
STELLAR
EVOLUTION

Central Concept:

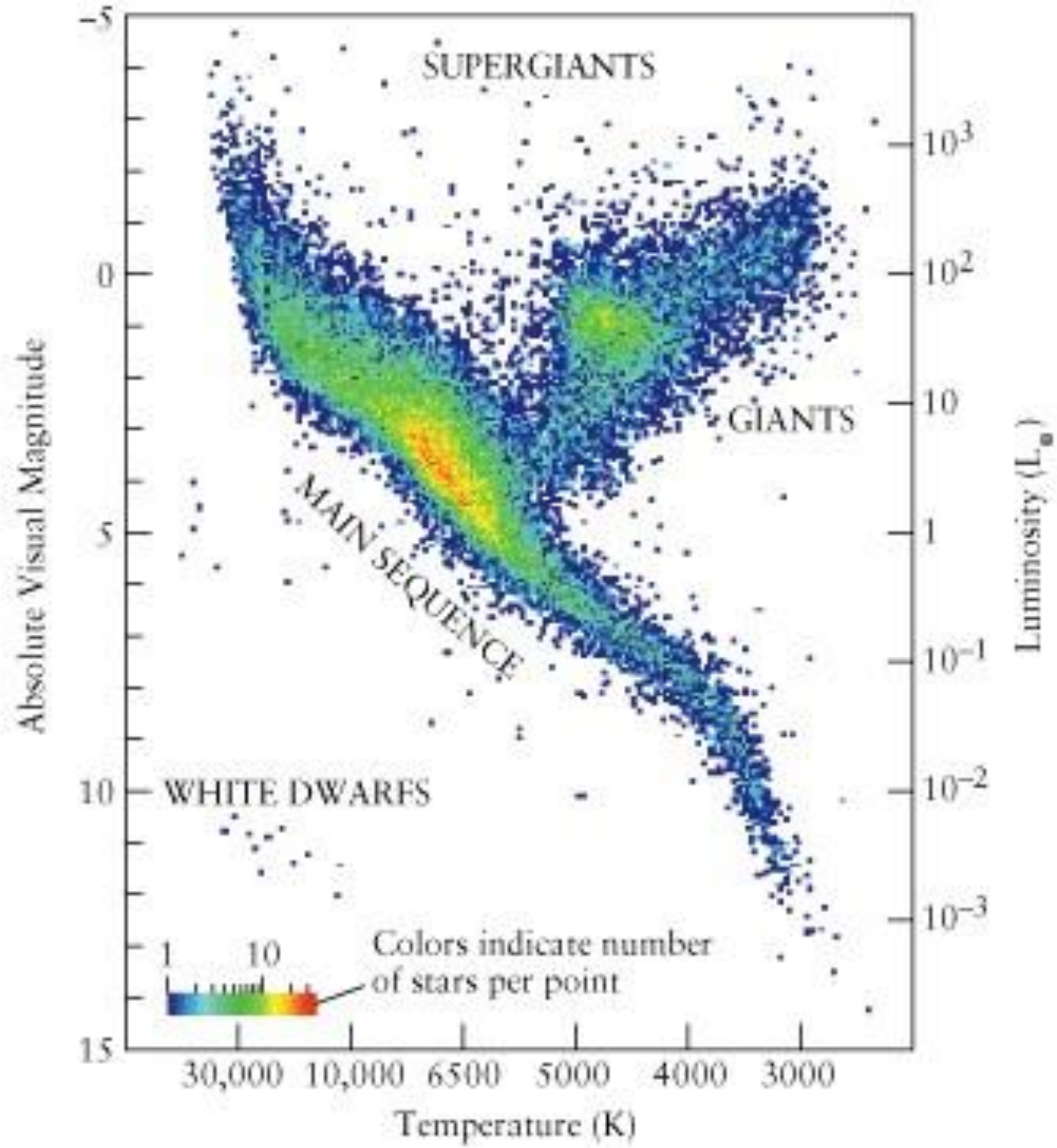
Mass controls the destiny of a star.

Main-Sequence Stellar Properties by Spectral Class

Spectral Class	Temperature (K)	Color	Mass M_{solar}	Luminosity L_{solar}	Lifetime 10^6 yr	Examples
O	>30,000	Electric Blue	>20	>100,000	<2	
B	20,000	Blue	8	3,000	30	Spica (B1)
A	10,000	White	3	75	400	Vega (A0) Sirius (A1)
F	7,000	Yellow-white	1.5	4	4,000	Procyon (F5)
G	6,000	Yellow	1.0	1.5	9,000	Sun (G2) Alpha Centauri (G2)
K	4,000	Orange	0.5	0.1	60,000	Epsilon Eridani (K2)
M	3,000	Red	0.1	0.005	200,000	Proxima Centauri Barnard's Star (M5)

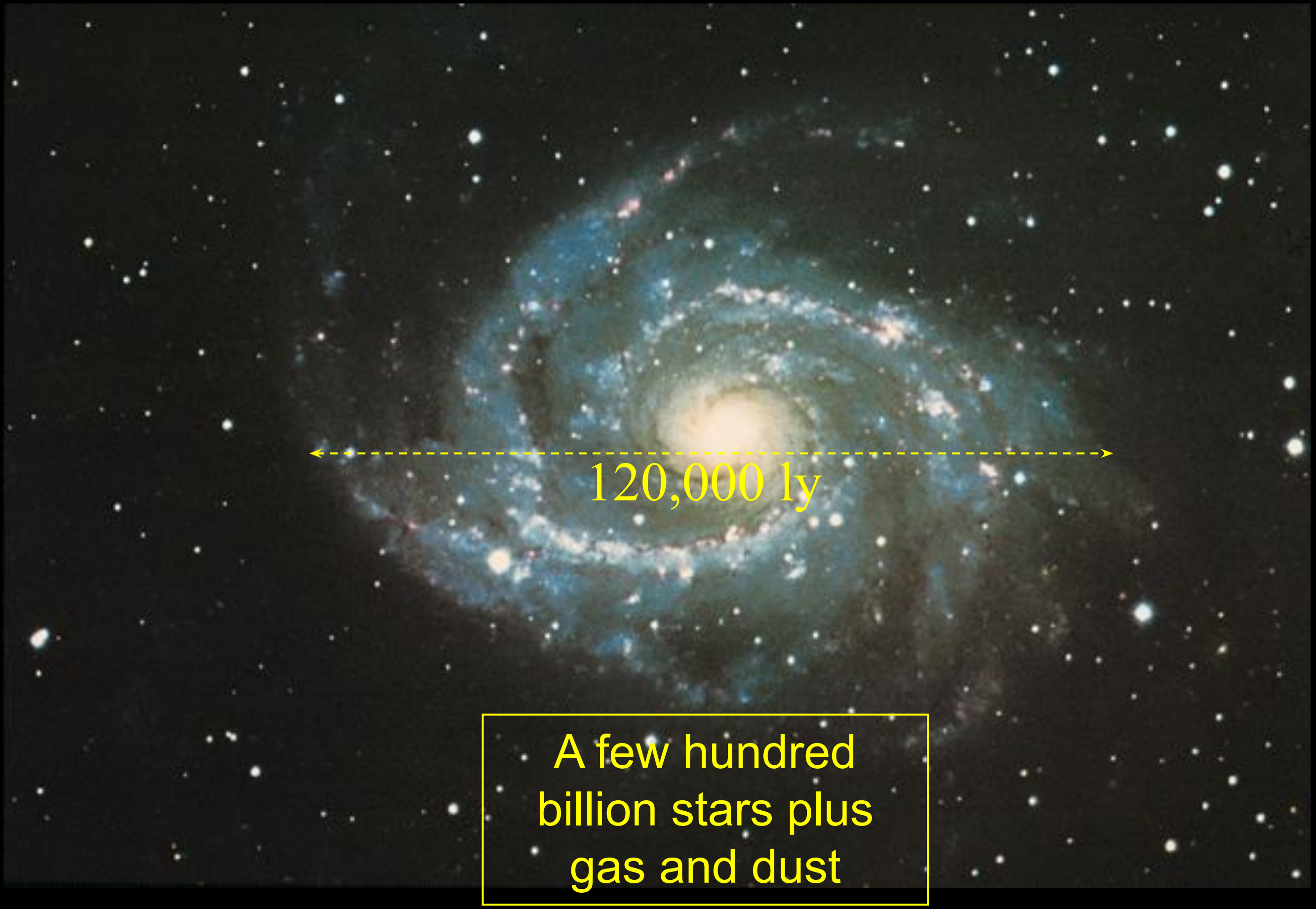
H-R Diagram

Plotted using Hipparcos data of 41,453 stars.

