# Stellar Evolution

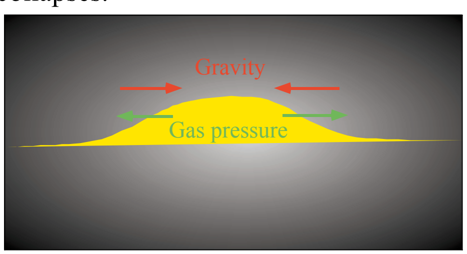
The Birth, Evolution and Death of Stars

## Stellar Evolution / Main Stages

- The Collapse of an Interstellar Cloud
- Fragmentation into smaller clumps ▯ Stars
- Hydrogen Burning - Main Sequence
- Helium Burning - Red Giant
- Higher "nuclear" fuels (depending on mass)
- Death, depending on mass:
  - **Planetary Nebula ▯ White Dwarf**
  - **Supernova ▯ Neutron Star**
  - **Supernova ▯ Black Hole**

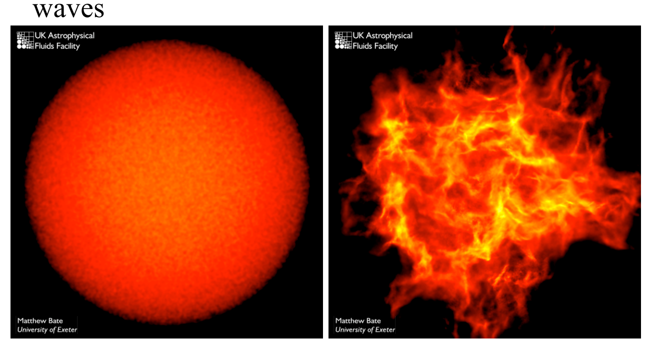
## Collapse of Interstellar Cloud

- Interstellar Medium Contains Clouds.
- T~10-100°K, M~10's-1000's of $M_{sun}$
- If gravitational pull exceeds gas (and B) pressure, gas collapses.

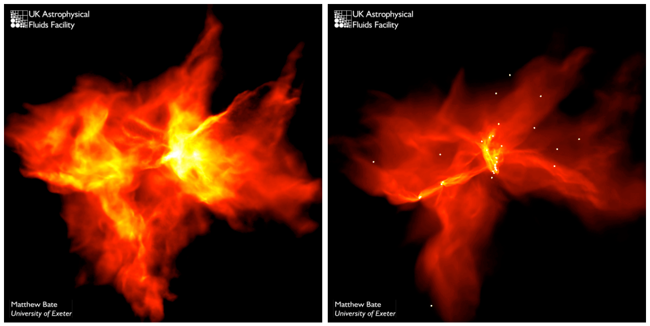



## Numerical Simulation of Cloud Interstellar Cloud Collapse

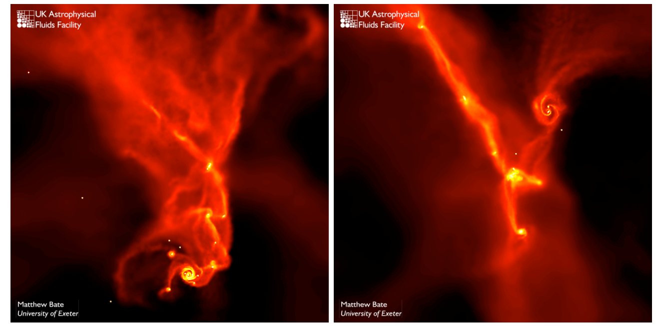
- Cloud Gravitationally unstable and starts collapsing. Flow limited by formation of shock waves



