

CH2. An Overview of Stellar Evolution

September 04, 2012

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ASTR730 / CSI661
Fall 2012

Outline

- **Part 1 ---- Basics (ASTR101)**
 - HR Diagram
- **Part 2 ---- Life Cycle of a Star (CH2.1 – CH2.8)**
 - Young Stellar Objects
 - Zero-Age Main Sequence (ZAMS)
 - Leaving the Main Sequence
 - Red Giants and Supergiants
 - Helium Flash ($M < 1.5 M_{\odot}$)
 - Later Phases ($M < 6 - 10 M_{\odot}$)
 - Advanced Phase ($M > 6 - 10 M_{\odot}$)
 - Core Collapse and Nucleosynthesis
- **Part 3 --- Variable and Explosive Stars(CH2.9 – CH2.14)**
 - Variable Stars
 - Explosive Variables: Novae and Supernovae
 - Exotic Stars: White dwarfs, neutron stars and black holes
 - Binary Stars
 - Star Formation

Overview – Part 2

- Part 2 ---- Stellar Evolution
 - Young Stellar Objects
 - Zero-Age Main Sequence (ZAMS)
 - Leaving the Main Sequence
 - Red Giants and Supergiants
 - Helium Flash ($M < 1.5 M_{\odot}$)
 - Later Phases ($M < 6 - 10 M_{\odot}$)
 - Advanced Phase ($M > 6 - 10 M_{\odot}$)
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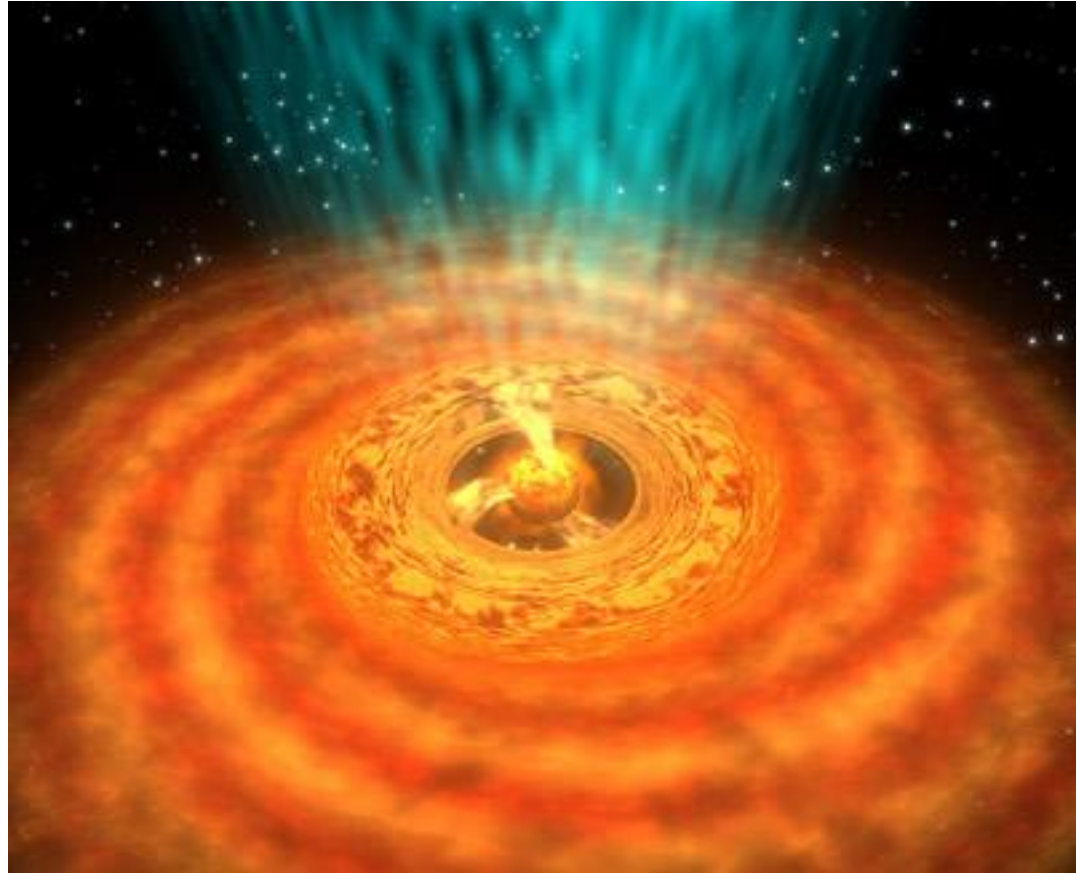
References:

