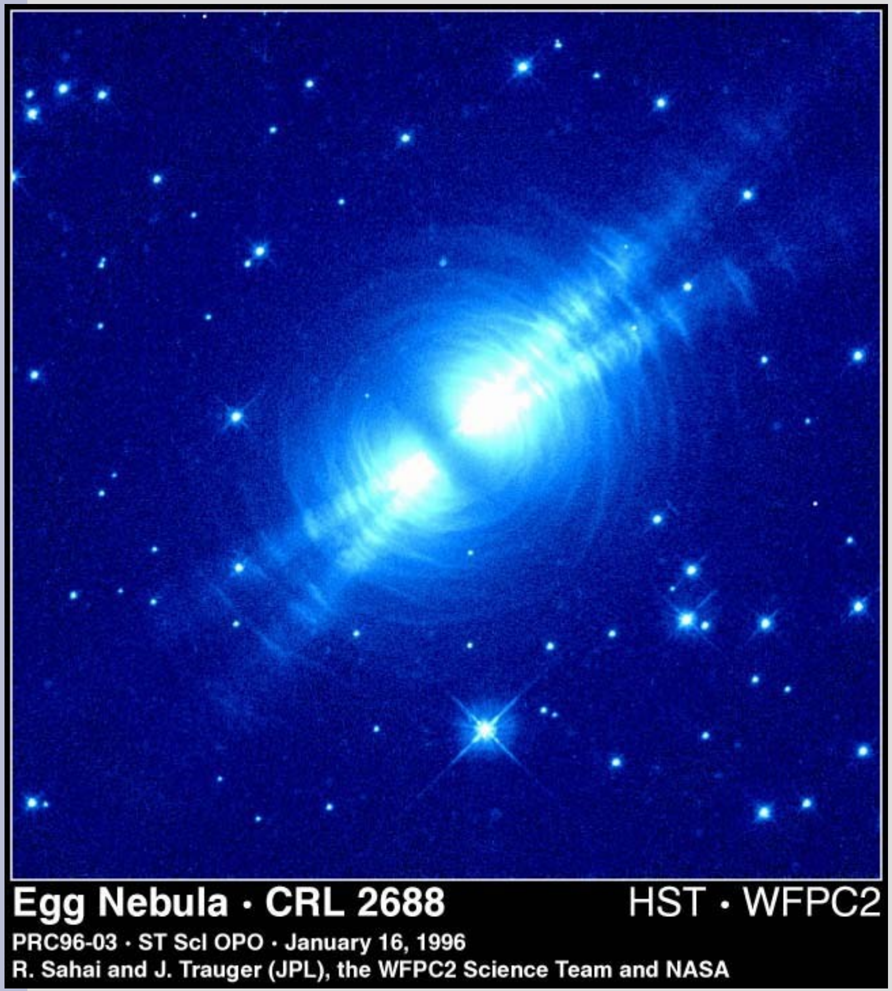


- PN ejection
  - When and how
  - Modes of mass loss
- Final masses
- Structure formation
  - When and how
- Dust and disks
- The future of the Sun



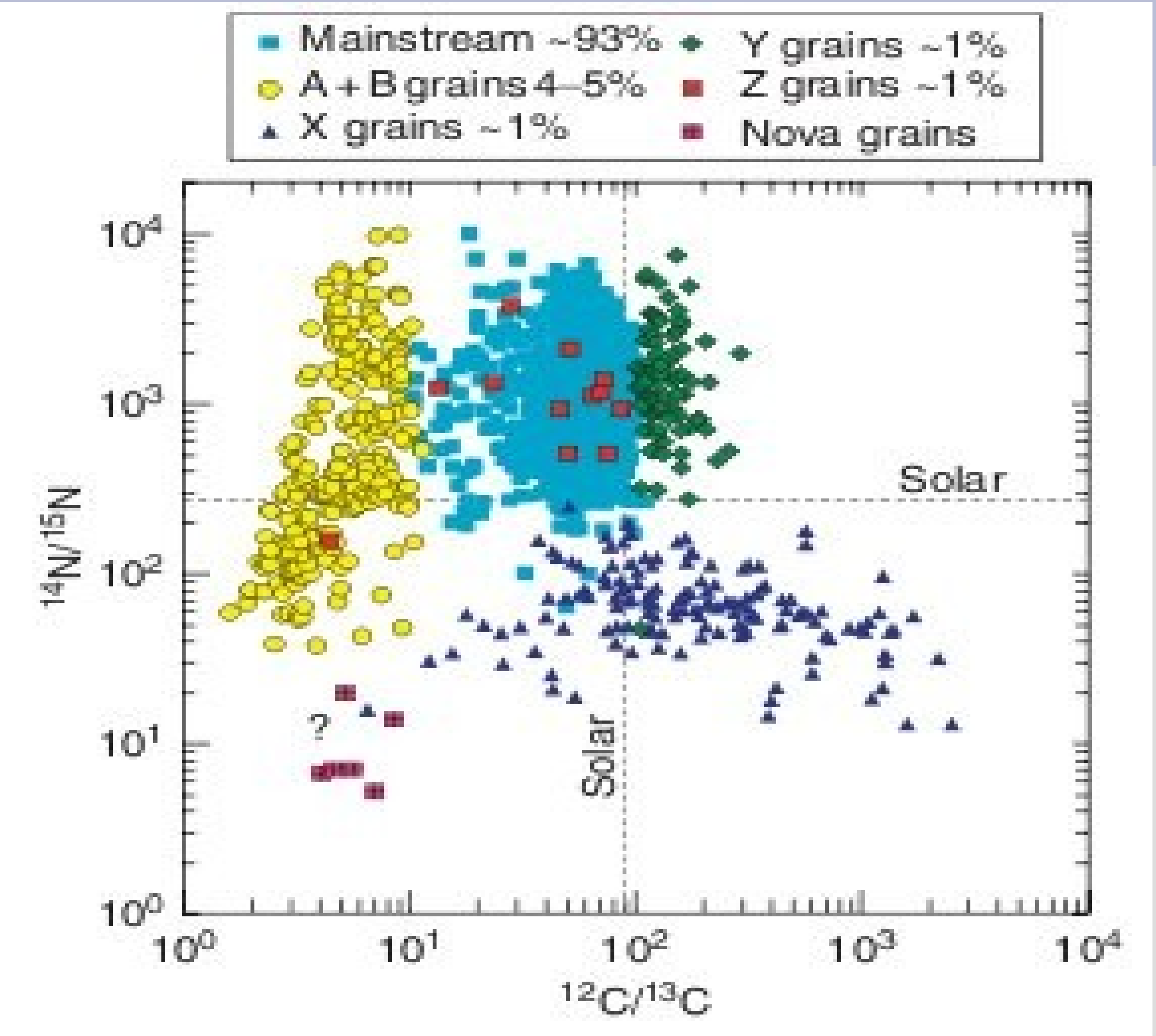
Egg Nebula · CRL 2688 HST · WFPC2
PRC96-03 · ST ScI OPO · January 16, 1996
R. Sahai and J. Trauger (JPL), the WFPC2 Science Team and NASA

What have Planetary nebulae ever done for us?



- Transform stars into white dwarfs
- Drive Galactic evolution
- Formed the Sun
- Prevent unnecessary supernovae

- PN: a star reflecting on its past
- PN: pain in the neck



Mainstream ~93%
A + B grains 4–5%
X grains ~1%
Y grains ~1%
Z grains ~1%
Nova grains
Solar
Solar
?
$^{14}N/^{15}N$
$^{12}C/^{13}C$
10^0
10^1
10^2
10^3
10^4

Planetary nebulae origins

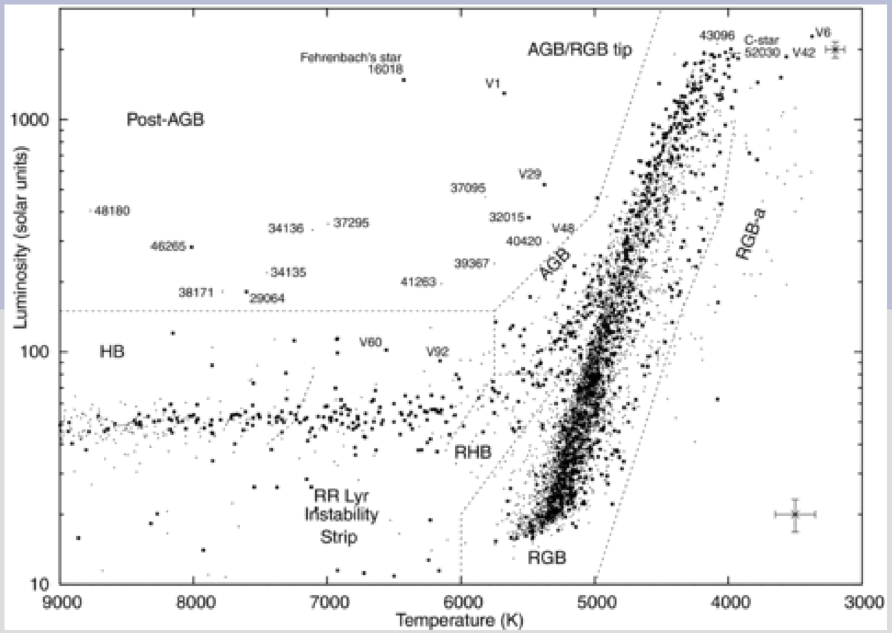
- Occur in all Galactic stellar populations

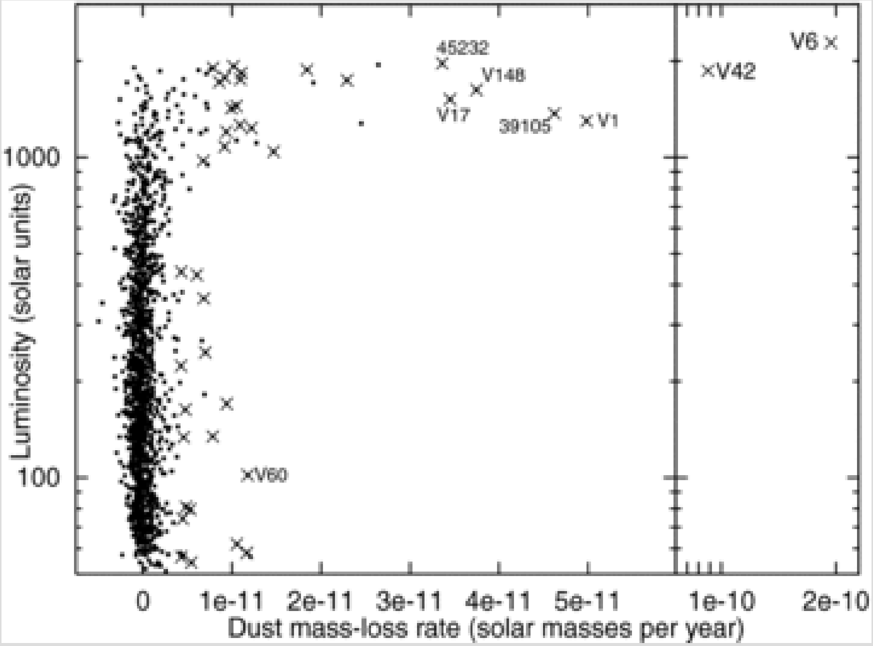
- Large majority of sun-like stars pass through the phase
- Require superwinds
  - Mass loss rate exceeds nuclear burning rate

- When, how long, how, .., does this wind occur?

