Post-AGB stars and Planetary Nebulae

- Stellar evolution
- Expansion and evolution
- Molecules and dust
- 3He
- SKA

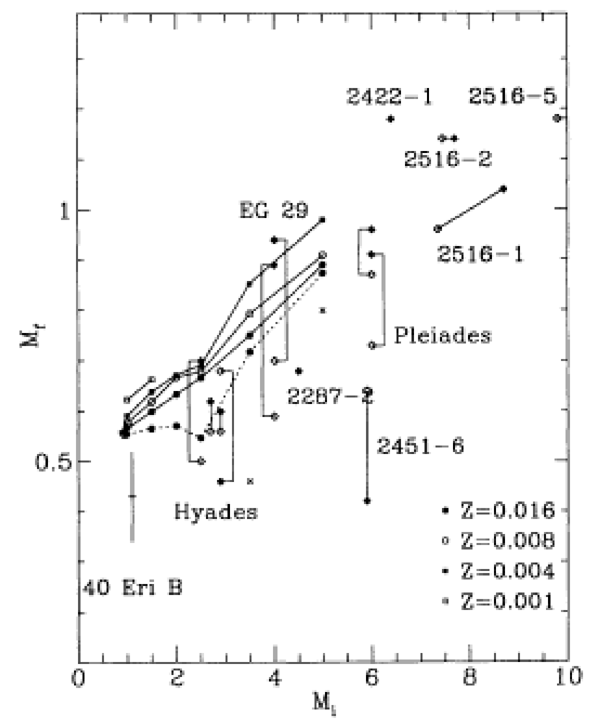
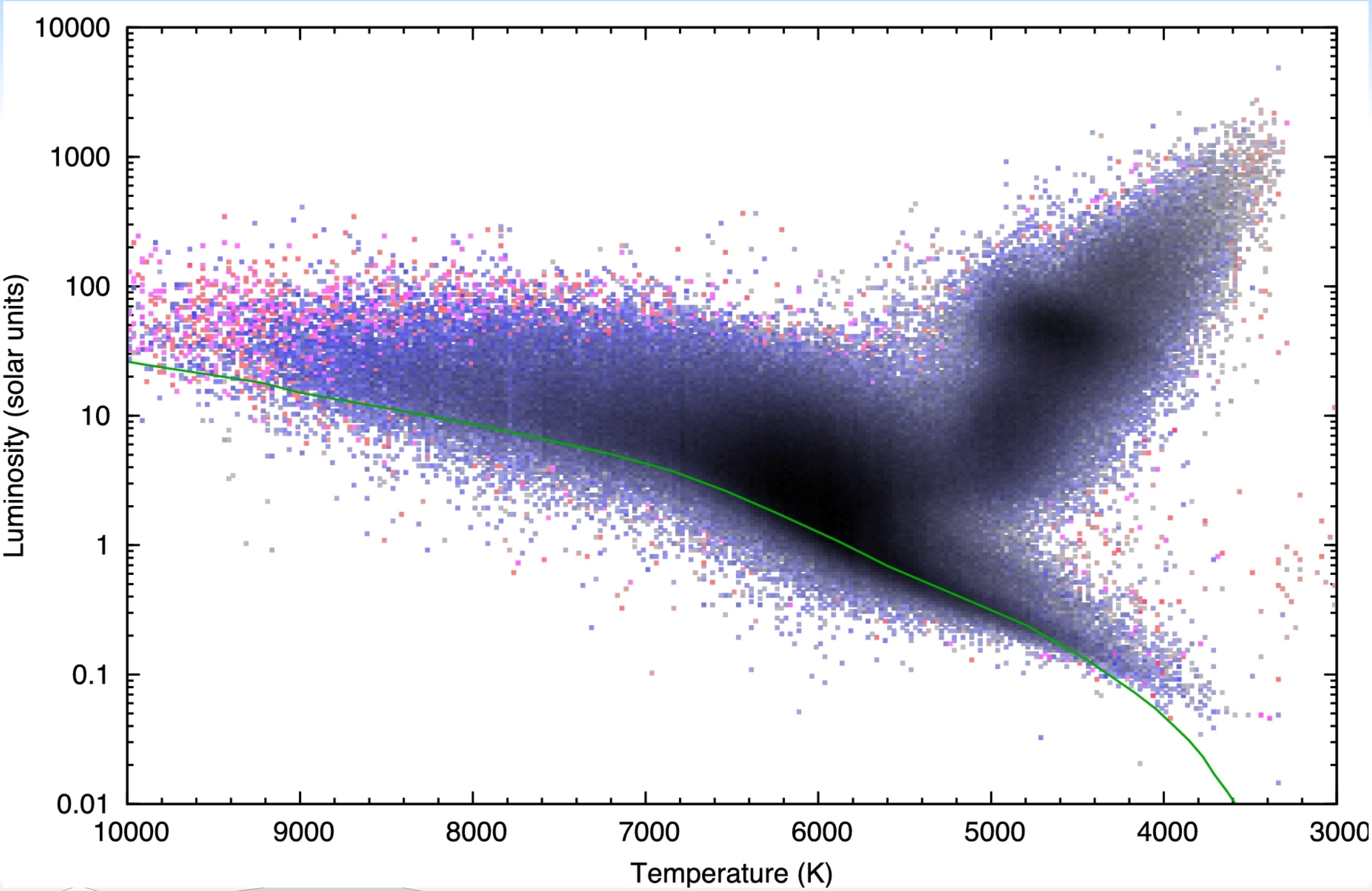


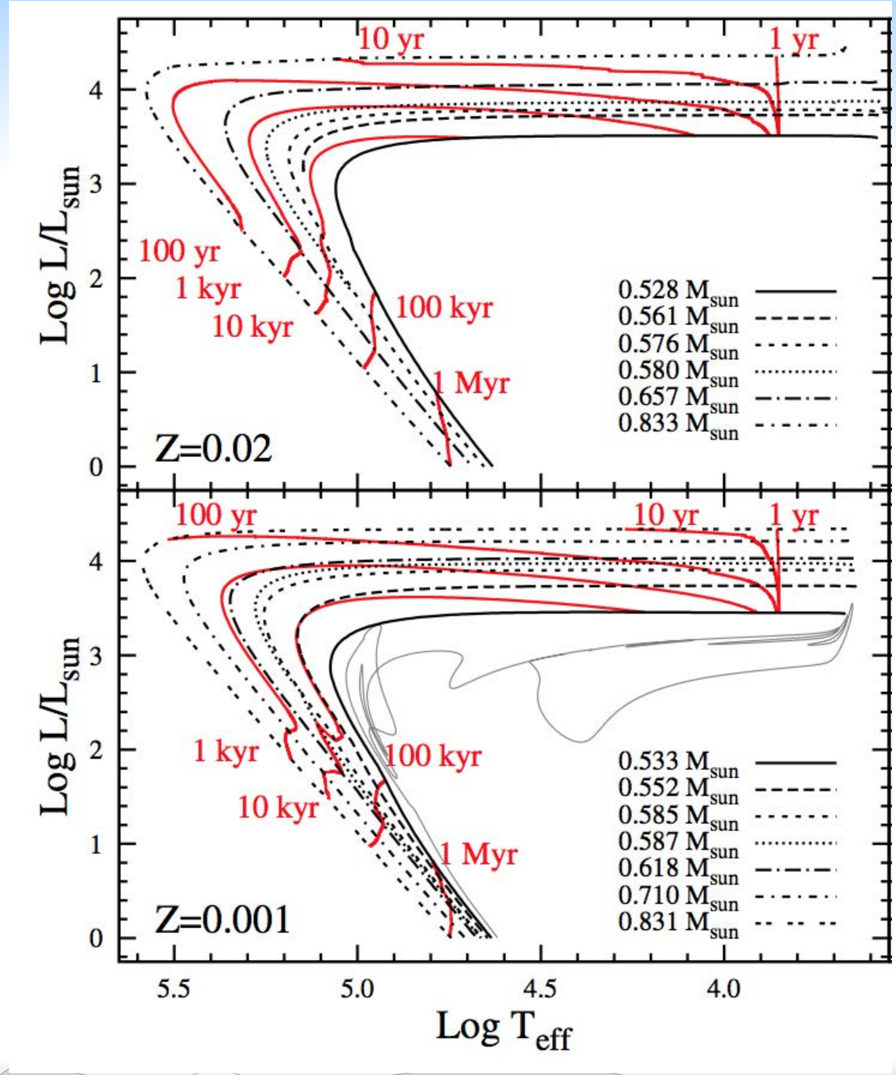
FIG. 21.—Final stellar remnant mass, after AGB mass loss, plotted as a function of the initial mass (*solid curves*). The dashed line represents the core mass at the first helium shell flash for the $Z = 0.016$ calculations. Observational points are taken from Weidemann (1987), and references therein. Annotation of the data points is similar to that presented in Fig. 1 of Weidemann & Koester (1983). Filled diamonds represent masses derived from log g, while open diamonds represent masses derived from the stellar radius. Mass determinations via log g and radius for the same object are joined by a line. The crosses represent the Sanduleak-Pesch binary (Greenstein, Dolez, & Vauclair 1983) where $M_f = 0.8$ was assumed for the primary.