1. CH2.1, CH2.2, CH2.3, CH2.4, CH2.5, CH2.6, CH2.7, CH2.8

(2.1) Young Stellar Objects

Four stages of star formation

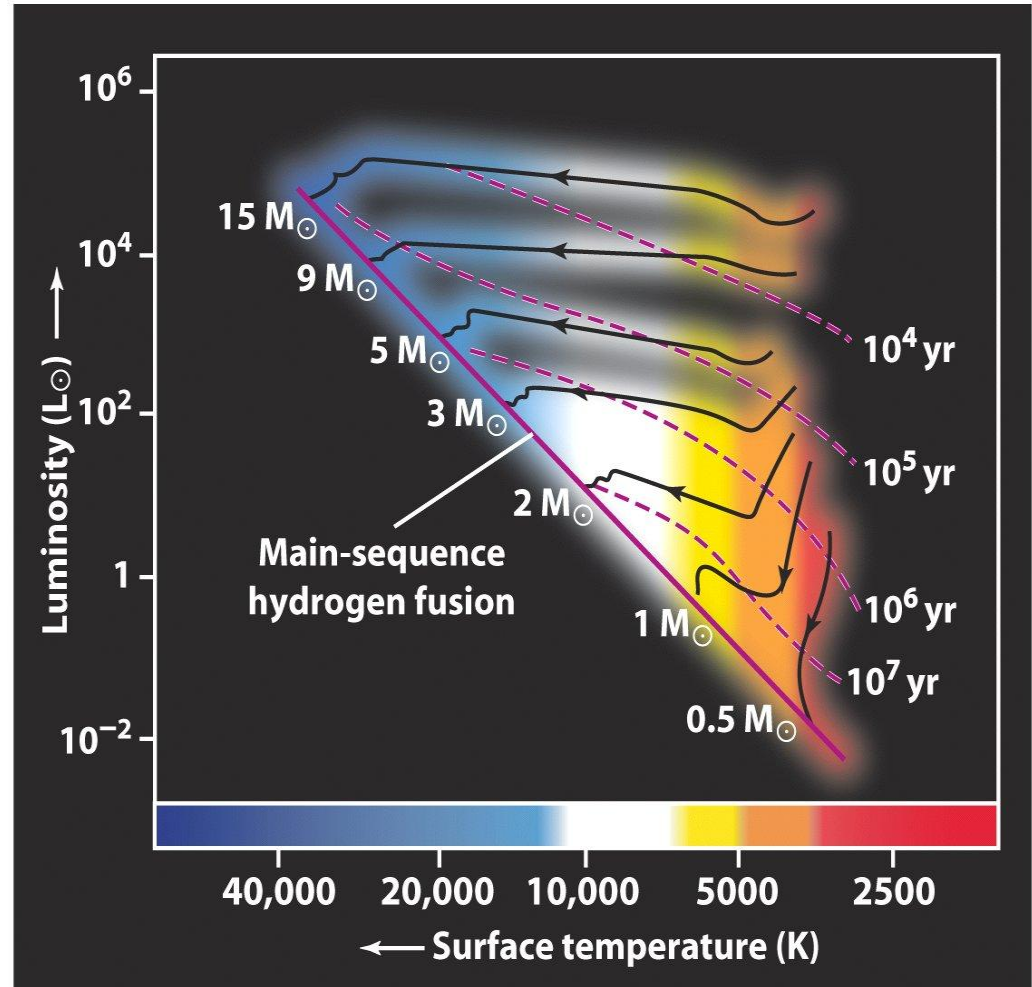
1. Form proto-star core within molecular cloud
2. Core grows from surrounding rotating disk
3. Bipolar flow along rotation axis
4. New star clears away the surrounding nebular material



http://www.skyofplenty.com/wp-content/uploads/2008/09/esa_-_star_formation1.jpg

(2.1) Young Stellar Objects

- Energy source for a proto-star is gravitational potential energy.
- The contract life is about 0.1% its potential nuclear life at the main sequence
- Proto-stars are convective throughout, thus a new star is chemically homogeneous



Proto-star Evolution Track

(2.2) ZAMS

- Zero-age main sequence star: a star just ignites the hydrogen fusion
- In practice, “zero-age” means that the star has changed so little in radius, effective temperature and luminosity
 - Means a few thousand years for a massive star
 - Means 10 million years for the Sun
 - Means 1 billion years for the least massive stars

(2.2.1) Main Sequence

- Two kinds of nuclear fusion converting H to He
 1. pp-chain
 - for stars less than 1.5 Msun
 2. CNO cycle
 - For stars more than 1.5 Msun, $T_c > 1.8 \times 10^7$ K
 - Fusion is much faster than PP-chain
 - C, N, O act as catalysts

(2.2.1) Main Sequence

- A star with a fusion core and an envelope is in hydrostatic equilibrium
- If there is a perturbation of T , say increasing T , the core expands and cools off, reduce the nuclear energy production; as a result, T goes back to normal
- But slowly, because of $P=nKT$, as number density decreases through nuclear fusion
 - Core must slowly contract, become denser and hotter
 - Faster energy generation, more luminous star

(2.2.2) Brown Dwarfs

- Proto-stars which never get hot enough to fuse hydrogen to helium
- The brown dwarf/main sequence cut is about $0.085 M_{\text{sun}}$

(2.3) Post-main Sequence

- < 0.05: No ^2D fusion → “planet”
- <0.085: No ^1H Fusion → brown dwarf
- =0.85: Hubble time scale, Helium WD
- <1.50: PP chain, Helium flash, radiative core, Carbon WD
- <5.0: CNO cycle, no He flash, convective core, Carbon WD
- <8.0: planetary nebula, O, Ne, Mg WD
- <25: supernovae, neutron star
- > 25: supernovae, black hole