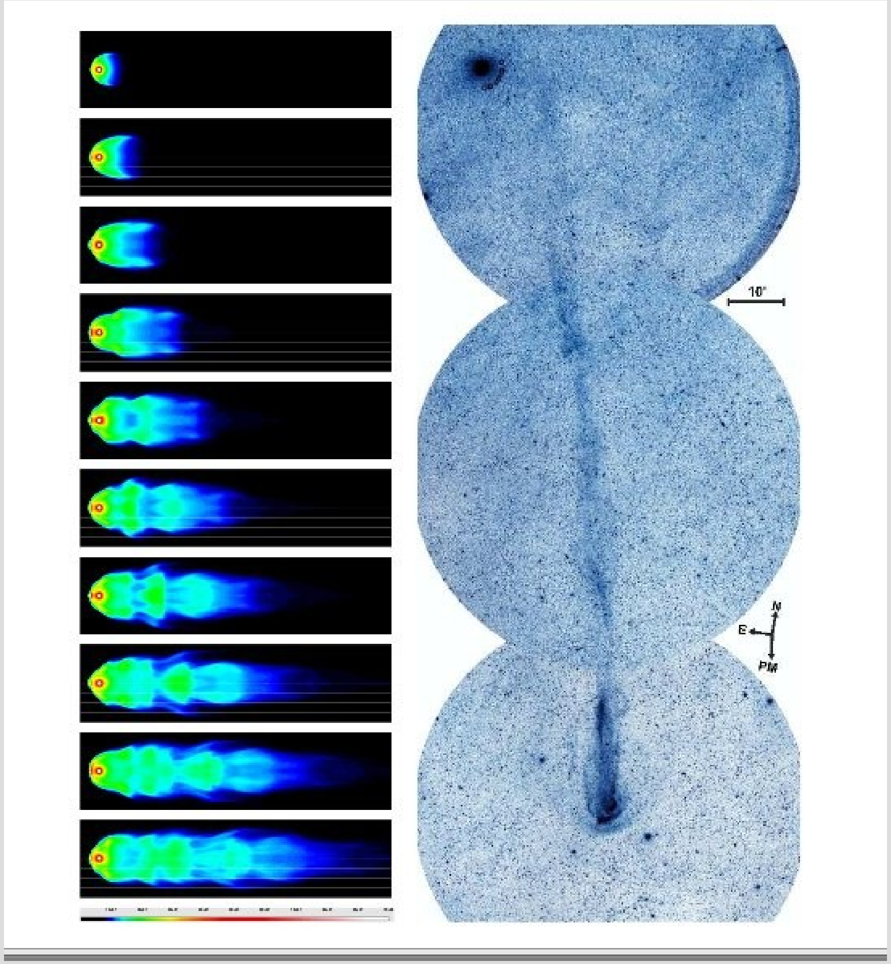
Dusty winds

- Mass loss traced by dust
- Omega Cen:dusty winds detected for
  - L>1000Lsun
  - T < 4400 K
  - (McDonald et al. 2009)
- RGB & AGB
  - Globular clusters: mostly at tip of RGB
  - Otherwise: TP-AGB





Timing the mass loss

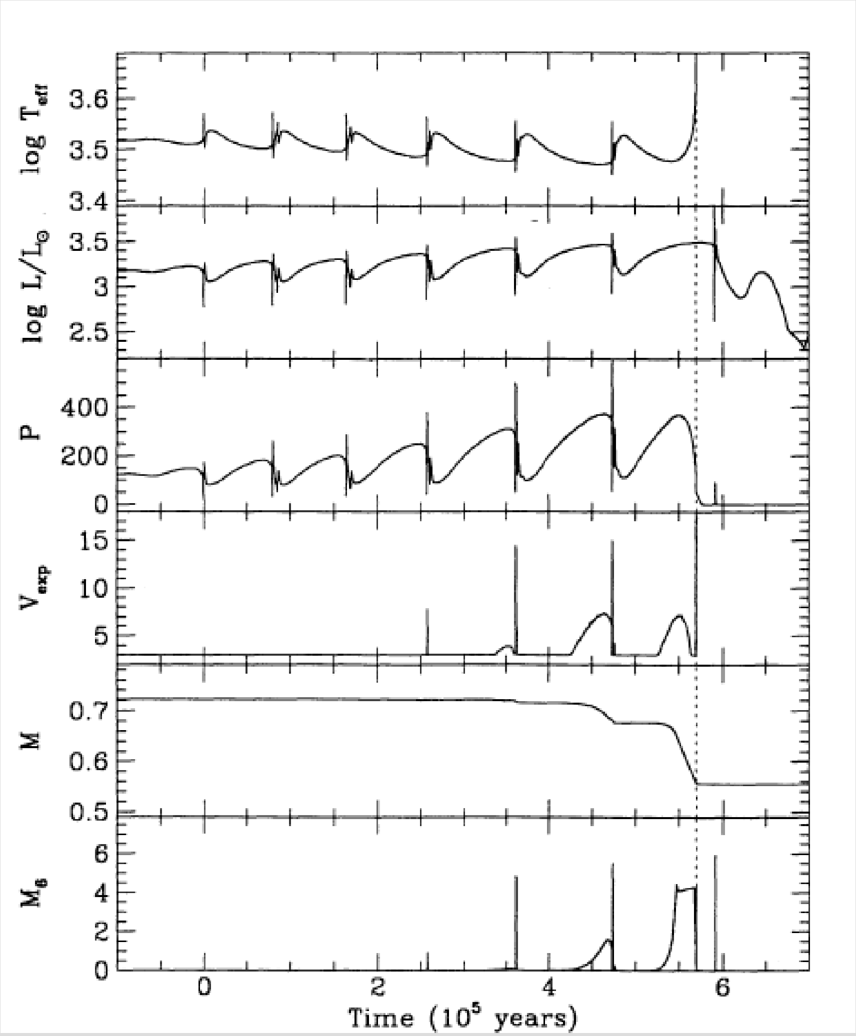


- Mira's tail
  - (Wareing et al. 2007)
- Models of ISM interaction
  - co-moving tail
  - Mdot 3 x 10^{-7} Msol yr^{-1}
  - Lasting ~2 x 10^{5} yr
  - stable
- Suggests a stable but rather weak (non-dusty?) wind

AGB winds

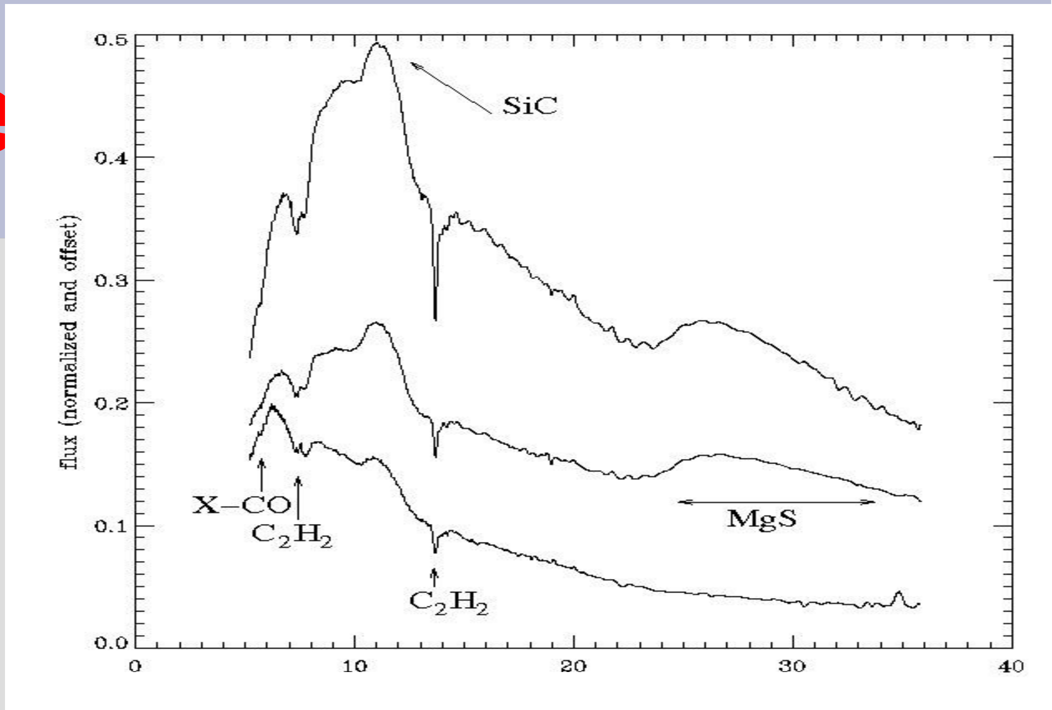
- Three-step process
  - Pulsations
  - Dust formation
  - Radiation pressure
- Limited by photon momentum
- Fairly sudden onset

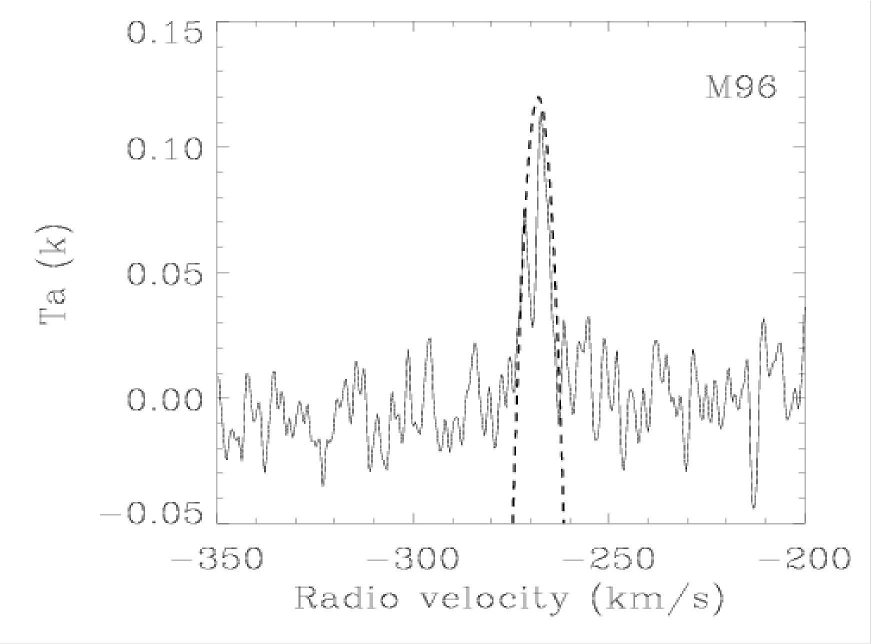
- Woitke: are dust-driven winds a myth?



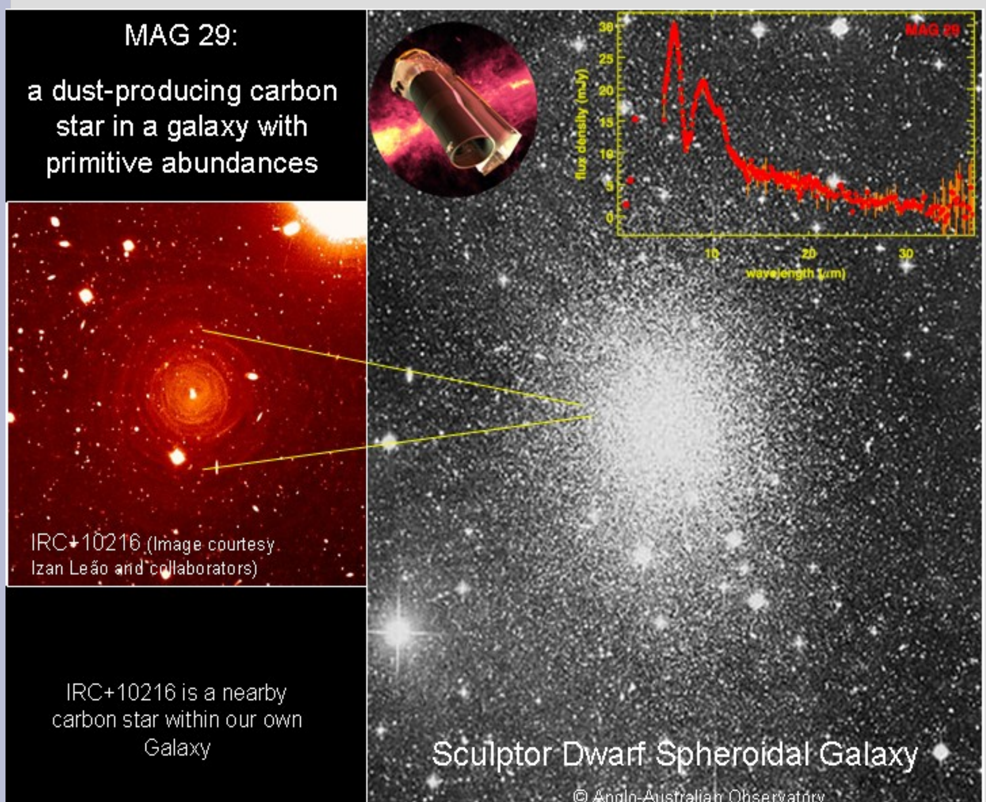
Dust driven winds should be

- Dusty
  - Always are
- Limited momentum
  - Generally satisfied
  - Not for fast, bipolar CO flows Bujarrabal et al. 2001
- Metallicity dependent
  - Reduced V_{exp} in LMC Wood and Halo Lagadec