GAIA HR diagram

McDonald et al. 2017



Post-AGB evolution

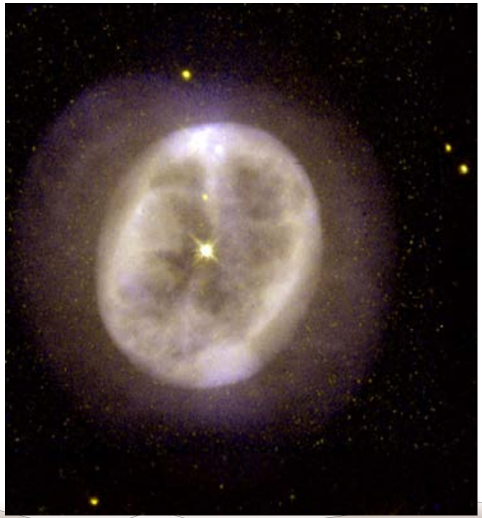


- Molecular shell detaches and expands
- Heating star drives a dissociation and ionization front
- Rate of heating highly mass dependent

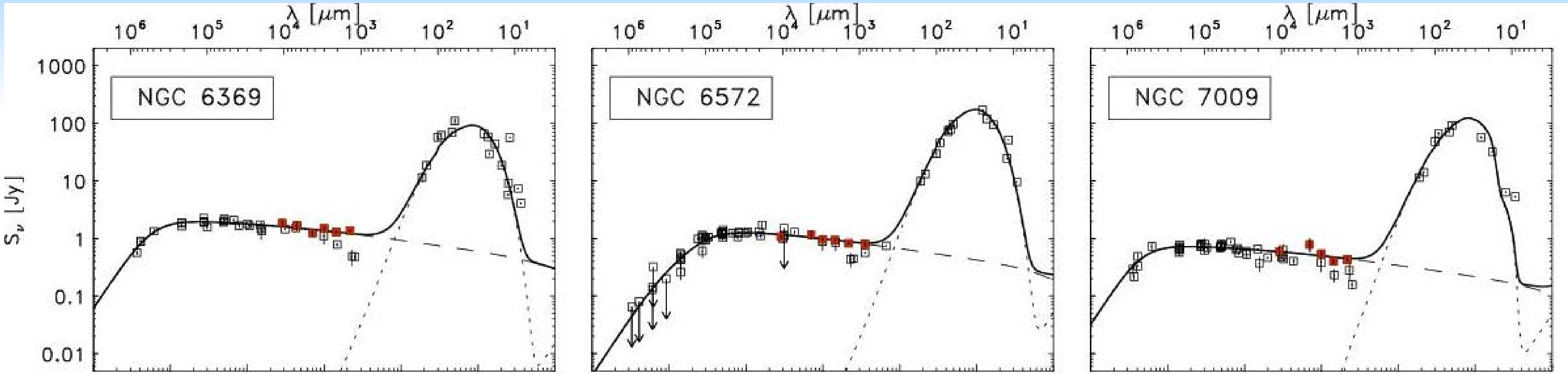
Miller-Bertolami 2016

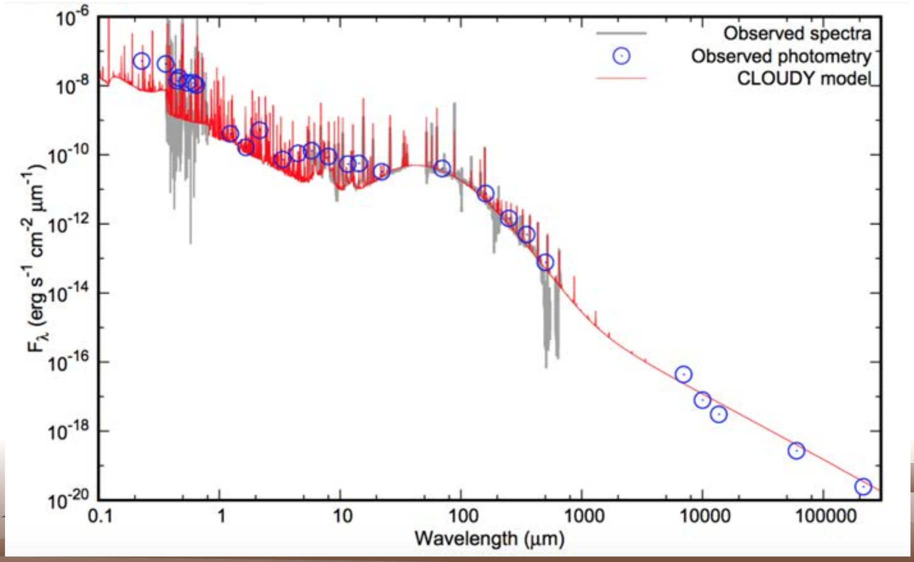
The role of binaries

- Wide binaries: some gravitation focussing
- Closer: Active shaping : accretion disks and jets
- Closest: common envelope ejection



Composite spectra: dust, free-free, atomic and molecular lines





As nebula expands:

- dust continuum fades
- Molecular lines disappear
- Free-free optical depth decreases

Radio planetary nebulae

- Many cm surveys

  Zijlstra et al. 1989

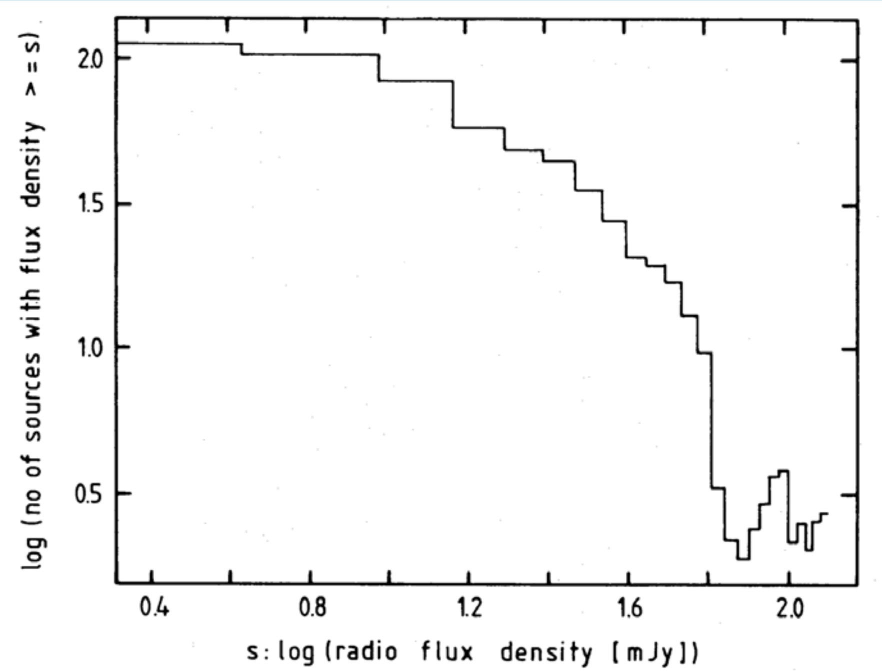
  Chhetri et al. 2013

- Typical flux densities 1-10^3 mJy

  T_B $10^4 – 10^{-4}$ K

- 31 radio PN in LMC

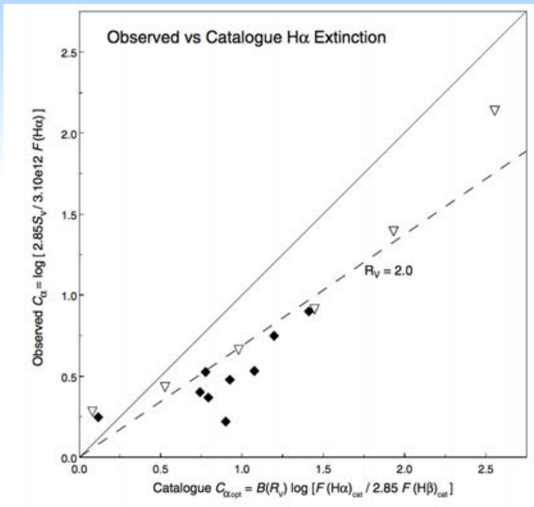
  Leverenz et al. 2017



Galactic bulge PN radio Luminosity function

Zijlstra 1990

The extinction problem



- Ruffle et al. 2005: R(Bulge)=2.5
- Pottasch & Bernard-Salas 2013

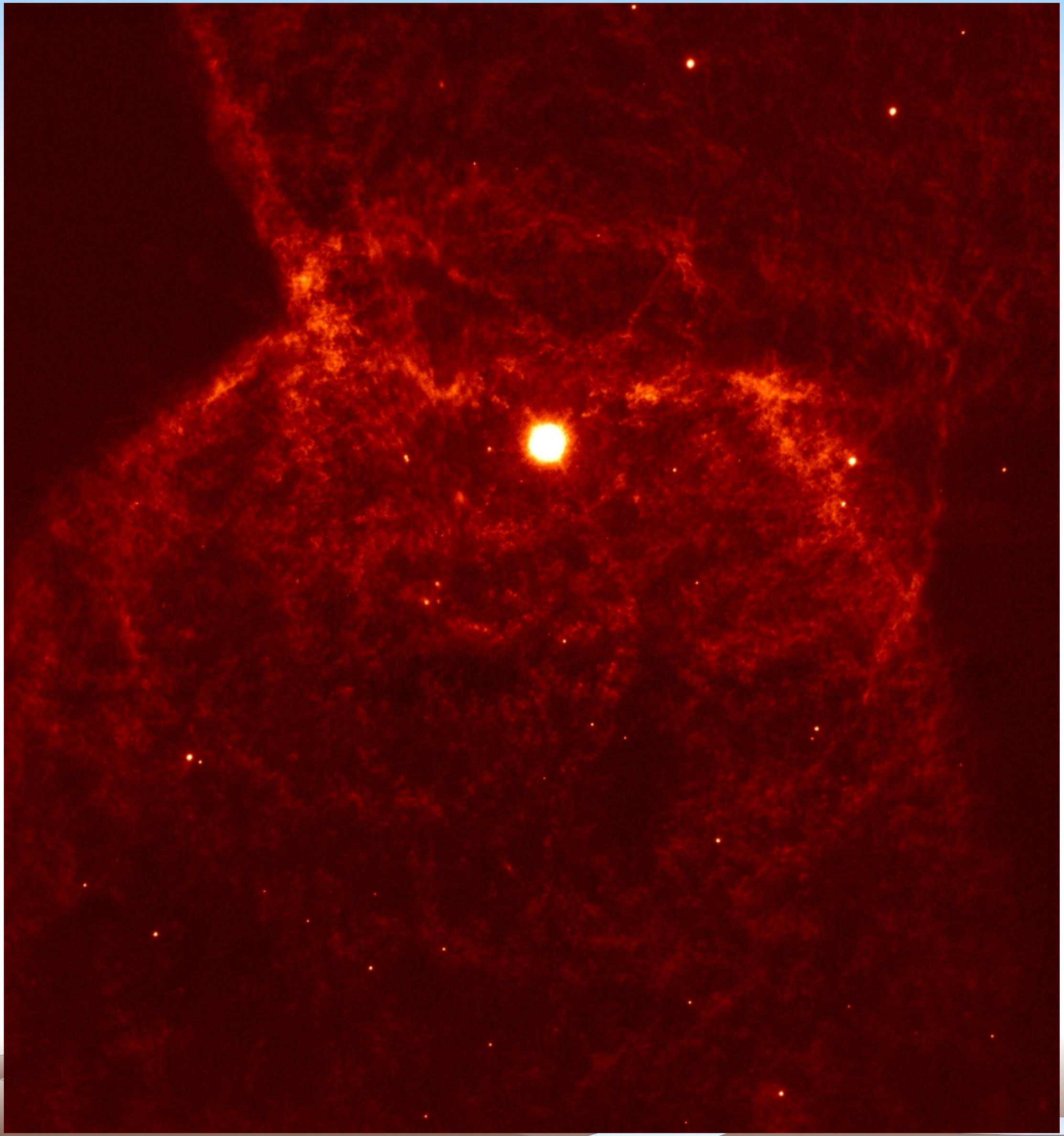
Radio flux affected by optical depth

- Extinction derived from
  - Radio over Hbeta
  - Hbeta over Halpha

disagree

- Radio flux too low compared to Halpha
- R lower than 3.1?