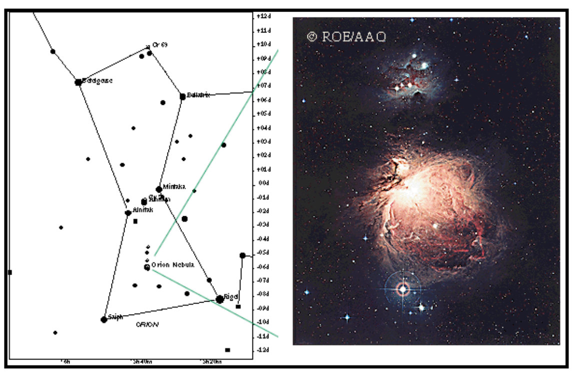
- At some point, gravitational collapse formes dense cores

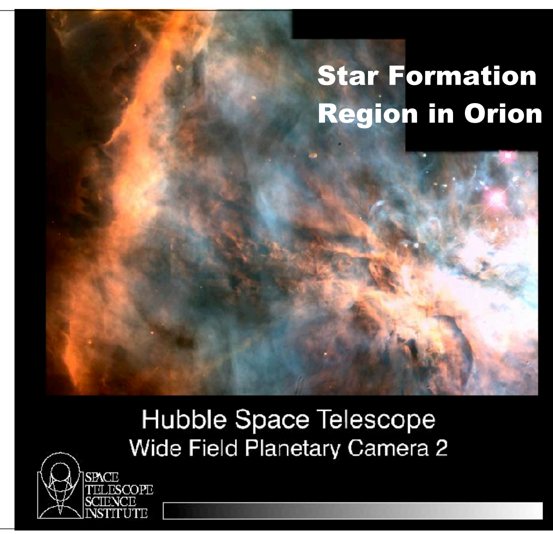



- Cores accrete through accretion disks
- Simulation by Matthew Bate http://www.ukaff.ac.uk/starcluster/



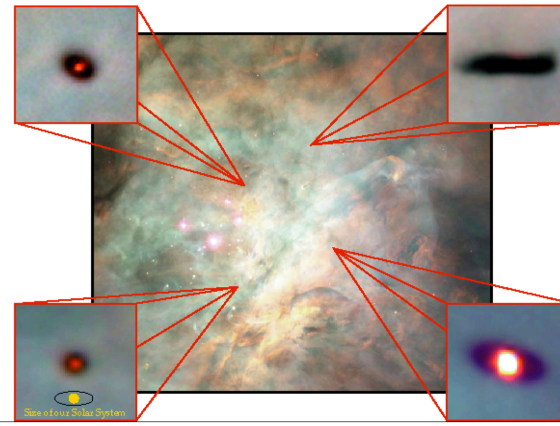

## Star Formation Region in Orion



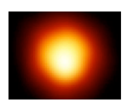
## Examples of real cores (with HST)

- Disks are formed at the "cores", from which a young star is born

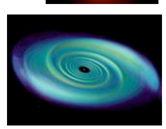



## Formation of Disks, why?

- It is easy for the gas to cool and lose energy.
- It is hard for gas to lose angular momentum as it contracts.
- $L \sim M r v \Rightarrow v \sim L/(M r)$
- Forces: $F_{centrifugal} \sim v^2/r \sim L^2/r^3$ & $F_{grav} \sim M/r^2$
- Force ratio: $F_{centrifugal} / F_{grav} \sim L^2/r$
- As collapse proceeds, $F_{centrifugal} / F_{grav}$ increases. Impossible to form star with too much angular momentum.



- Result:
  - **2/3 of stellar systems are double stars!**
  - **1/3 of stellar systems should have planets.**
  - **(e.g., 99% of *L* in solar system, is in Jupiter!)**



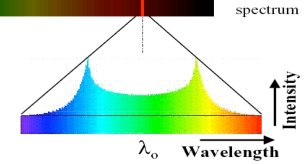
## Disks are ubiquitous to nature.

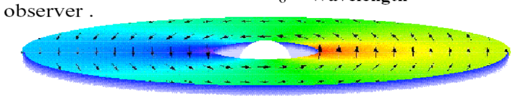
**(disks of Be stars form from stellar winds, not accretion disks)**

### Be stars

- Hot, bright, & rapidly rotating stars.
- Discovered by Father Secchi in 1868
- The "e" stands for emission lines in the star's spectrum


- Detailed spectra show emission intensity is split into peaks to blue and red of line-center.
- This is from Doppler shift of gas moving toward and away from the observer .



