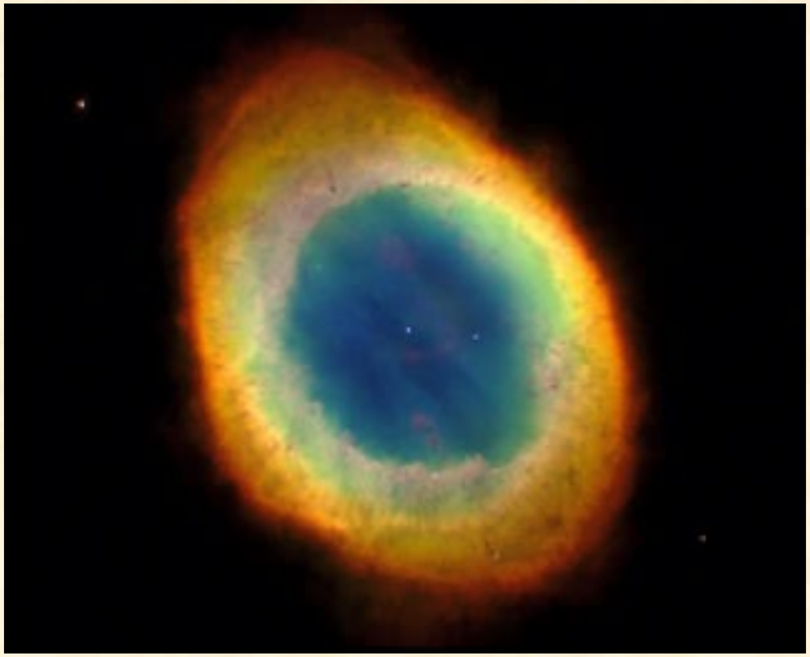
Planetary Nebulae

- Detection
- Distribution in the Galaxy
- Central Stars
- Evolution
- Bipolar Nebulae



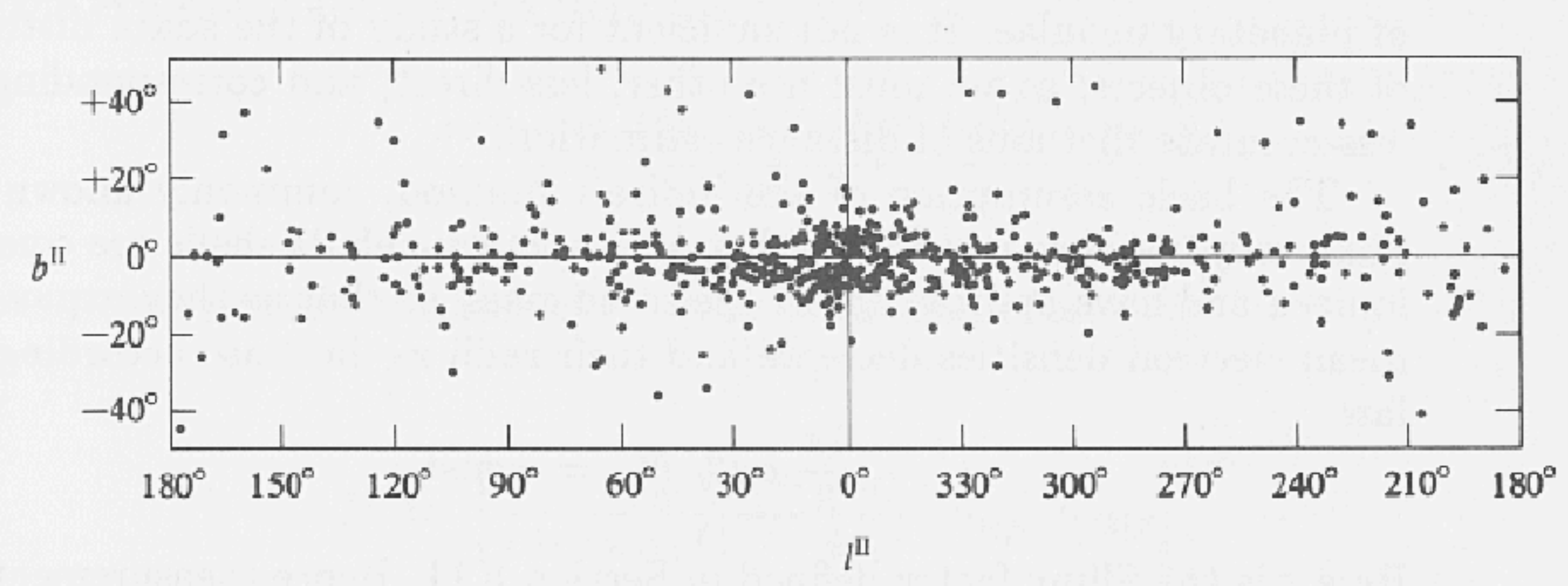
Ring Nebula
(HST image)
Red – [N II]
Green – [O III]
Blue – He II