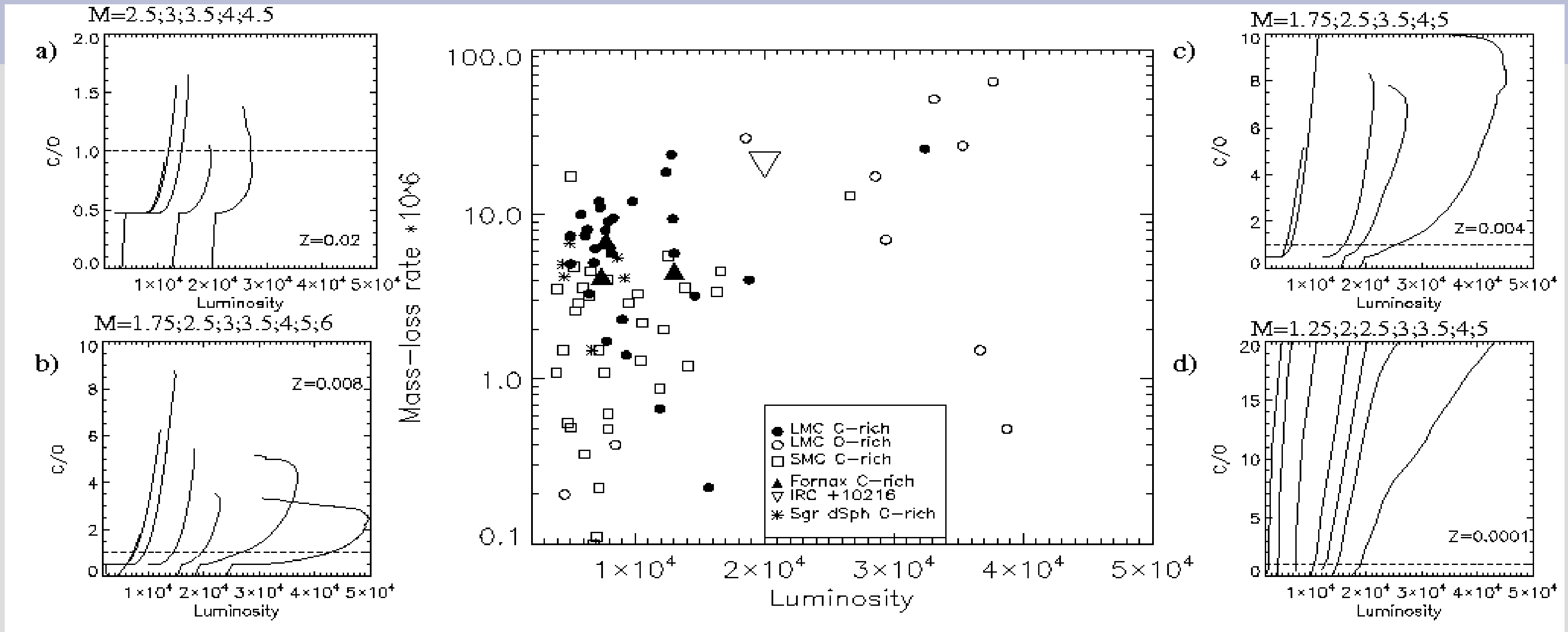


Subsolar metallicity



- Carbon stars show evidence of dust-driven at very low Z Sloan et al. 2009
- Oxygen-rich stars show much much less dust at low Z

Dual Wind



- O-rich stars need critical luminosity
- C-stars don't
- O-AGB winds are dust-driven in Galaxy but not in the SMC ? Lagadec 2008

Other winds

Need to predict right mass loss rates, expansion velocities, dust content, timing, ..

- Pulsation-driven winds
- Binary hypothesis (de Marco)
  - Close binaries increase mass loss rates and make it more likely to form a planetary nebula
  - (Do single stars make faint or failed PNe?)
  - Predicts larger range of final masses

PN stellar masses

- Schoenberner bottleneck
- HR diagram mass-insensitive
- Heating time scale best mass determinant

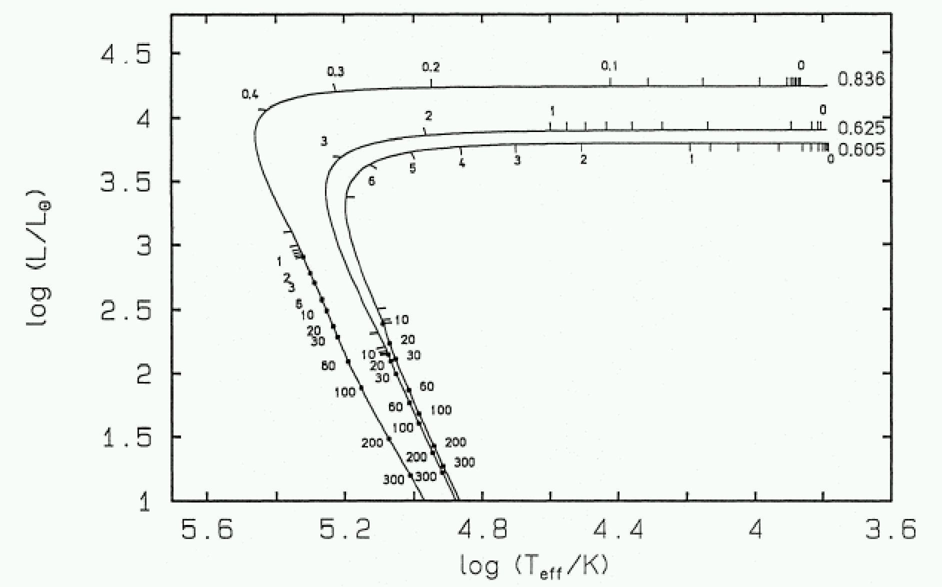
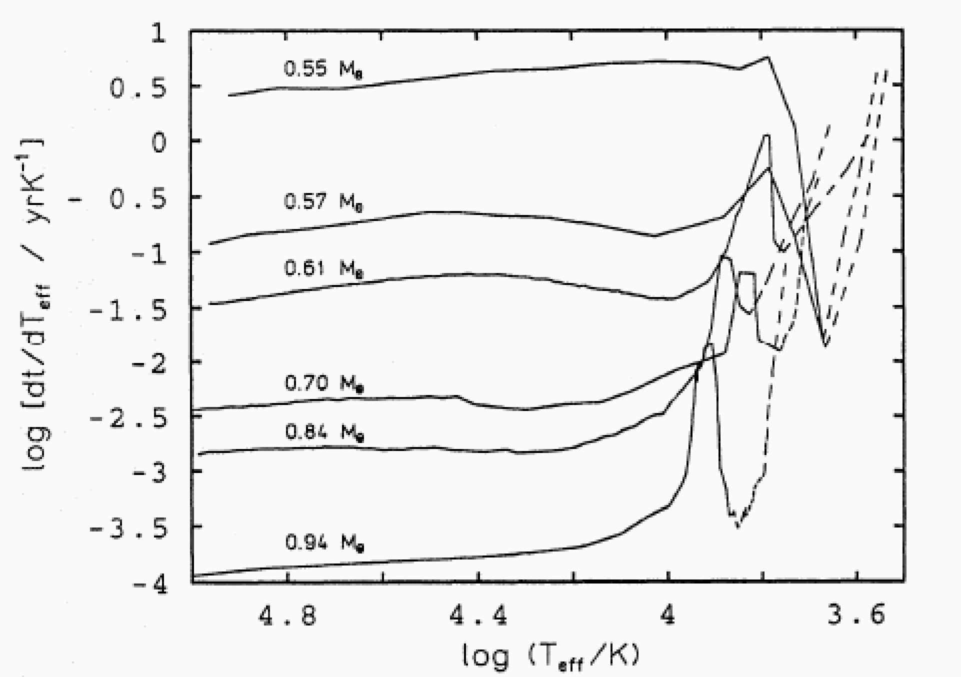
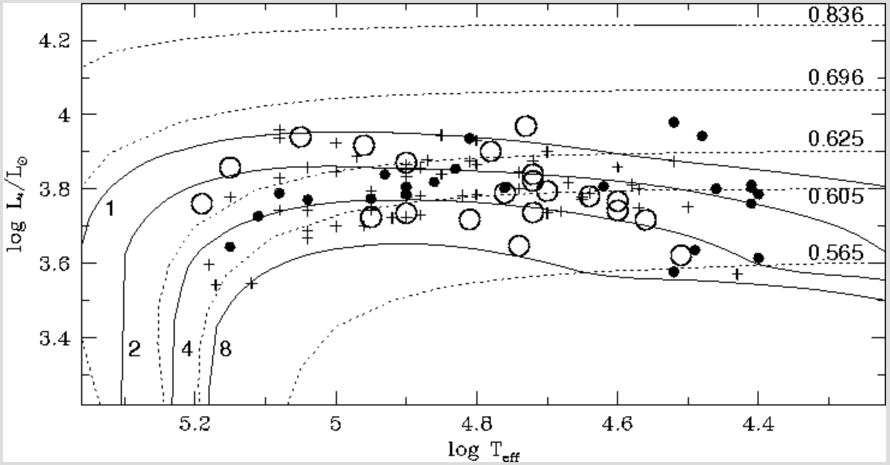


Fig. 7. Evolution of post-AGB models with (M_{ZAMS}, M_H) = ($3M_\odot$, $0.605M_\odot$), ($3M_\odot$, $0.625M_\odot$) and ($5M_\odot$, $0.836M_\odot$). Time marks are in units of 10^3 yrs



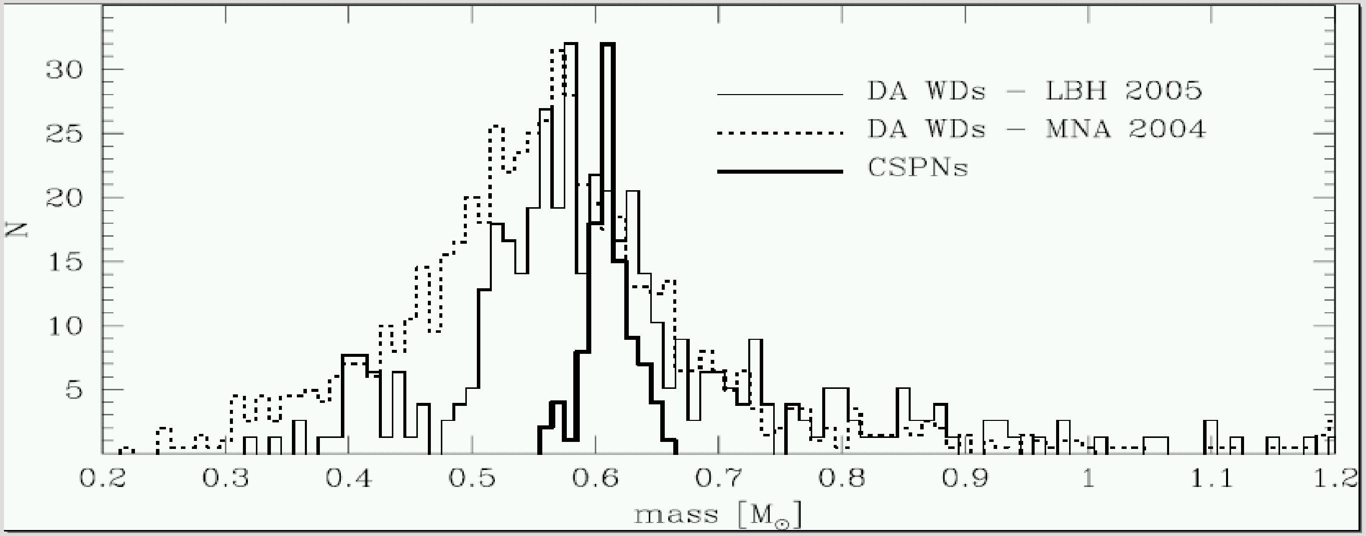
Kinematic masses

- Bulge and disk PNe
- Age from nebula kinematics
- Stellar temperature from ionization models
- Mass from Bloecker models



Narrow mass distribution

Comparison with WD masses



- PNe show very narrow range
- 0.58-0.63Msun
- WD broad mass range
- Peaks slightly lower masses

Which one is wrong?

- PN masses may be shifted by ~0.02 Msun
- Extreme WD masses may be overestimated

TABLE 3
RESULTS FROM ASTEROSEISMOLOGY OF PG1159 STARS AND THE [WC4] CENTRAL STAR OF NGC 1501

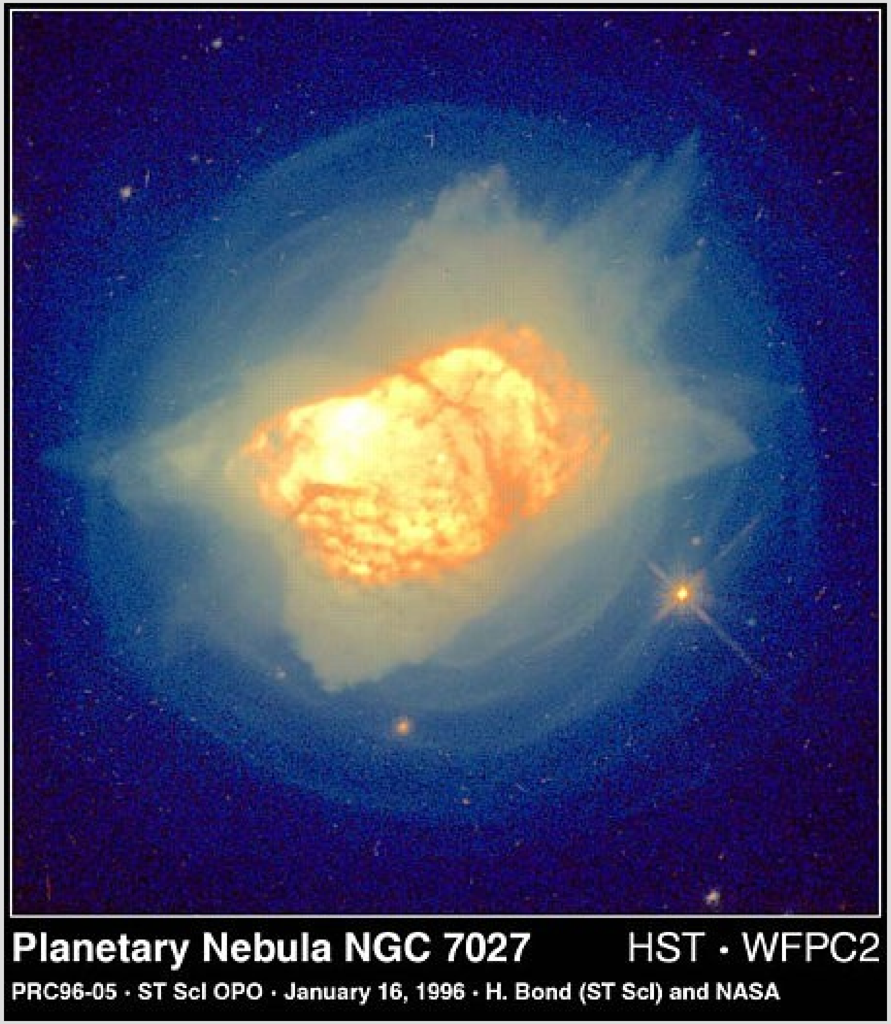
Star	M_{spec}	M_{puls}	M_{env}	P_{rot}	Reference
PG 2131+066	0.58	0.61	0.006	0.21	1
PG 0122+200	0.58	0.59	...	1.66	2
RX J2117.1+3412	0.70	0.56	0.045	1.16	3
PG 1159−035	0.60	0.59	0.004	1.38	4
PG 1707+427	0.59	0.57	...	...	5
NGC 1501	...	0.55	...	1.17	6

NOTE.—We compare the stellar mass derived by spectroscopic means M_{spec} (from Table 2) with the pulsational mass M_{puls}. Other columns list envelope mass M_{env} (all masses in solar units) and rotation period P_{rot} in days.

