Stellar Evolution
Stellar Aging & Star Death

Background: Static Stellar Structure

Basic Principles

Energy & Mass Conservation
"Mechanical Equilibrium"
"Thermal Equilibrium"
"Energy Equilibrium"

Energy Production

Thermonuclear Reactions
(Gravitational Contraction)

Energy Transport

Radiation
Convection
(Conduction)

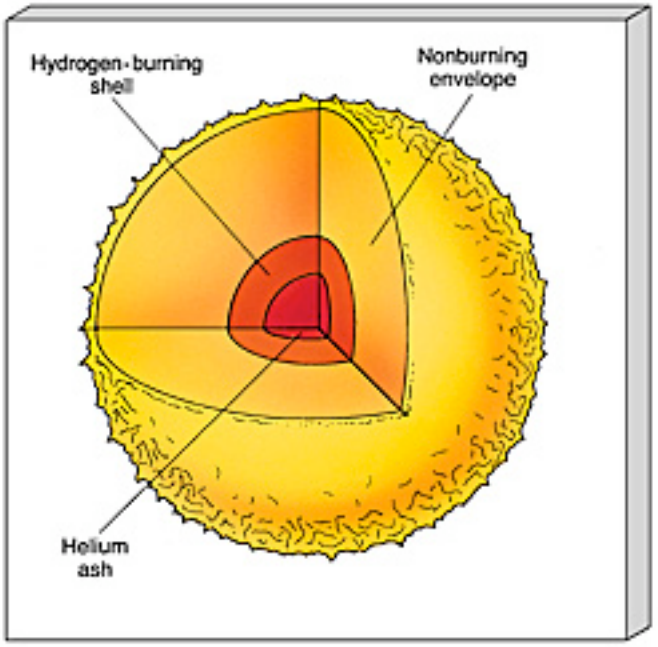
An Overview of Stellar Structure

Pressure, Density, and Temperature Gradients
Core Energy Production & Energy Transport