Detection and Distribution of Planetary Nebulae (PN)

- Direct imaging: narrow-band filters centered on Hα + [N II] λλ 6548, 6583 or Hβ + [O III] λλ 4959, 5007
  - detects PN with large angular sizes
- Objective prism
  - small PN with high surface brightnesses
- About 1500 Galactic PN have been detected locally
  - limited to ~1 kpc in the Galactic plane due to dust)
- Difficult to detect in radio (fainter than H II regions)
- Projected number based on surveys:

  ~25,000 PN in Galaxy

Angular Distribution of Planetary Nebulae (PN)



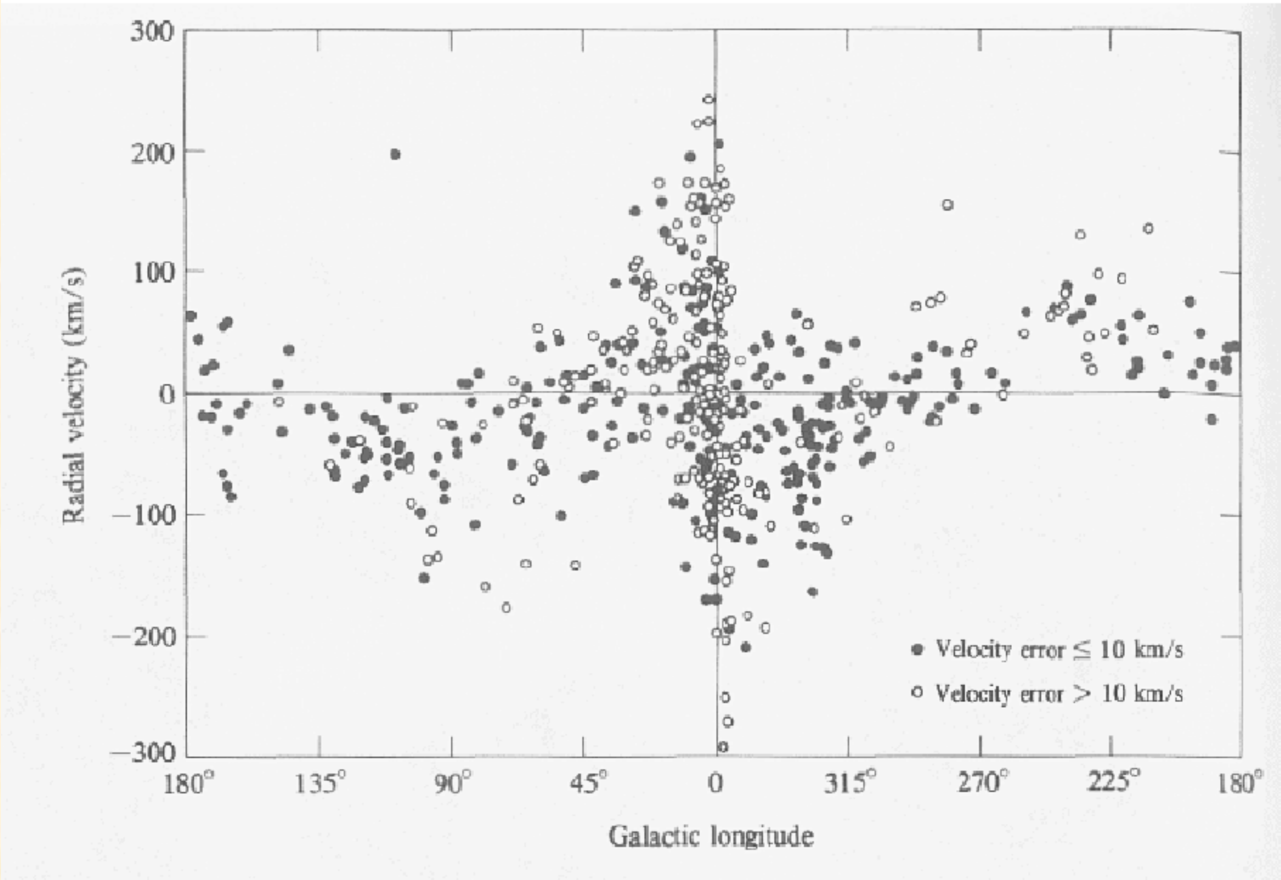
(Osterbrock & Ferland, p. 251)

