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 H$\alpha$ + [N II] $\lambda\lambda$ 6548, 6583 or H$\beta$ + [O III] $\lambda\lambda$ 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 $\sim$1 kpc in the Galactic plane due to dust)
- Difficult to detect in radio (fainter than H II regions)
- Projected number based on surveys:
  $\sim$25,000 PN in Galaxy
Angular Distribution of Planetary Nebulae (PN)

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

(Osterbrock & Ferland, p. 251)
Distances of PN

1. Trigonometric parallax (problem: only a few close enough)
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, $\mu$ 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 $\varepsilon$ 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 $\varepsilon$ 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 $\sim 250$ 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
- **$T_{\text{eff}}$** from Zanstra method:
  - Count H$\beta$ photons to get the number of ionizing photons
  - Compare with star’s optical continuum photons to get $T_{\text{eff}}$
- Plot in an H-R diagram: PN stars are found in region indicating they are precursors to white dwarfs
  - initial contraction: $\sim$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 $\sim$ 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☉, the mass of the remaining core is < 1.4 M☉
• 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 ~25 M☉ of material to Galaxy per year (AGB + PN stages)
Comparison of Theory with Observations

(Osterbrock & Ferland, p. 254)

- Central stars can reach temperatures of $\sim200,000$ K $\rightarrow$ 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

- 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).

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