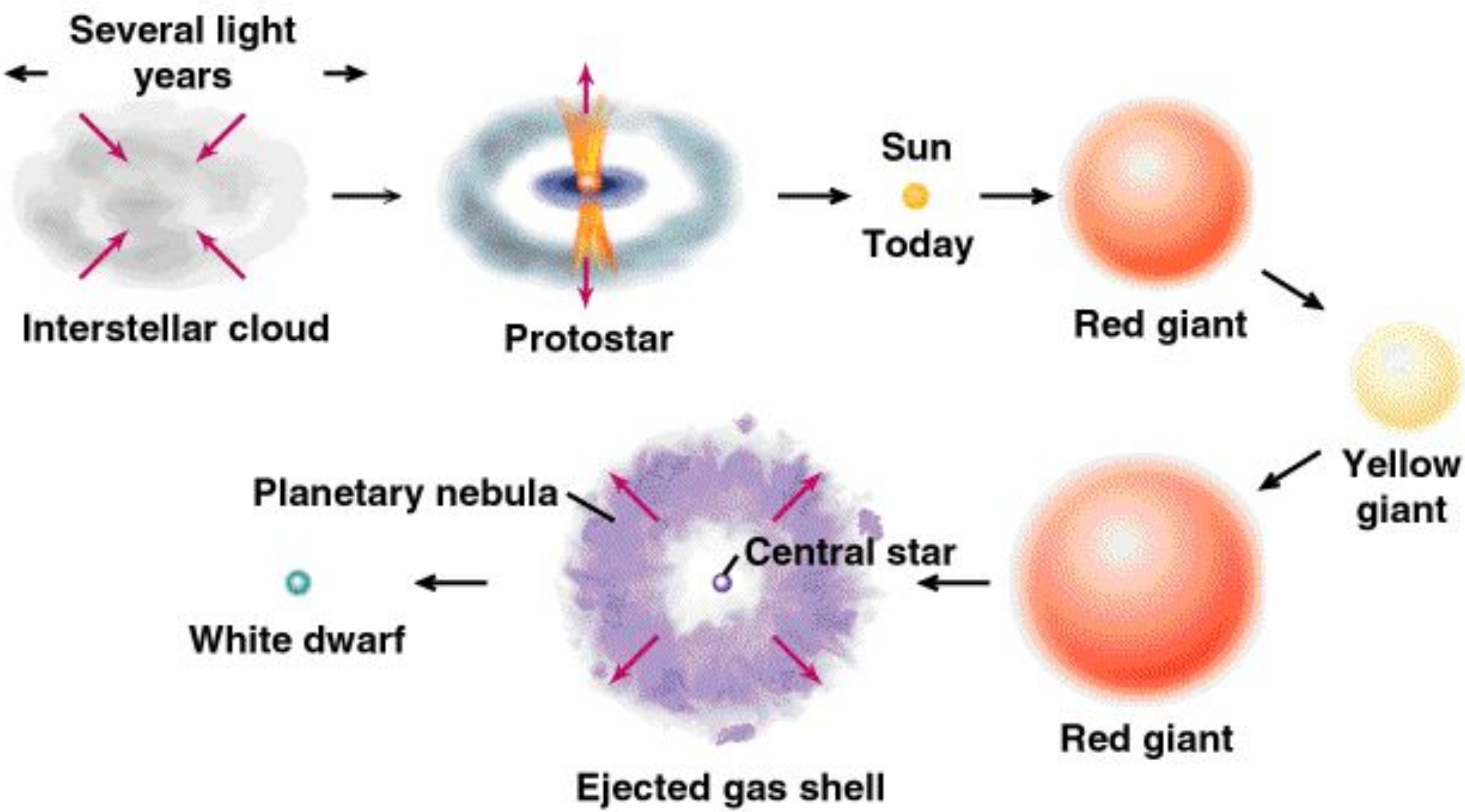


A Spiral Galaxy

(Milky Way Type)

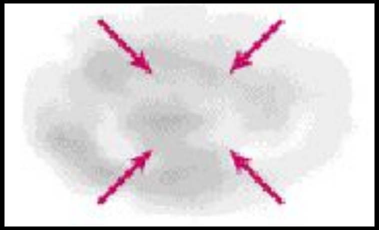


Life of the Sun



Evolution of Low-Mass Stars

1. The Sun began its life like all stars as an interstellar cloud that collapsed.
   - possible causes include
     - Spiral density waves
     - Shockwaves from Supernovae *
     - Galactic Collisions



2. This cloud collapses due to gravity into a dense core. As the cloud collapses, it spins faster (conservation of angular momentum). Rate of collapse is greater nearer the center ($F \sim 1/d^2$).

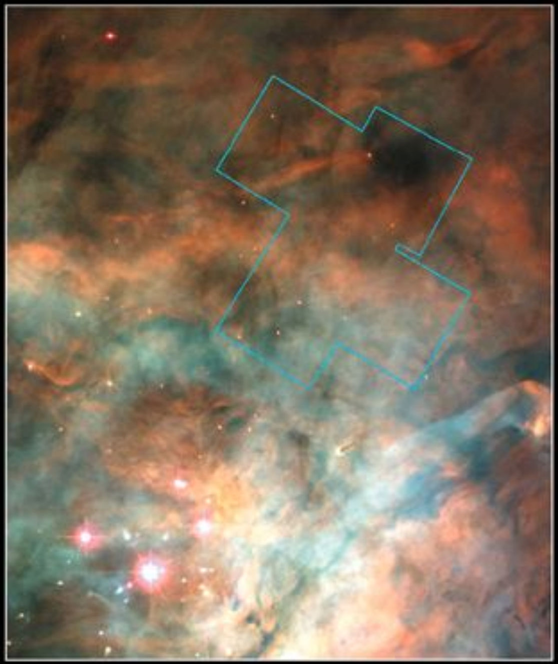
Evolution of Low-Mass Stars

3a. Over the next few million years a <u>protostar</u> forms that is heated by gas compression (ideal gas law: $PV=nRT$).

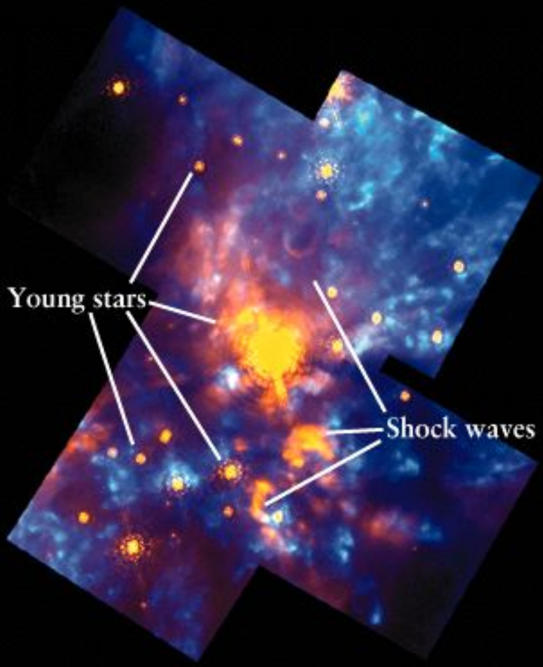
Radius = ~50 R_{sun}
Core Temp = 150,000K
Surface Temp = 3500K
Energy Source = Gravity

Protostar is large and appears red. Shrouded by the nebula, it is only visible in the infrared.

Core of the Orion Nebula

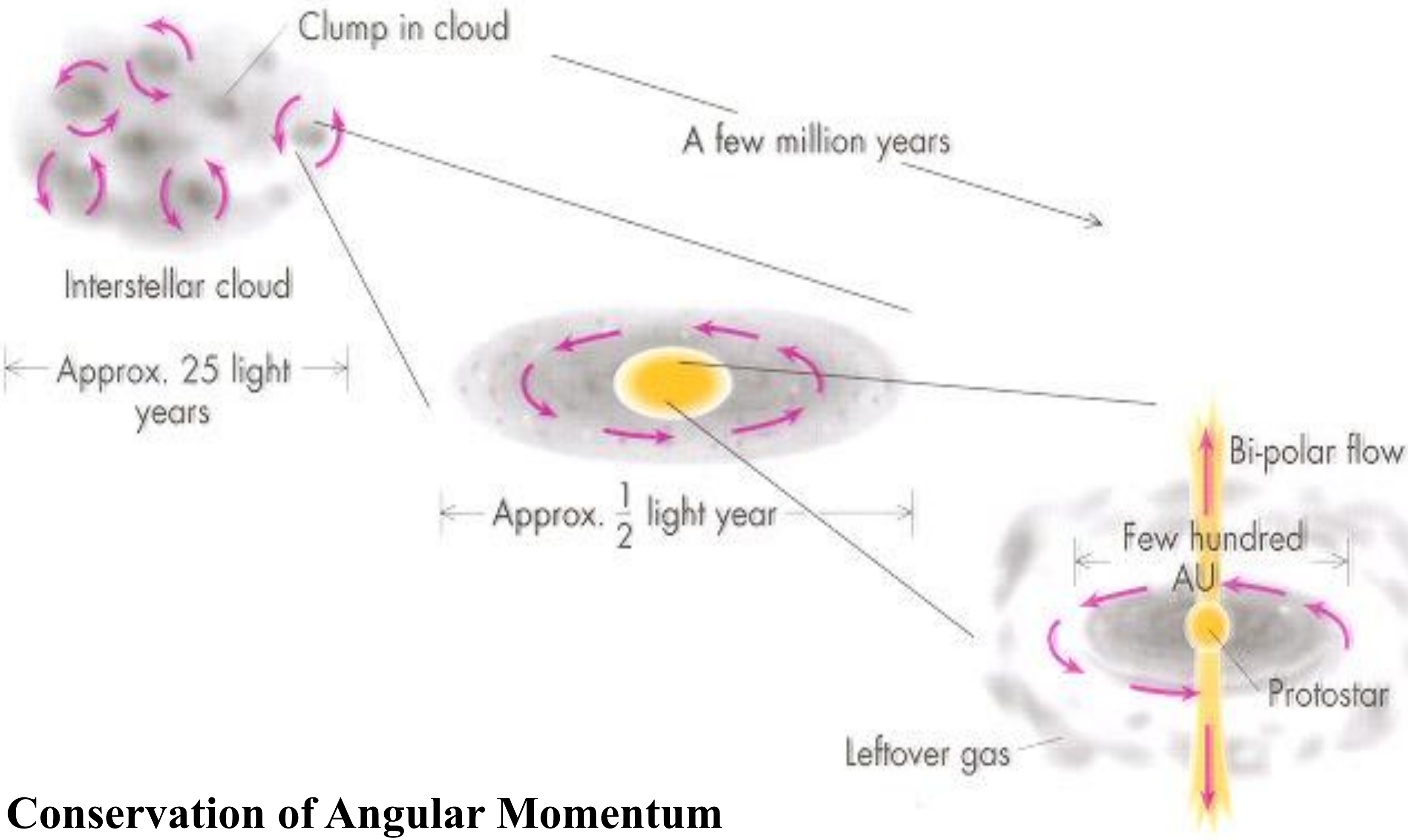


Visible



Infrared

Gravitational collapse causes the cloud to flatten as it spins faster.



Conservation of Angular Momentum

Product of mass, velocity, and radial distance.

Evolution of Low-Mass Stars

3b. Approaching the 10 million year mark, pressures and temperatures in the core of the protostar are ripe for nuclear fusion (proton-proton chain). The protostar becomes a <u>pre-main sequence star</u>.