Mass Cut versus star fate (also see Fig. 2.4)

(2.3.1) Cluster HR Diagram

- Stars in a cluster form at nearly the same time
- “TOP” turnoff point can be used to determine the age of a cluster
- SGB: sub-giant branch
- RGB: red-giant branch
 - H-shell burning
- Horizontal Branch
 - Helium core burning
- AGB: Asymptotic Giant Branch
 - Helium shell burning
 - Variable stars caused RR Lyrae
 - by thermal instability

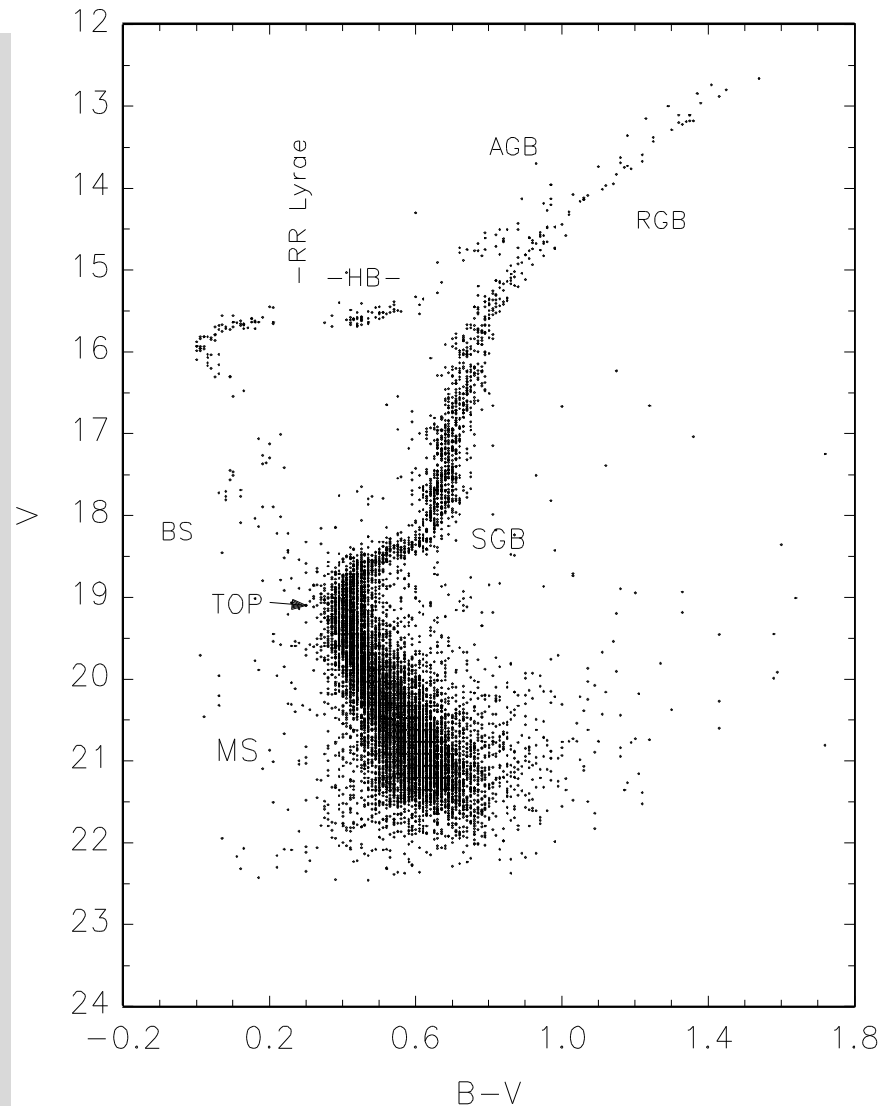


Fig. 2.7. HR diagram of globular cluster M3

(2.3.1) Cluster HR Diagram

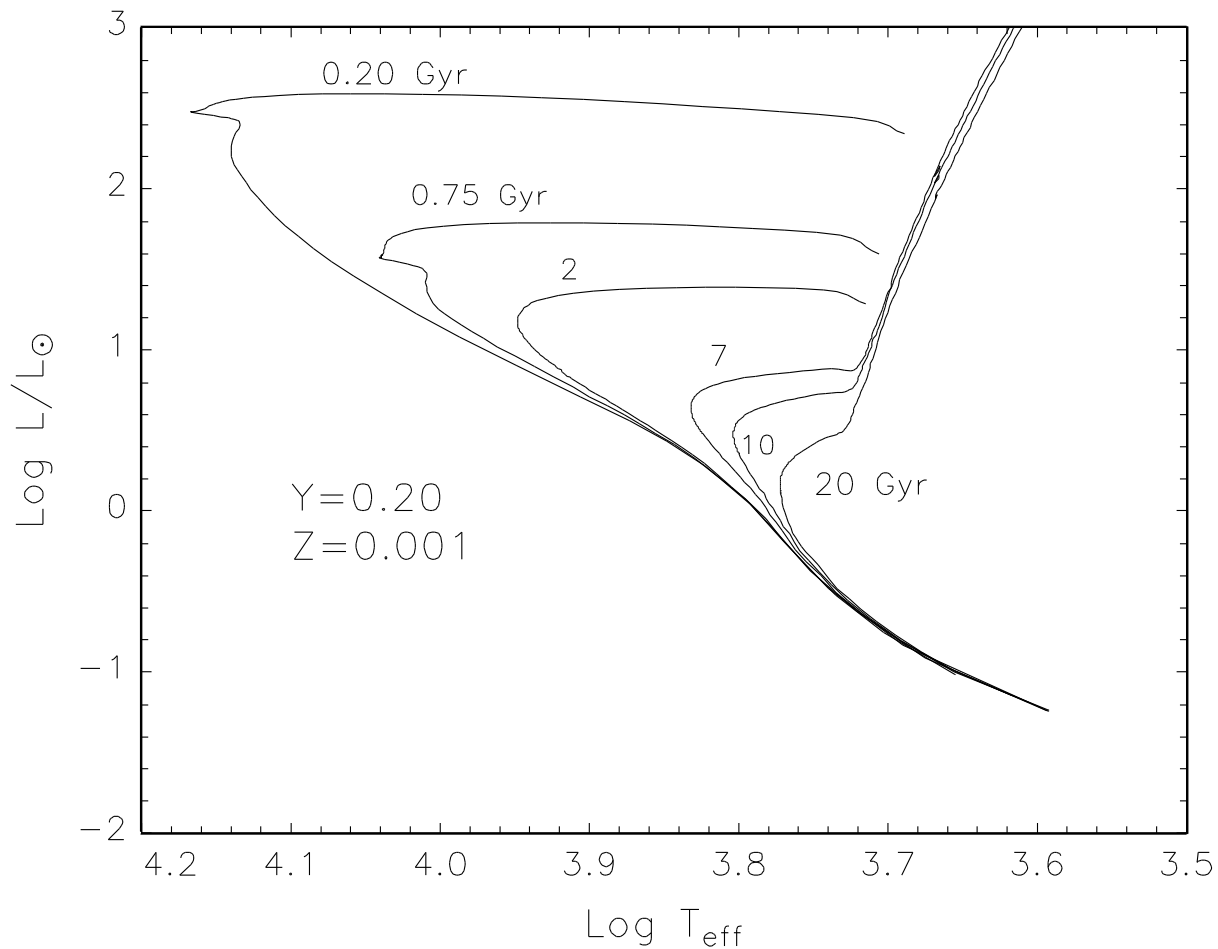


Fig. 2.8: theoretical HR for clusters

(2.4) Red Giants

- The stage that hydrogen shell burning ignites
- The shell burning adds helium ash into the core, causing the dormant core to contract
- The shell burning causes the outer envelope to expand and thus cooling, producing red giants
- The hydrogen shell burning occurs via the CNO cycle, the main source of N in the universe

(2.5) Helium Flash

- Core contracts, and density increases
- Core becomes degenerate, that is the electron degeneracy pressure is larger than the gas thermal pressure

$$P_e = 1.004 \times 10^{13} \left(\frac{\rho}{\mu_e} \right)^{5/3} \text{ dyne cm}^{-2}$$

- Degeneracy pressure is caused by the electron momentum associated with the Heisenberg uncertainty principle ($\Delta x \Delta p = \hbar$). It is also associated with Pauli-exclusive principle