Red Giants & Supergiants

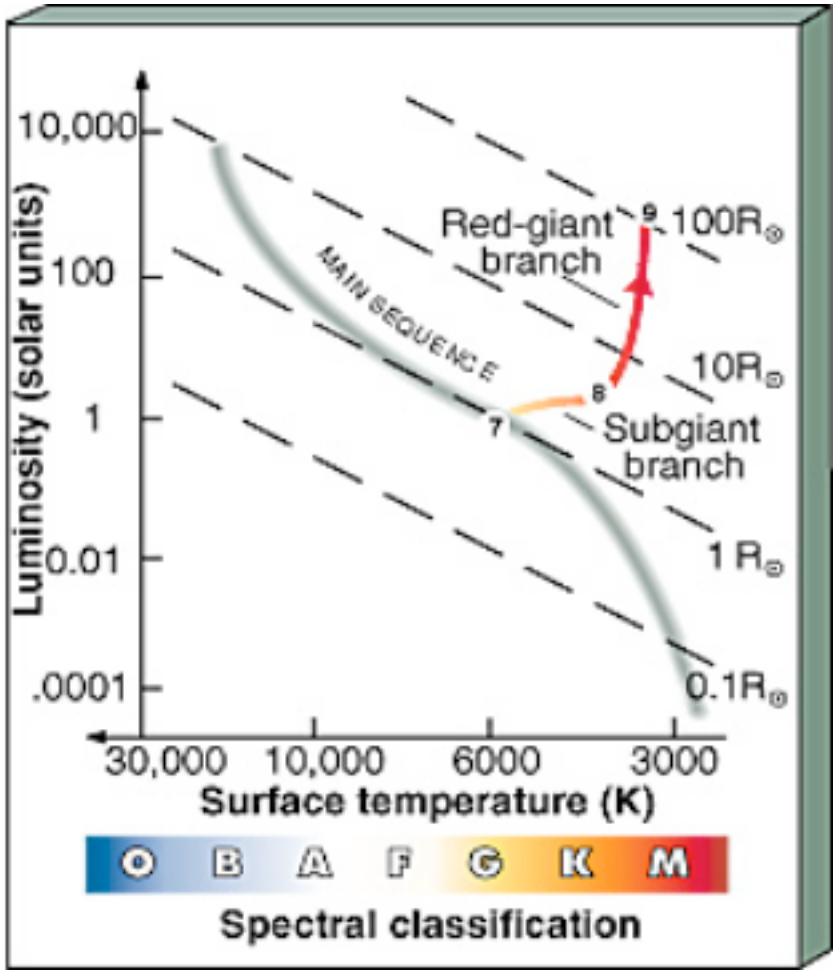
Main Sequence Stars

"Hydrogen Burning"
... towards hydrogen exhaustion
... and a growing helium core



Red Giants and Supergiants

A contracting (and heating) helium core
Hydrogen "shell burning"
Envelope expansion



"Helium Burning"

The Triple-Alpha (3α) Process

$$_2He^4 + {}_2He^4 \leftrightarrow {}_4Be^8 + \gamma$$

$$_4Be^8 + {}_2He^4 \rightarrow {}_6C^{12} + \gamma$$

... and a growing carbon core.