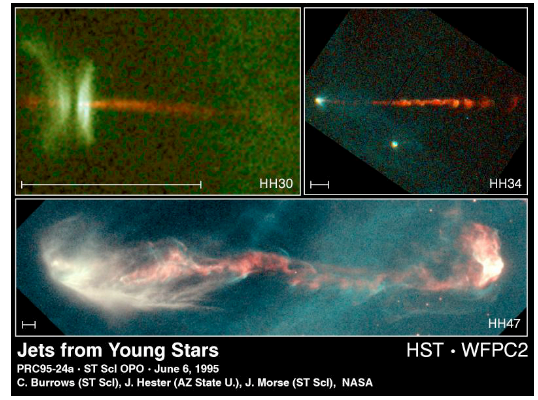



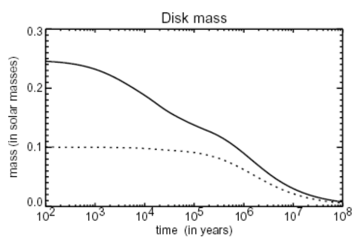
- Indicates a disk of gas orbits the star.

## Loss of angular momentum:

- Probably using magnetic fields
- Magnetic field is probably responsible for the acceleration of jets

- Strong winds from the young star can form jets!




The disk loses its mass by accretion and outflow

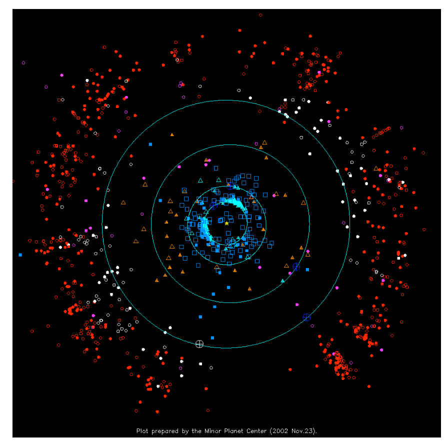
At the same time, condensations take place inside the disk

The clumps collide with one another and merge to form planets

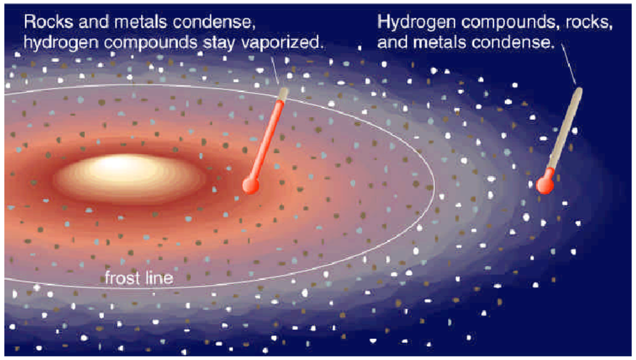
The clumps that did not merge to planets form the asteroids belt, the Kuiper belt and the Oort cloud.

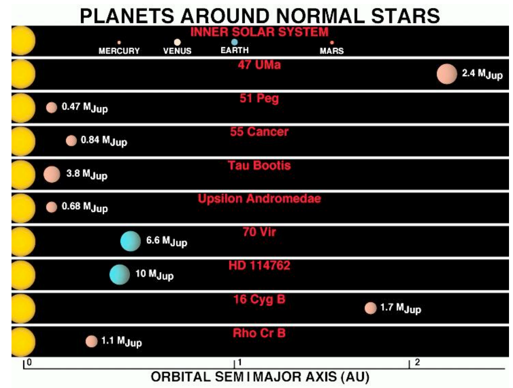
Largest Kuiper belt object: Pluto!