Radius: ~1.33 R_{sun}

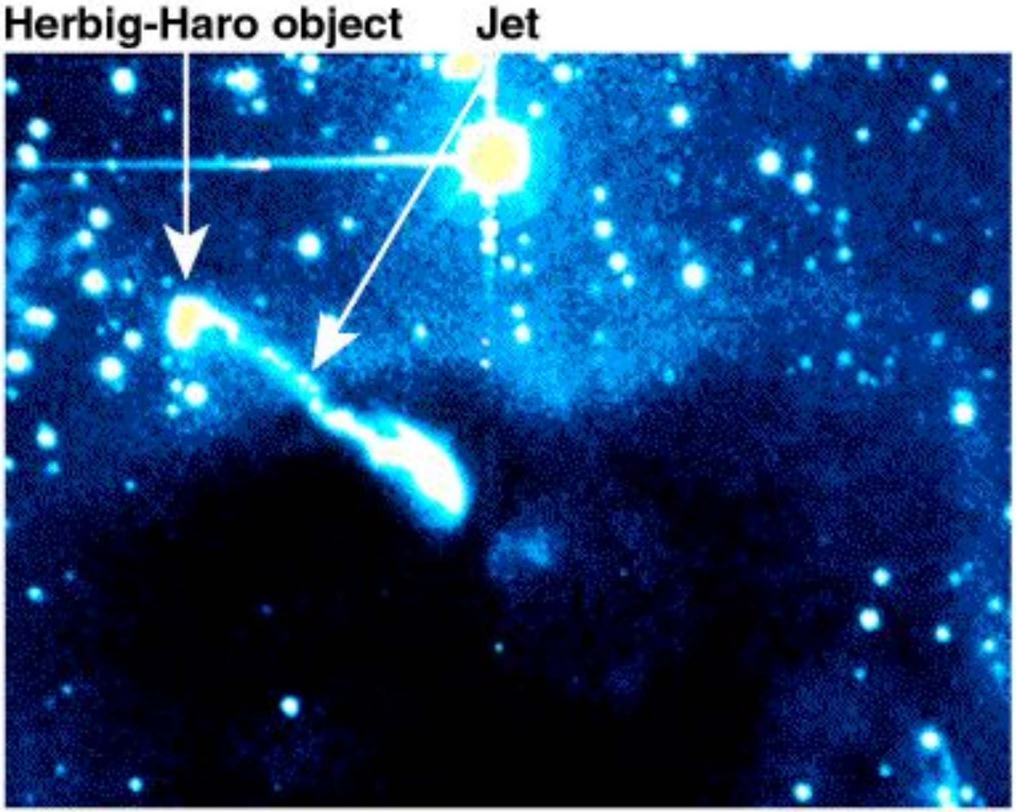
Core Temp: ~10,000,000 K

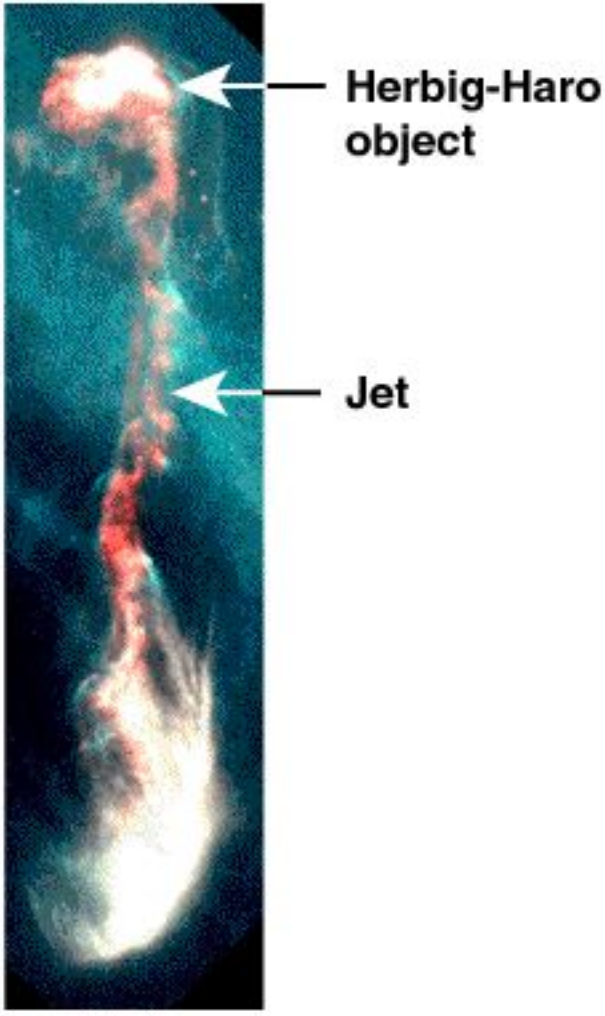
Surface Temp: 4500 K

Energy Source: H fusion begins

The star is approaching hydrostatic equilibrium. In falling material is ejected by strong stellar winds that are sometimes seen as jets.

Pre-Main Sequence Stars – Jets!





BROWN DWARFS

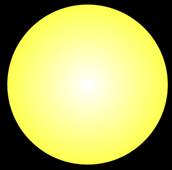
Some protostars never make it to the main sequence.

If the mass $\leq$ 0.08 solar masses, H fusion never begins.

Brown dwarfs are basically orbs of H and He approximately 13 times the mass of Jupiter.

4. ZERO AGE MAIN SEQUENCE STAR - temperature reaches a steady 15,000,000 K (~27 million degrees F) and the pressure reaches 1 billion ATM in the core, fusion is sustained in the core and we now have a <u>main-sequence star</u>.

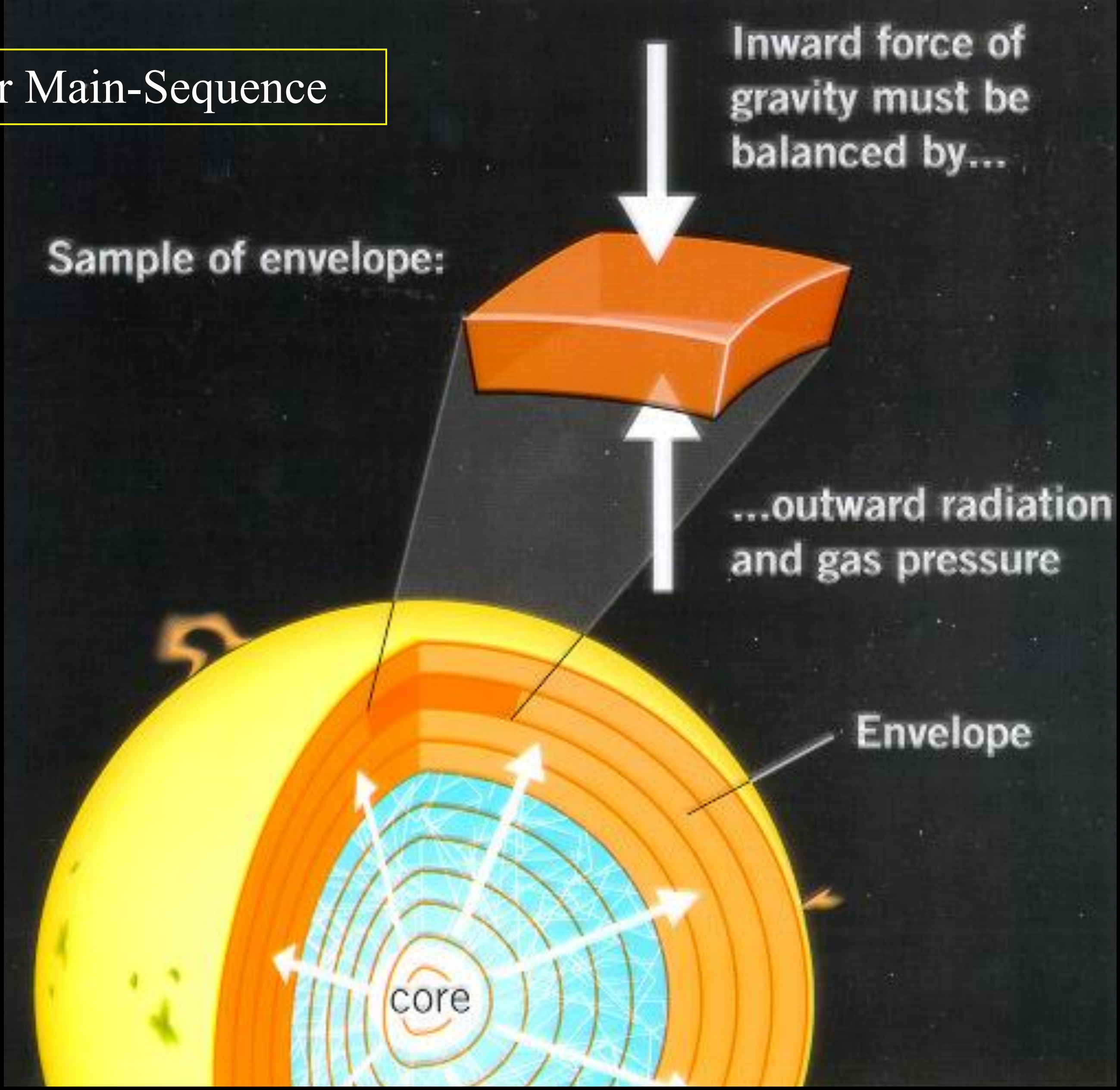
Radius: ~ R_{sun}
Core Temp: ~15,000,000 K
Surface Temp: 6000 K
Energy Source: H fusion is sustained