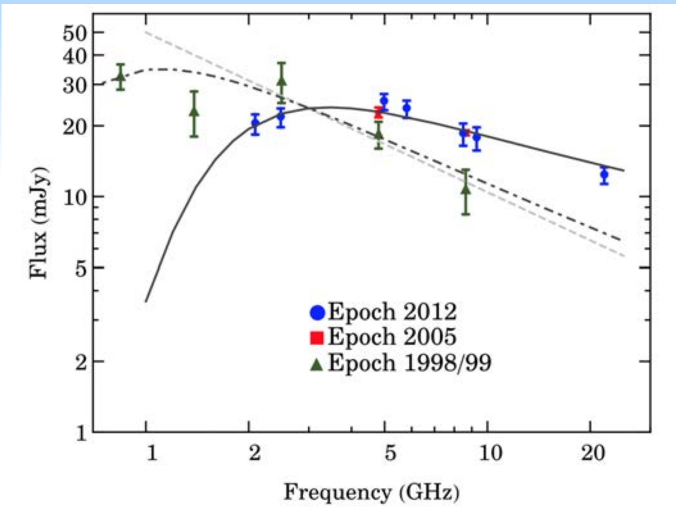
Dense clumps in ionized region?

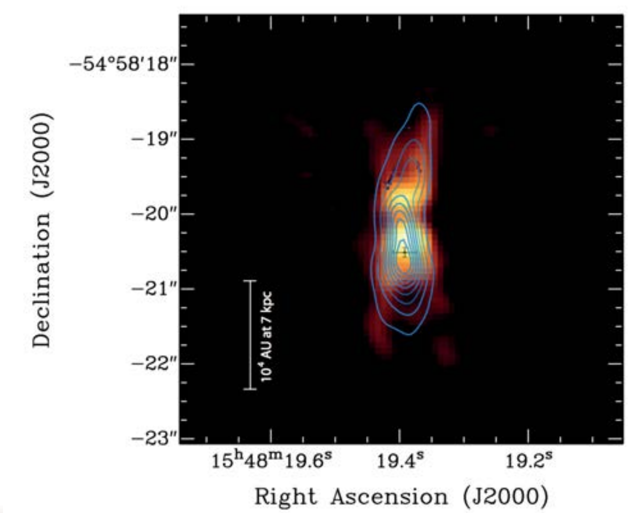


Synchroton emission

- Predicted by Dgani & Soker 1997
- Shock acceleration gives ~1mJy at 1kpc at 1 GHz
- Not detected inside PNe
- Bains et al: 3 out of 28 post-AGB stars have non-thermal, variable emission

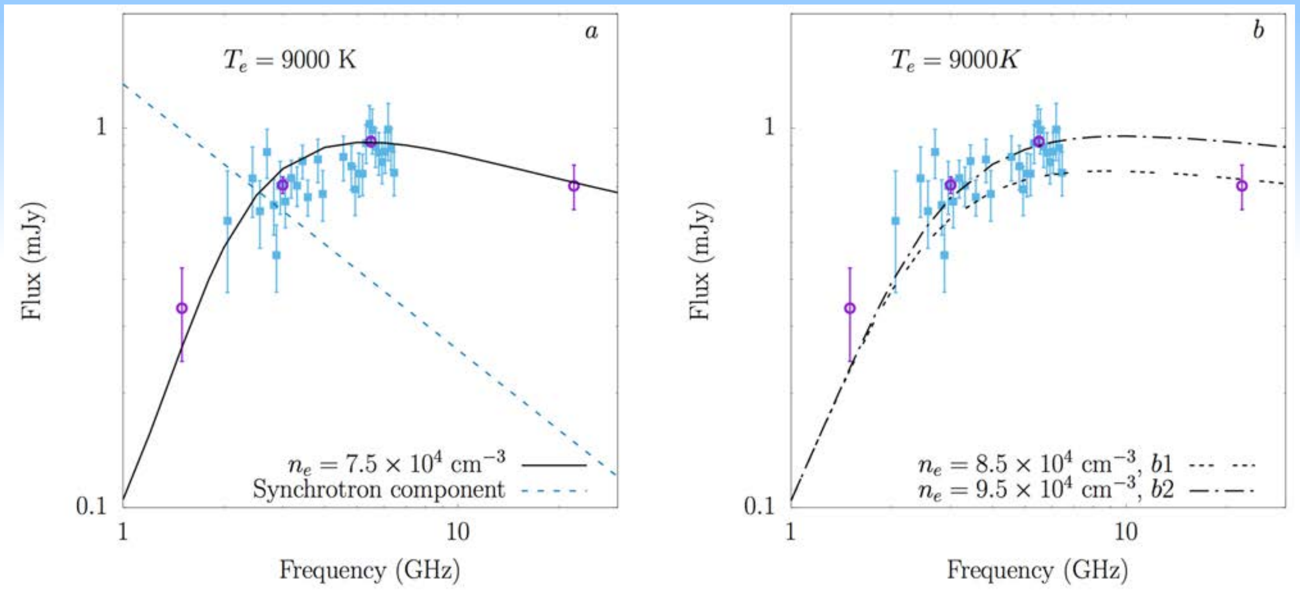
IRAS 15445–5449





- Perez-Sanchez et al. 2013
- Variable synchroton jet in post-AGB star
- Fermi acceleration, B = 5mG
- Note obscuration by thermal free-free emission

IRAS18041-2116

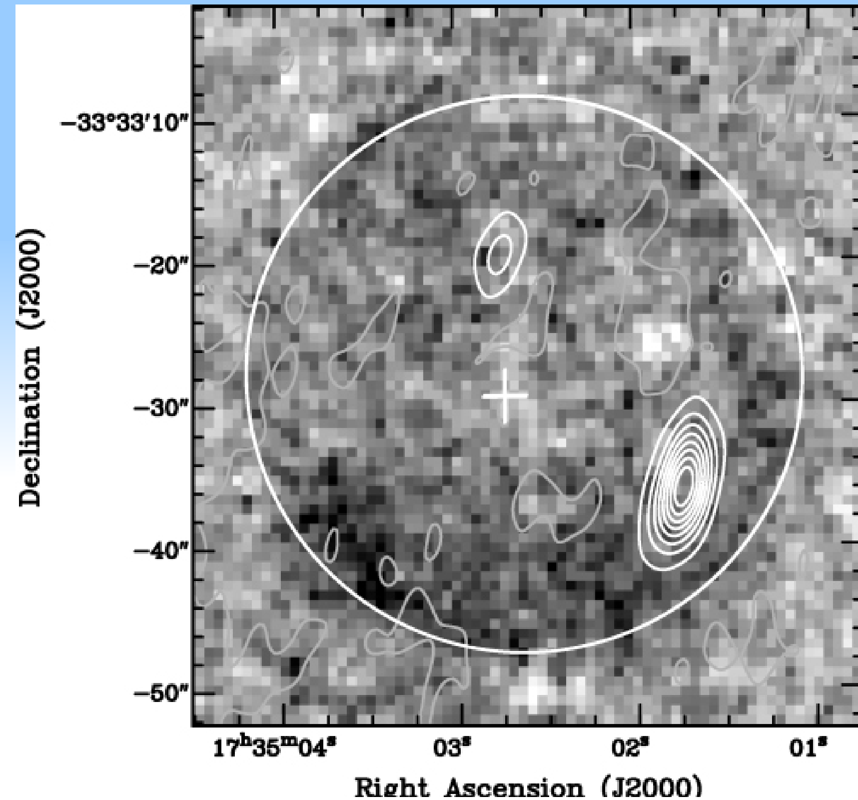


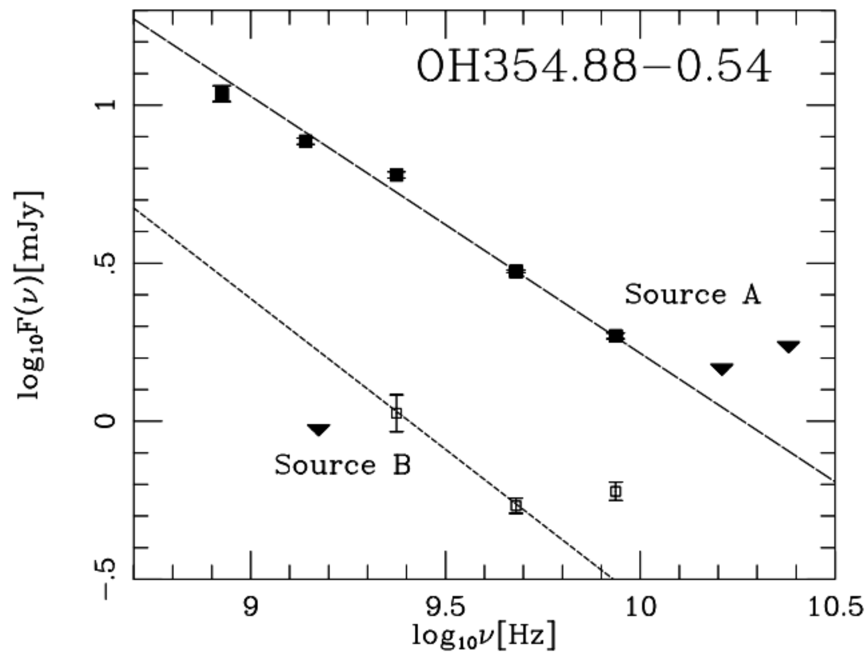
- Difficult to distinguish a small synchroton contribution from temporal variability
- Low frequency flux is hidden behind optical thick free-free emission

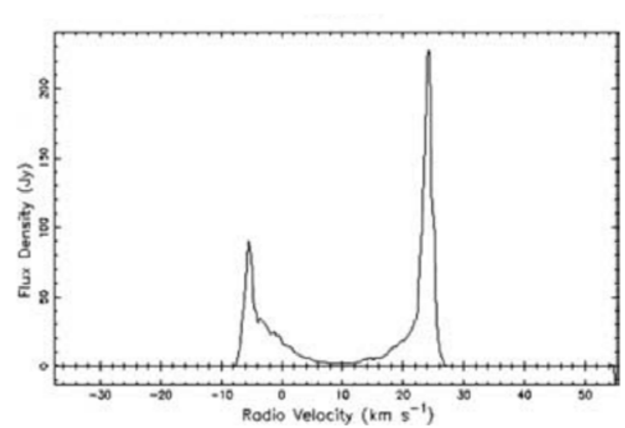
Perez-Sanchez et al. 2017

V1018 Sco

- Cohen et al 2006
- OH/IR star with PN and synchroton emission
- Jet powered?