A Helium Burning Main Sequence

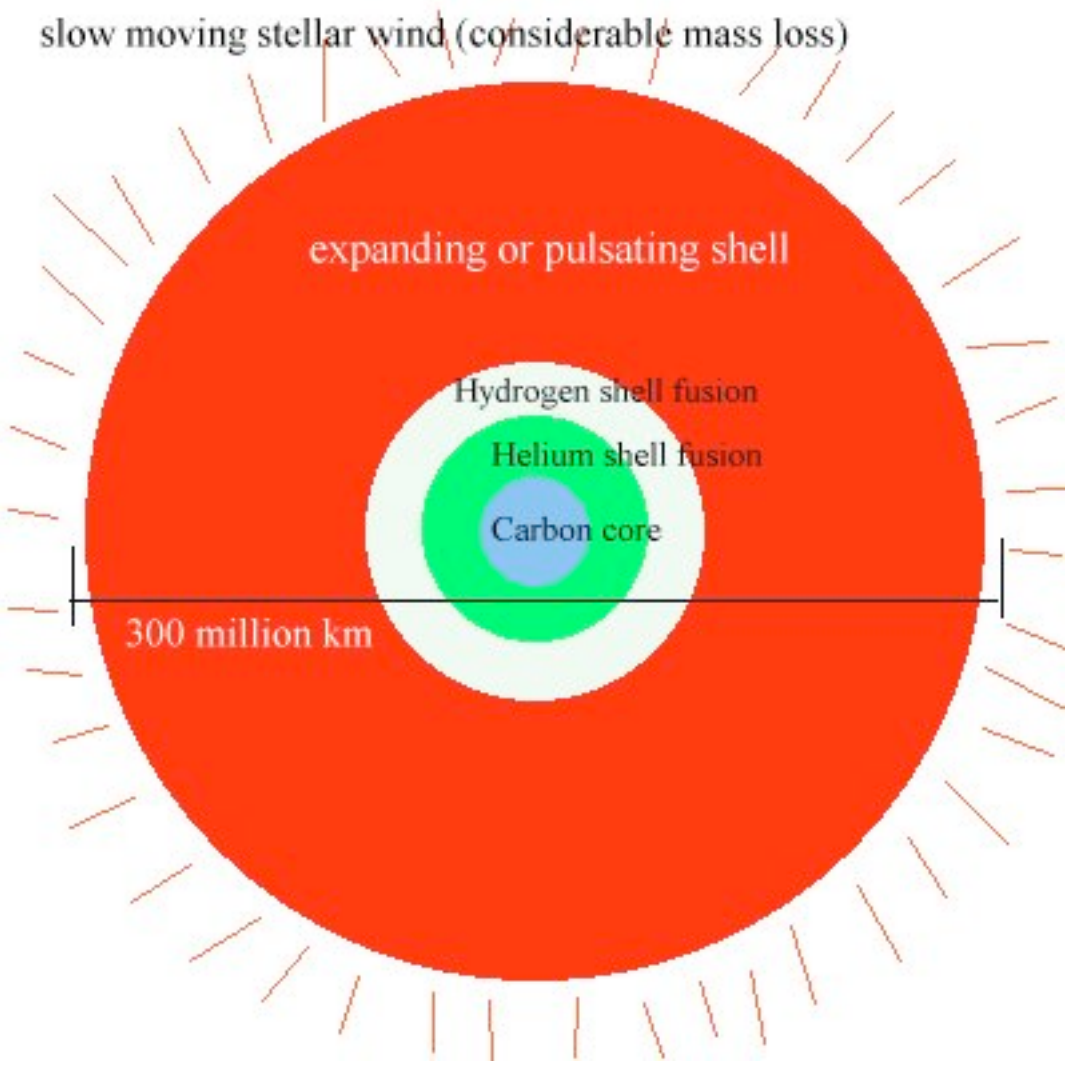
A Second Ascent of the Giant Branch

