## 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 $\mathrm{H} \alpha+$ [N II] $\lambda \lambda$ 6548, 6583 or $\mathrm{H} \beta+[\mathrm{O} \mathrm{III}] \lambda \lambda 4959,5007$
- detects PN with large angular sizes
- Objective prism
- small PN with high surface brightnesses
- About 1500 Galactic PN have been detected locally
- limited to $\sim 1 \mathrm{kpc}$ 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)


## 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 $(\mu)$; measure radial velocity $\left(\mathrm{v}_{\mathrm{r}}\right)$ and assume tangential velocity $\left(\mathrm{v}_{\mathrm{t}}\right)$ is the same: $\mathrm{v}_{\mathrm{t}}=4.74 \mu \mathrm{~d}\left(\mathrm{v}_{\mathrm{t}}\right.$ in $\mathrm{km} / \mathrm{s}, \mu$ in "/year, d in pc$)$
(problem: assumes expanding spherical shell)
4. Shklovsky method: assume all PN have the same mass:
$4 / 3 \pi \mathrm{r}^{3} \mathrm{n}_{\mathrm{e}} \varepsilon=$ const. (where $\varepsilon$ is the "filling factor")

- measure $\mathrm{n}_{\mathrm{e}}$ 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 $1=90$ (direction we are heading), positive at $1=270$
$\rightarrow$ Galactic rotation velocity smaller compared to younger Population I
- Distribution: Concentrated to plane, but scale height is $\sim 250 \mathrm{pc}$ $\rightarrow$ Planetary Nebulae are old Population I objects


## Central Stars of PN

How do we know their characteristics?

- Luminosities from measured fluxes, distances to PN
- $\mathrm{T}_{\text {eff }}$ from Zanstra method:
- Count $\mathrm{H} \beta$ 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 ( $\mathrm{L}=4 \pi \mathrm{R}^{2} \sigma \mathrm{~T}^{4}$ )
- Ages: $\mathrm{t}=\mathrm{r} / \mathrm{v}_{\mathrm{r}}$ ( r from distance, angular size; $\mathrm{v}_{\mathrm{r}}=$ 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: $1-8 \mathrm{M}_{\odot}$
- 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 $\mathrm{M} \leq 2 \mathrm{M}_{\odot}$ ).
- On horizontal branch, star burns He in core and H in shell
- Star moves up the asymptotic giant branch
- $\mathrm{C}+\mathrm{O}$ 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 $10^{4} \mathrm{~L}_{\odot}$
- 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 $20 \mathrm{~km} / \mathrm{sec}$, in agreement with observed PN velocities
- The PN material is photoionized by the hot remaining core (which is nearly all $\mathrm{C}+\mathrm{O}$ )
- Note that most of the mass has already been lost due to pulsations and stellar winds. Thus for an initial mass $<8 \mathrm{M}_{\odot}$, the mass of the remaining core is $<1.4 \mathrm{M}_{\odot}$
- 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 $\mathrm{He}, \mathrm{C}, \mathrm{N}$, and O are enhanced (due to earlier dredge up of material from regions of nuclear fusion)
- PNe return $\sim 25 \mathrm{M}_{\odot}$ of material to Galaxy per year (AGB + PN stages)


## Comparison of Theory with Observations


(Osterbrock \& Ferland, p. 254)

- Central stars can reach temperatures of $\sim 200,000 \mathrm{~K} \rightarrow \mathrm{He} \mathrm{II}$, [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



IC 418


Red - [N II], Green - H $\alpha$, blue - [O III]
"Elliptical"


Bipolar - "bi-lobed"

## Planetary Nebula Mz3



Red - [S II], Green - [N II], blue - H $\alpha$, violet - [O III]
Bipolar - "butterfly"

## Planetary Nebula M2-9



## A Model for PN Structure


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

- Slow-moving ( $\sim 10 \mathrm{~km} \mathrm{~s}^{-1}$ ) molecular dusty wind forms shell around AGB star
- AGB star ejects equatorial disk or torus in last stages of evolution.
- Fast-moving wind ( $\sim 1000 \mathrm{~km} \mathrm{~s}^{-1}$ ) 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)

 CCD HC/mages Mode/ Hc /mages
(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)