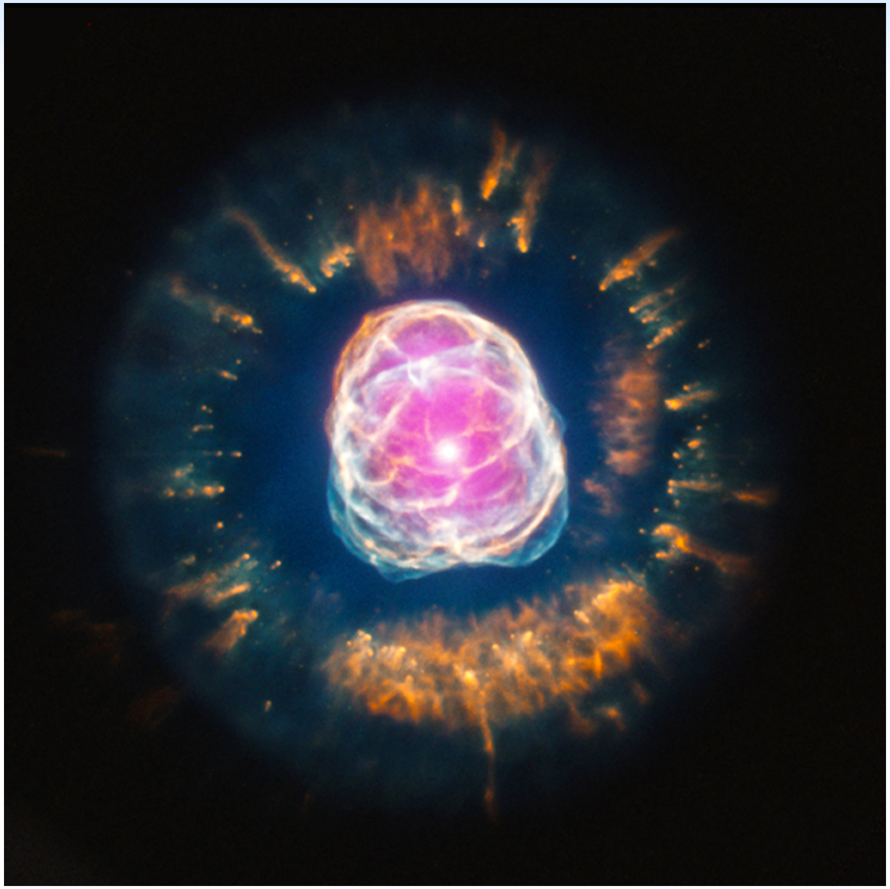






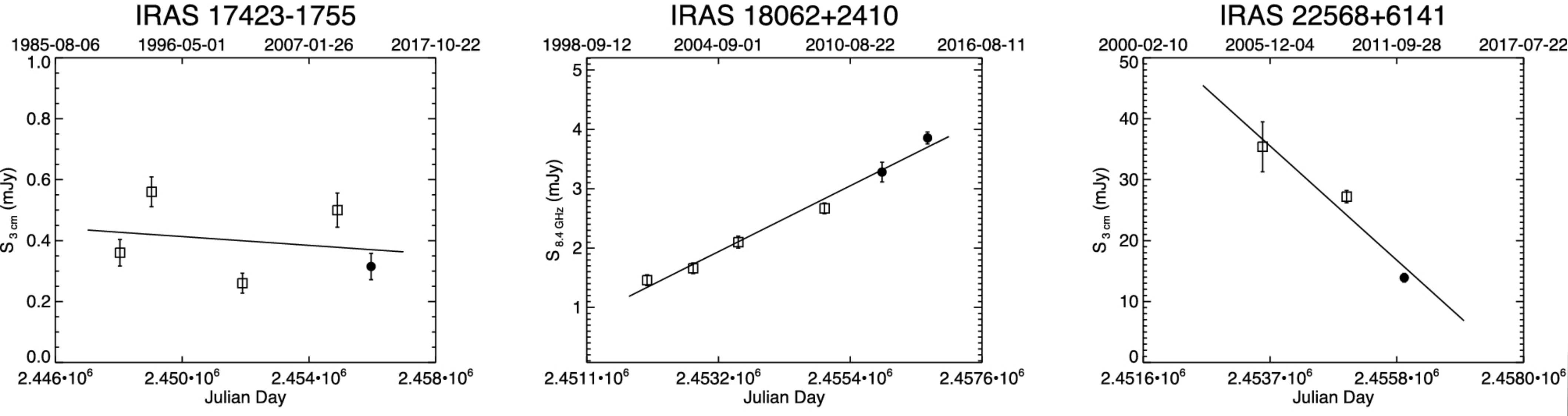
X-ray riddle

- Chandra: hard X-ray point sources from centre of ~15% of PNe
- Origin unclear
- Most likely: Rejuventated (spun-up) main-sequence companions
- Not yet detected in radio



Radio flux evolution

- Expected rapid onset of ionization
- Sudden rise in radio flux
- Cerrigone et al. 2017
- But no unambiguous cases of evolution over variability



(a) (b) (c)

Flux variability

- CRL618: periodic ‘increase

  Sanchez-Contreras et al. 2017

- Vy2-2: regular flux increase

  Christianto & Seaquist 1998

- Expansion of optically thick emission

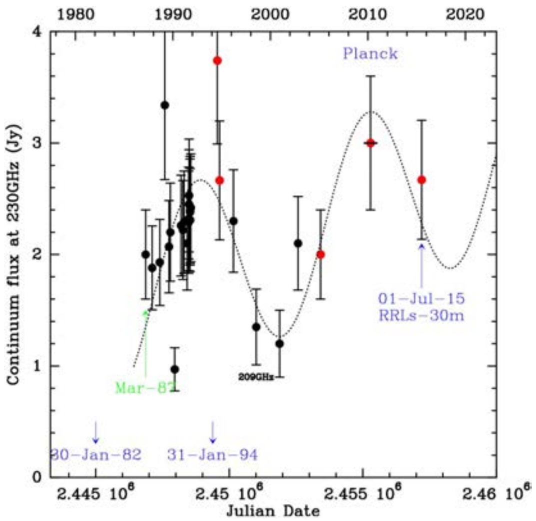
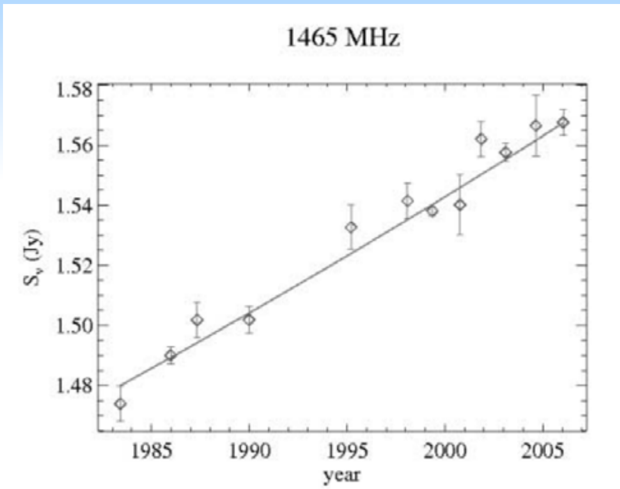


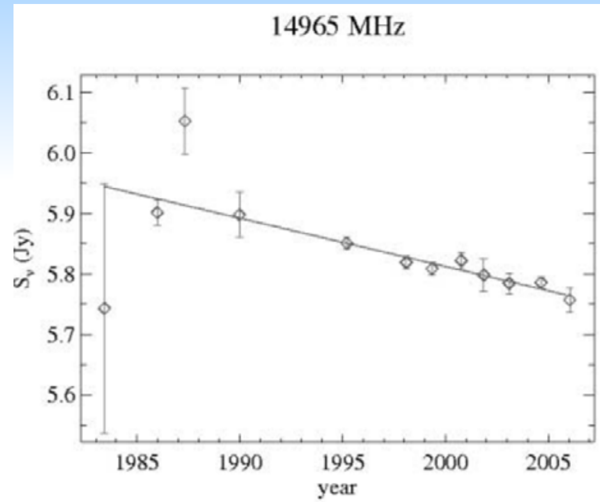
TABLE 2

FLUX DENSITIES

Frequency (GHz)	1982 Flux (mJy)	1987 Flux (mJy)	1992 Flux (mJy)	1997 Flux (mJy)
1.465	6.7 ± 0.8	8.1 ± 1.3	8.2 ± 1.1	11.7 ± 2.4
4.885	39 ± 2	41 ± 2	43 ± 2	43 ± 2
8.415	...	...	96 ± 5	99 ± 5
14.965......	185 ± 19	199 ± 20	178 ± 18	180 ± 18
22.485......	...	247 ± 28	224 ± 23	...