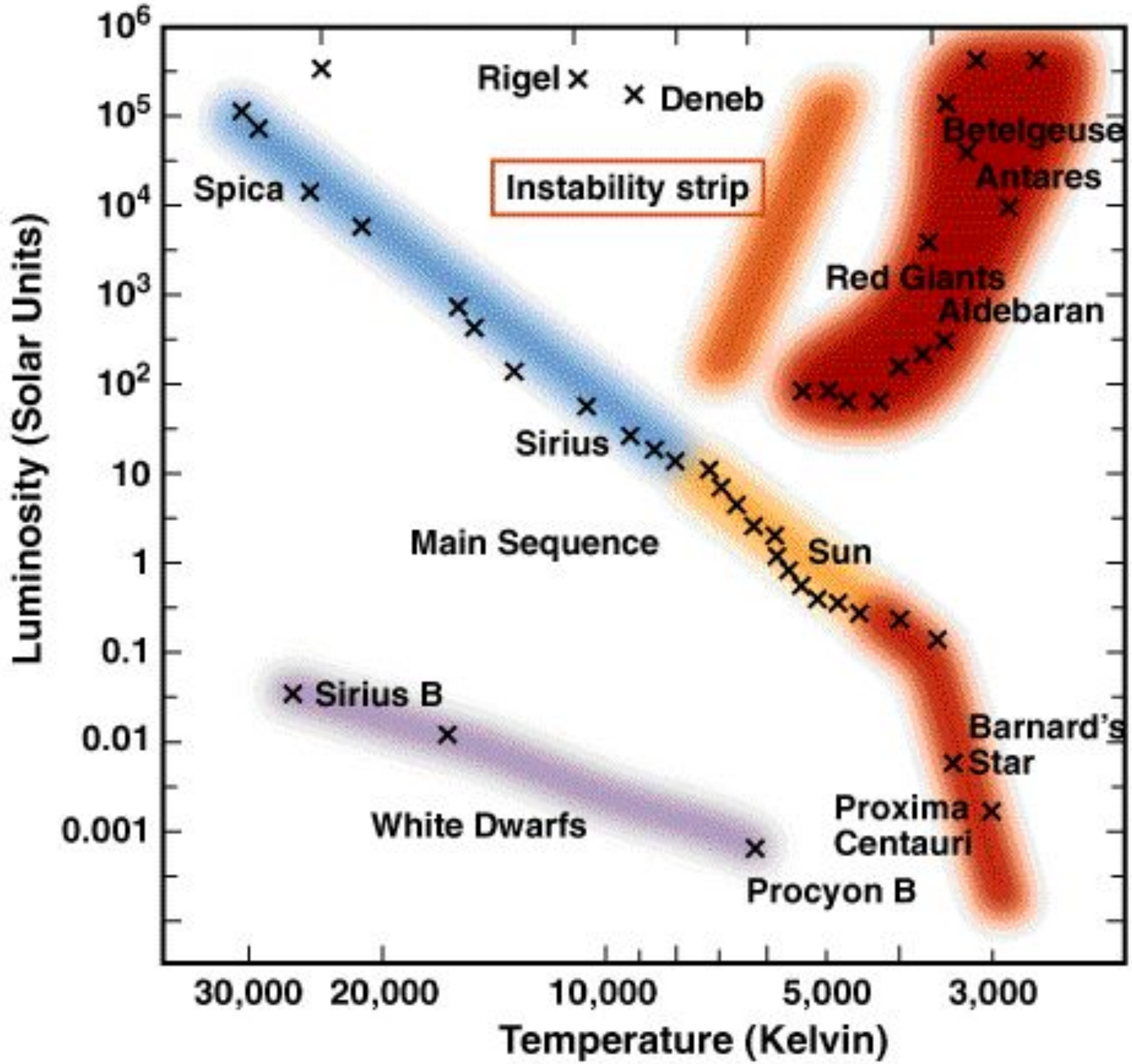


5. Low mass stars like the Sun remain on the main-sequence for about <u>10 billion years</u>. They are in a state of hydrostatic equilibrium.

Note: Massive stars stay on the main-sequence for about 1 billion years.

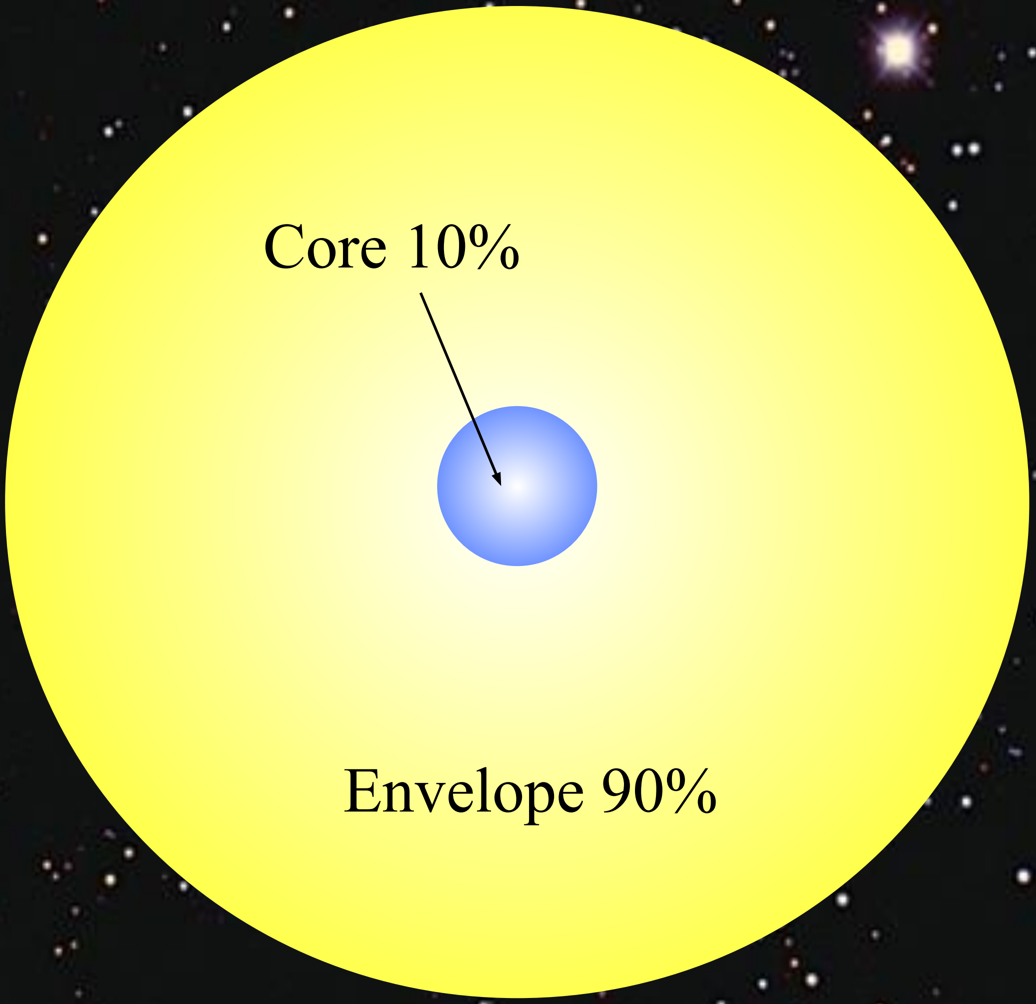
Stellar Main-Sequence



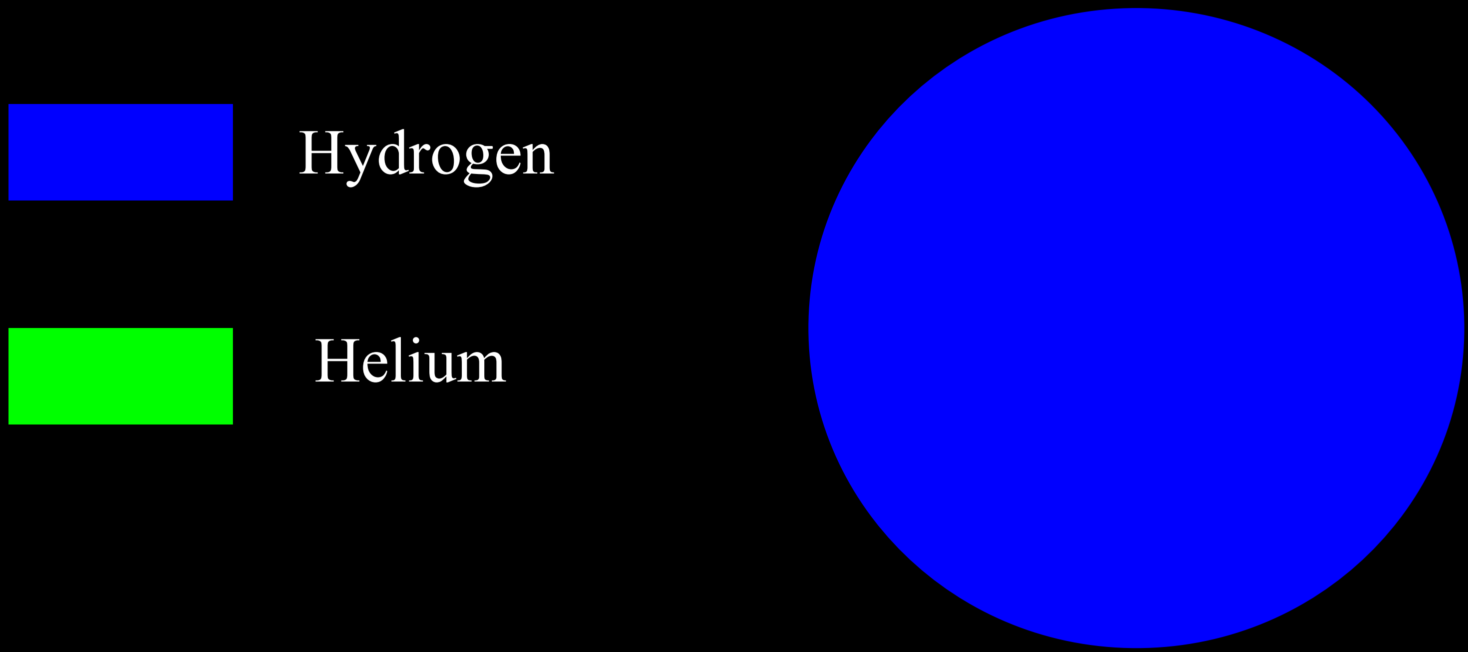


Luminosity (Solar Units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
0.01
0.001
30,000
20,000
10,000
5,000
3,000
Temperature (Kelvin)
Rigel
Deneb
Instability strip
Spica
Betelgeuse
Antares
Red Giants
Aldebaran
Sirius
Main Sequence
Sun
Sirius B
Barnard's Star
Proxima Centauri
White Dwarfs
Procyon B

Basic Star Structure



Star Core Evolution



ZAMS – Zero Age Main Sequence Star

Core is completely Hydrogen.

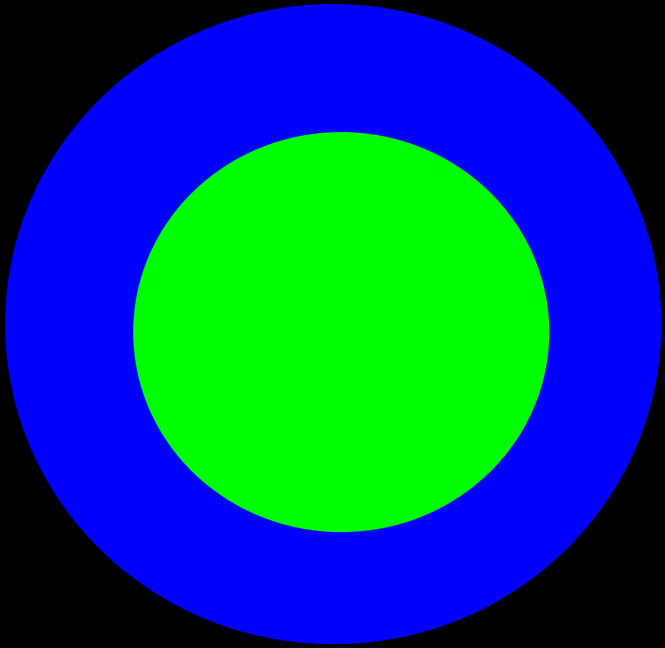
Time = 0 years

Star Core Evolution

As the star ages, core hydrogen is depleted and replaced with helium.