Oort Cloud: Reservoir of Comets



- Only rocks and metals could condense out near the Sun
- Farther away, lower temperatures allow lighter condensates



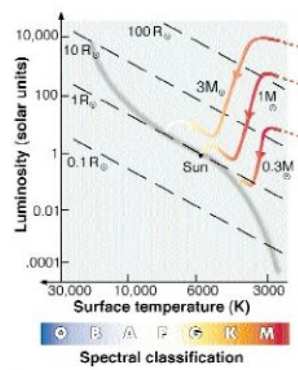

Most observed Jupiters are significanlty closer to their Sun

Need "planet migration"

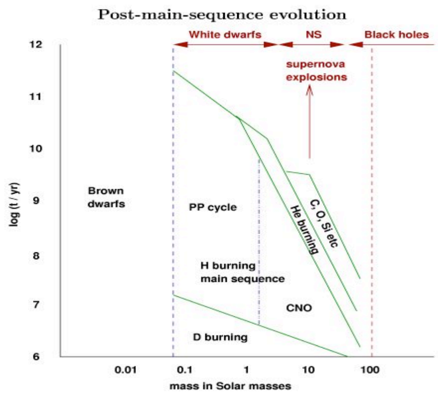
## A young cluster: Pleiades

**(7 daughters of Atlas)**

## On the H-R diagram:



## Fuels burnt in stars:

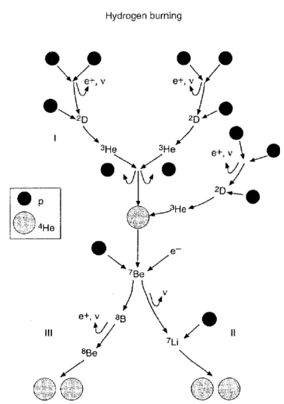



Credit: Phil Armitage

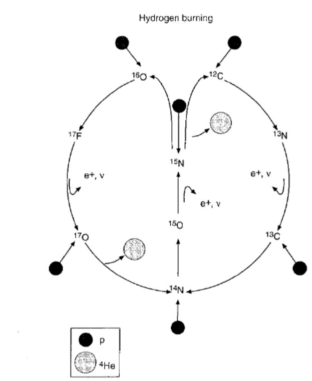
## Evolution of Stars / Gross Features:

- $M < 0.08\ M_{sun}$ – Brown Dwarf (no nuclear brurning)
- $0.08\ M_{sun} < M < 0.5\ M_{sun}$ – Central hydrogen bruning. Formation of a degenerate core. No helium ignition  End as a He white dwarf
- $0.5\ M_{sun} < M < 2\ M_{sun}$ – Central Hydrogen burning, Helium flash, Helium burning  End as CO White dwarf.
- $2\ M_{sun} < M < 8\ M_{sun}$ – Central Hydrogen burning, Helium ignites non degenerately  End as CO White dwarf.
- $8\ M_{sun} < M < 20\ M_{sun}$ – Numerous burning stages after Helium burning. Type II Supernova  ends as Neutron Star.
- $20\ M_{sun} < M$ – As above, but ends as a Black Hole.
- Note: High masses are inaccurately known due to large wind mass loss during evolution.

## Hydrogen Burning



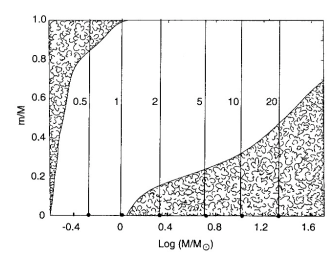

The nuclear reactions of the *p–p* I, II, and III chains.




The nuclear reactions of the CNO bi-cycle.

## Zones of Convection

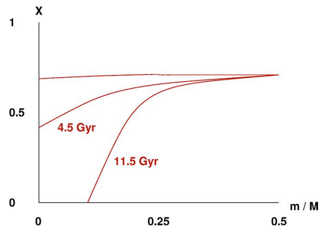
- Low mass stars: Outer convection because T is low (opacity, ionization)
- High mass stars: Core convection because CNO H-burning (high T dependence)



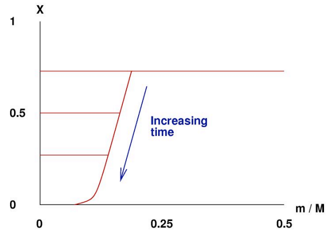

The extent of convective zones (shaded areas) in main-sequence star models as a function of the stellar mass [adapted from R. Kippenhahn & A. Weigert (1990), *Stellar Structure and Evolution*, Springer-Verlag].