REFERENCES.—(1) Kawaler et al. 1995; (2) Fu & Vauclair 2006; (3) Vauclair et al. 2002; (4) Kawaler & Bradley 1994; (5) Kawaler et al. 2004; (6) Bond et al. 1996.

Werner & Herwig 2007

Test: NGC 7027 mass



- Brightest PN
- Initial mass 3 Msun

- Very hot star
  - 170 000 K
- Expected high mass

- Kinematic mass 0.65 Msun

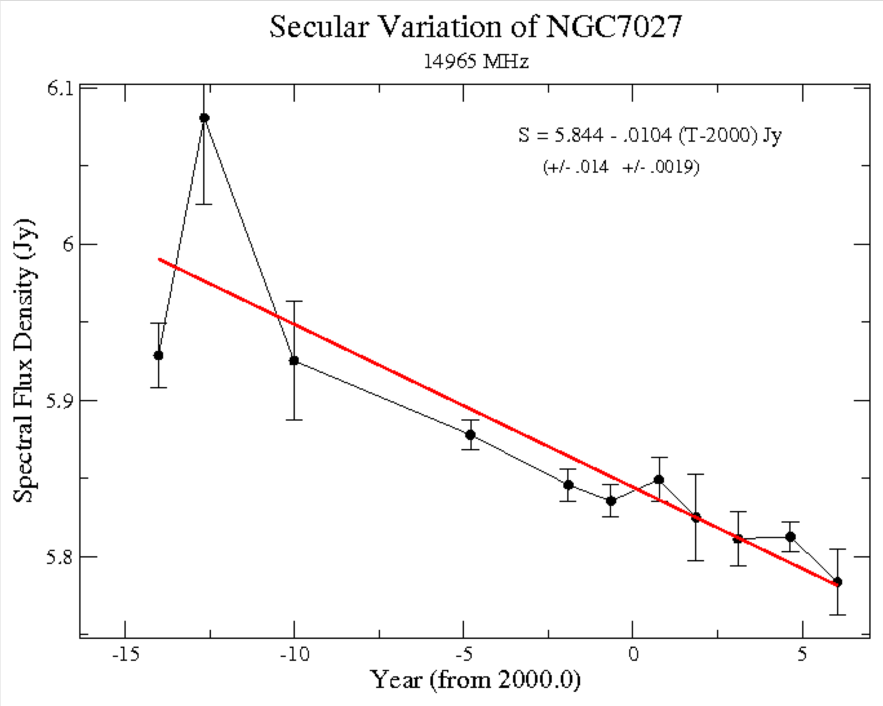
Radio evolution

- Radio flux declining
- Indicates
  - dT = 155 +/- 30 K/yr
  - dL = 0.1 +- 0.015 %/yr

Mass

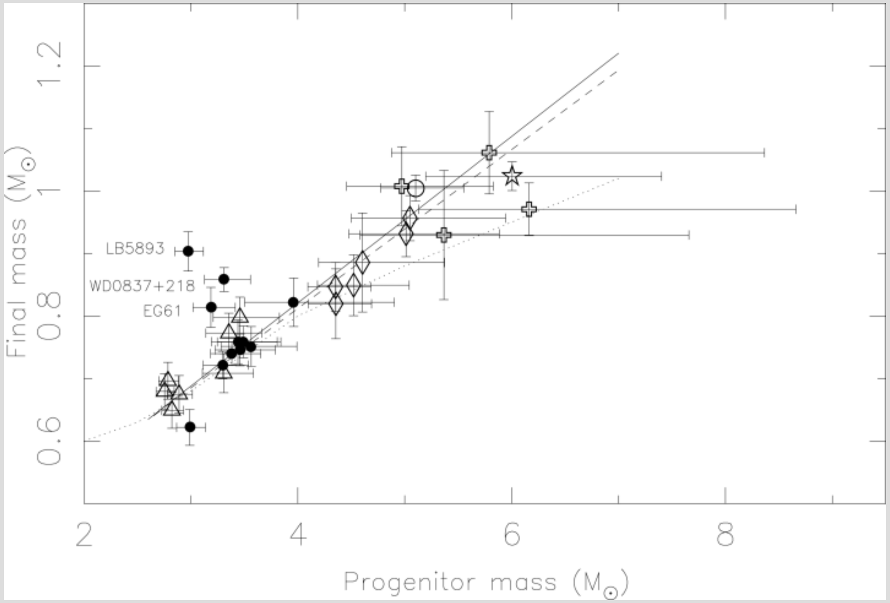
0.655 +/- 0.010 Msol

-



Zijlstra et al. 2008

Initial final mass relations



Dobbie et al. 2006

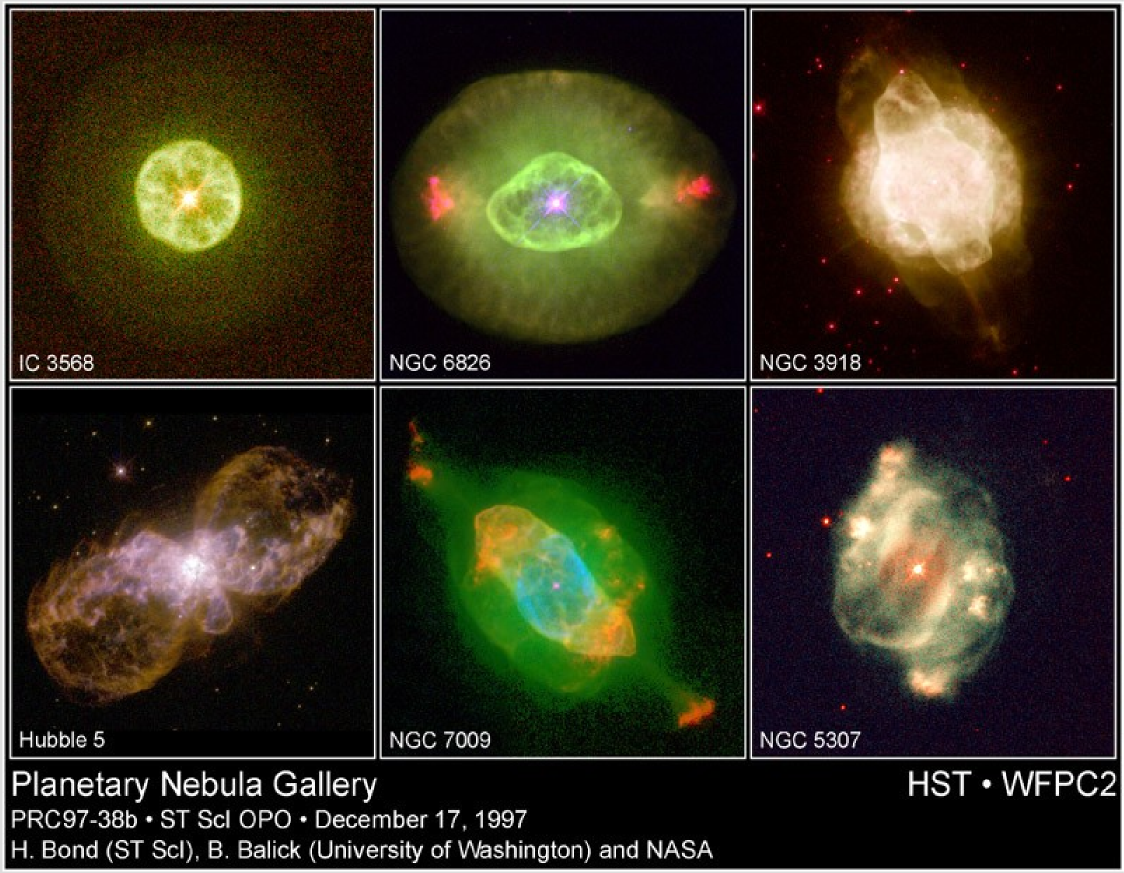
- Obtained from clusters
- Large dispersion
- PNe indicate
  - Initial 1 - 3 Msun
  - Final 0.6 - 0.7Msun

Structure formation

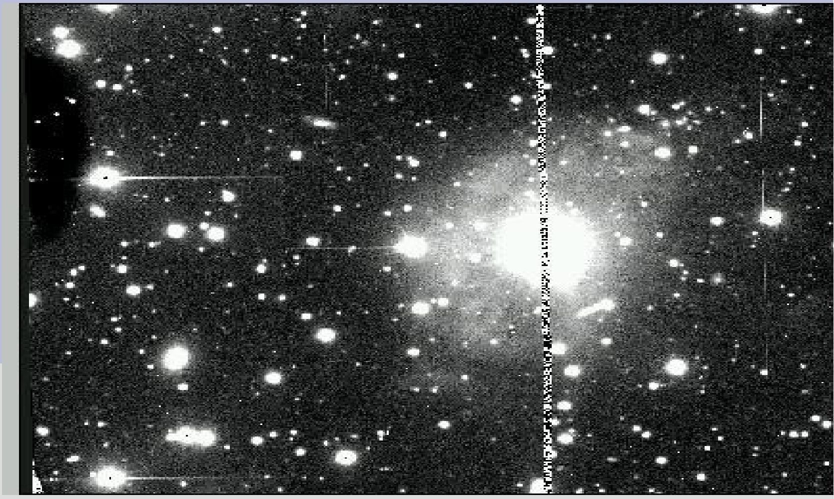
- PNe are always aspherical
- Structures are amplified by post-AGB wind

- AGB winds are assumed spherical

- Asymmetry forms late?

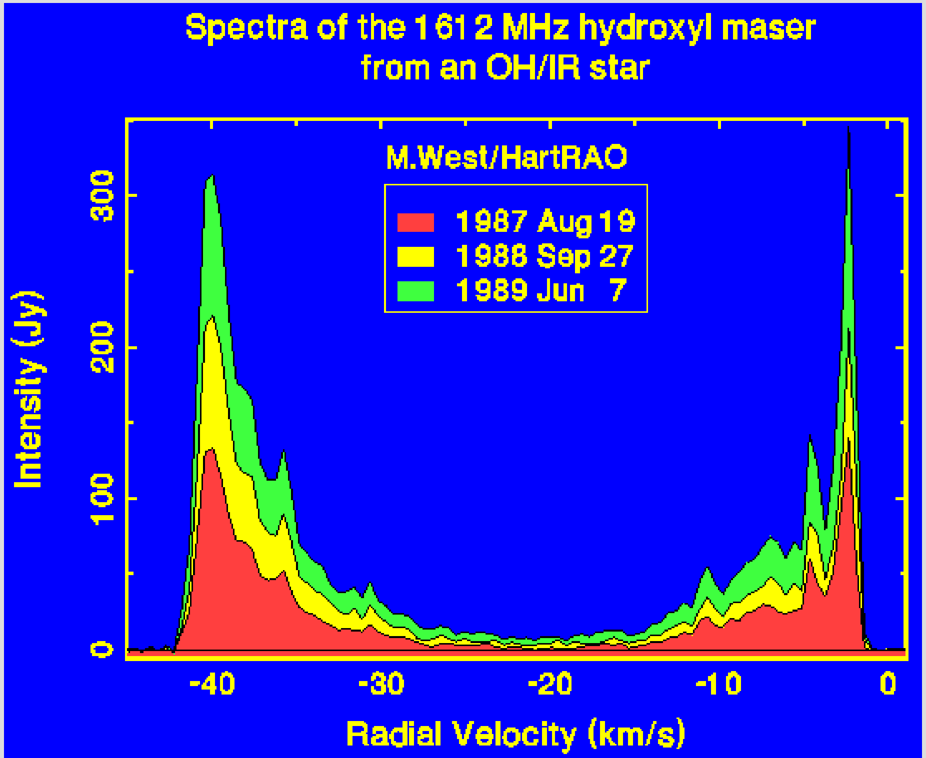


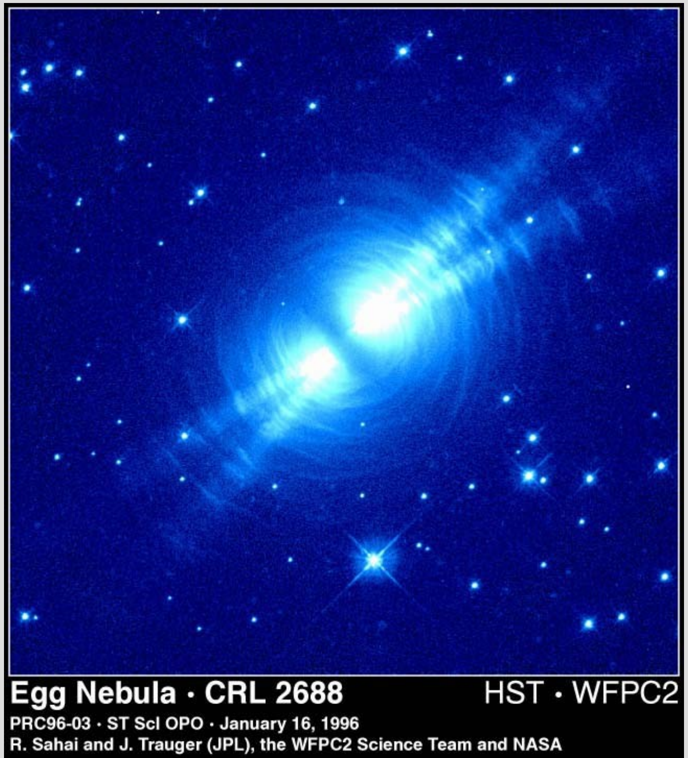
Are AGB wind spherical?