- concentrated to Galactic plane and towards Galactic center (but not as much as young Population I stars)

Distances of PN

1. Trigonometric parallax (previously: only a few close enough).
   - Gaia is now measuring parallaxes (1725 PNe in EDR3)
2. Measure reddening from recombination lines; use map of reddening as function of Galactic coordinates and distance (problem: Galactic dust is very patchy)
3. Measure proper motion of shell (μ); measure radial velocity(v_r) and assume tangential velocity (v_t) is the same:
   $v_t = 4.74\ \mu d$ (v_t in km/s, μ in "/year, d in pc)
   (problem: assumes expanding spherical shell)
4. Shklovsky method: assume all PN have the same mass:
   $4/3\pi\ r^3\ n_e\ \varepsilon = \text{const.}$ (where ε is the "filling factor")
   - measure n_e from [O II], [S II], etc.
   - calculate r and determine angular size, you get distance
   (problem: don't know ε very well)

Velocities of PN



(Osterbrock & Ferland, p. 252)

- Negative velocities at l = 90 (direction we are heading), positive at l = 270
  → Galactic rotation velocity smaller compared to younger Population I
- Distribution: Concentrated to plane, but scale height is ~ 250 pc
  → Planetary Nebulae are old Population I objects

Central Stars of PN

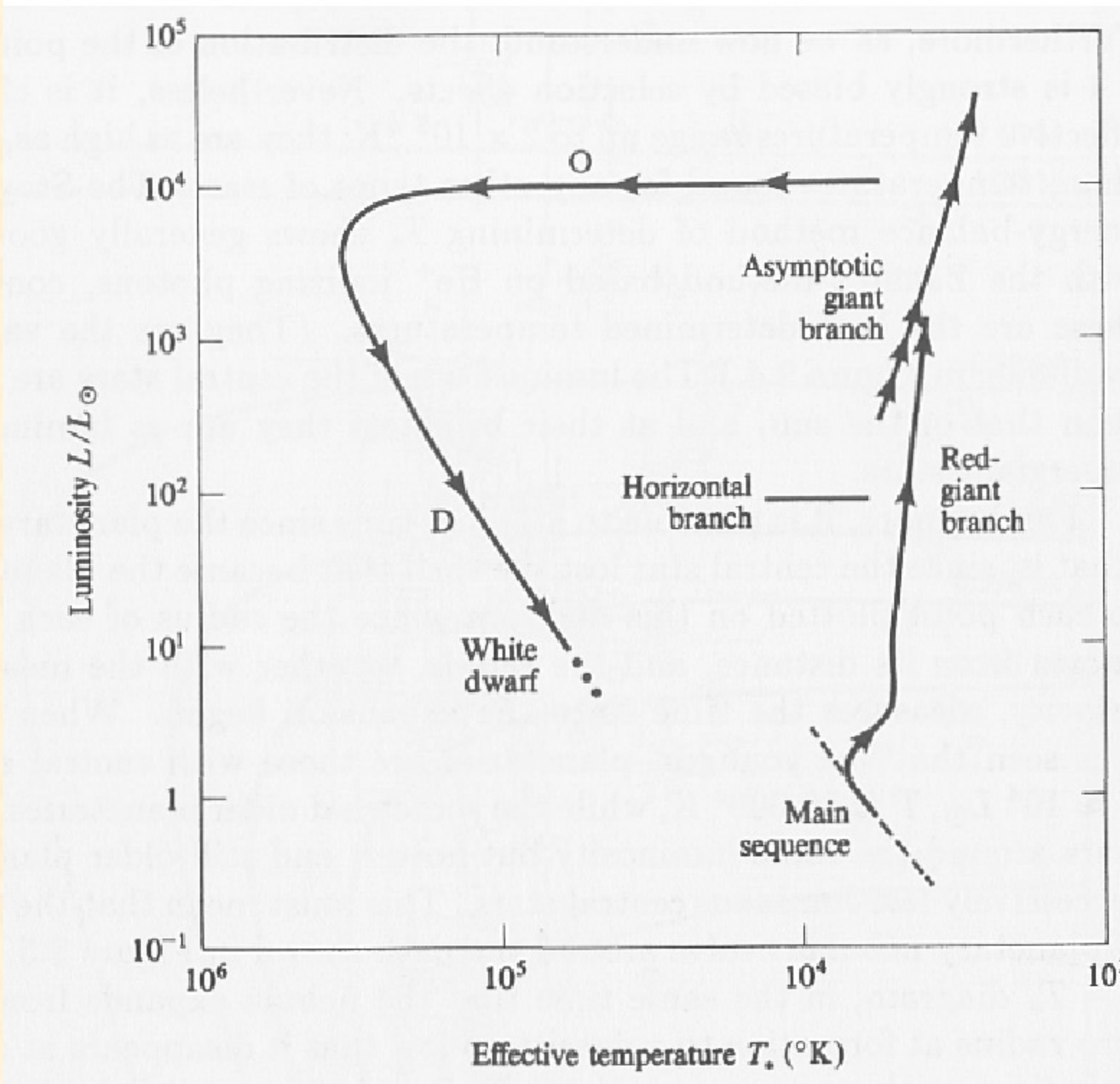
How do we know their characteristics?