## Depletion of Hydrogen in Core

- In low mass stars (solar mass or less), pp-chain, and no convection in core:
- In high mass stars (higher than solar mass), CNO cycle, convection in core:



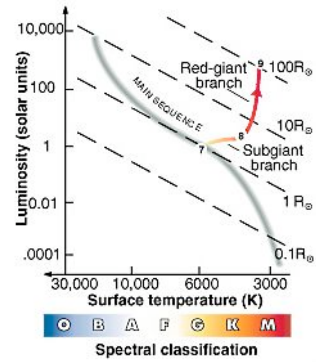

1 $M_{sun}$



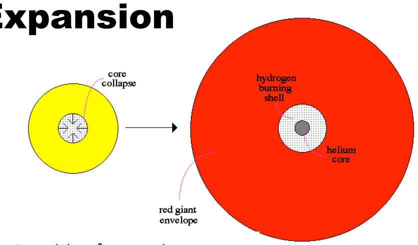

5 $M_{sun}$

## Evolution of low mass star

• End of Hydrogen in Core while core is contracting (7)
• Burning of H  He in thick shell ("shell burning") (7-8)
• Burning of H  He in thin shell ("shell burning") (8-9)
• Helium ignition in degenerate core  Helium Flash (9)

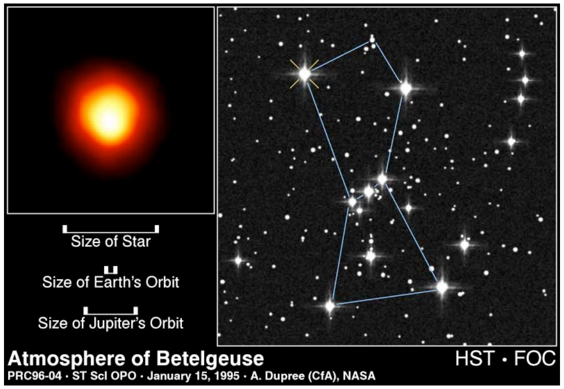



## Red Giant Expansion



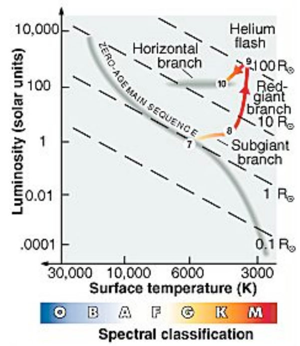

- Iben, ApJ, 415, 767 (1993), *'the transition from main sequence to giant branch involves a complicated interplay between a core, an envelope, and a nuclear-burning shell'.*
- Renzini & Ritossa, ApJ, 433, 293 (1994), expansion is driven by increased opacity in the envelope.
- Laughlin, Bodenheimer & Adams, ApJ, 482, 420 (1997), expansion is due to (1) increased core luminosity, (2) $\mu$ gradients, (3) atmospheric opacity.

## An Example of a Red Giant



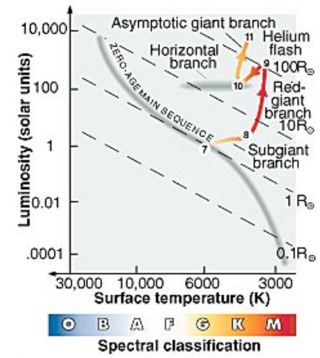
## Stable Burning of Helium in Core

- In low mass (< 2 $M_{sun}$), Helium Flash → Stable Helium burning after core expansion. (10)
- In High Mass (> 2 $M_{sun}$), Stable Core bruning without Helium Flash.
- Burning through 3α → $^{12}$C reaction, at T ~ $10^8$ °K
- O formed through α capture.