Yes
- Regular OH maser profiles
- Circular arcs

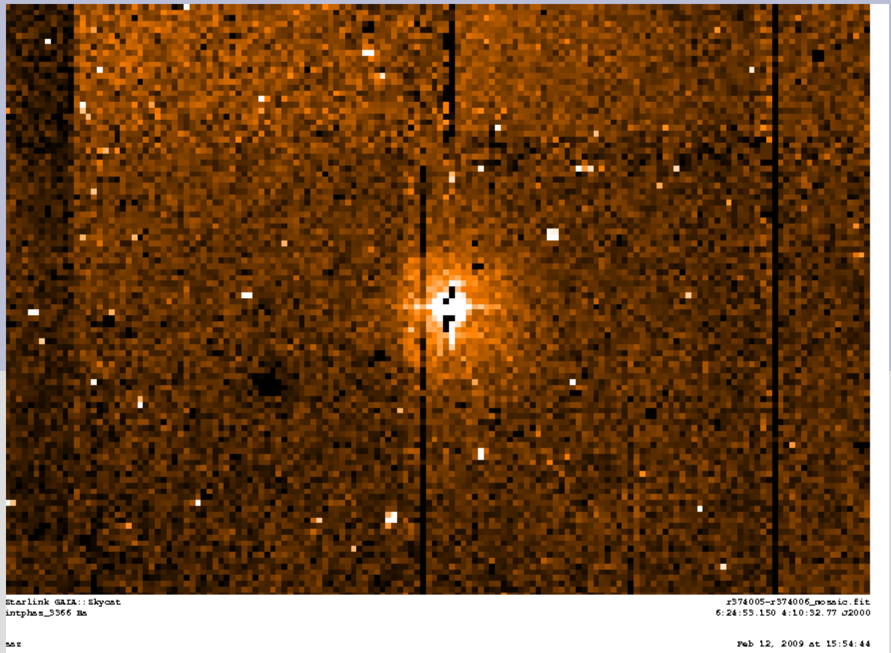
No
- RZ Sgr, X Her, ..
- Linear polarization

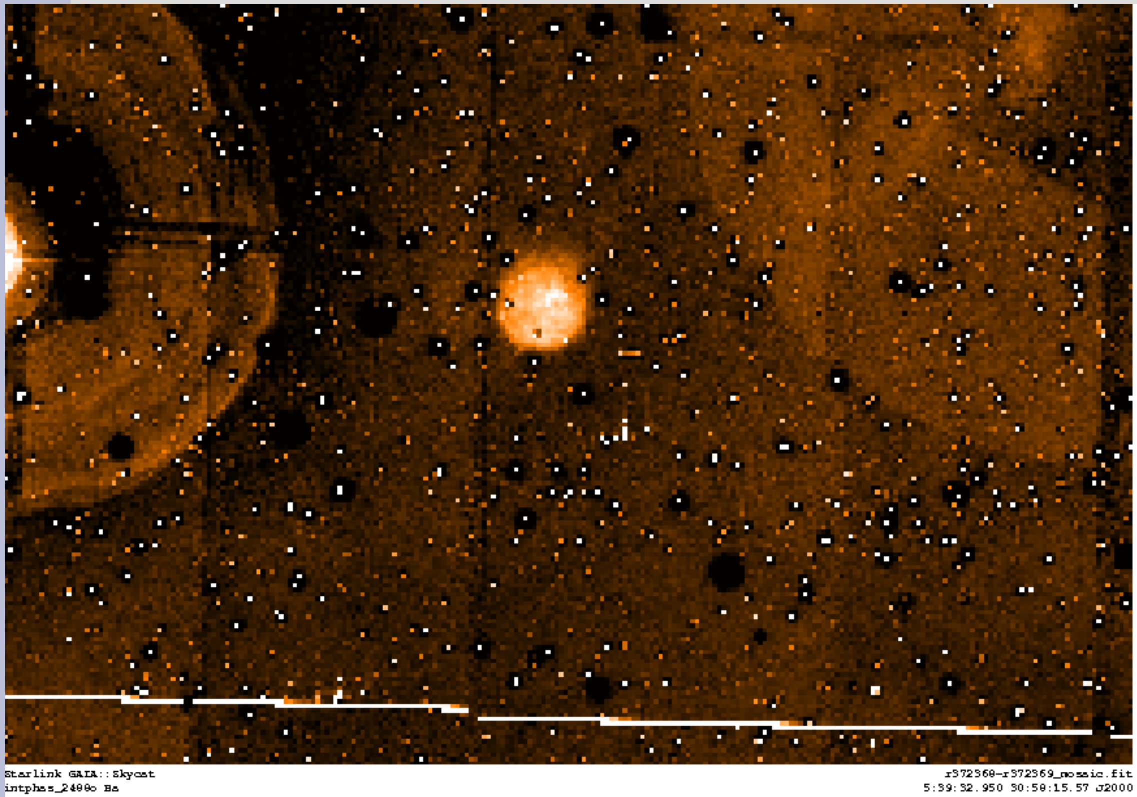




Sometimes

- Bipolar AGB winds exist
- Round PNe exist





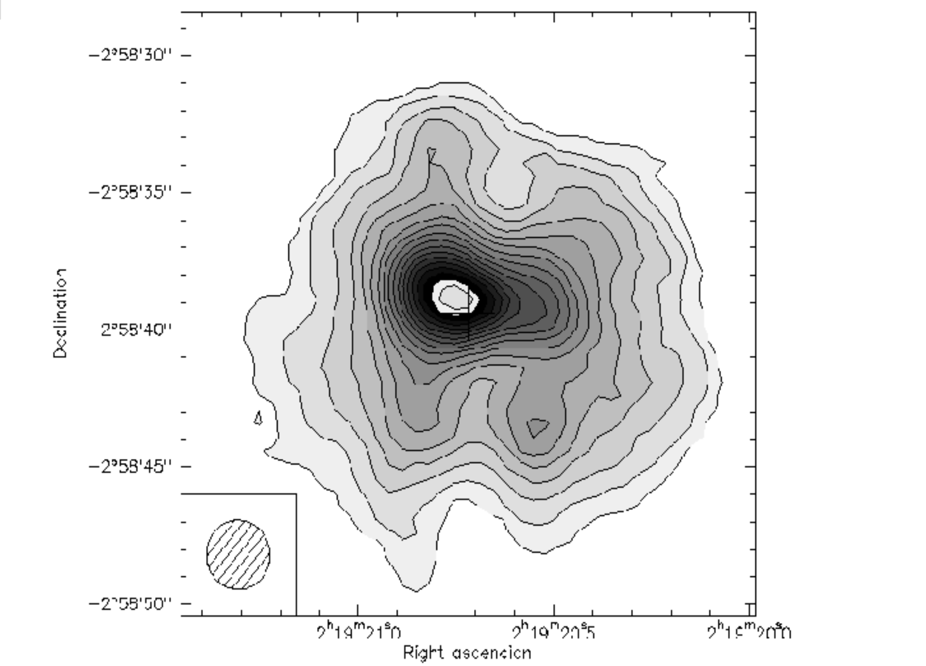
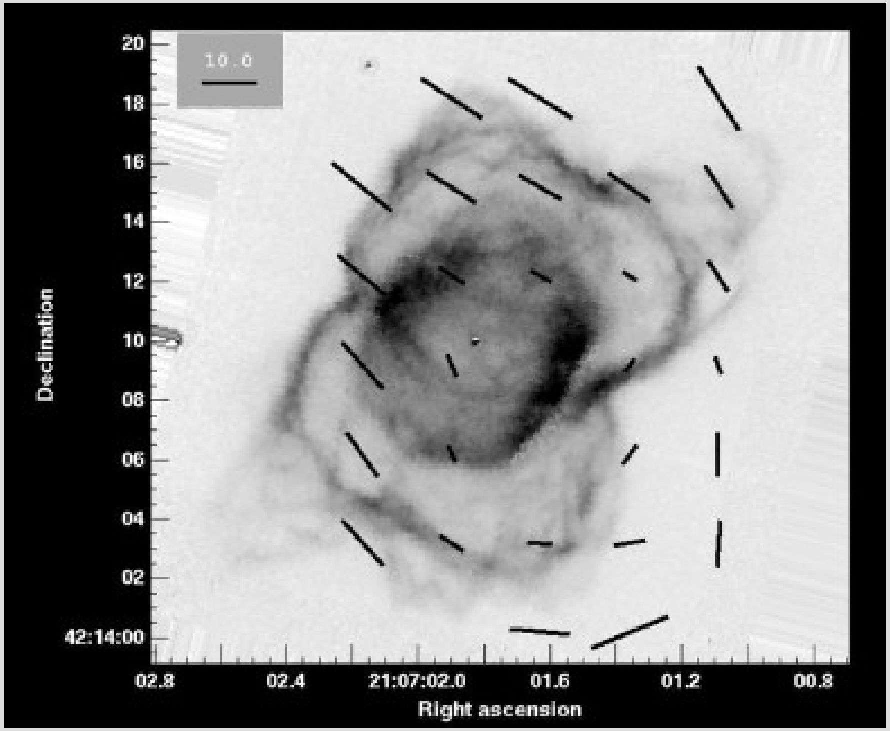


Fig. 1. Contour map of the integrated $^{12}CO(2\text{-}1)$ emission from o Ceti over the whole velocity range of emission. The lower level contour and the contour spacing are 2 Jy beam^{-1} km s^{-1}. The beam after cleaning is shown in the box in the lower left corner.

Shaping mechanisms

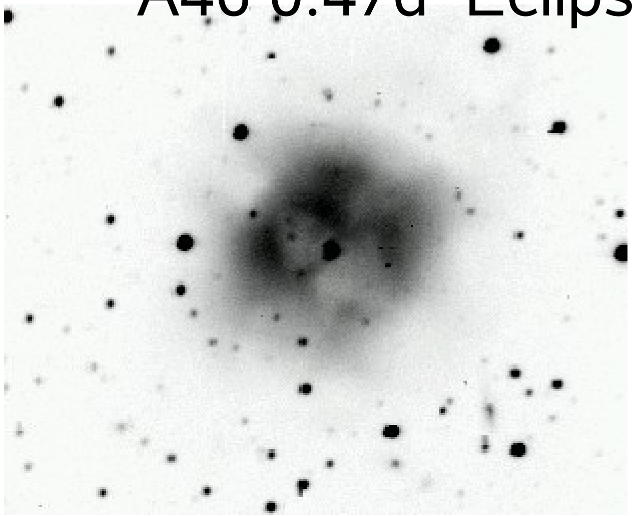
- Magnetic fields
  - Fields are detected: maser emission (Richards, Vlemming, Bains), sub-mm polarization (Sabin)
  - Torii contain toroidal fields
  - Insufficient to dominate shaping?