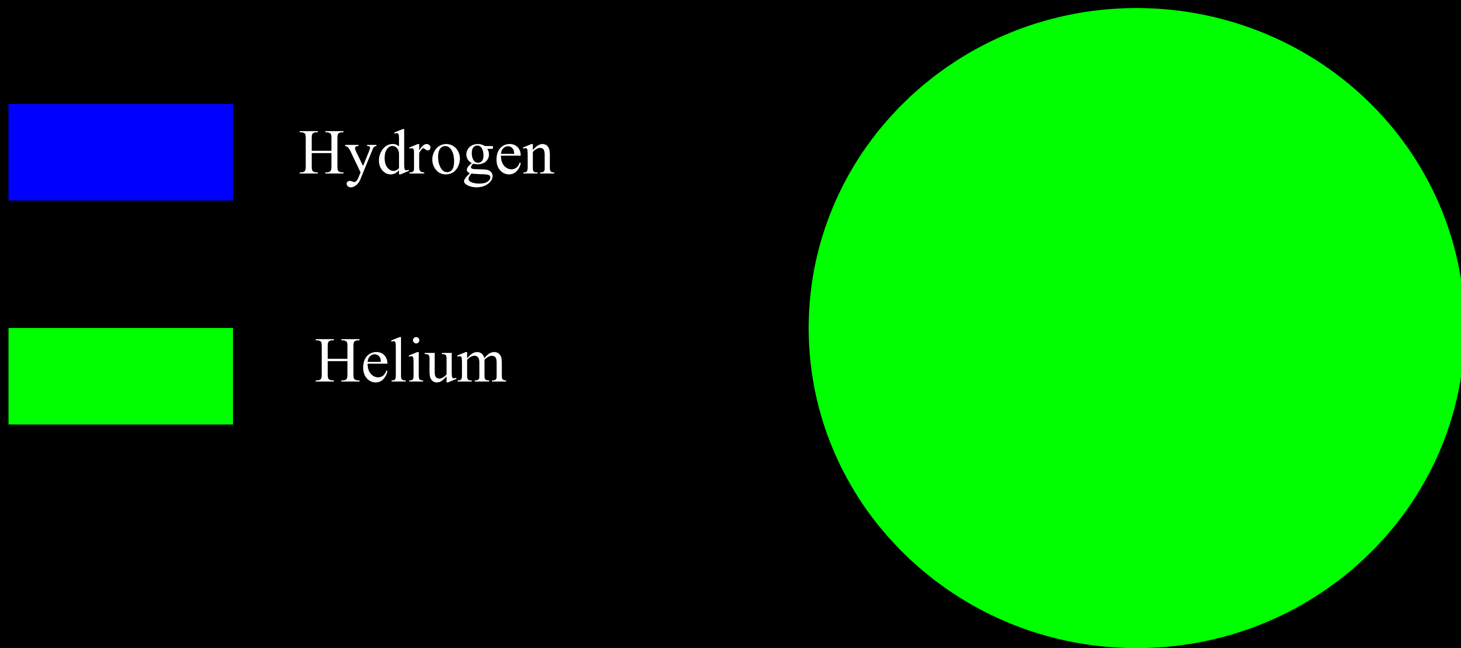
Hydrogen

Helium



Time = ~5 billion years

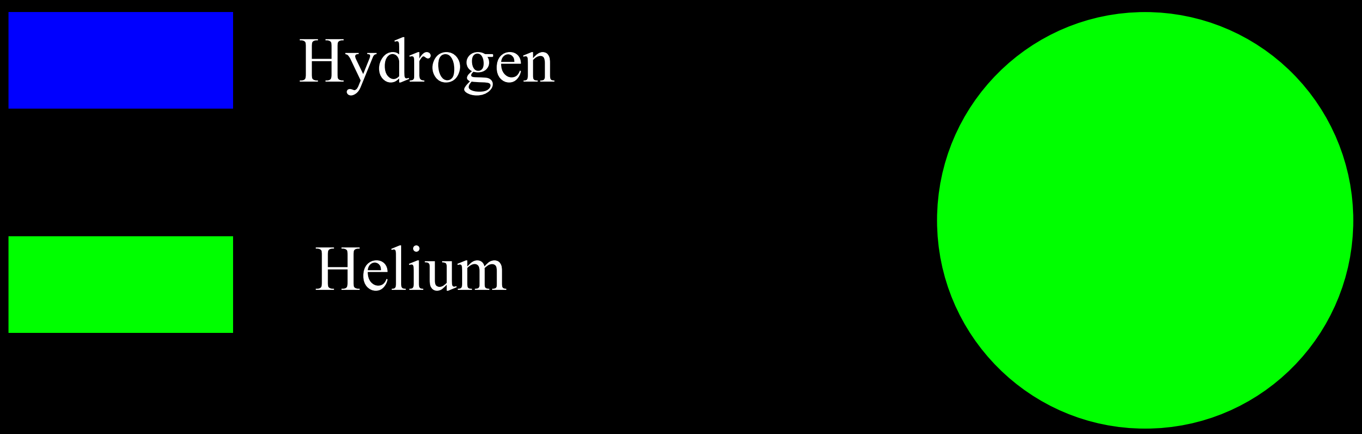
Star Core Evolution



Eventually, the entire core is converted to helium.

Time = ~10 billion years

Star Core Evolution



Radiation pressure weakens, the core begins to collapse.

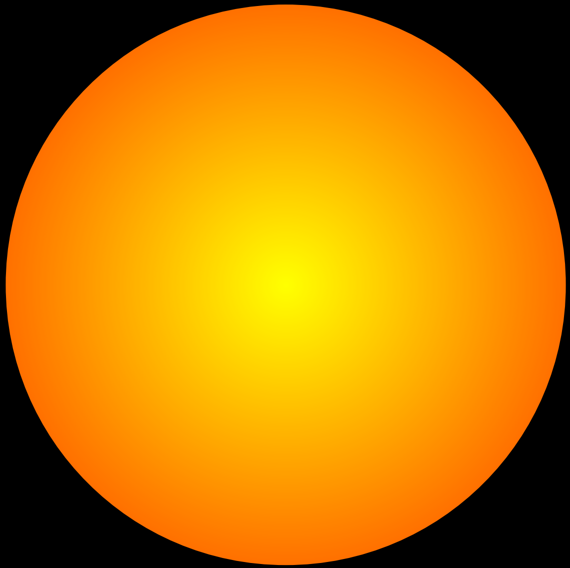
Time = 100 million years later

6. When hydrogen fusion begins in a shell around the core, the star expands into a <u>Red Giant</u>.

7. After most of the hydrogen is fused into helium the core begins to collapse.

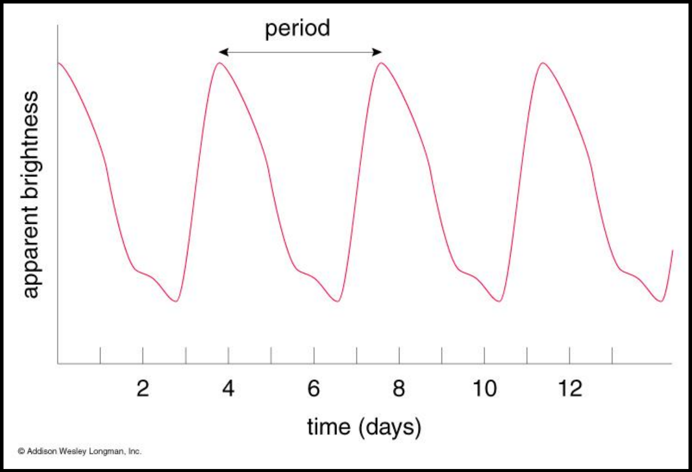
Core pressure increases temperature to 200,000,000 K (~360 million degrees F).

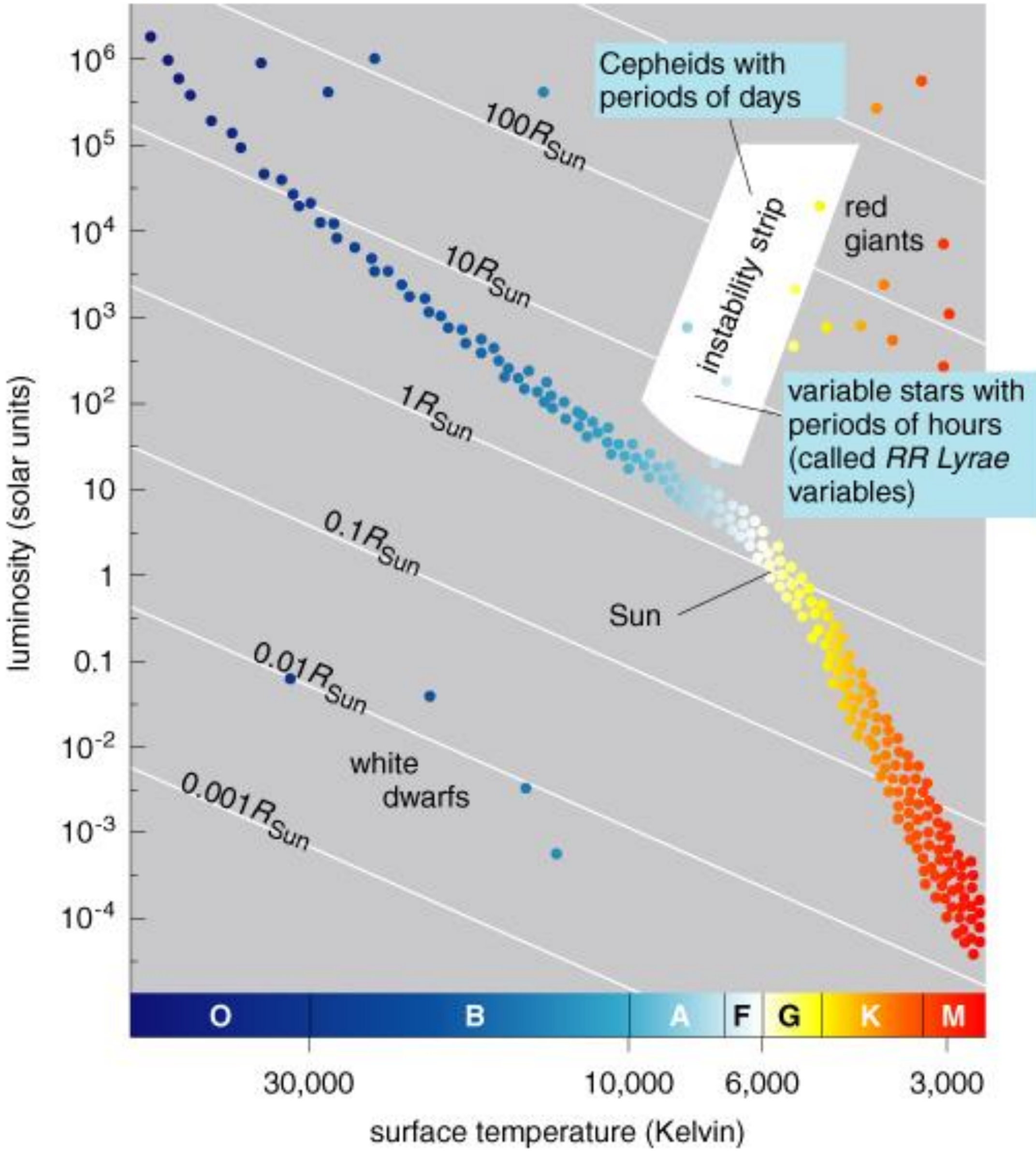
Helium fusion begins in an event called the <u>Helium Flash</u>.