## Final evolution of low mass stars

- Low mass stars (<2 $M_{sun}$) cannot ignite C & O
- Shell burning of Helium (AGB = Asymptotic Giant Branch). (10-11)
- Envelope is very “lose” and shed through instabilities. (11)




## Evolution of various masses

- Below 2 $M_{sun}$, no Hydrogen Flash.
- Below 8 $M_{sun}$, no ignition of C, O
- Above 8 $M_{sun}$, burn heavier and heavier fuels

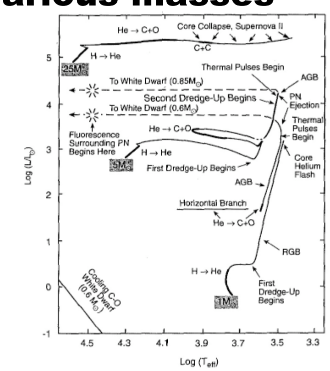
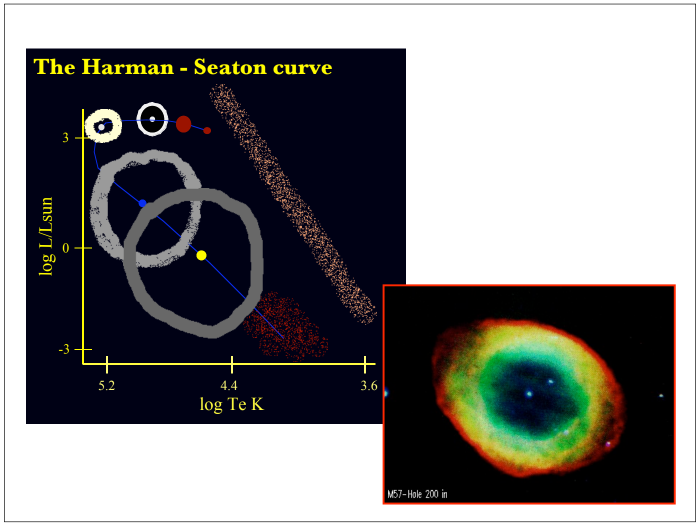


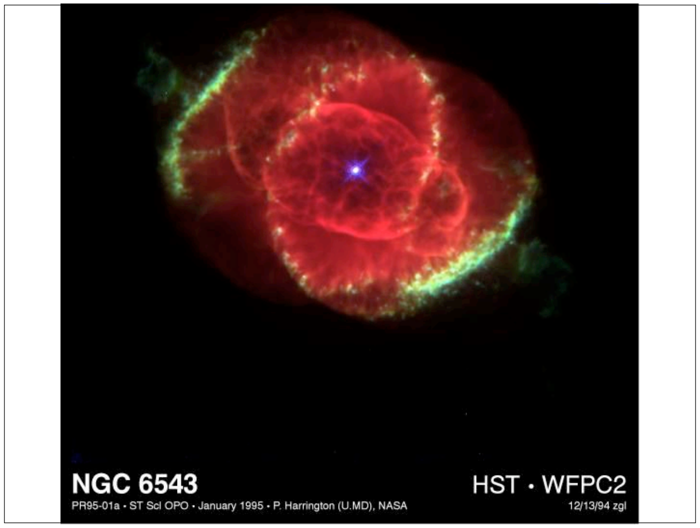

**Figure 8.19** Evolutionary tracks of $1M_\odot$, $5M_\odot$, and $25M_\odot$ star models in the H-R diagram. Thick segments of the line denote long, nuclear burning, evolutionary phases. The turnoff points from the AGB are determined empirically [from I. Iben Jr. (1985), *Quart. J. Roy. Astron. Soc.*, 26].