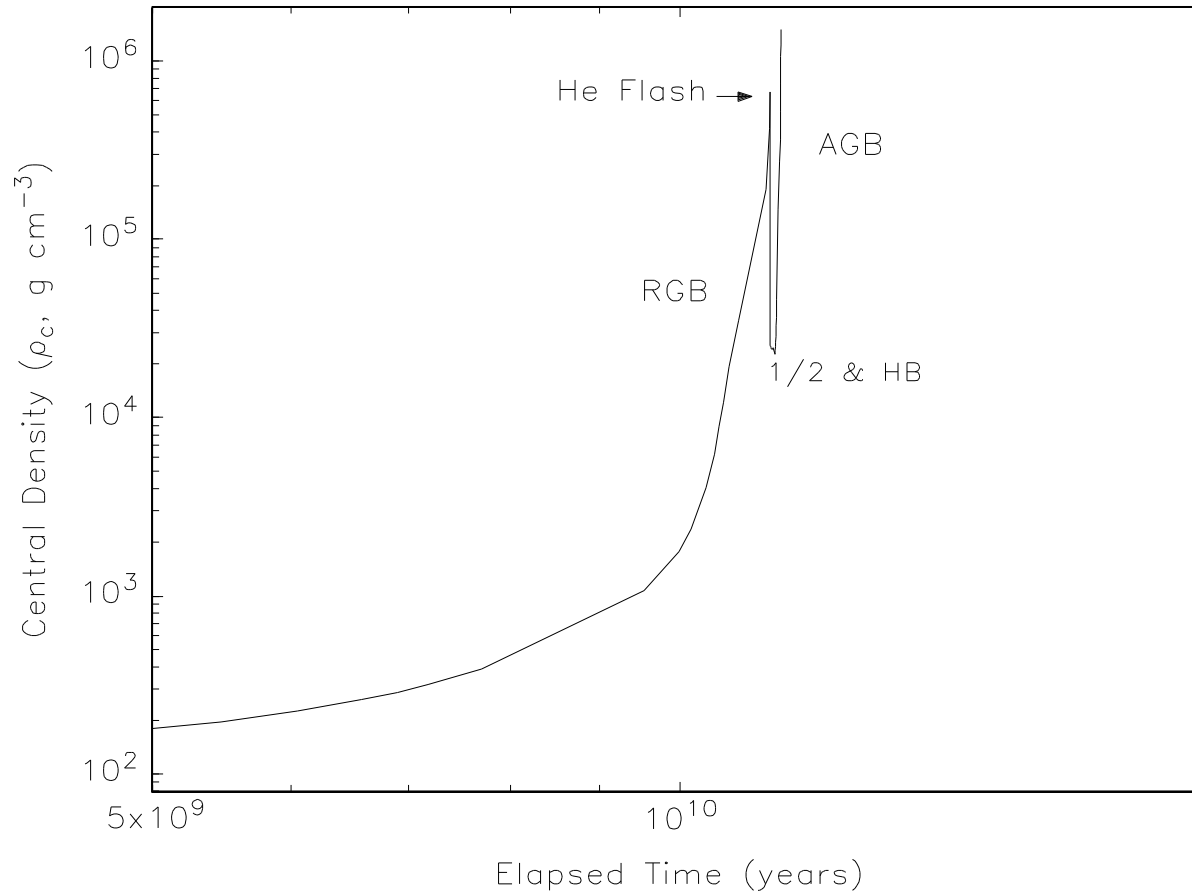
(2.5) Helium Flash

- Star $M < 0.4 M_{\text{sun}}$
 - core degenerate ($\rho > 10^6 \text{ g cm}^{-3}$)
 - low temperature ($< 10^7 \text{ K}$)
 - no further helium burning, produce helium white dwarf
- Star $M > 1.5 M_{\text{sun}}$
 - core not degenerate ($\rho < 10^6 \text{ g cm}^{-3}$)
 - high temperature ($> 10^8 \text{ K}$), ignite helium burning
 - Peaceful transition to helium burning
- Star $0.4 M_{\text{sun}} < M < 1.5 M_{\text{sun}}$
 - core degenerate ($\rho > 10^6 \text{ g cm}^{-3}$)
 - As temperature reaches $> 10^8 \text{ K}$
 - **helium flash: one explosive nuclear reaction**

(2.5) Helium Flash

- For a degenerate gas, the ignition of helium burning will heat the gas, but do not cause expand
- The increased temperature makes the reaction go faster, which further heats the gas, which makes the reaction goes faster.
- This cycle of explosive nuclear reaction continues until temperature is high enough so that thermal pressure exceeds degenerate pressure.
- After helium flash, the core expands to a density about 10^3 g cm^{-3}
- It is mirrored by envelope contraction
- Luminosity decreases, and effective temperature increases; the star heads to the left in the HR diagram

(2.5) Helium Flash



**Density Evolution for model
1 Msun, $z=0.02$**

(2.5.1) Horizontal Branches (HB)

- Giant stars with
 - Helium burning in the core
 - Through triple- α reaction
 - $3^4\text{He} \rightarrow ^{12}\text{C}$ and $^{12}\text{C} (^4\text{He}, \gamma)^{16}\text{O}$
 - Hydrogen burning in the surrounding shell through CNO cycle

(2.5.2) Asymptotic Giant Branches (AGB)

- When helium core is exhausted, HB star becomes AGB
- The C-O core contracts and heats up
- Double shell burning
 - Helium burning in the shell surrounding the core
 - Hydrogen burning in the shell surrounding He shell
- The second red giant phase