8. Stars can then become unstable and turn into pulsating stars like RR Lyrae Variables or Cepheid Variables.

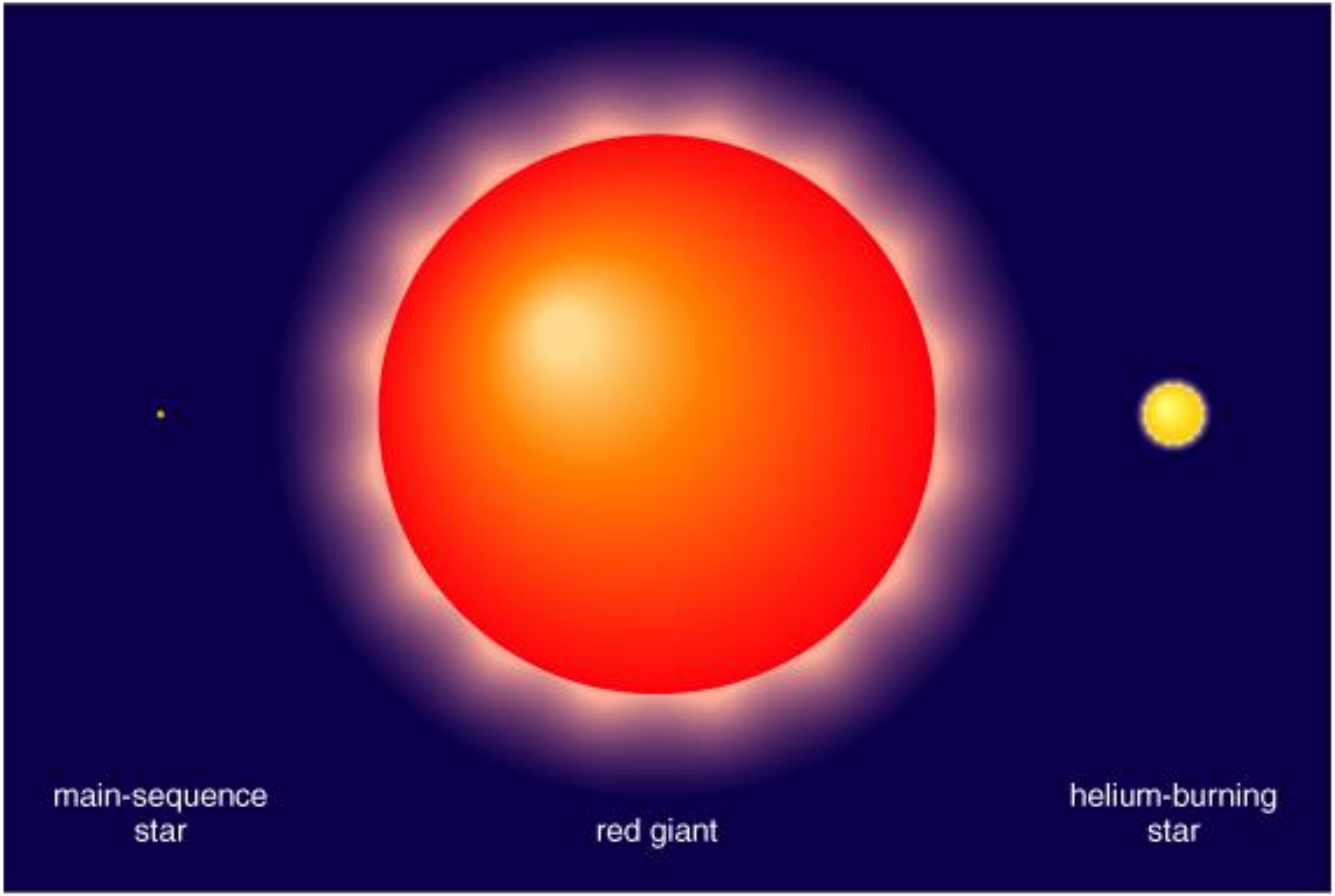
- Cepheid Variables-High Mass (periods=several hundred days)
- RR Lyrae-Low Mass (periods < day)



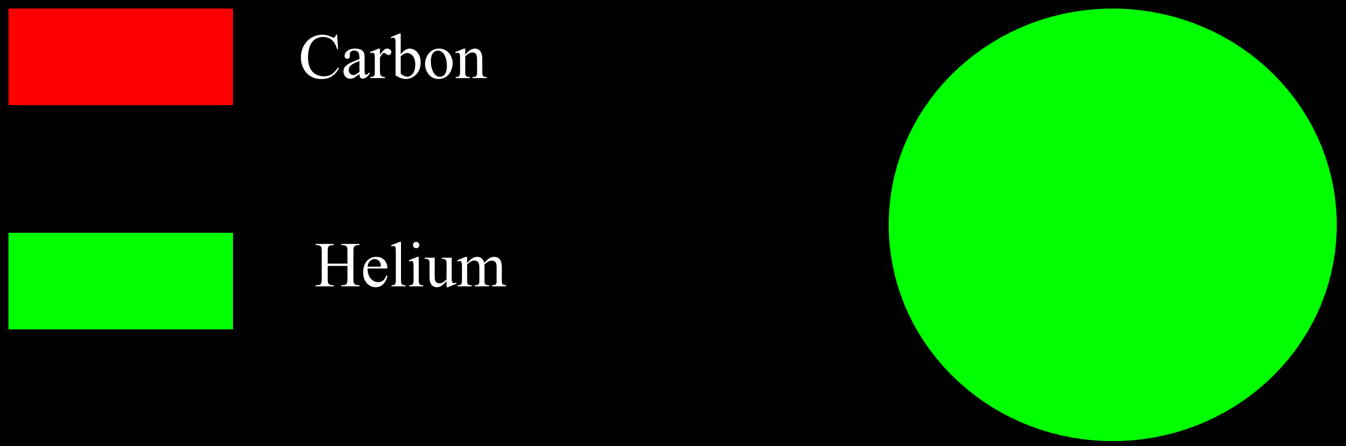


Cepheids with periods of days
instability strip
red giants
variable stars with periods of hours (called *RR Lyrae* variables)
100R Sun
10R Sun
1R Sun
0.1R Sun
0.01R Sun
0.001R Sun
Sun
white dwarfs
luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
surface temperature (Kelvin)

Life of a 1 M_{sun} Star



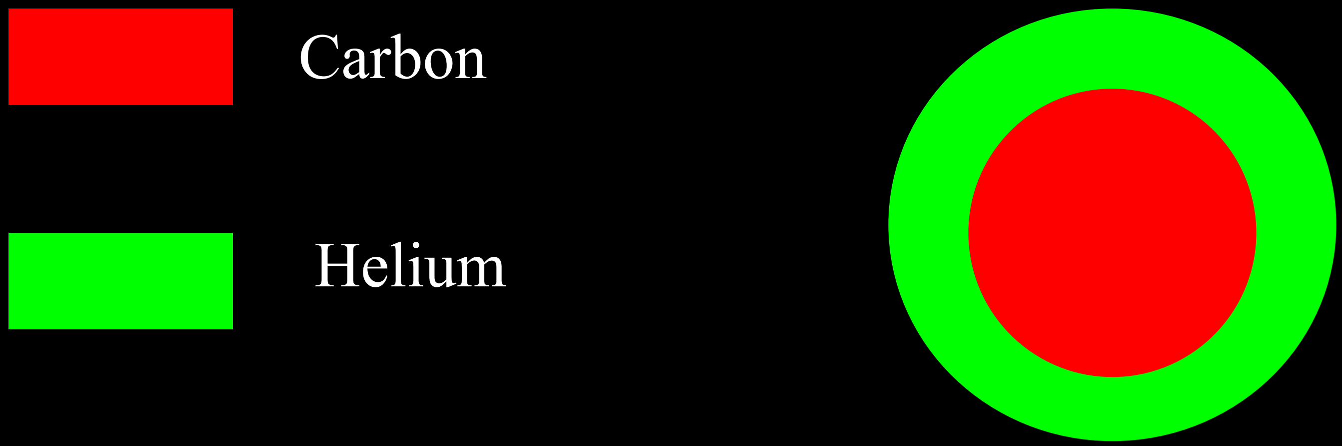
Star Core Evolution – Post Helium Flash



Helium fusion is underway in the core (triple-alpha process).

Helium nuclei + Helium nuclei -> Beryllium nuclei + Energy
Helium nuclei + Beryllium nuclei -> Carbon nuclei + Energy

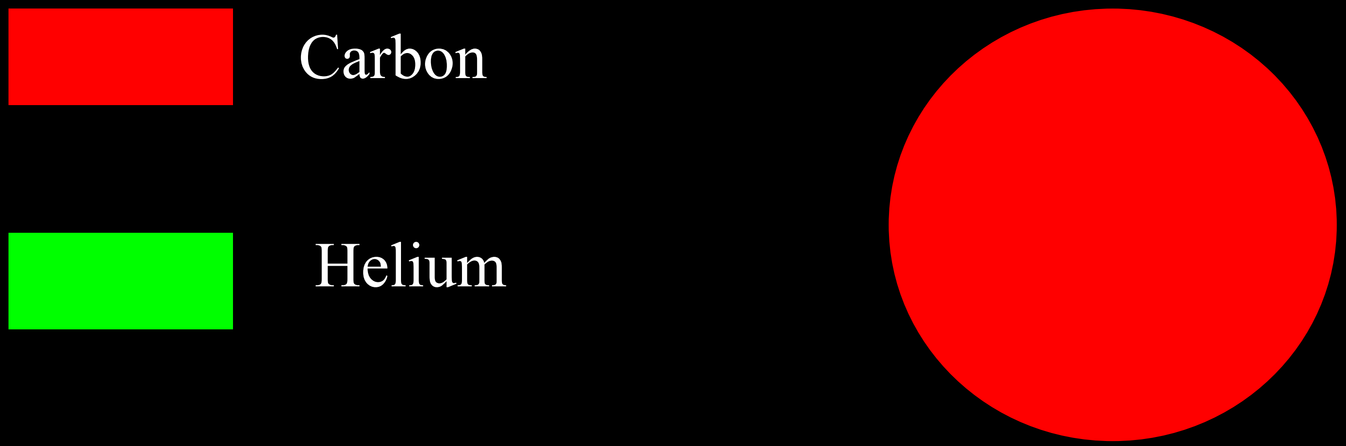
Star Core Evolution – Post Helium Flash



As the carbon builds, another fusion process can begin.