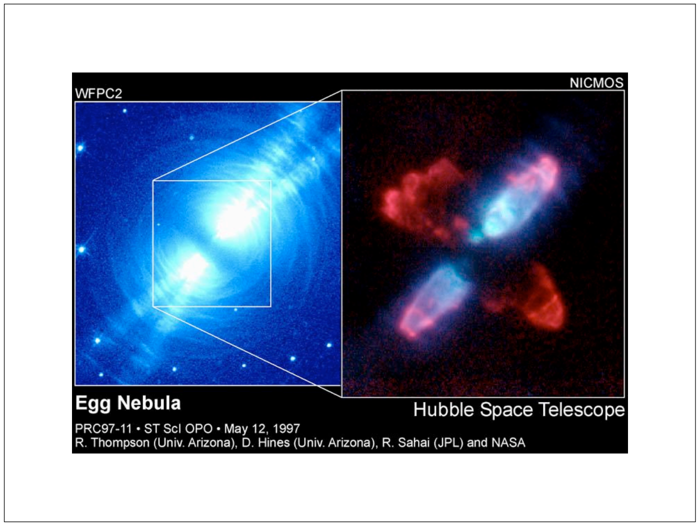
## Asymptotic Giant Branch Stars & Planetary Nebulae

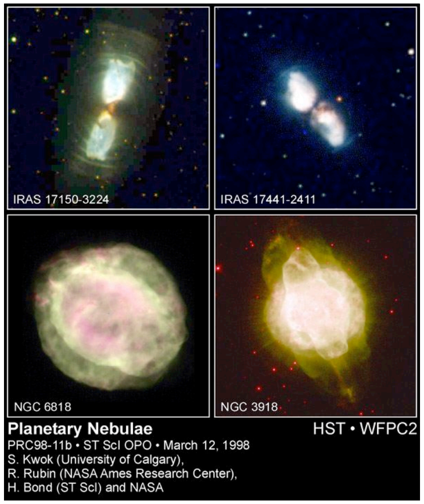
- Once He is exhausted in core, core continues to contract, He & H burn in shells, envelope expands.
- At some point, envelope becomes unstable, and starts to pulsates, each time sheding some material.
- Envelope ejected at ~ 30 km/s, and core contracts and cools
- Envelope becomes planetary nebula
- Core becomes white dwarf

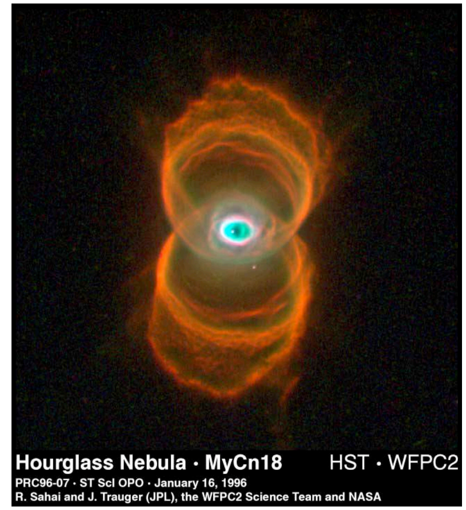

The Harman - Seaton curve
log L/Lsun
3
0
-3
5.2
4.4
3.6
log Te K
M57-Hole 200 in

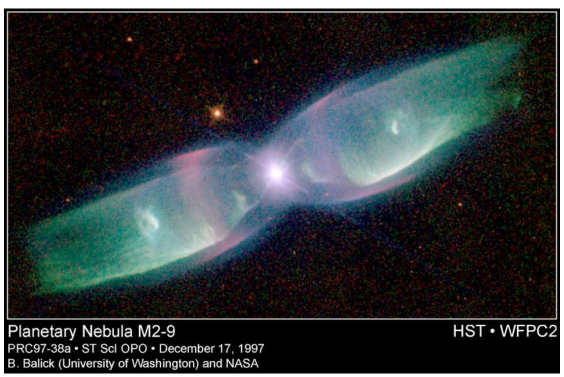

Planetary Nebula NGC 3132
Hubble Heritage
PRC98-39 • Space Telescope Science Institute • Hubble Heritage Team