(2.5.2) AGB

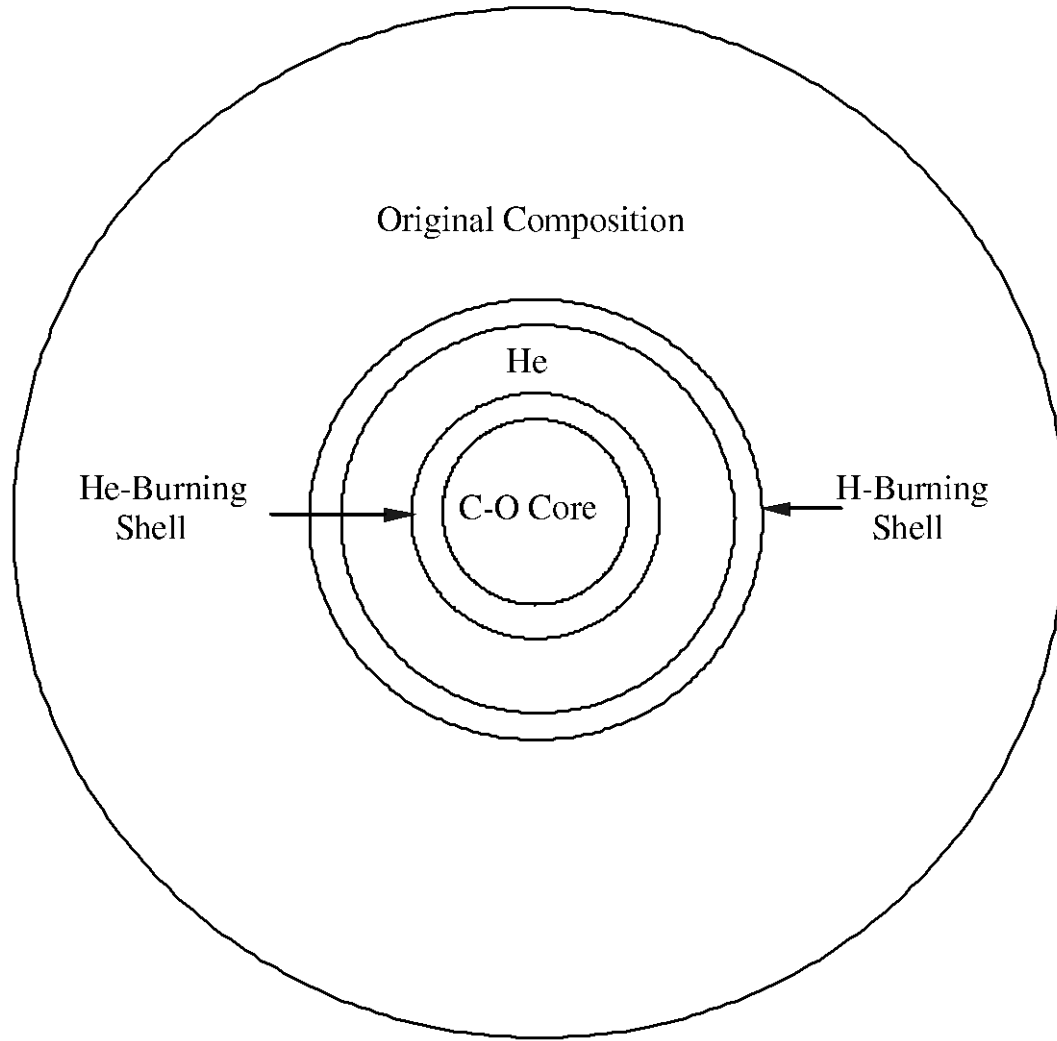
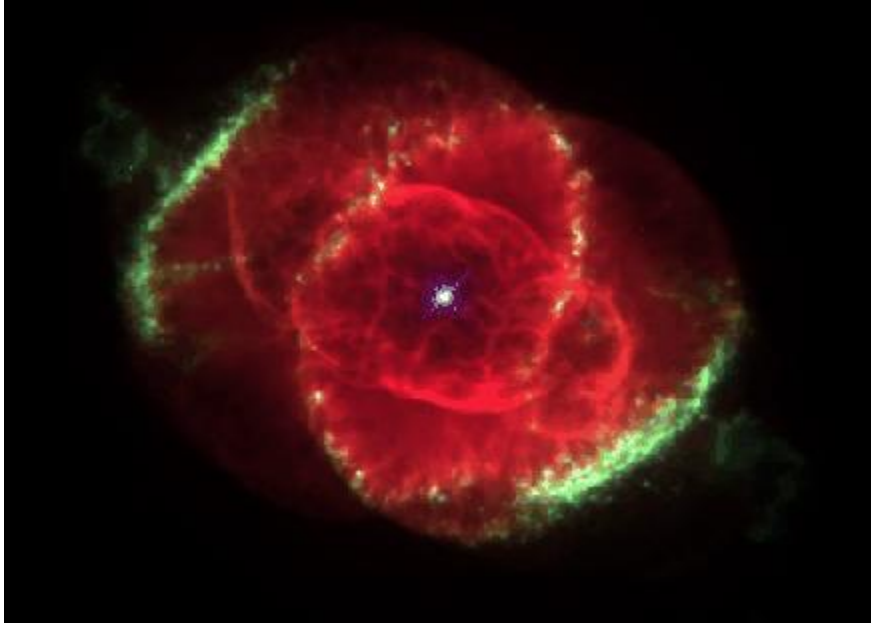


Fig. 2.14. Double Shell Burning

(2.6) Later Phases, Initial Masses < 6-10 Msun

- During the Giant star phases, a star may lose a large fraction of mass through
 - Super wind
 - Pulsation
- The blown-off envelope becomes planetary nebula (PN)
- The residual core becomes a white dwarf
 - Composition: Carbon-oxygen
 - Mass: 0.55 – 1.3 Ms
 - Radius: 10^{-2} Rsun, or the size of the Earth
 - Energy source: residual heat of the atomic nuclei
 - Luminosity: 10^{-5} Lsun
 - Fading time: 10^{10} years