- Luminosities from measured fluxes, distances to PN
- T_{eff} from Zanstra method:
  - Count Hβ photons to get the number of ionizing photons
  - Compare with star's optical continuum photons to get T_{eff}
- Plot in an H-R diagram: PN stars are found in region indicating they are precursors to white dwarfs
  - initial contraction: ~constant luminosity, increasing temperature
  - subsequent cooling at constant radius, luminosity decreases rapidly ($L = 4\pi R^2 \sigma T^4$)
- Ages: $t = r/v_r$ (r from distance, angular size; v_r = radial vel.)
- Lifetimes: PN disperse into the ISM at about 1 pc in size

  Lifetime ~ 35,000 years (short-lived, but numerous)

  - must be a common phase of stellar evolution

Evolution of PN



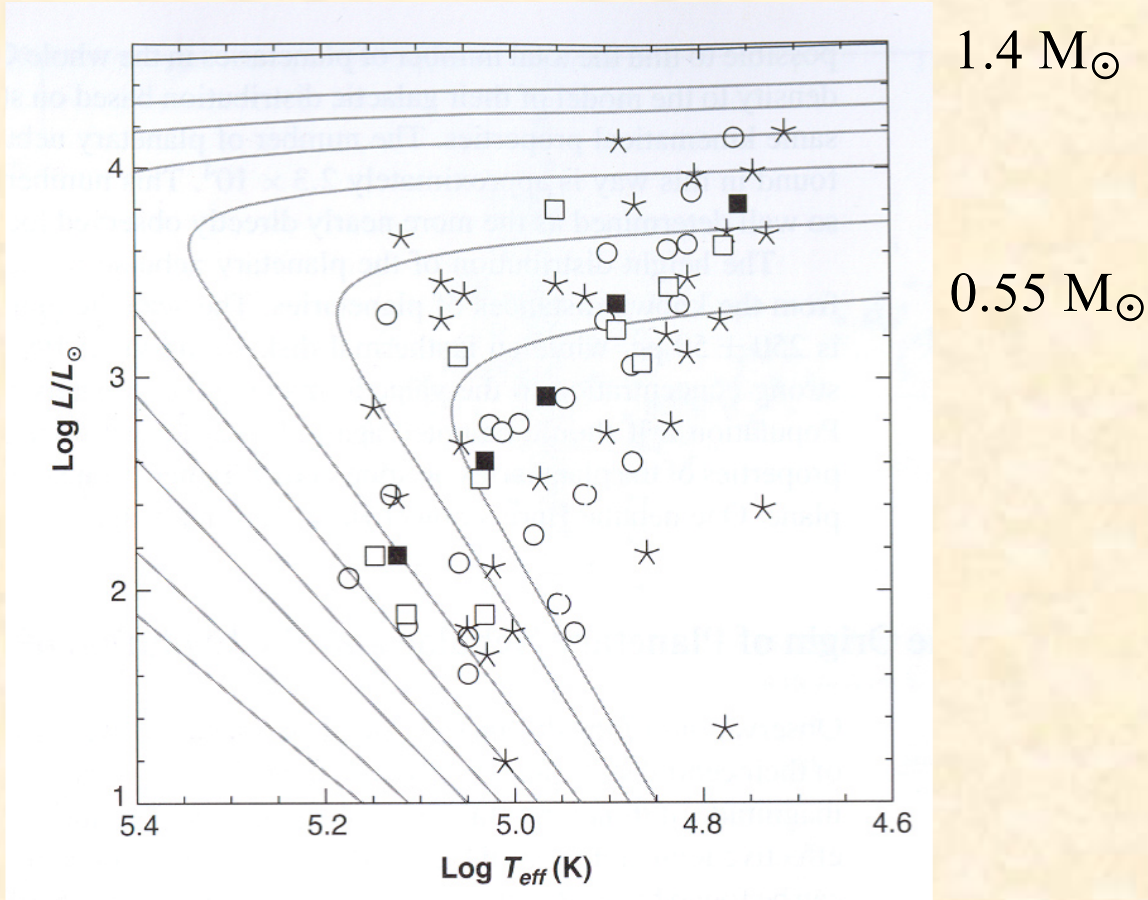
(Osterbrock & Ferland, p. 255)