NGC 6543
HST • WFPC2
PR95-01a • ST ScI OPO • January 1995 • P. Harrington (U.MD), NASA
12/13/94 zgl


WFPC2
NICMOS
Egg Nebula
Hubble Space Telescope
PRC97-11 • ST ScI OPO • May 12, 1997
R. Thompson (Univ. Arizona), D. Hines (Univ. Arizona), R. Sahai (JPL) and NASA

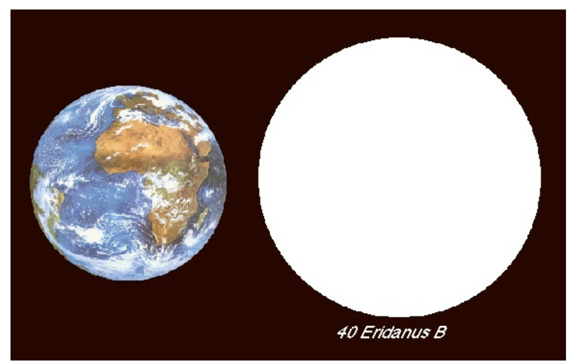


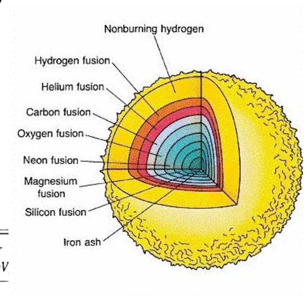

## Leftover: White Dwarf

- Held by degeneracy pressure of electrons



## Advanced burning in massive stars

- Shells:

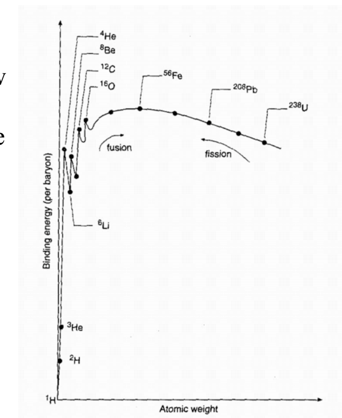



Major nuclear burning processes

| Nuclear Fuel | Process | $T_{threshold}$ $10^6$ K | Products | Energy per Nucleon (MeV |
|---|---|---|---|---|
| H | p–p | ~4 | He | 6.55 |
| H | CNO | 15 | He | 6.25 |
| He | 3α | 100 | C, O | 0.61 |
| C | C + C | 600 | O, Ne, Na, Mg | 0.54 |
| O | O + O | 1000 | Mg, S, P, Si | ~0.3 |
| Si | Nuc. eq. | 3000 | Co, Fe, Ni | <0.18 |

## Reactions Proceed up to Iron

- $^{56}$Fe is the most stable isotope. Reactions can release energy only below $^{56}$Fe.
- When temperature in core ~ 7 $10^9$ °K, $^{56}$Fe photodisintegrates: $^{56}$Fe  13 $^4$He + 4 n taking 100 MeV of energy! (At higher temperature, higher S is favored)
- This cools the core very quickly and it collapses.




## Supernovae

- One Iron photodisintegration takes place, core collapses on time scale of 10's of ms.
- At "Low" masses, Neutron star is formed, and shock appears.
- As long as there is large fluxes of infalling material, shock cannot "leave" the core. Once shock does propagates outwards (perhaps using  heating) it:
  - **Heats the envelope (fast nuclear processes take place (making Trans-Iron isotopes).**
  - **Accelerates the envelope, and it is ejected with speeds of order 10,000's km/s**

## Ejecta velocities of ~10000 km/s

## Left overs of massive stars

•The remnant left can be either a Neutron Star Or a Black Hole!

•Neutron stars are held by degeneracy pressure of neutrons (and not electrons)

## Neutron Stars can be active!

- Rotation+magnetic field can power objects called pulsars.
- Acceleration of high energy particles along magnetic poles.
- If magnetic axis passes close enough to observer’s line of sight, we see a pulsar. (a lighthouse of high energy particles, radiation)