Stellar Winds and Mass Ejection

Subsequent Evolution?

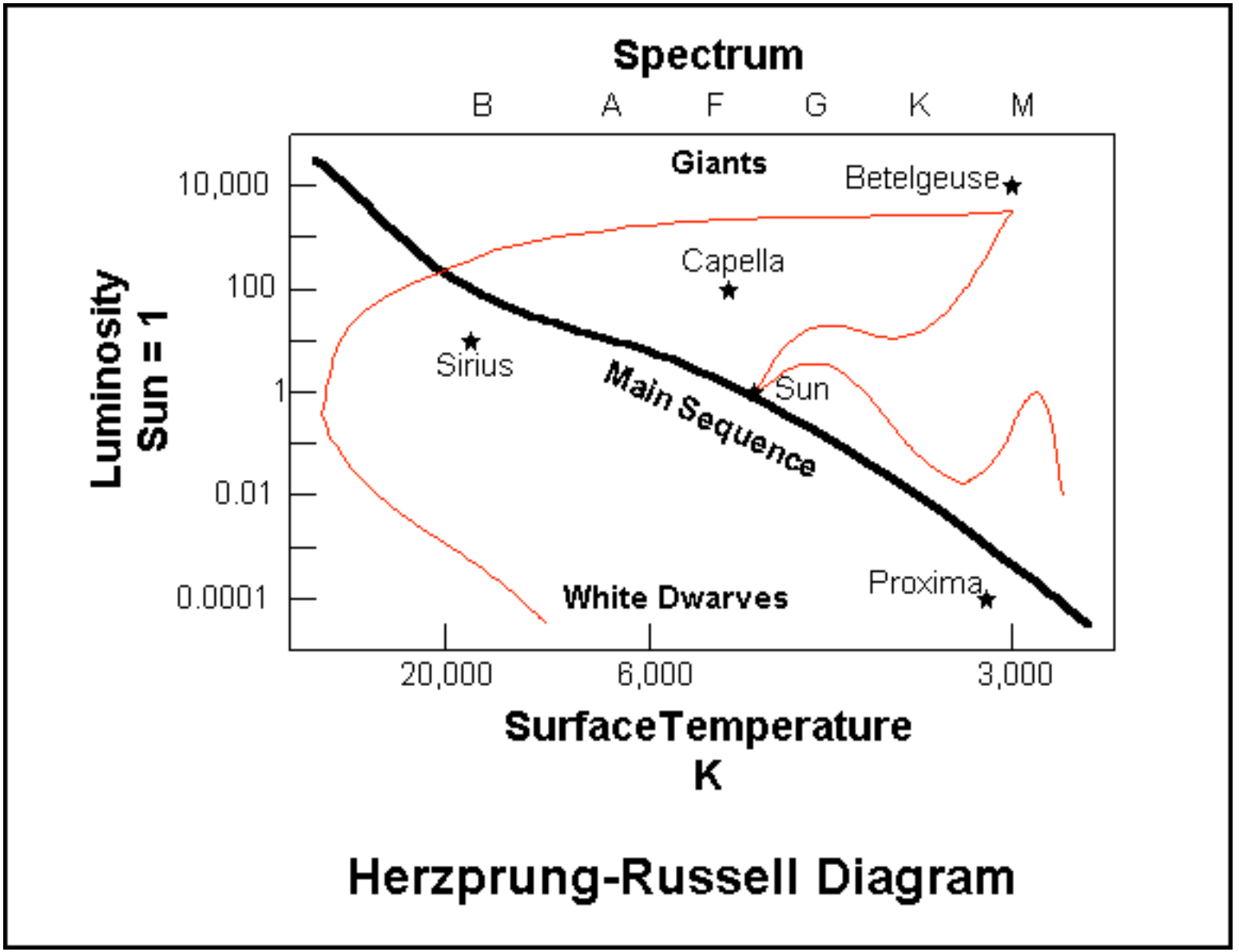
... and heavier element production ...