Evolution of evolved PNe



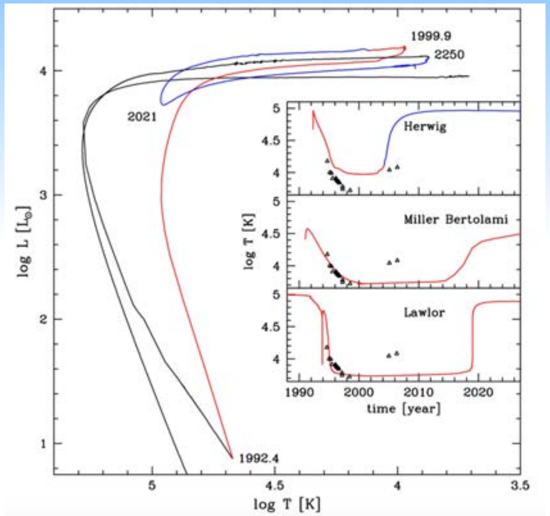


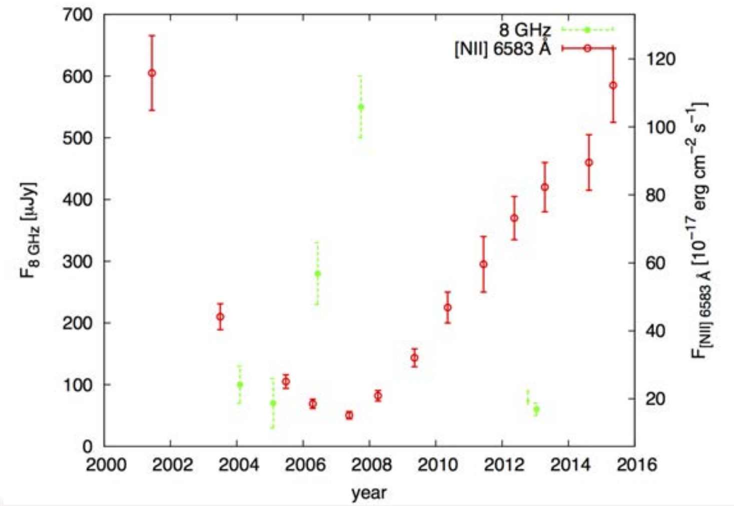
- NGC 7027: increase at low frequencies
  - $S = T_e A$
- Decrease at high frequencies
  - Less ionizing photons dT=+150 K/yr
  - Gives accurate mass of star   Zijlstra et al. 2008

Sakurai's Object

- Helium flash inside old PN
- Ejected a H-poor nebula
- Radio flux from carbon free-free emission traces the re-heating of the star

or does it?



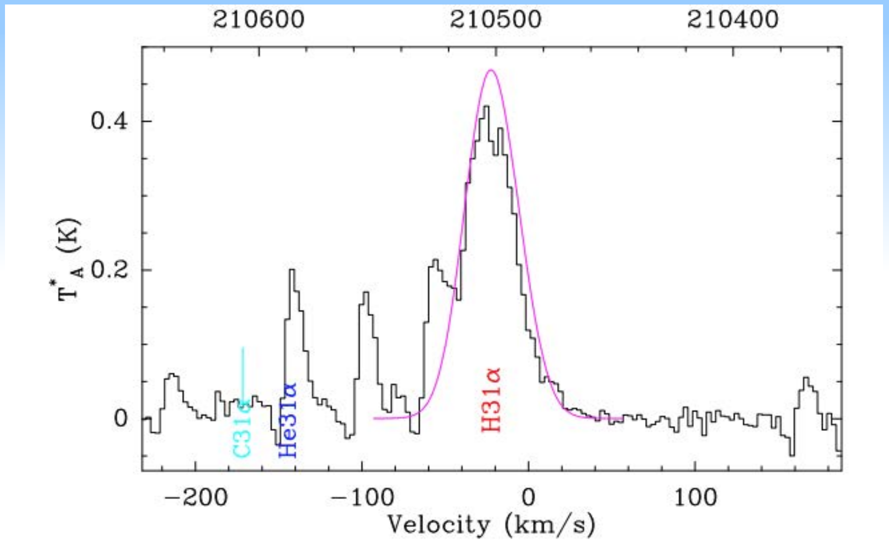


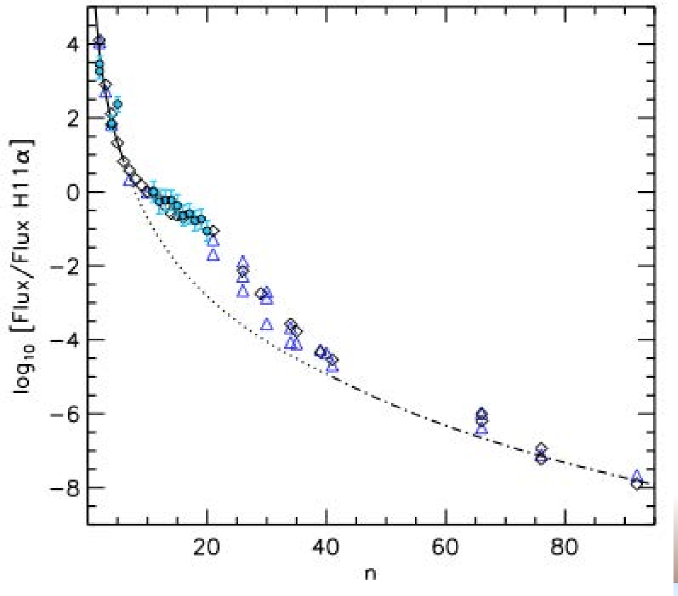
Radio recombination lines

- Relatively little used
- Good tracers of obscured regions
- Masing around H30: indicative of rotating disk?

Sanchez-Contreras et al. 2017; Aleman et al in prep.

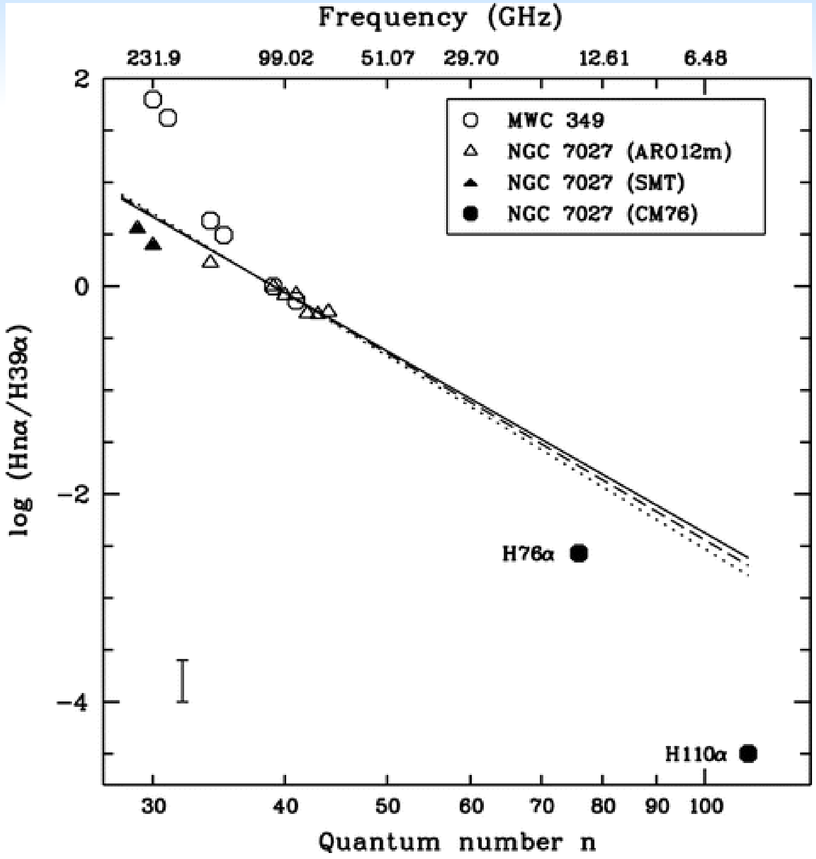
CRL618





Aleman et al

Radio recombination lines



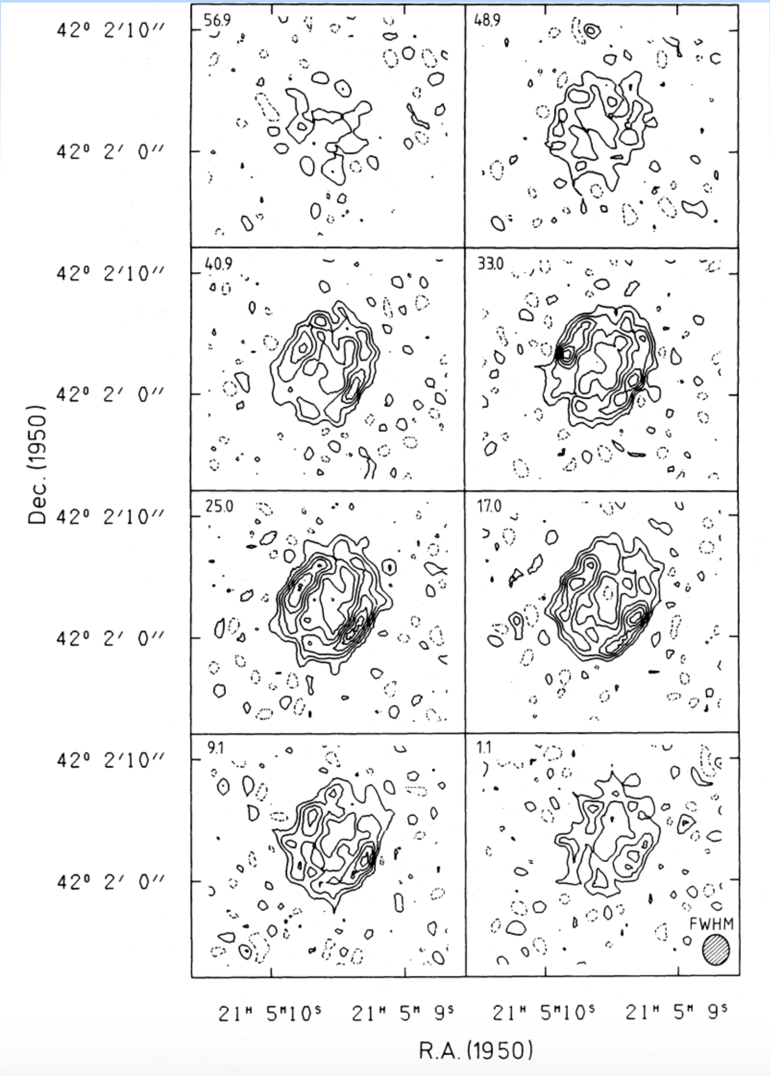
Zhang et al. 2008

- PNe: NGC7027
- High-order lines are optically thick
- Low-order lines are optically thin