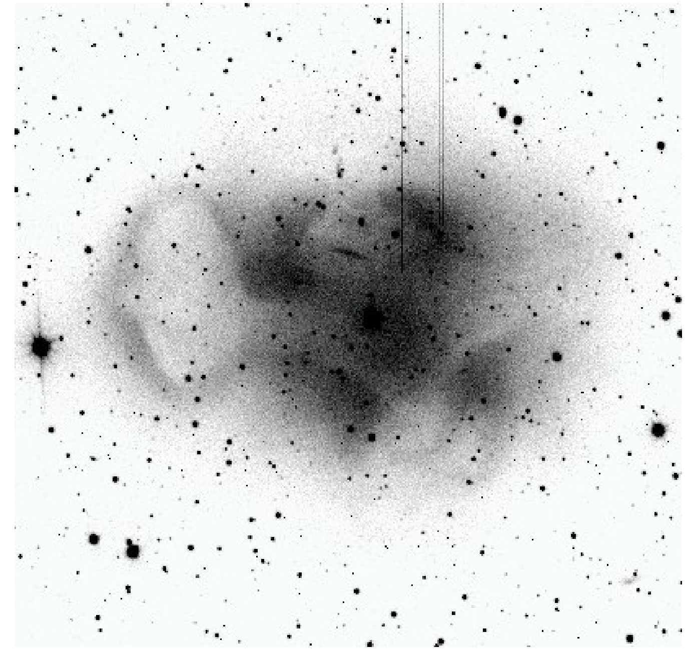
Binary interactions

- Post- common envelope systems
  - ~10% of PNe
  - Sudden envelope ejection
  - Thin, expanding rings; jets
- Intermediate binaries {~1 AU)
  - Common atmosphere systems
  - Source of disks and dense torii?
- Wide binaries (~100AU)
  - Mass loss rates as in single stars
  - Weak shaping

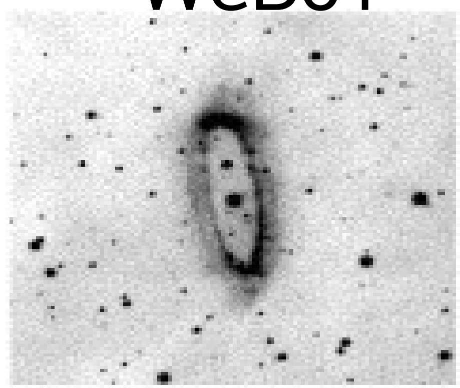
A46 0.47d Eclipsing



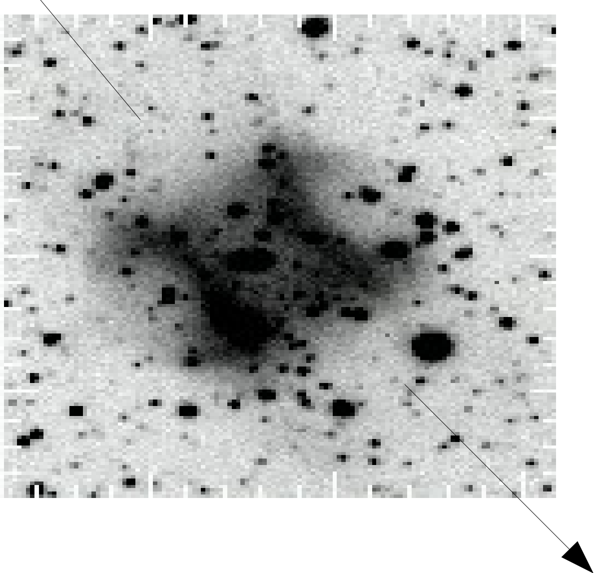
Ds1 0.36d



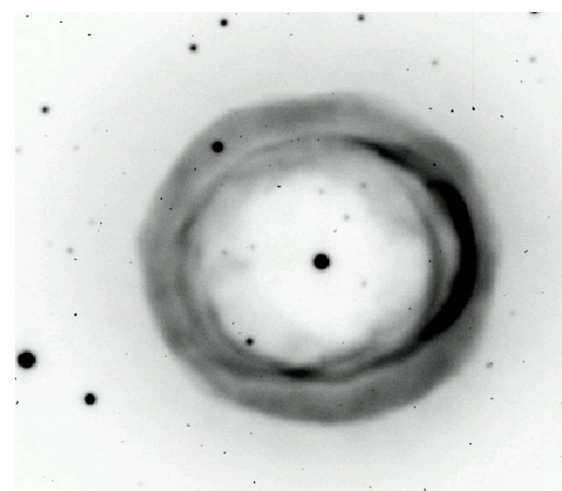
WeBo1



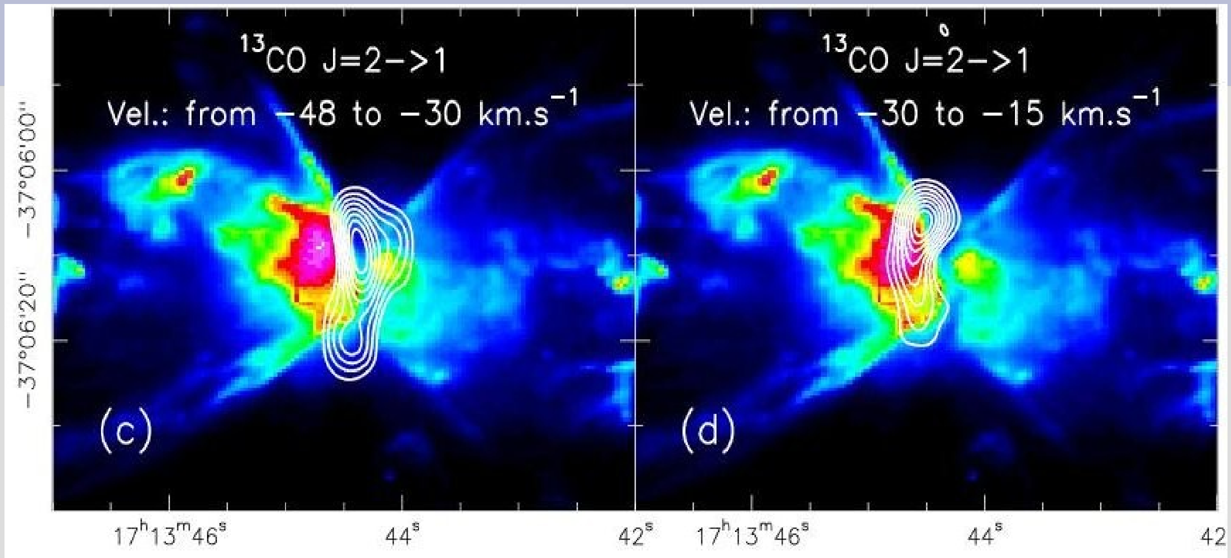
A63 0.45d, Ecl.



Sp1 2.91d



NGC 6302



- Massive CO torus Peretto et al. 2007
- Slowly expanding 8 km/s
- Momentum excess >8
  - Not expelled by a dust-driven wind ?

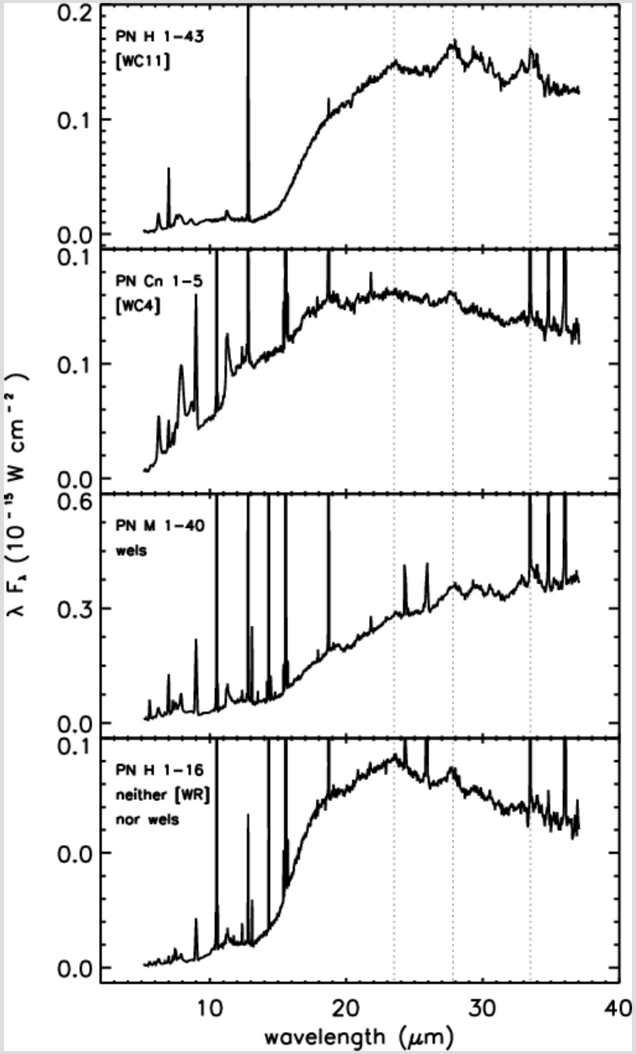
Gravitational lifting

- Peretto et al. propose a binary companion
- Infall to 0.1 AU would provide energy to eject the torus
- Corresponds to period of 15 days
- Do butterfly nebulae correspond to such intermediate-distance binaries ?

Angular momentum

- Binary shaping acts through transfer of angular momentum
  - In 'cold storage' during the main sequence
- Compact binaries have less angular momentum
- Highest shaping efficacy occurs for widest binary which still shows efficient interaction

Dust

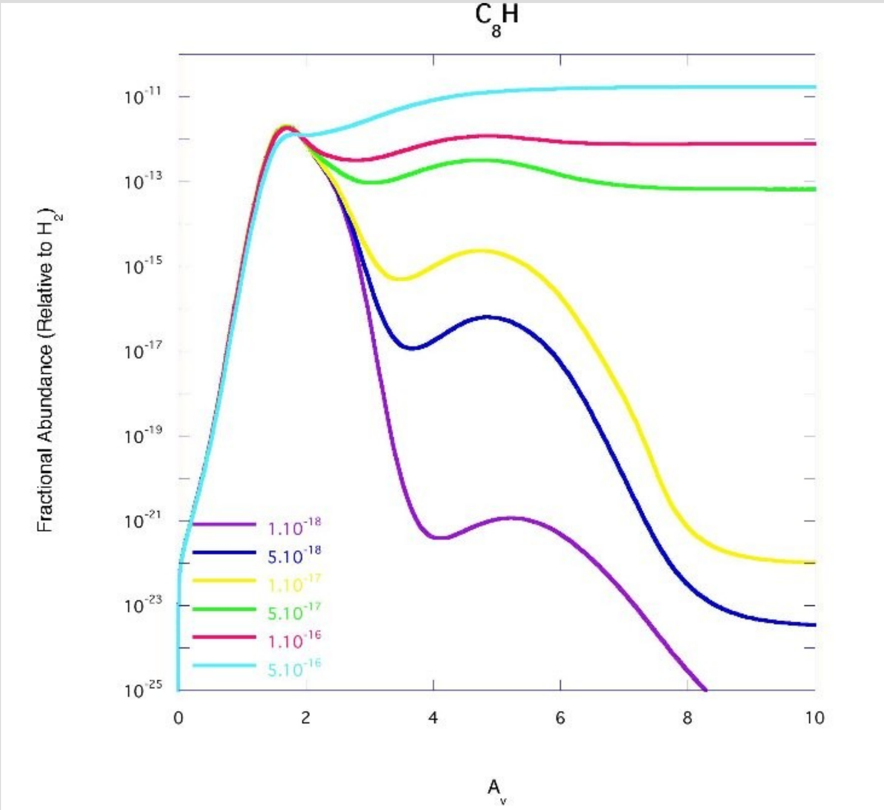


- AGB: dust and wind same composition
- PNe: mixed chemistry fairly common
- PAHs plus silicates
  - Seen in O-rich nebulae in Bulge
  - Perea-Calderon et al. 2009

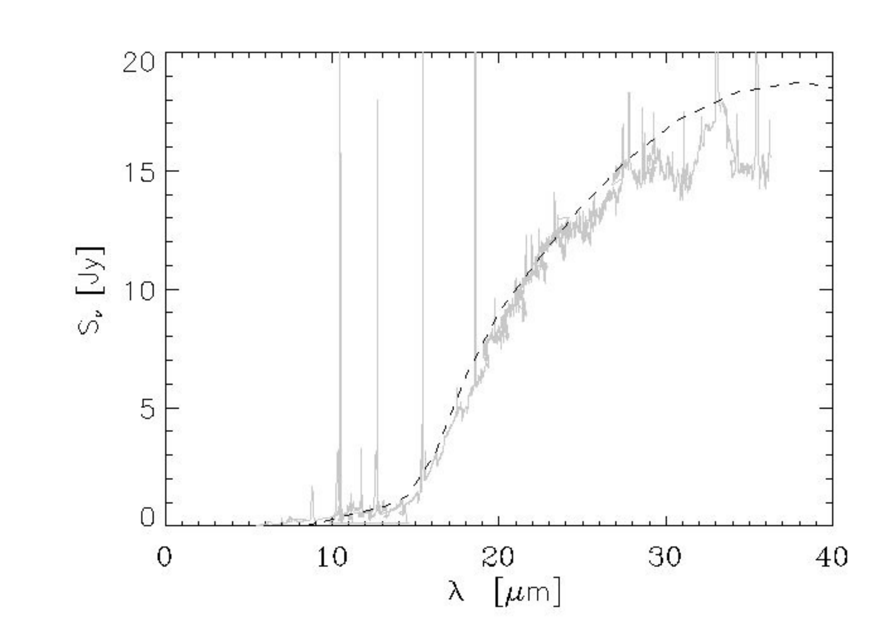
Mixed chemistry

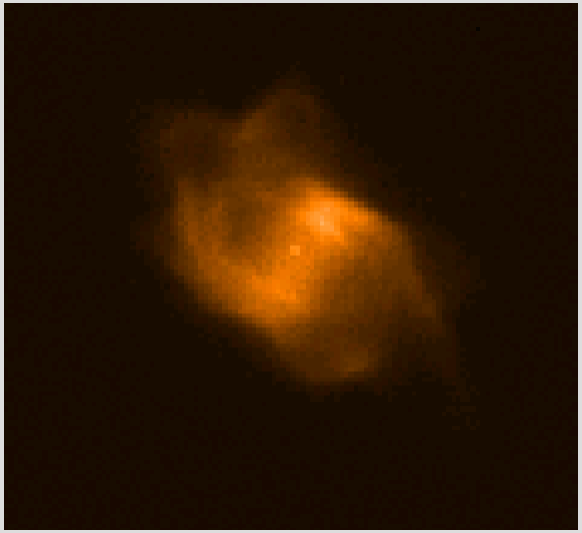
- Crystallization in spiral shocks? Nordhaus
- PAHs in injected C-rich material?