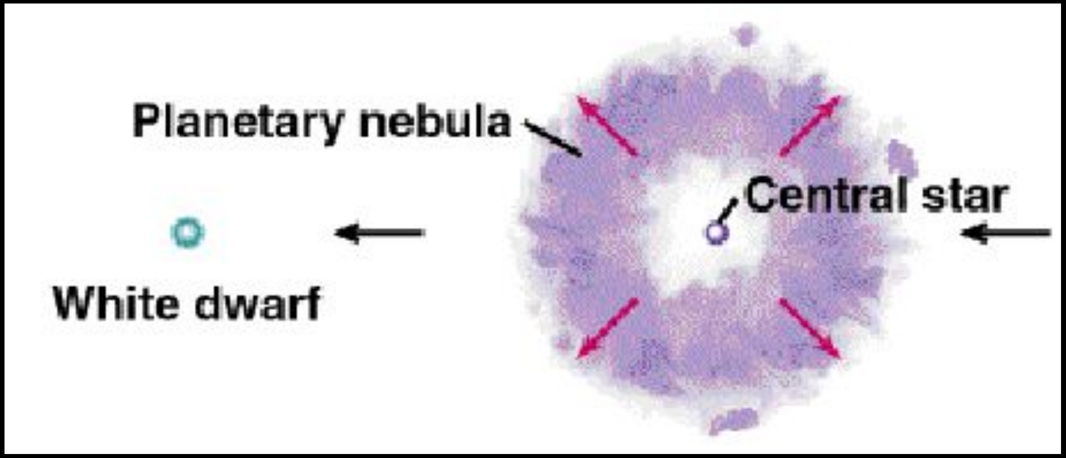
Helium nuclei + Carbon nuclei -> Oxygen nuclei + Energy

Star Core Evolution – Post Helium Flash



As carbon builds, the core begins to collapse again. The temperature tries to build to 600 million K (the temperature for Carbon fusion). However, there isn't enough mass in the core to create these pressures. In fact, the collapse is halted by <u>electron degeneracy</u>.

9. As a star burns helium into carbon the radiation pressure pushes the star's outer atmosphere away from the core creating a Planetary Nebula.



10. This leaves an exposed core called a White Dwarf. These have about the same diameter as the Earth.

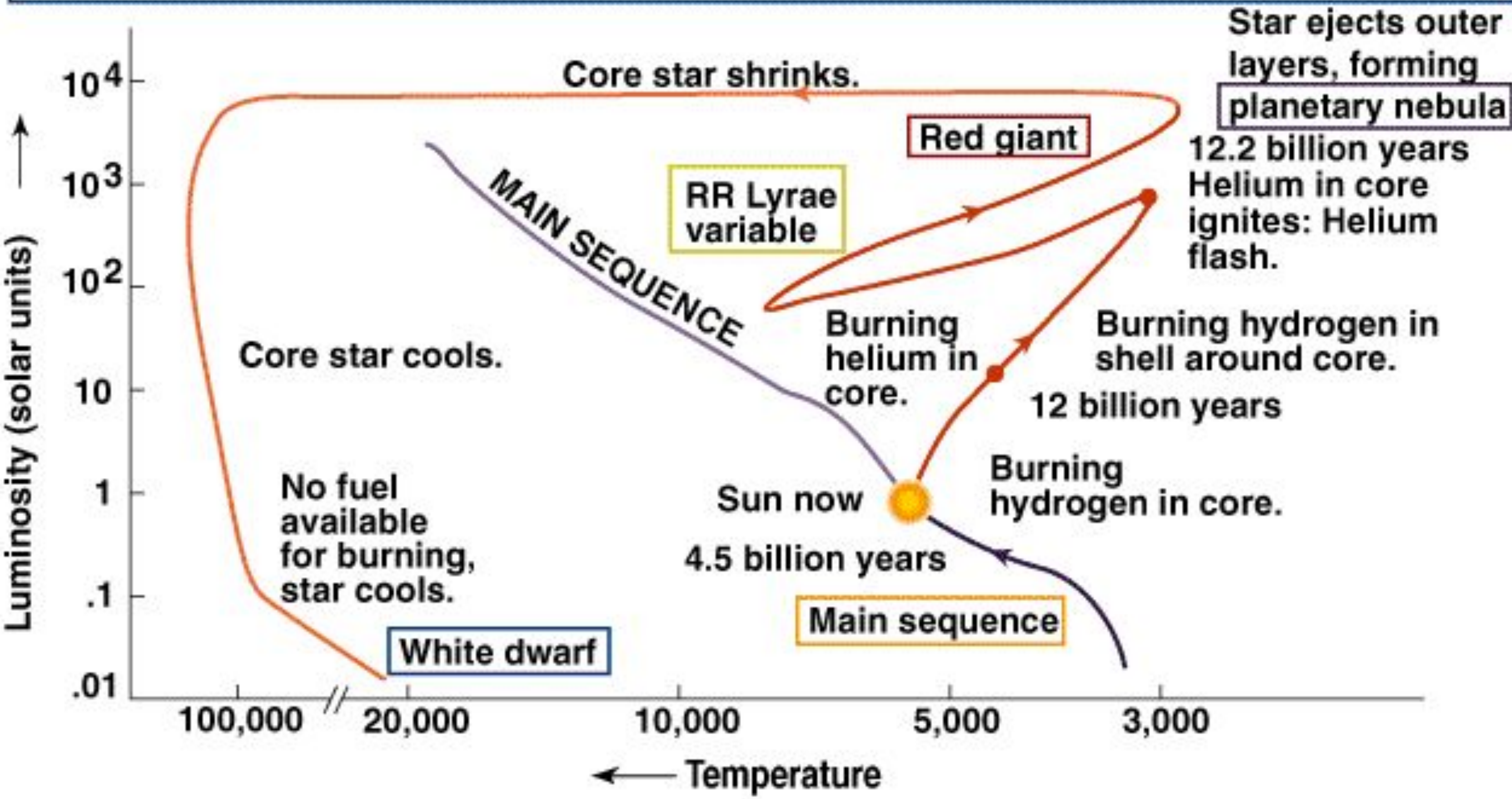
The Helix Nebula

visible image

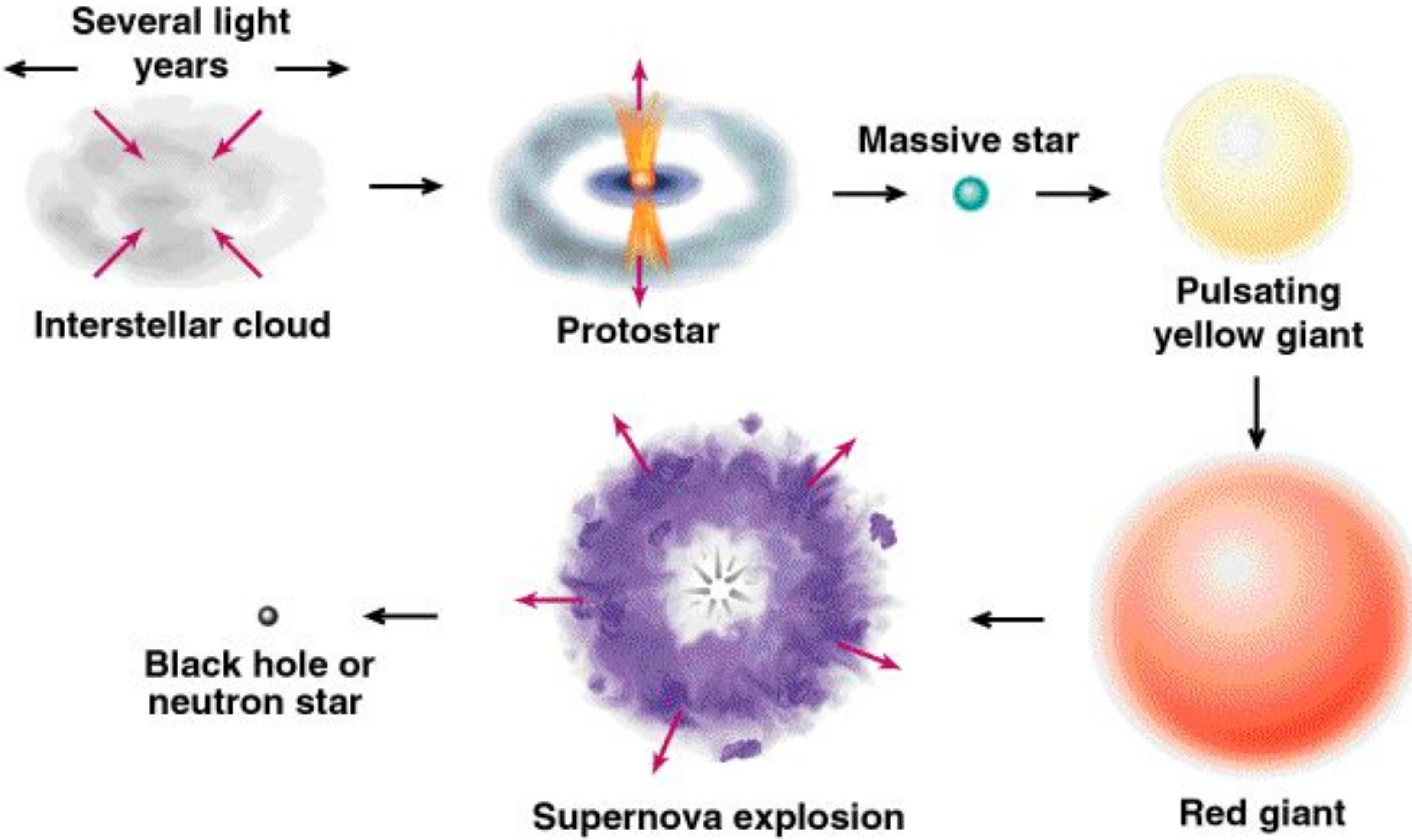
450 ly

Evolution of a Low-Mass Star

	~11 billion yrs	~1 billion yrs	~100 million yrs	~10,000 yrs	
Time spent as	Main sequence →	Red giant →	RR Lyrae variable →	Planetary nebula →	White dwarf
Sun's age	4.5 billion yrs (now)	12.2 billion yrs	12.3 billion yrs	12.3305 billion yrs	12.3306 billion yrs



Life of a High Mass Star



Evolution of High-Mass Stars

1 to 5. Same as before…

- interstellar cloud
- dense core
- protostar
- pre-main sequence star
- main-sequence star

"Live fast and die young!"