Radio recombination lines

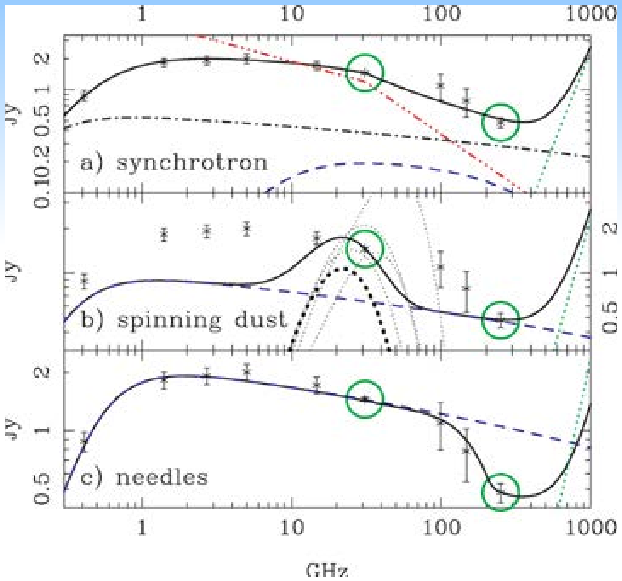
- Roelfsema et al. 1991

  H76A maps of NGC 7027
- Indication for faster polar outflow



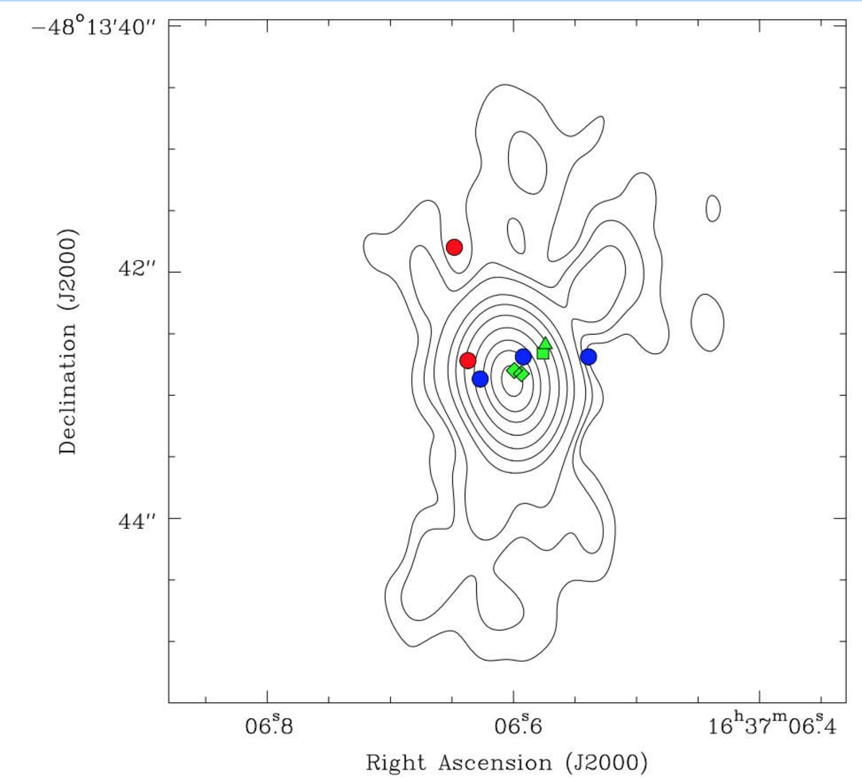
Spinning dust

- 20-40 GHz component of the ISM
- Not detected in post-AGB stars/planetary nebulae
    - Cassasus et al. 2007
    - Umana et al. 2008
    - Padzerska et al 2009
- Even though carrier is likely present



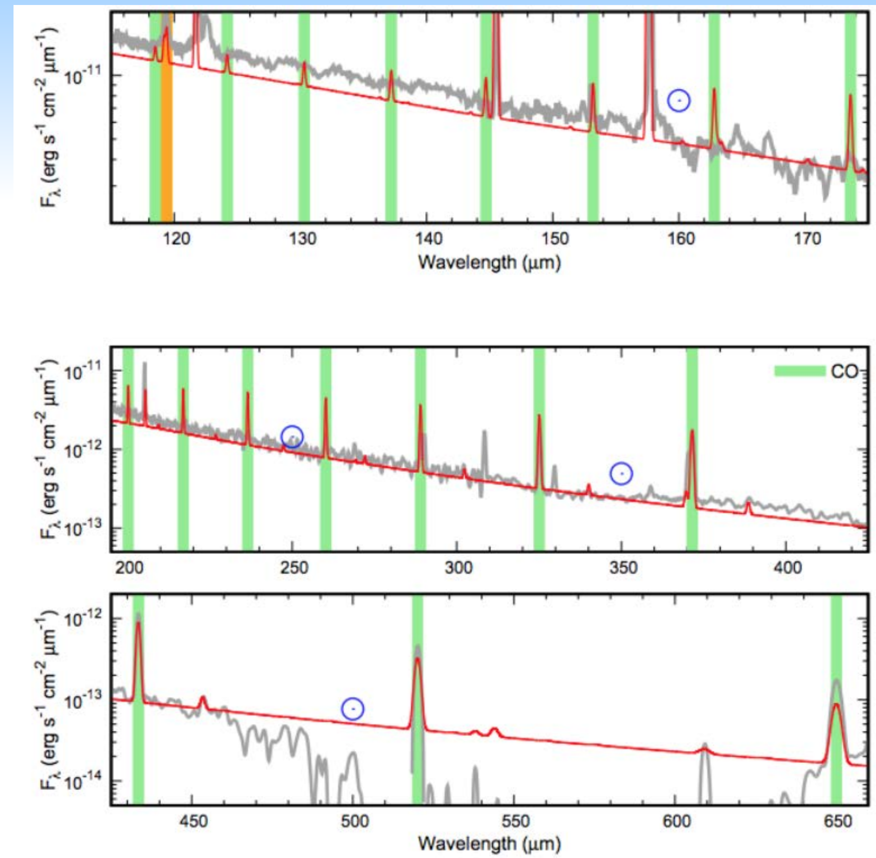
OHPN

- OH masers decay rapidly after the AGB
- Only 7 known PNe have OH masers
- Two with 1720 MHz: shock excited
  - Qiao et al. 2015
  - Uscanga et al. 2012



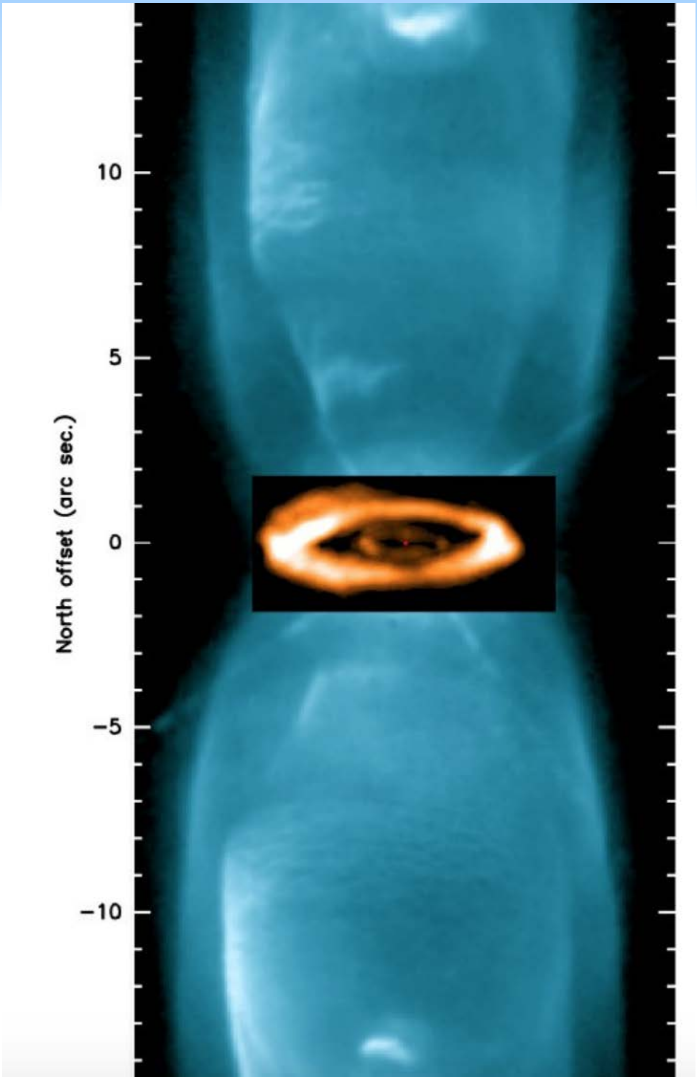
Molecules

- Molecules present in youngest PNe only
- But CO survives in bipolar PNe
  - Outer shell (NGC 7027)
  - Cometary globules (Helix)
- HCN, HCO^{+}, CN also common Schmidt & Ziurys 2016; Smith et al. 2015