Evolution

- Begin with a star on the main sequence: 1 – 8 $M_\odot$
- Star evolves along red giant branch: He core contracts, H burning in shell
- Outer layers develop deep convective zone, surface expands, mass loss due to stellar wind
- Star moves from tip of red giant branch to horizontal branch (He flash occurs for $M \leq 2\ M_\odot$).
- On horizontal branch, star burns He in core and H in shell
- Star moves up the asymptotic giant branch
  - C+O core, He burning in shell, H burning in shell
- At tip of AGB, planetary nebula is ejected:
- The red giant star is subject to pulsations, which grow out of control at a luminosity of about $10^4\ L_\odot$

- The instability penetrates to the bottom of the H-rich zone, and is stopped by the discontinuity in density.
- The PN is lifted off the core. Radiation pressure helps to drive off the PN shell. The escape velocity is about 20 km/sec, in agreement with observed PN velocities
- The PN material is photoionized by the hot remaining core (which is nearly all C+O)
- Note that most of the mass has already been lost due to pulsations and stellar winds. Thus for an initial mass $< 8\ M_{\odot}$, the mass of the remaining core is $< 1.4\ M_{\odot}$
- The core (PN central star) shrinks and cools along the lines discussed earlier, to become a white dwarf
- The PN eventually merges with the ISM. Elemental abundances of He, C, N, and O are enhanced (due to earlier dredge up of material from regions of nuclear fusion)
- PNe return $\sim 25\ M_{\odot}$ of material to Galaxy per year (AGB + PN stages)