6. When a high-mass star exhausts the hydrogen fuel in its core the star leaves the main sequence and begins to burn helium. At this stage the star becomes a Cepheid Variable.

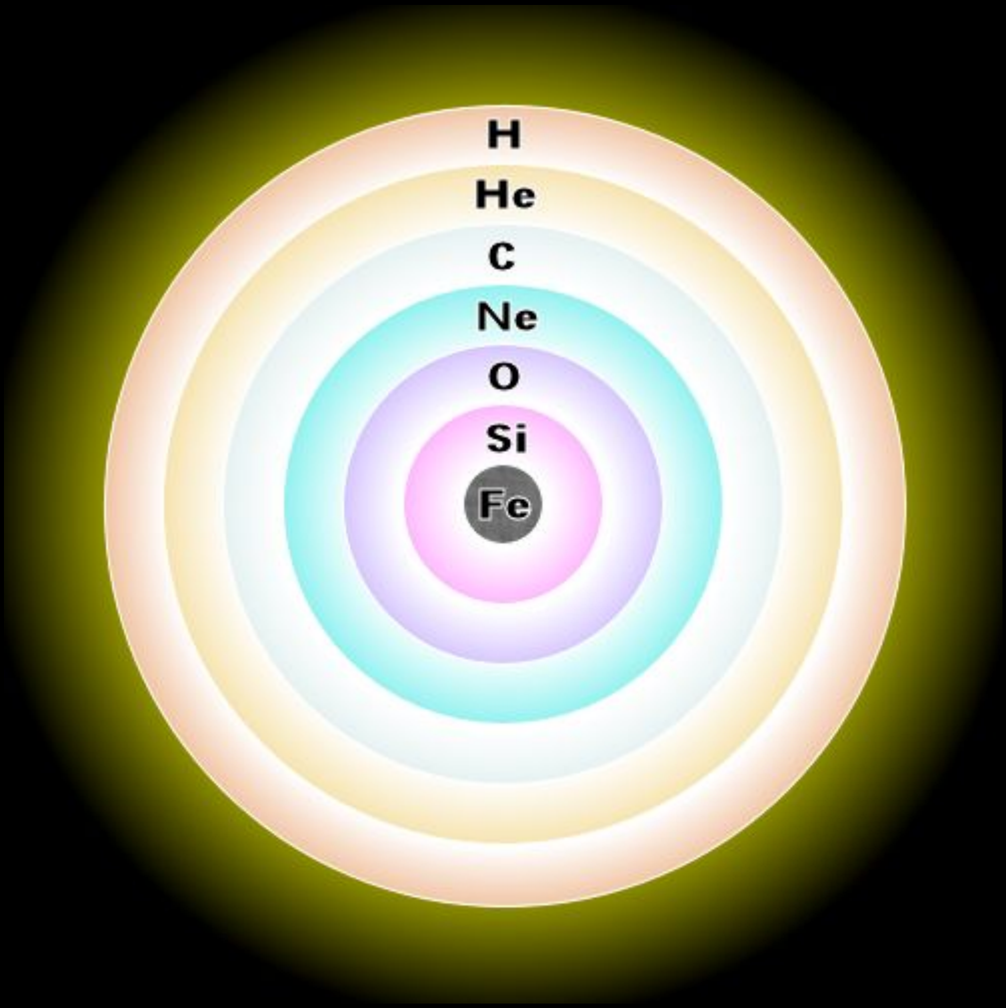
7. The star becomes a <u>Red Supergiant</u> after millions of years of helium fusion.

8. When helium is depleted, fusion of heavier elements begins. This process is called <u>nucleosynthesis</u>.

H -> He -> C -> O -> Si -> Fe

H burning (main sequence) = ~10 million years
He burning (triple alpha) = ~1 million years
C burning = ~300 years
O burning = ~2/3 year
Si burning = ~2 days

Massive Star's Core – Just prior to collapse!



9. A star with an iron core is out of fuel.

Reason: Iron atoms cannot fuse *and* release energy.

10. The core collapses due to reduced pressure converting the iron core into mostly neutrons.

- Core temperature is on the rise which begins the following sequence of events.
  - Some nuclei convert back into He which then breaks down…
  - He -> $p^+ + n$
  - $p^+ + e^-$ -> $n + \nu$

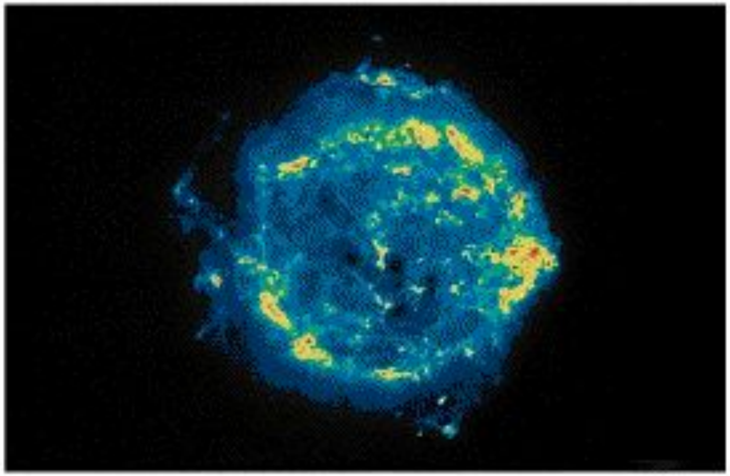
11. The core pressure then surges and lifts the outer layers from the star in a titanic explosion - a supernova!

Supernova Remnants

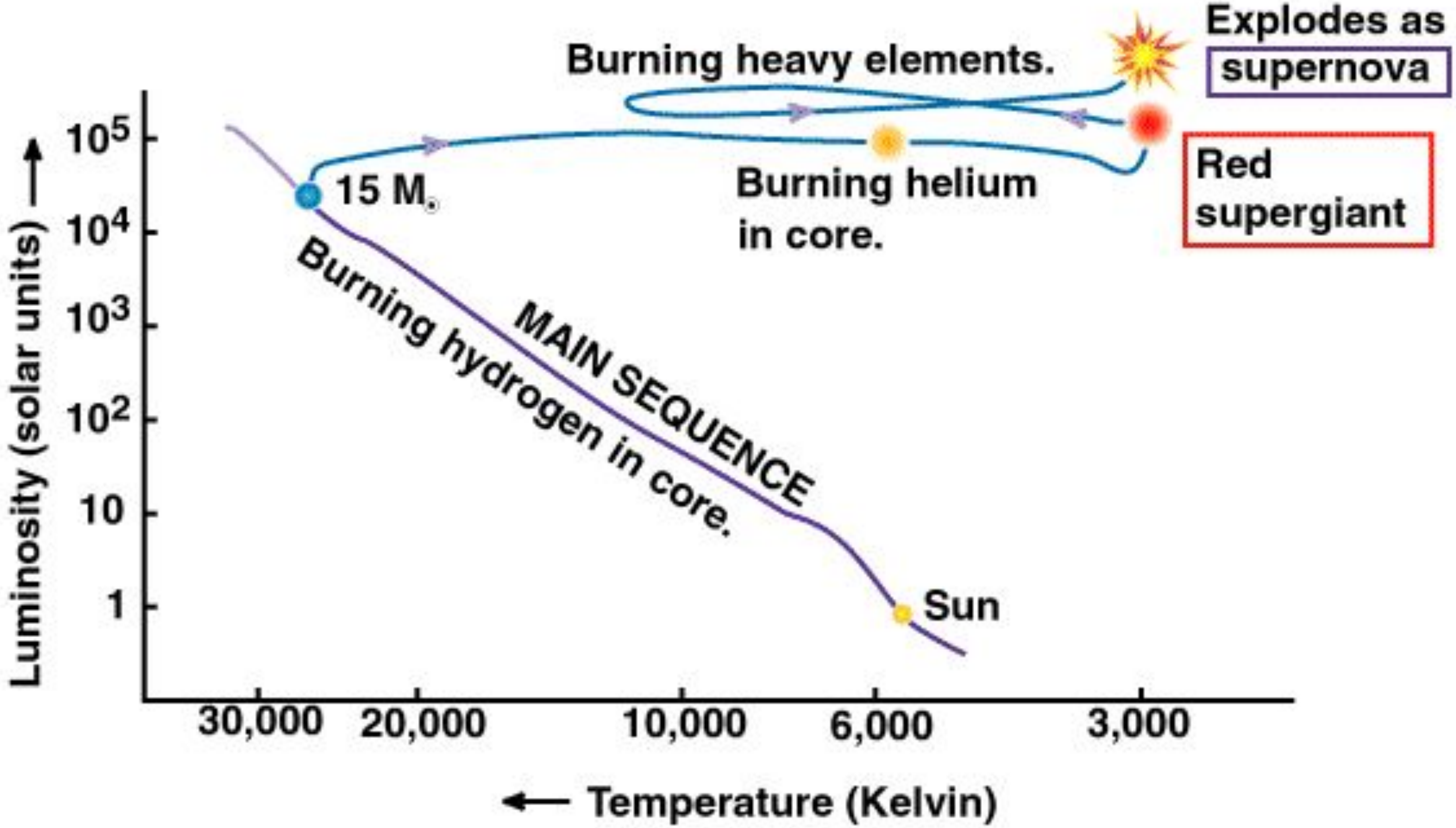
A

B

C



HR Diagram for High-Mass Stars



Russel-Vogt Theorem

- M*<0.01 Solar Masses = Planet
  - Jupiter mass = 0.001 Solar Mass
    - Heated Internally (PV=nRT)

- 0.01 Solar Masses < M*<0.085 Solar Masses = Brown Dwarfs
  - Never become hot enough for H fusion.
  - Heated internally (PV=nRT).
    - Core Temp = 3 million K
    - Surface Temp < 2000K (seen in IR)

- 0.085 Solar Masses <M*<0.4 Solar Masses = Red Dwarfs
  - H fusion happens.
  - Never get hot enough for helium fusion later.
  - Very long lived stars.

Russel-Vogt Theorem

- 0.4 Solar Masses < M* < 1.2 Solar Masses – Sun Like
  - Typical sun-like star.
  - Burns H to He via P-P chain.
  - Burns He to C via the Triple-alpha process.
  - Core fusion ends at electron degeneracy.

- M*> 1.2 Solar Masses
  - Core temps can get high enough to burn H via the CNO cycle.

- M*>8 Solar Masses
  - Can have a large number of fusion processes at work in the core.
  - Cores are larger than 1.4 solar masses.
  - End lives as *supernovae.*