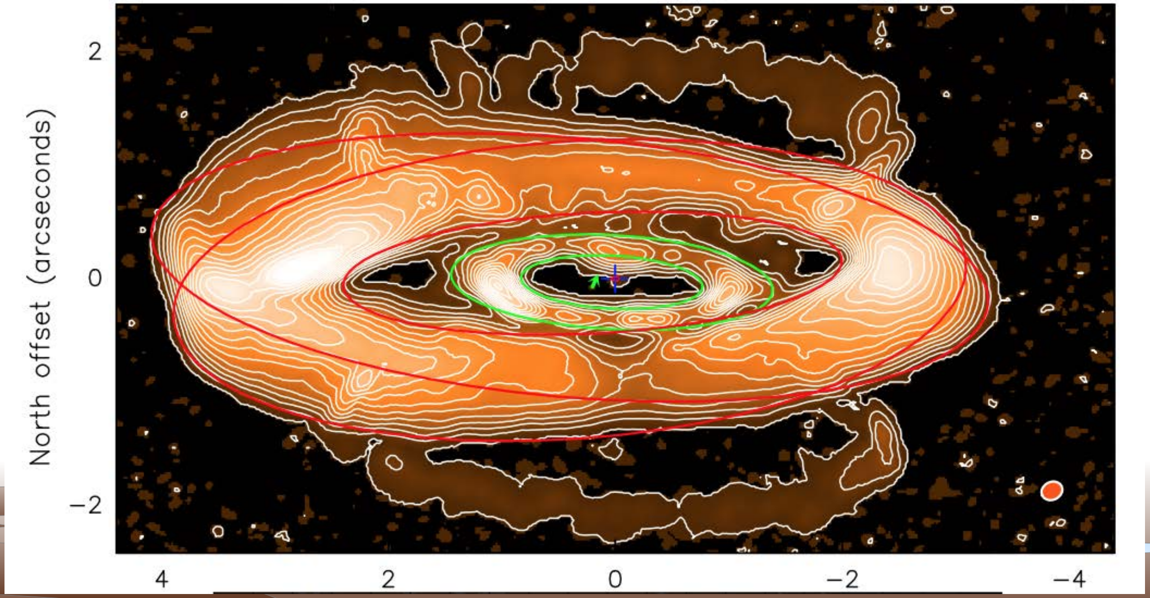
NGC 6781: Otsuka et al. 2017

CO mapping with ALMA

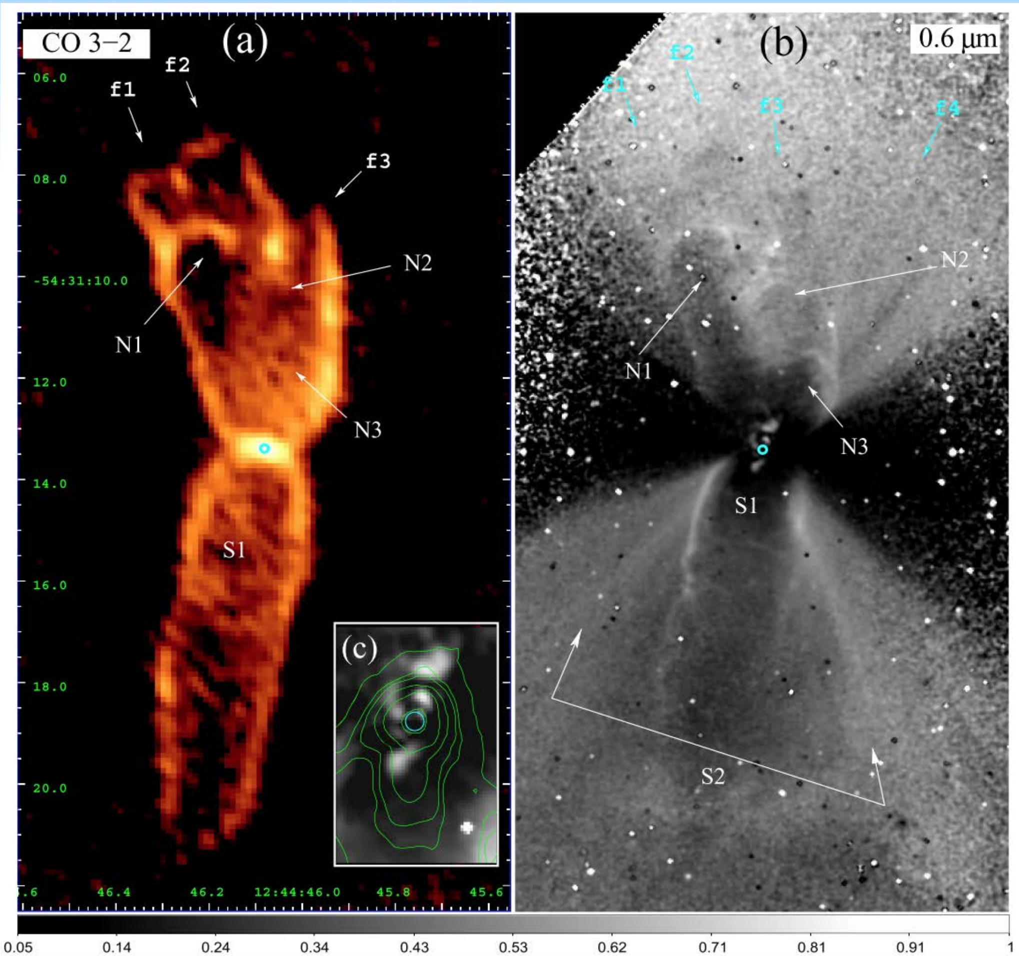


- M2-9: CO ring indicates two mass loss events, 500 yr apart.

Castro-Carrizo et al. 2017



Boomerang nebula

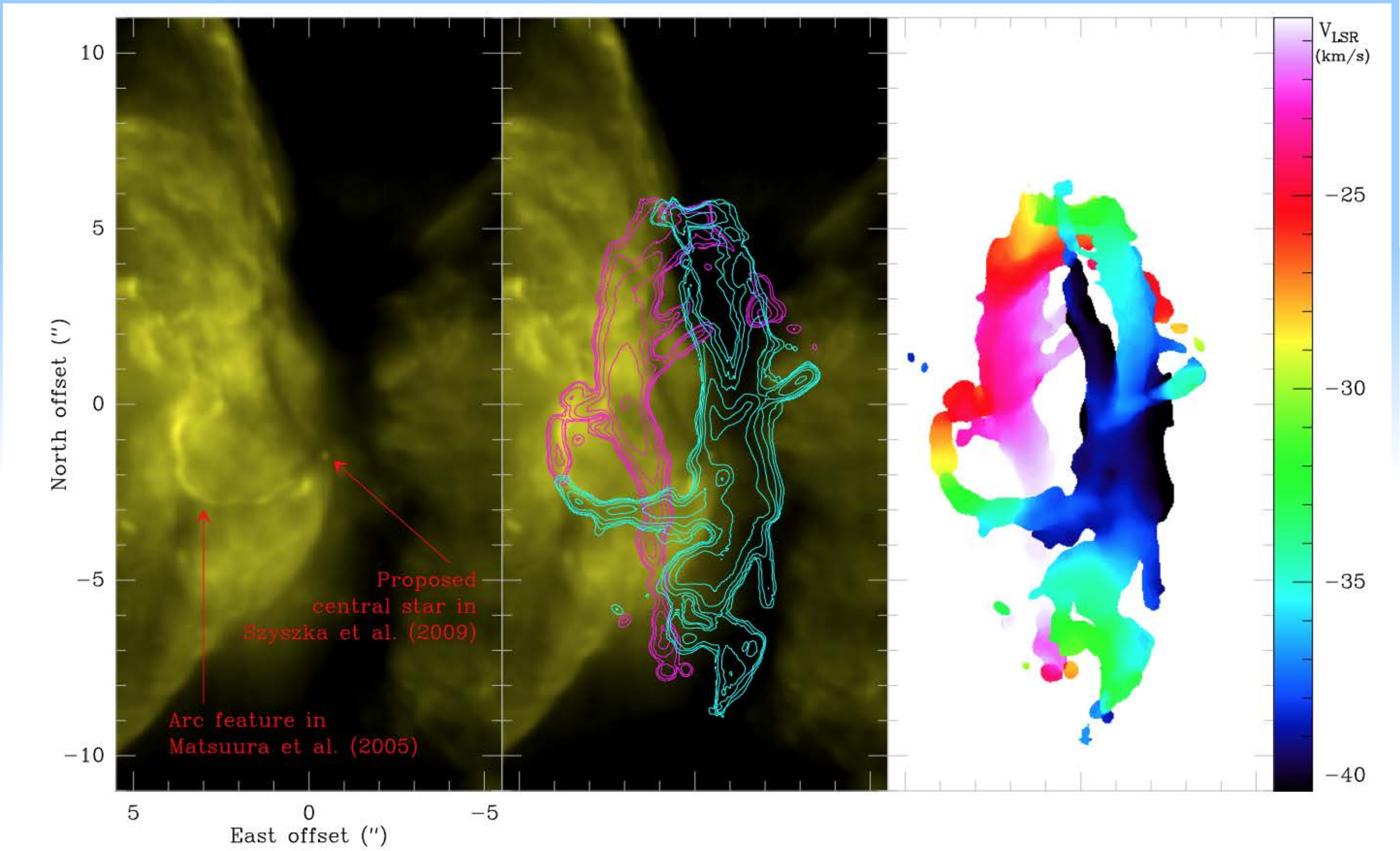


- ALMA vs HST
- CO shows torus plus polar lobes
- Hubble lobes; slowly expanding torus.
- Ultra-cold CO
- High-mass common envelope system?

Sahai et al. 2017

NGC 6302

PN with hot central star

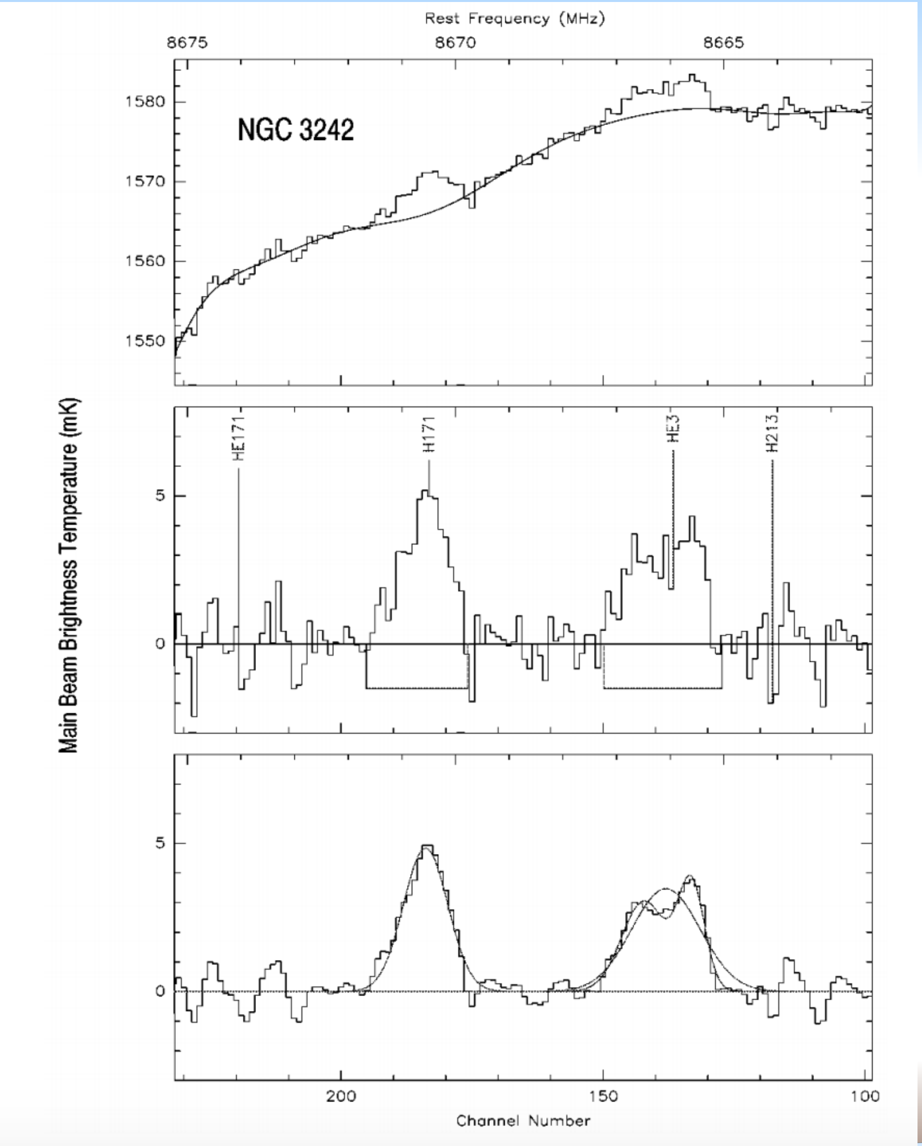


- Expanding torus 5000-3000 yr old
- Younger inner ring 2200 old
- Two sets of lobes   Santander-Garcia et al. 2017
- Double ejection event