Comparison of Theory with Observations

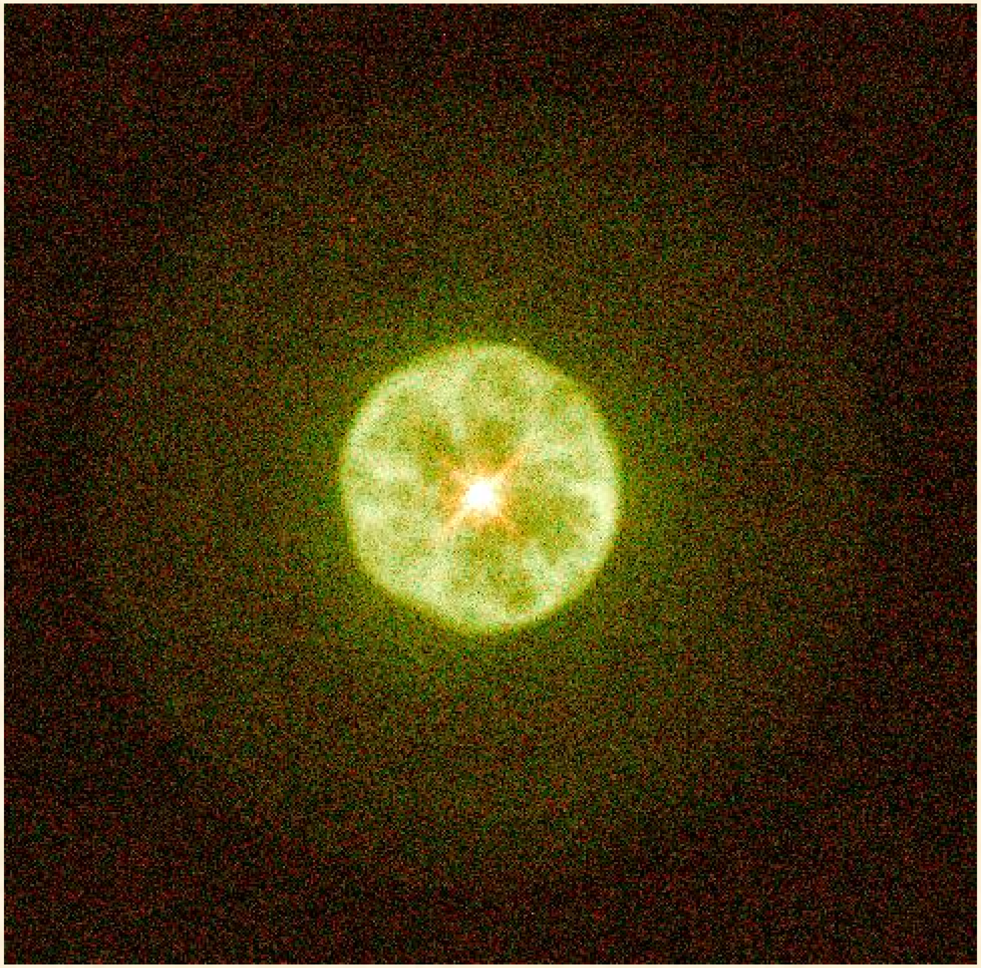


(Osterbrock & Ferland, p. 254)

- Central stars can reach temperatures of ~200,000 K → He II, [N V] emission
- Young PN are at upper right, middle age at lower left, oldest moving toward WDs

PN Morphology - Round, Elliptical, and Bipolar

IC 3568

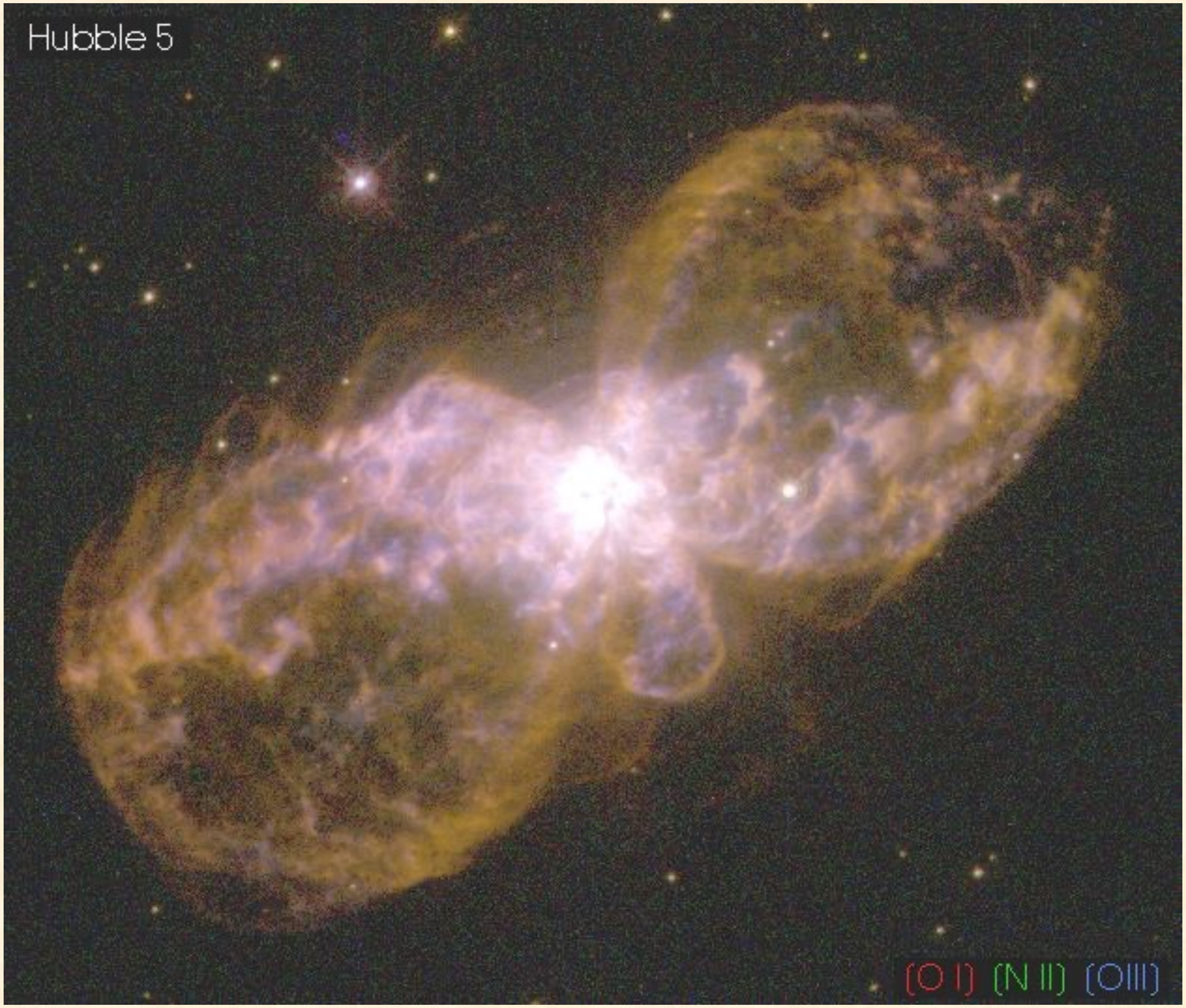


"Round"