The Structure of Helium Burning Red Giants

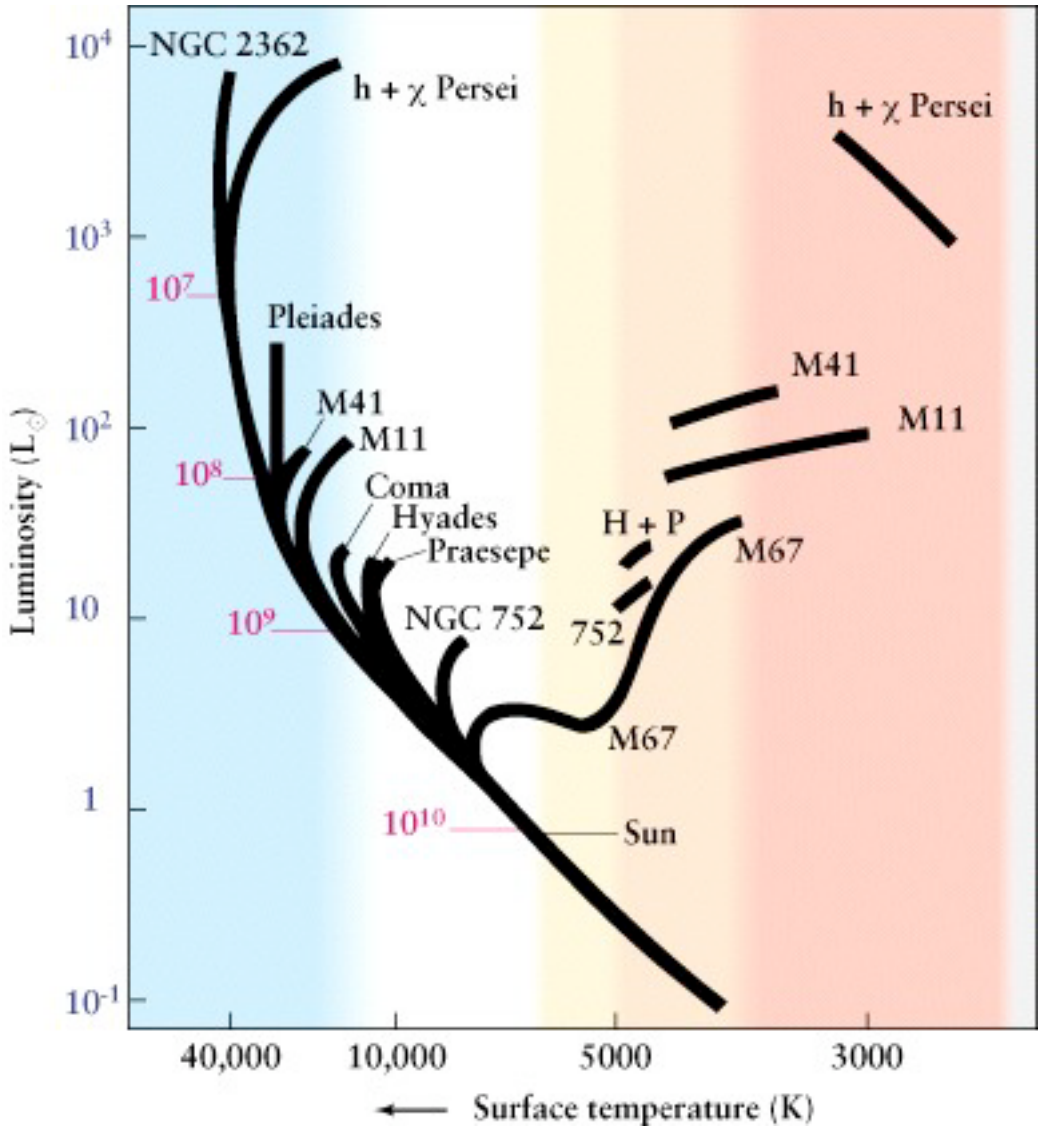


Note: 300 million km is 