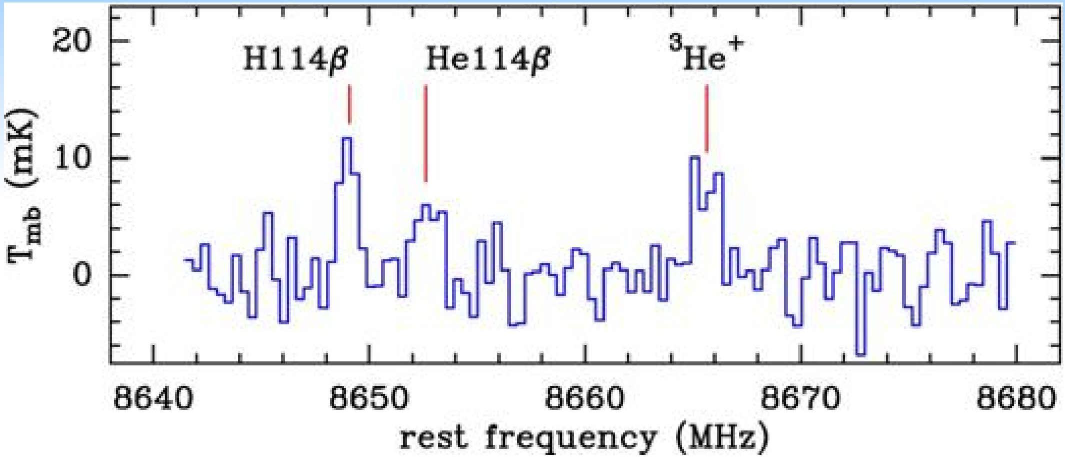
$^3He^+$

- Last addition to the chemical Universe
- Only solar-mass stars contribute
- Detectable through spin-flip transition at 8.6GHz
- But line is very weak

Pioneered by Dana Balser

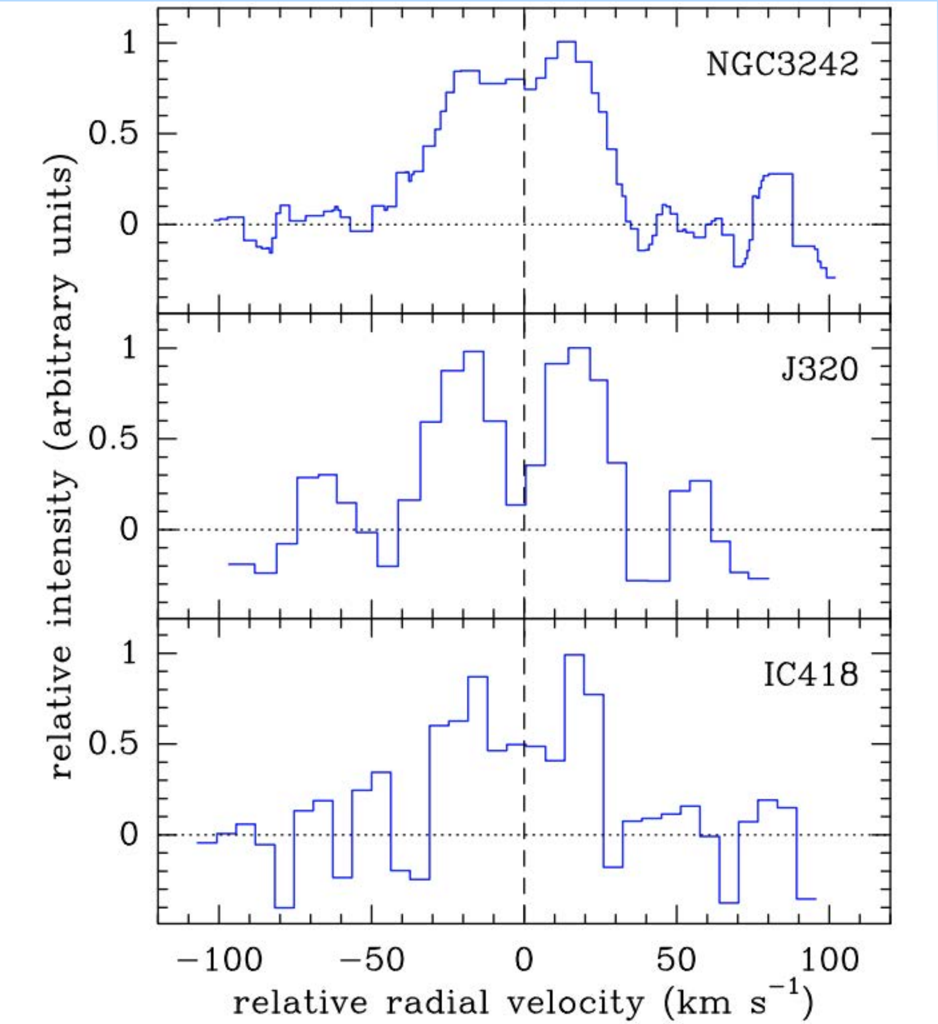


3He: the mysterious element

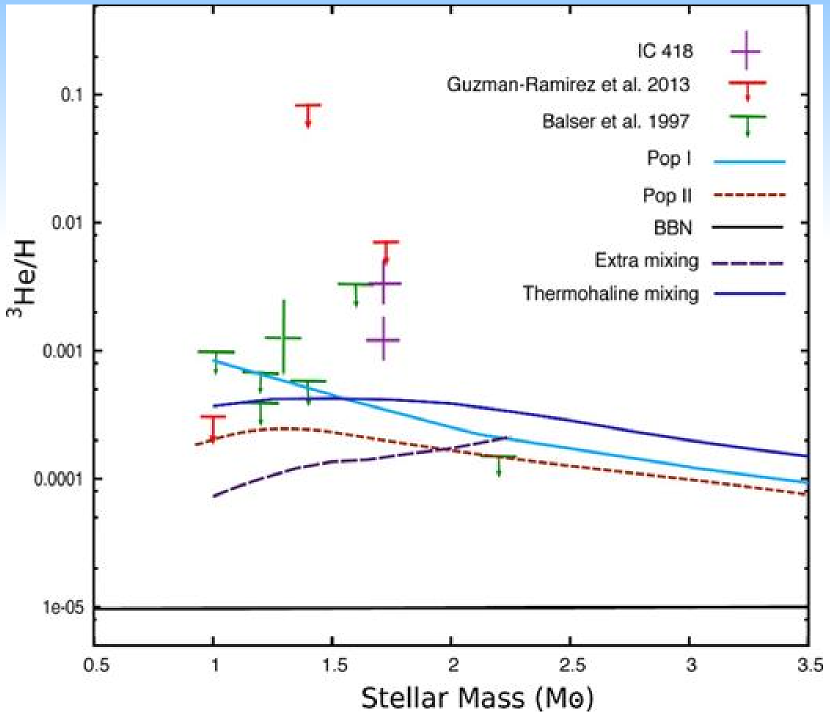


- Detected in three PNe

Guzman-Ramirez et al. 2016, Balser et al. 2006, 1997



3He: the mysterious element



- Abundances too large for cosmological or nucleosynthesis origin
- Originate from PN halo?
- A maser pumped by $^4He^{++}$ recombination?

Projects with the SKA

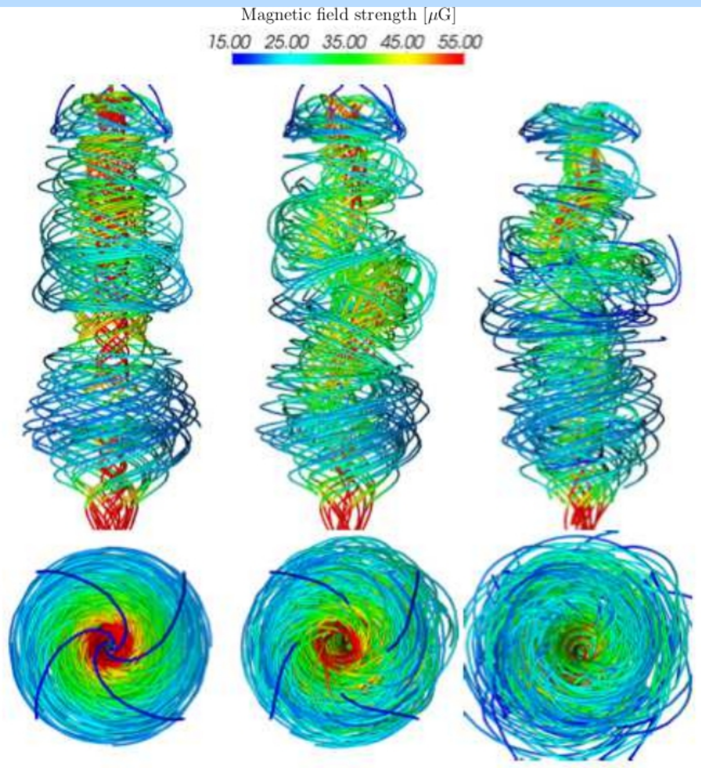


Fig. 6.— Central ($r \lesssim 1.2\ r_e$) magnetic field lines at $t = 118$ yr. From left to right these are the adiabatic, the rotating and the cooling magnetic towers, respectively. Bottom panels show an upper view, pole-on. Open field lines are a visualization effect.

- Test magnetic towers: Jet formation by magnetic acceleration
- Accretion on main-sequence companions: expected 1 microJy at 1kpc
- Milky Way surveys: flux variability at microJy level
- Nail the $^3He^+$ evolution

Stars
The End