IC 418

Red – [N II], Green – Hα, blue – [O III]

"Elliptical"



Bipolar - “bi-lobed”

Planetary Nebula Mz3

Red – [S II], Green – [N II], blue – Hα, violet – [O III]

Bipolar - “butterfly”

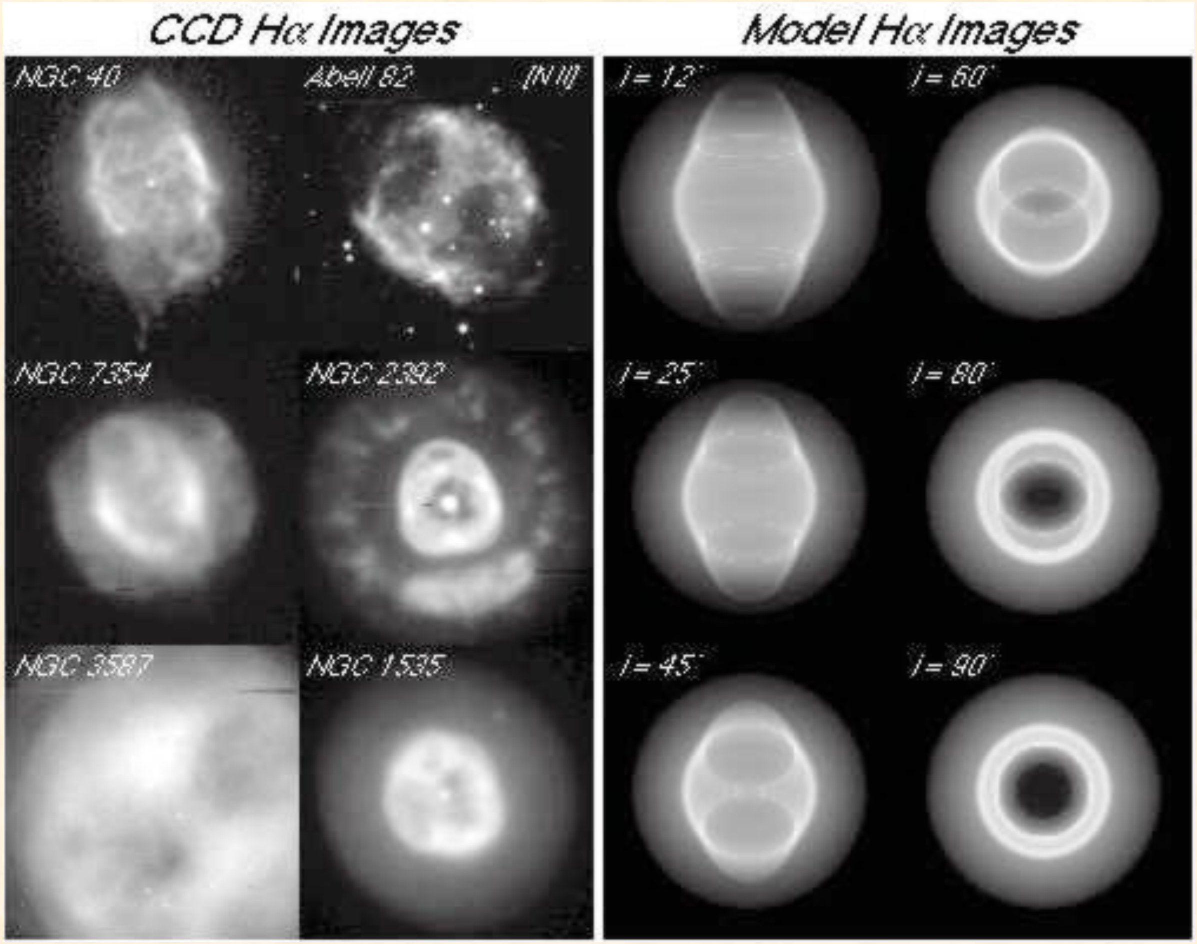
Planetary Nebula M2-9

A Model for PN Structure

(Balick, B. 1987, AJ, 94, 671)

- Slow-moving (~10 km s^{-1}) molecular dusty wind forms shell around AGB star
- AGB star ejects equatorial disk or torus in last stages of evolution.
- Fast-moving wind (~1000 km s^{-1}) from exposed hot core pushes out to form an elliptical or bipolar geometry. UV photons ionize the PN shell.
- A bright “rim” develops around the bubble’s leading edge (mild shock).