- Ni Chuim 2009: irradiation at AV ~2 breaks CO bond
  - Initiates carbon chemstry



Torus chemistry



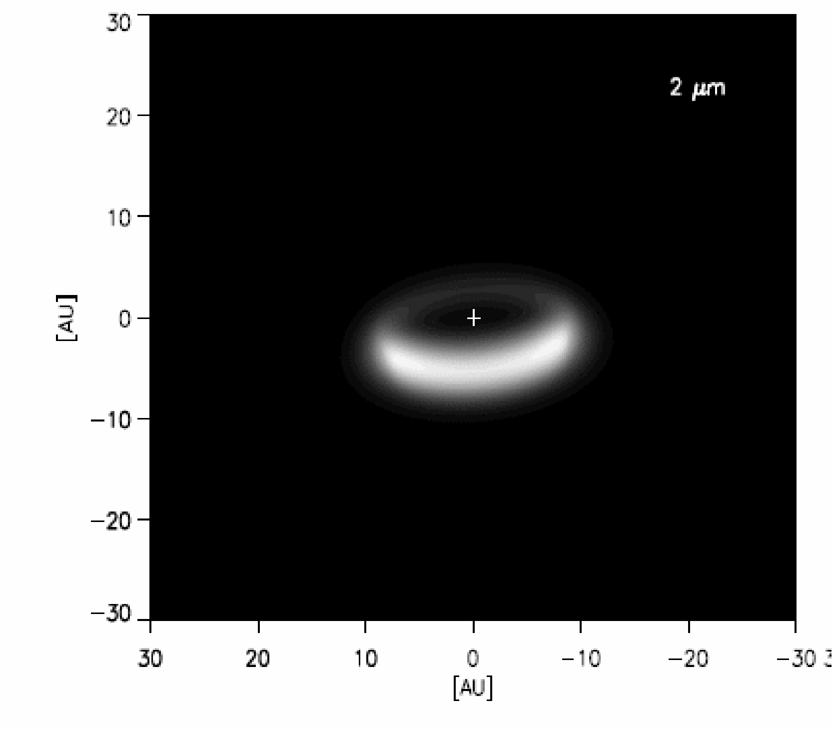


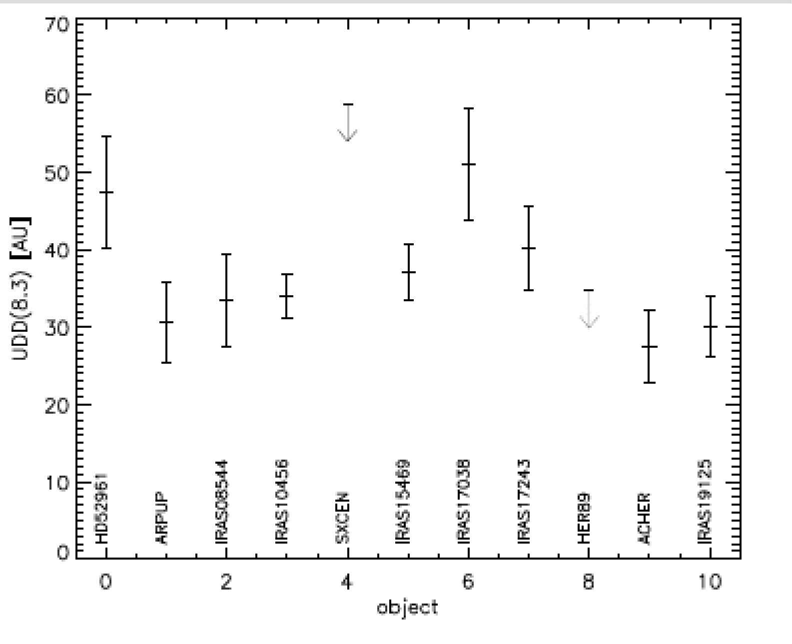
- Double chemistry objects show pronounced torii
- Trapped PDR region

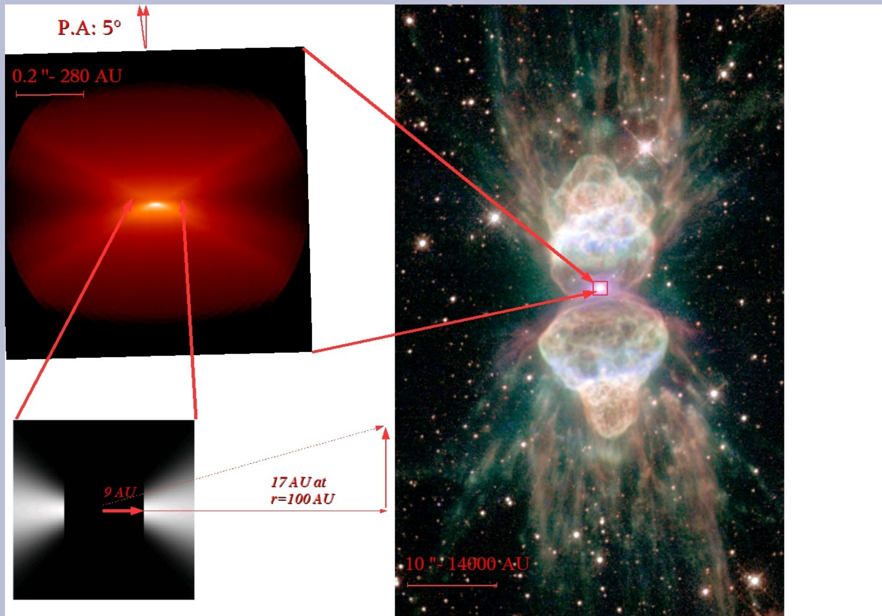
- Is PAH formation enhanced by high CR rate in Bulge?

Disks
van Winckel

- Dust disks common around pAGB stars
- Long lived
- Circumbinary
  - Periods 100-1200 days
- Companion mass 0.5-2 Msol

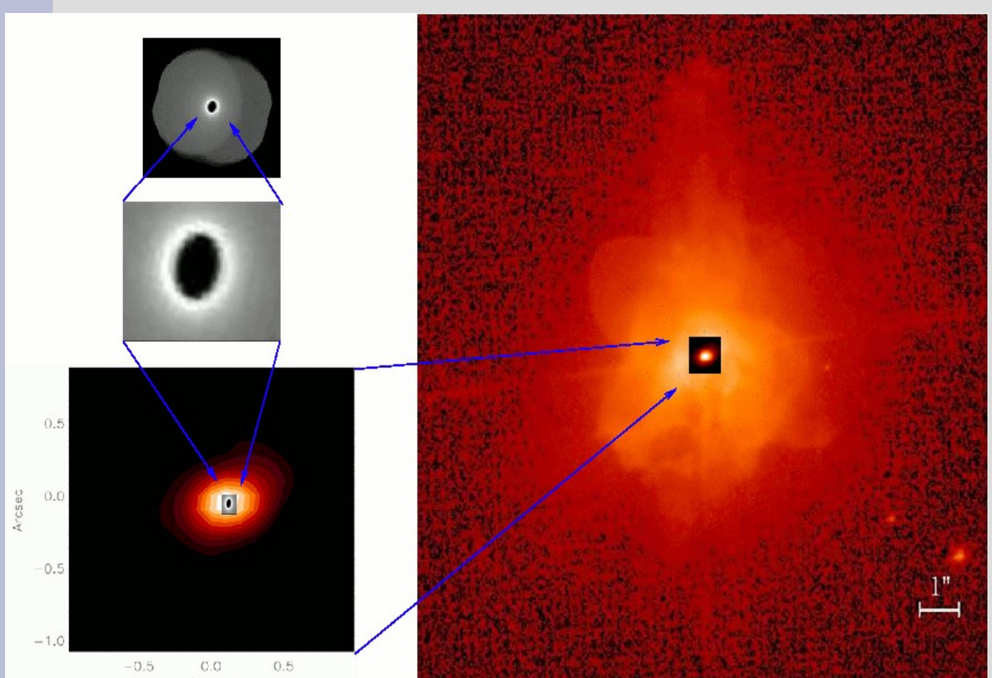






PN disks

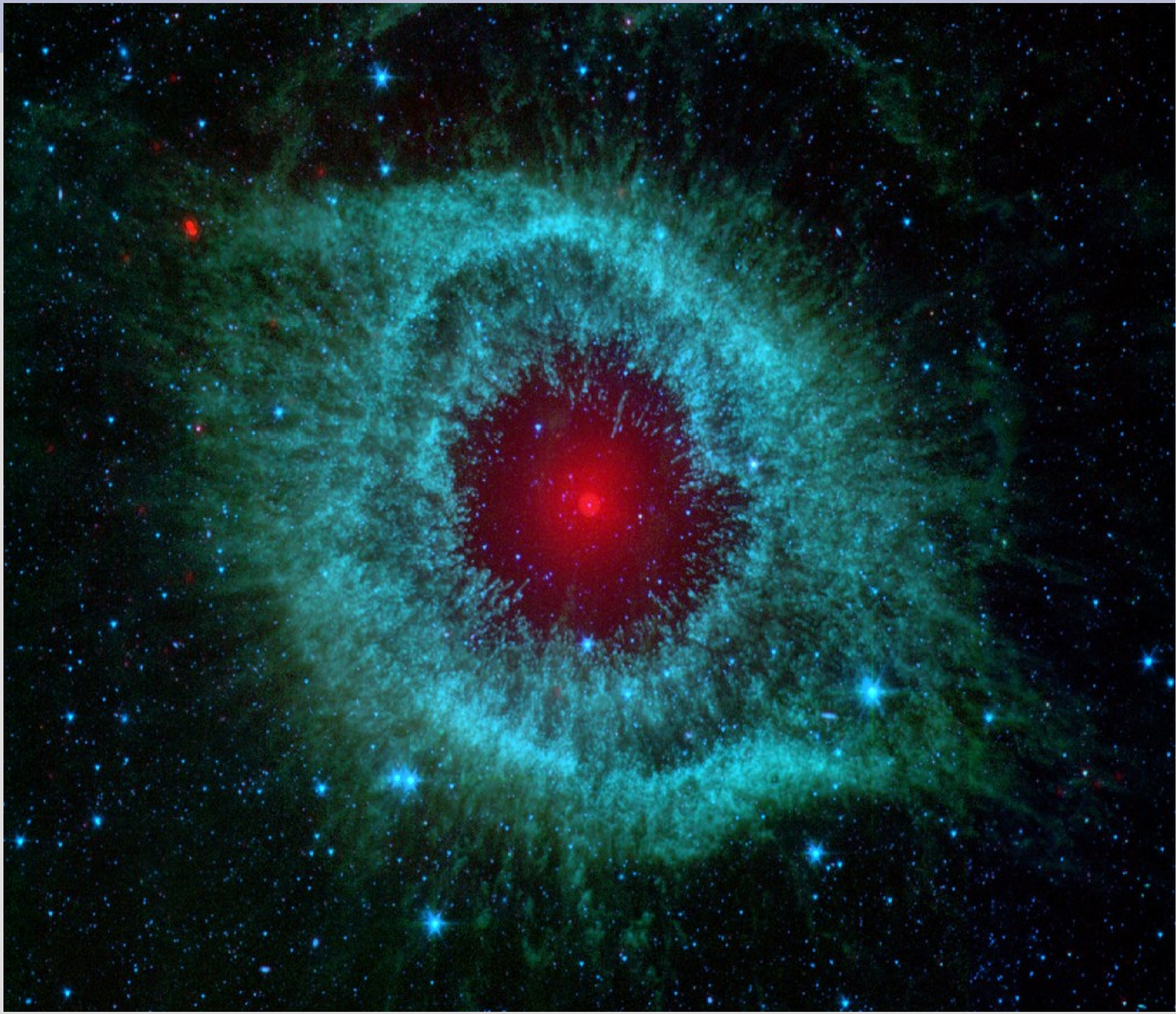
- Ant nebula, Menzel 3, CPD -56
- Disks in equatorial plane of main PN