(2.6) Planetary Nebula



NGC 6543



IC 418

(2.6.1) White Dwarfs

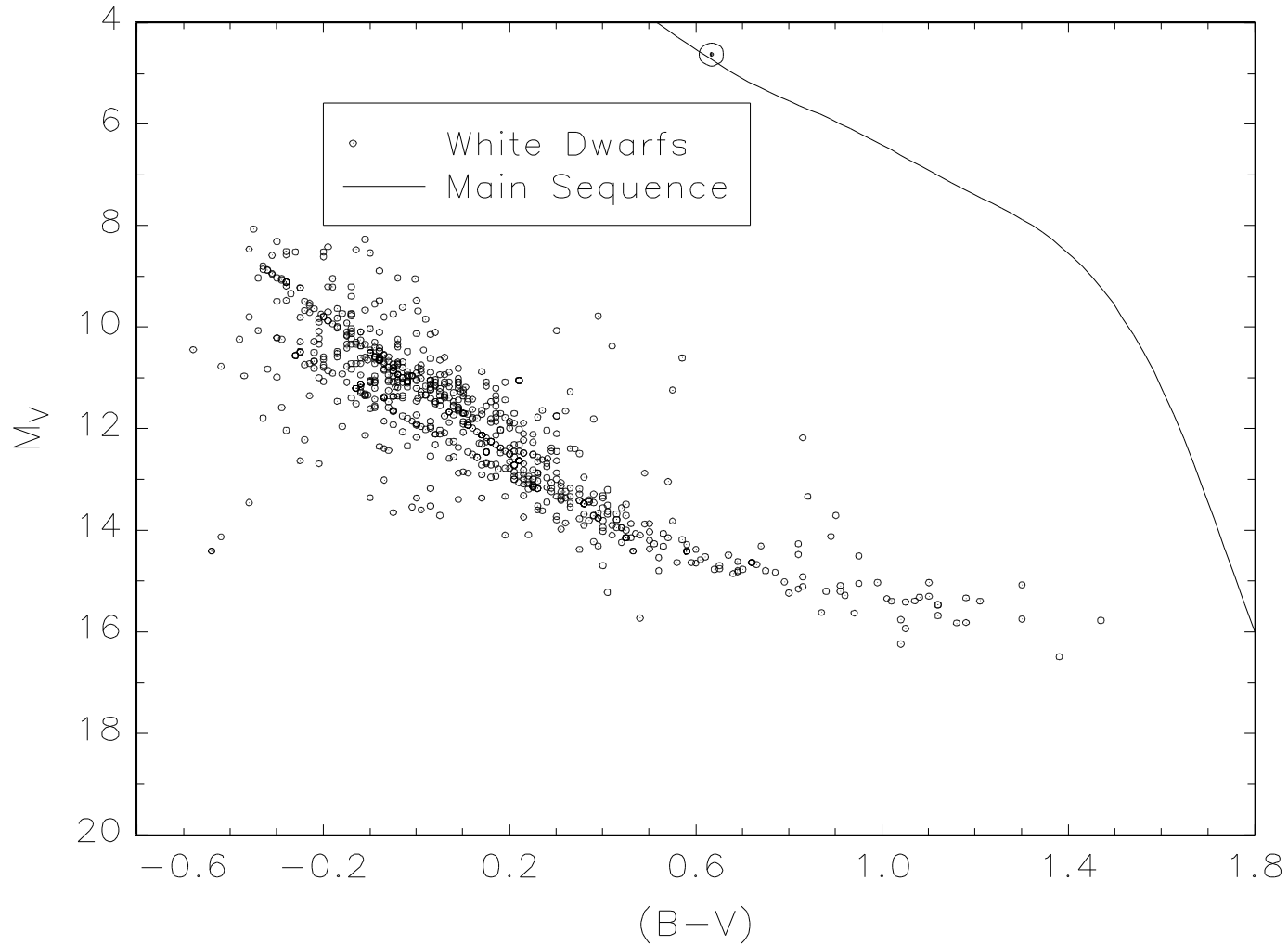
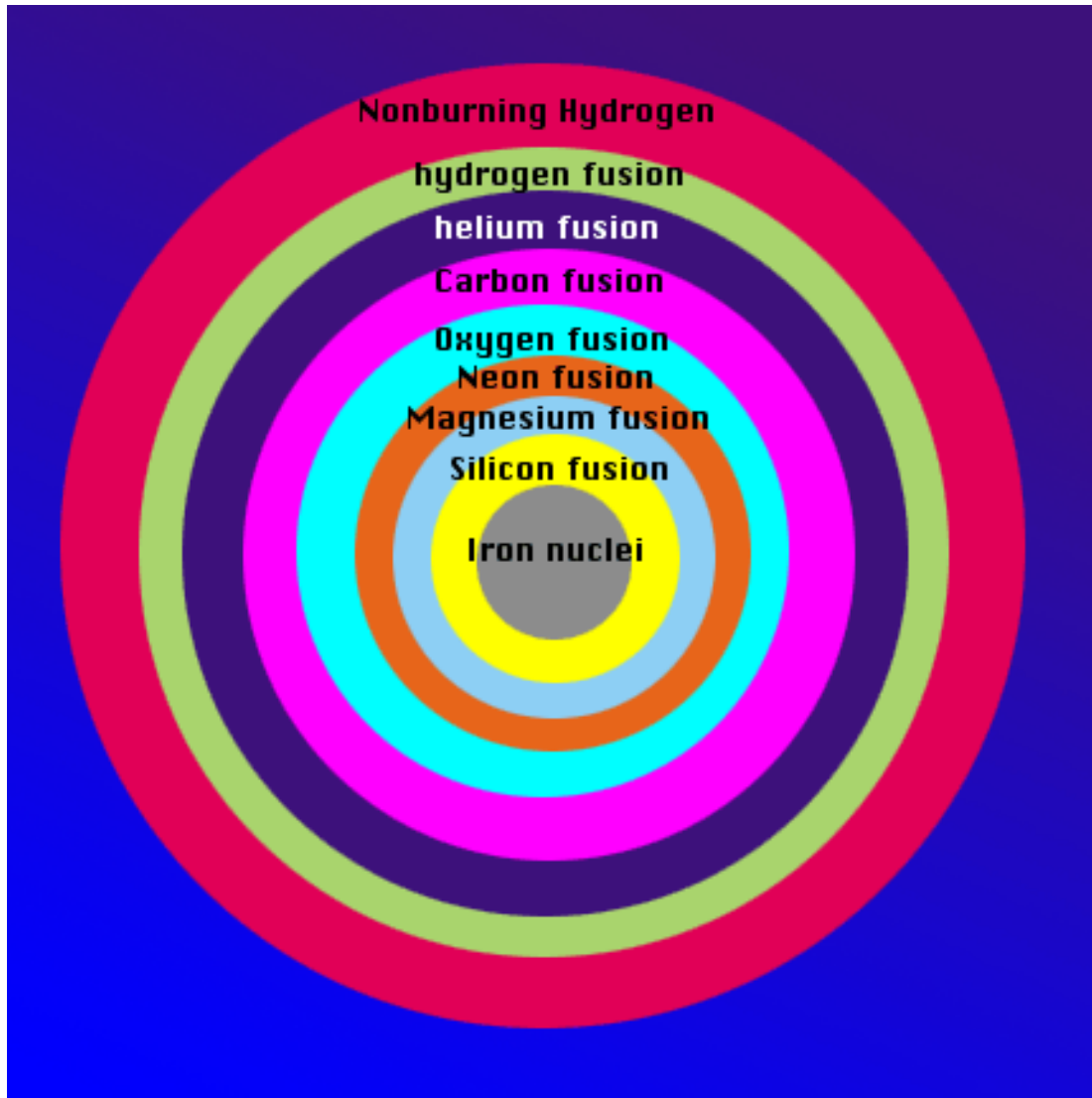