2 astronomical units

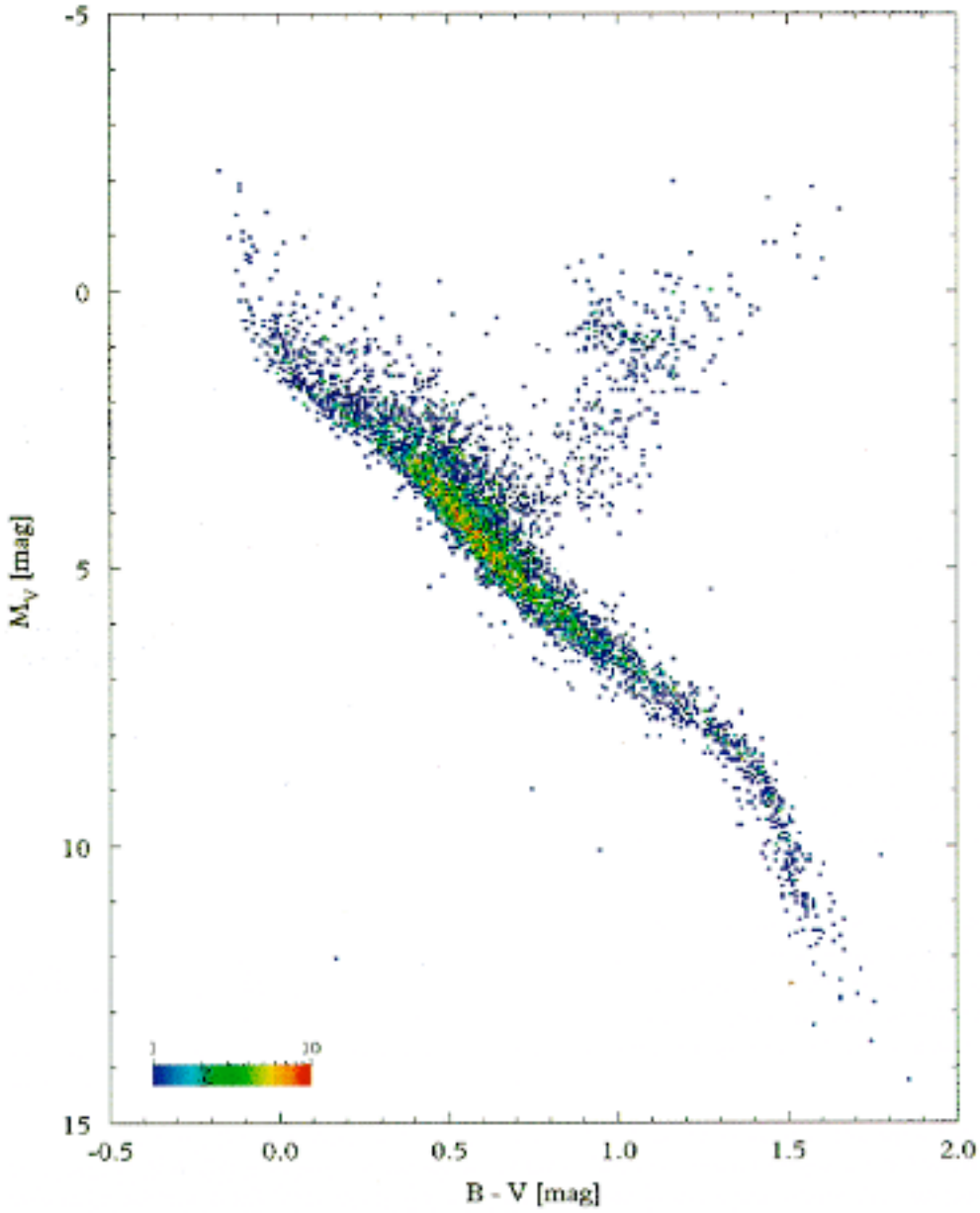
FROM BIRTH TO DEATH: The Evolution of the Sun