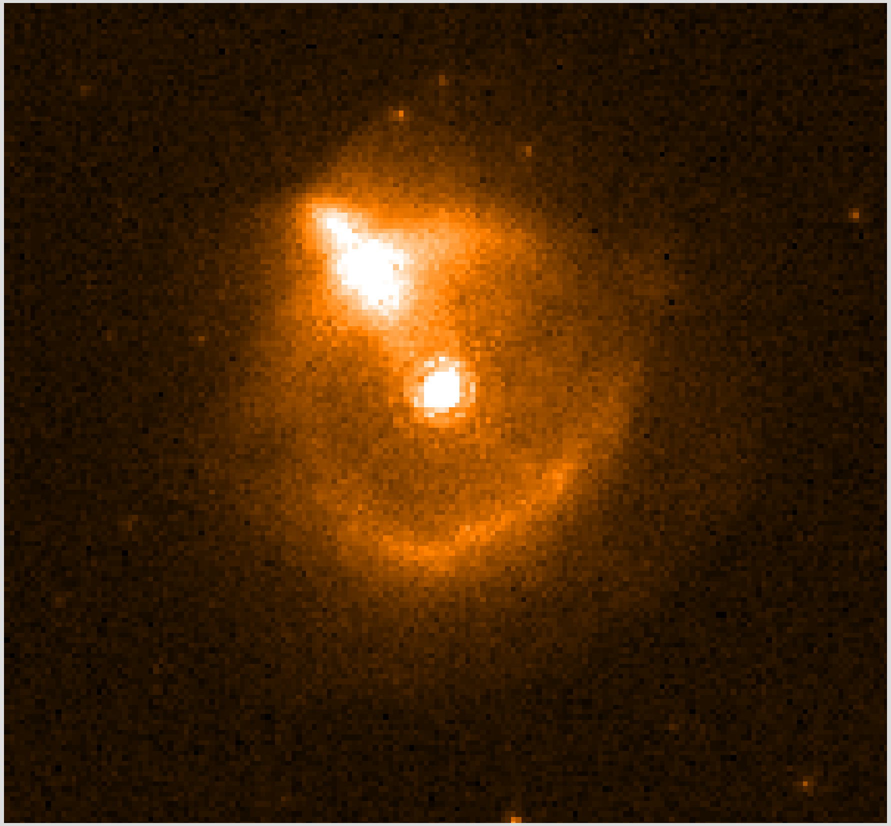
Helix nebula

Post-AGB
Dust disk

Bipolar nebula



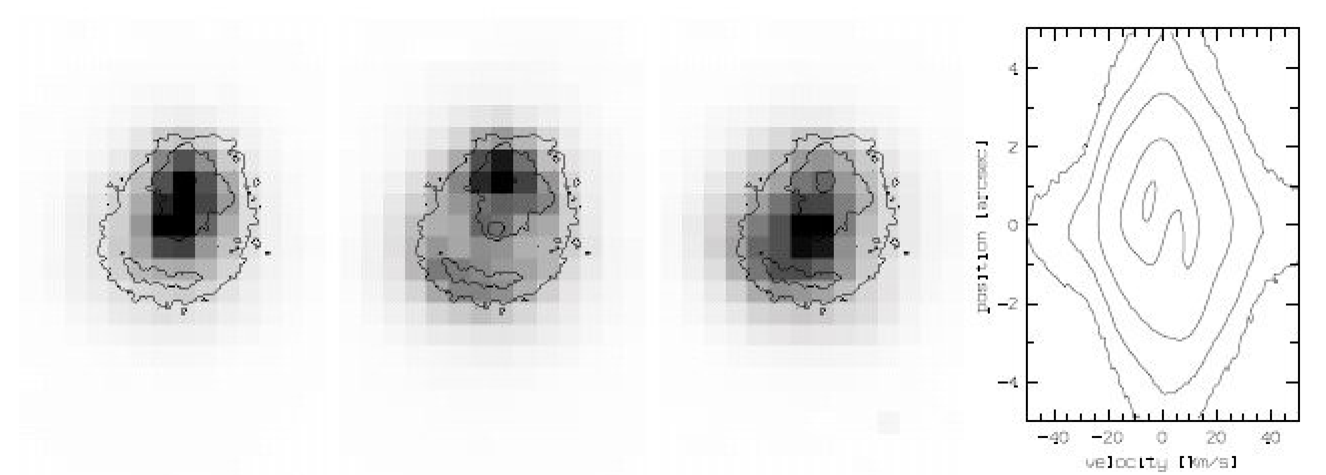
M2-29 : disk evaporation



- Central source: ionized core, <250 AU, containing dust disk
- 'jet' is partial outer ring
- Nebula filled with continuing wind of 10^-8 Msol/yr

M2-29

- Partial ring:
  - interpreted as early, intermittent ejection triggered by eccentric binary
- Core:
  - Modeled as rotating disk
- Current wind
  - Mass loss from ionized, evaporating gas disk



(a) [O III] 5007Å at -12 km s^{-1} (b) [O III] 5007Å at system velocity (c) [O III] 5007Å at +12 km s^{-1} (d) [O III] 5007Å long-slit spectrum

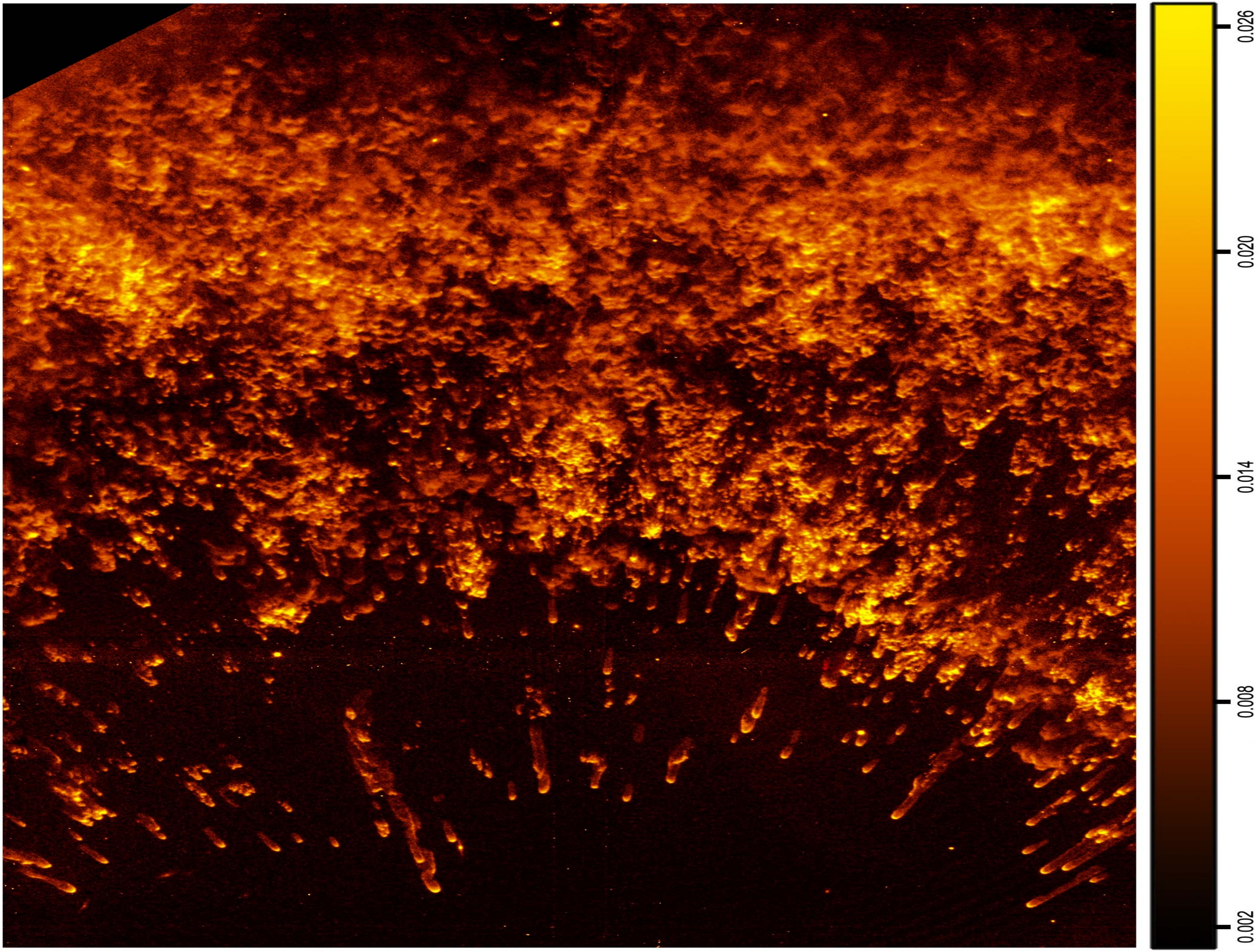
Disk evolution

Table 2. Ages and dust masses of the disks in planetary nebulae

Nebula	Nebular age [yr]	Dust mass [$M_\odot$]	Reference
CPD−56 deg 8032	10^2	3×10^{-4}	De Marco et al. (1997); Chesneau et al. (2007)
Ant nebula (Mz 3)	10^3	1×10^{-5}	Guerrero et al. (2004); Chesneau et al. (2006)
M 2-29	5×10^3	10^{-6}	- This paper
Helix nebula	1.1×10^4	4×10^{-7}	Meaburn et al. (2008); Su et al. (2007)

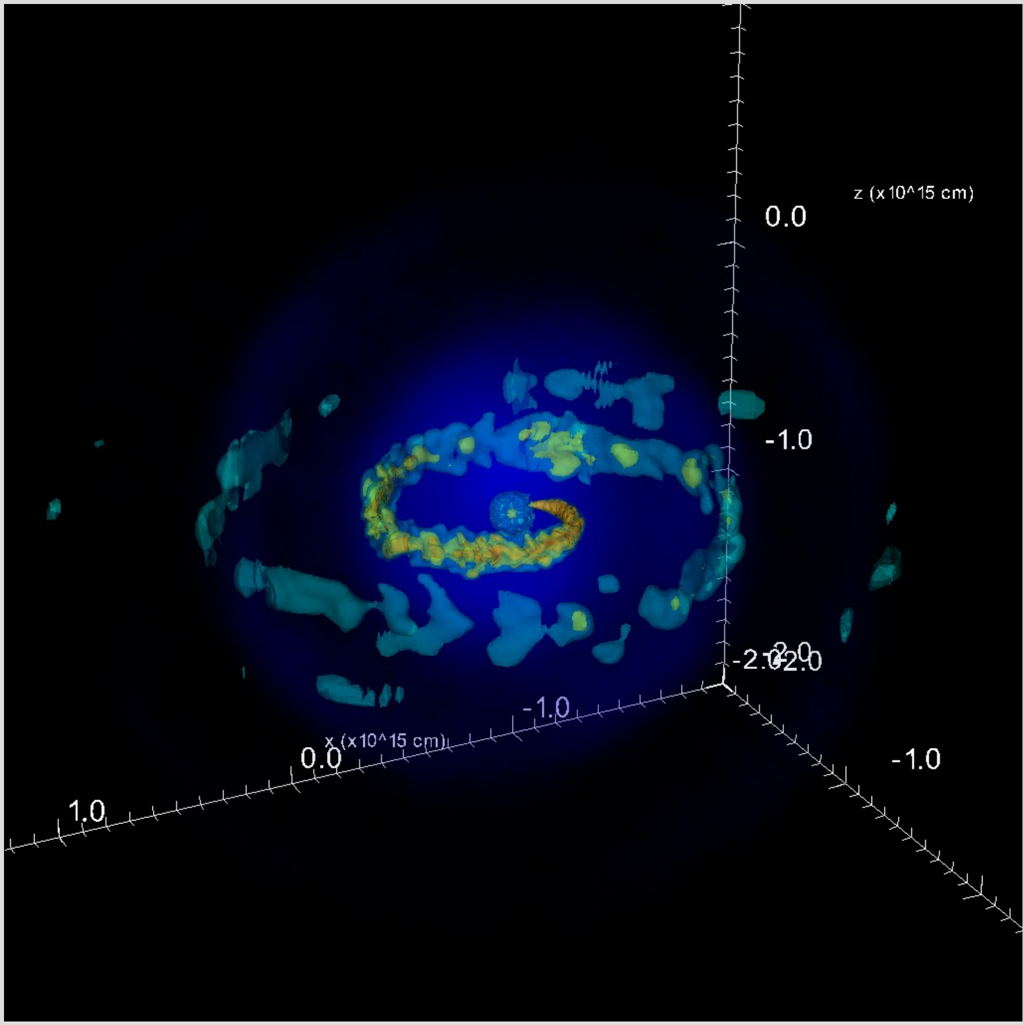
- Initial gas mass ~ 10^-2 Msol
- decreases rapidly after ionization
- Dust remnant of 10^-7 Msol
- May survive around white dwarfs for ~10^8-10^9 yr.

Gesicki et al. 2010


0.026
0.020
0.014
0.008
0.002

Helix globules

- Proposed formation
  - AGB wind (unlikely)
  - Ionization front (but innermost appear youngest)
  - Any other overdense region ?
- Perhaps the spiral wake behind a binary companion



Blackman

Planetary nebulae

- Narrow final mass distribution shows AGB mass loss is well defined process
- Majority of progenitors have a source of angular momentum
- Of order 1% of mass loss can be caught in a (circumbinary) disk

Future of the Sun

- Bulge PNe indicate Sun will form a PN
- Final mass 0.58-0.61Msun
- Single, and no accessible angular momentum:
  - A rare, spherical PN is expected

- Temporally reversed anthropocentric principle (TRAP)

  - Intelligent life requires progenitors of spherical planetary nebulae

Want to know more?

APN V

June 20-25, 2010
Lake District, UK