Fig. 2.15. Color-Magnitude HR diagram

(2.7) Advanced Phases, Initial Masses > 6-10 Msun

- The core is hot enough to ignite the burning of carbon and oxygen
 - Carbon burning produces Neon (~ 1000 yrs)
 - Oxygen burning produces Silicon (~ 1 yr)
- Silicon burning produces ^{56}Ni
- ^{56}Ni then beta-decays to ^{56}Fe (days)
- ^{56}Fe is the most tight element, meaning no more energy can be generated by burning ^{56}Fe
- ^{56}Fe ash accumulates in the core
- When the core reaches a critical mass (~ 1.2 Msun), degenerate electron pressure can not support the gravity
- The core collapses, and the star explodes as a supernova

(2.7) Advanced Phases, Initial Masses $> 6-10 M_{\text{sun}}$



**Onion
structure of
nuclear
reaction at the
core of a
massive star**

(2.8) Core Collapse and Nucleosynthesis

Two triggers of core collapse

1. Temperature is high enough, so the photons are able to disintegrate the irons, cool the gas, remove the support of thermal pressure
2. The density is high enough, so that electrons get enough kinetic energy from the quantum effect to exceed the neutron-proton mass difference. Electron capture (inverse beta-decay) sets in, turning protons to neutrons, and the degeneracy pressure drops.

(2.8) Core Collapse and Nucleosynthesis

- The core collapses at the dynamic time scale, i.e. seconds
- For a core of 1.2 Ms contracting from a density of 10^9 cm^{-3} (degenerate electron state, Earth size) to 10^{15} cm^{-3} (neutron star, city size), it releases the gravitational energy in the order of 10^{53} ergs, comparable to the energy released by the Sun over its whole main sequence life.
- The catastrophic consequence is a supernova explosion.
 - The product at the core is a neutral star, or even a black hole (if the degenerate pressure of neutrons can not withhold the gravitational pressure)
 - Heavy elements generated in the core collapse are send into the interstellar space through the explosion

(2.8) Core Collapse and Nucleosynthesis

- Heavy elements ($Z=30$ and beyond) are generated in the process of core collapse
- There is a “soup” of iron-peak elements, neutrons and protons.
- “r-process” (r stands for “rapid”): a neutron capture process that successive neutrons are captured before there is time for beta decays. The immediate products are highly unstable nuclides. But, they decay back to the neutron-rich stable isotopes of heavy elements like tungsten (W, 74, 183), Radon (Rn, 86, 222), and uranium (U, 92, 238)

End

Note: This is the end of the part 2 of the overview.

Part 3 covers variable stars and explosive stars such as novae and supernovae

Part 3 is subject to self-study.