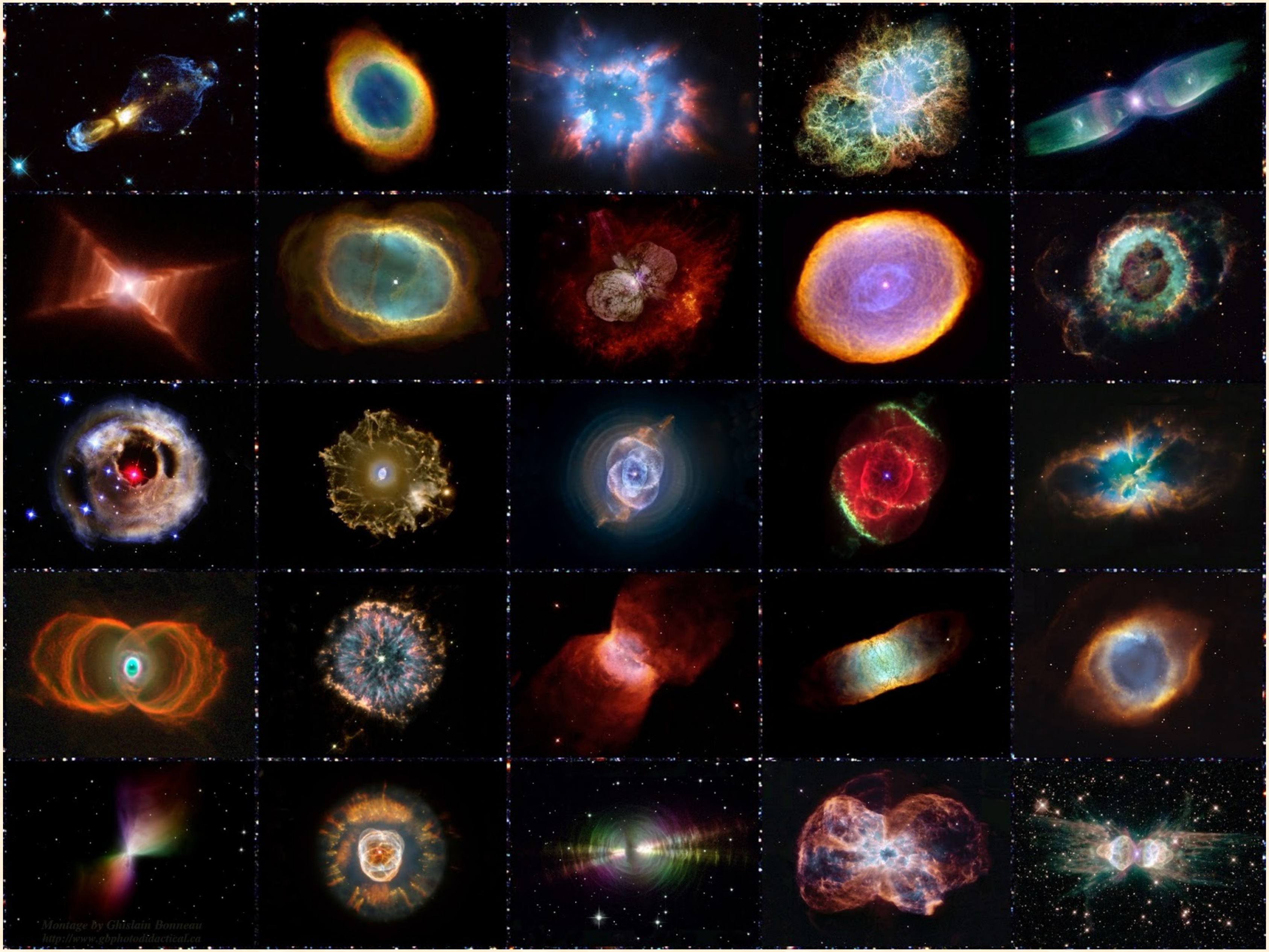
Two-Dimensional Hydrodynamic Model (changing inclination)



(Frank et al. 2000, AJ, 100, 1903)

- doesn't explain "butterfly" nebulae or other weird shapes
- binary companion or magnetic fields likely play roles
  (Balick & Frank (2002, ARAA, 40, 439)
- hydro simulations: PNe shapes a complicated mixture of stellar ejections, winds, changing photoionization (and inclination)

HST Sampler of PNe



Credit: NASA/ESA