Testing the Model: Star Clusters of Different Ages



A Mixed-Age Population (Hipparchos Stars)



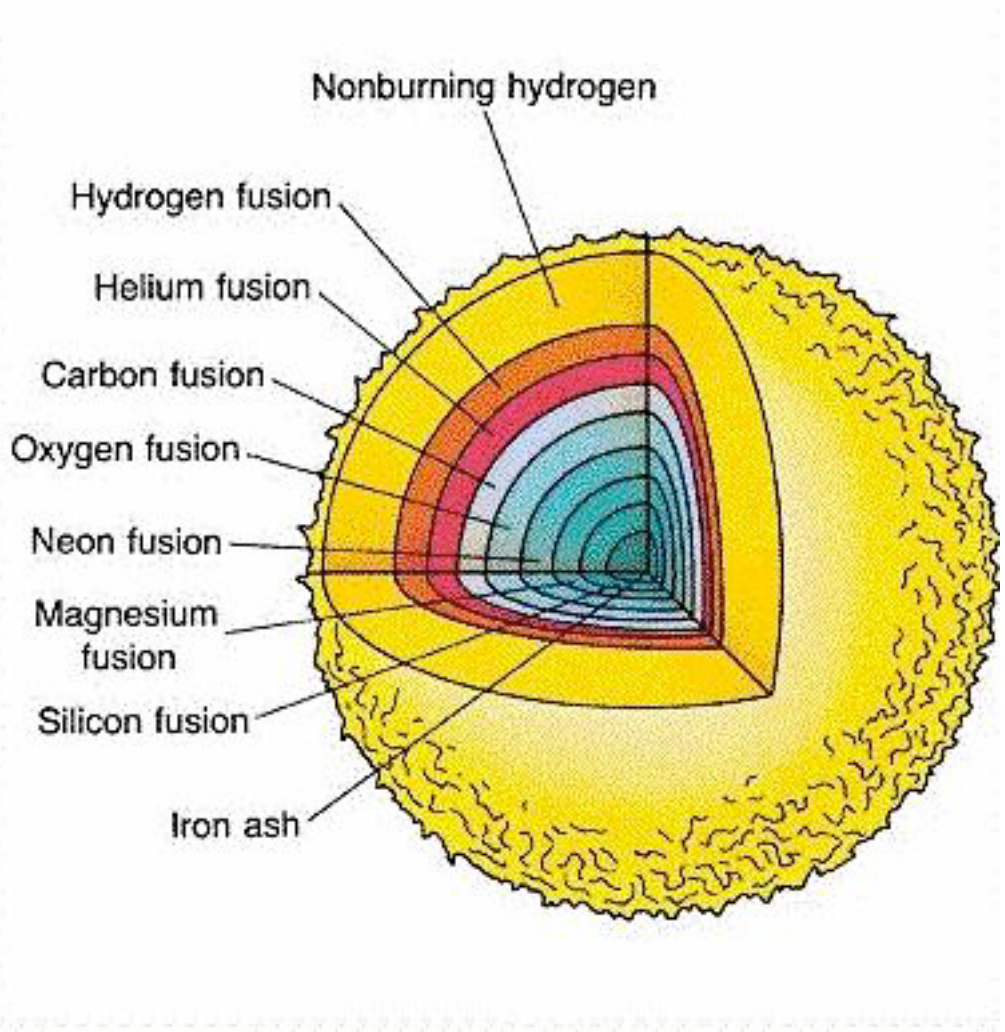
Stellar Corpses

Review, Overview & Preliminaries
Star Formation
Main Sequence: “Hydrogen Burning”
Giant Branch: Hydrogen Exhaustion
Giant Branch: “Helium Burning”
... a Helium Main Sequence?
A Return to the Giant Branch
... Carbon Burning?
Subsequent Cycles

Stars of Moderate Mass (0.1 M_{Sun} to 8 M_{Sun})
Envelope Ejection: Planetary Nebulae
White Dwarfs

Massive Stars (M > 8 M_{Sun})
Explosive Ejection: The Iron Limit
Supernovae & Heavy Element Production
Neutron Stars & Black Holes

A Massive Star Approaching the Supernova Stage



.... and then....

Necrophilia:
The Structure of Stellar Corpses

The Anatomy of White Dwarfs

Equilibrium: Pressure and Gravity

The Exclusion Principle & Electron Degeneracy

$P_{gas} = n_{gas}kT$ *versus* $P_e = Kn_e^{5/3}$

The Structure of White Dwarfs
(Size, Mass, Density & Conduction)

$R_{wd} \sim 0.01\ R_{Sun}$ but $M_{wd} \sim 1\ M_{Sun}$

$\rho_{wd} \sim 10^6$ gm/cm^3

The Chandrasekhar Limit: $M_{max} = 1.44\ M_{Sun}$

The Anatomy of Neutron Stars

Neutron Decay

$$_0n^1 \rightarrow {}_1H^1 + e^- + \nu^*$$

or the reverse

$$_1H^1 + e^- \rightarrow {}_0n^1 + \nu$$

The Exclusion Principle & Neutron Degeneracy

$$P_n = Kn_n^{5/3}$$

The Structure of Neutron Stars
Size, Mass, Density & Conduction

$$R_{ns} \sim 10^{-5}\ R_{Sun} \text{ but } M_{ns} \sim 2 - 3\ M_{Sun}$$

$$\rho_{wd} \sim 3 \times 10^{15}\ \text{gm/cm}^3$$

The Black Hole Limit

Black Holes

Surface Gravity and Escape Velocity

$$v_{esc}^2 = 2GM/R$$

The Schwarzschild Radius

$$v_{esc} = c \ ?$$

$$R_S = 2GM/c^2$$

(c = 300,000 km/s)

Object	Escape Velocity (km/s)	Radius (km)	Schwarzschild Radius (km)
Earth	11	6,738	0.00001 (1 cm)
Sun	620	700,000	2.95
White Dwarf	6,200	7,000	3
Neutron Star	280,000	7	6

Digression: Photon Trajectories & Gravitational Redshifts

Observing Dead Stars

White Dwarfs: Sirius B

0.17 to 1.2 M_{Sun}

Neutron Stars: Binaries & Pulsars

The Crab Nebula

Black Holes & Accretion

X- and γ-Ray Sources