Life Cycle of the Stars

Classification of Stars

Classification of Stars- Hertzsprung–Russell diagram

- **Hertzsprung–Russell diagram (HR diagram)** is a plot of the temperature (or spectral class) of a selected group of nearby stars against their luminosity
- The diagram was created independently around 1910 by **Ejnar Hertzsprung** and **Henry Norris Russell**
- It represented a major step towards an understanding of stellar evolution
- Before Russell, American astronomers devoted themselves mainly to surveying the stars and making impressive catalogs of their properties, especially their spectra
- The **H-R diagram** shows that stars are not randomly distributed as far as their luminosities and effective temperatures are concerned
- They can be arranged in groups

Ejnar Hertzsprung

(1873–1967)

Henry Norris Russell

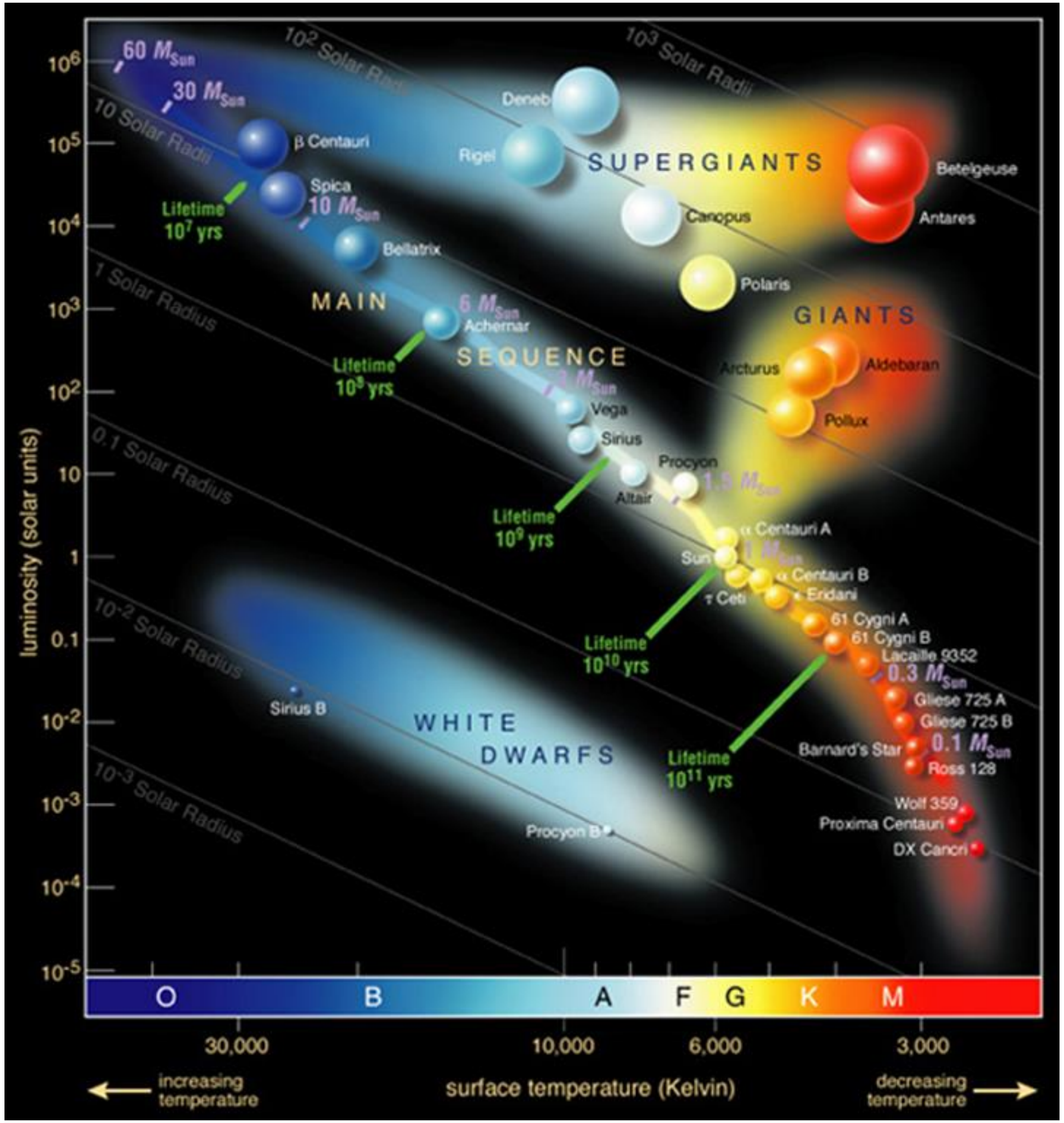
(1877–1957)

Hertzsprung–Russell diagram

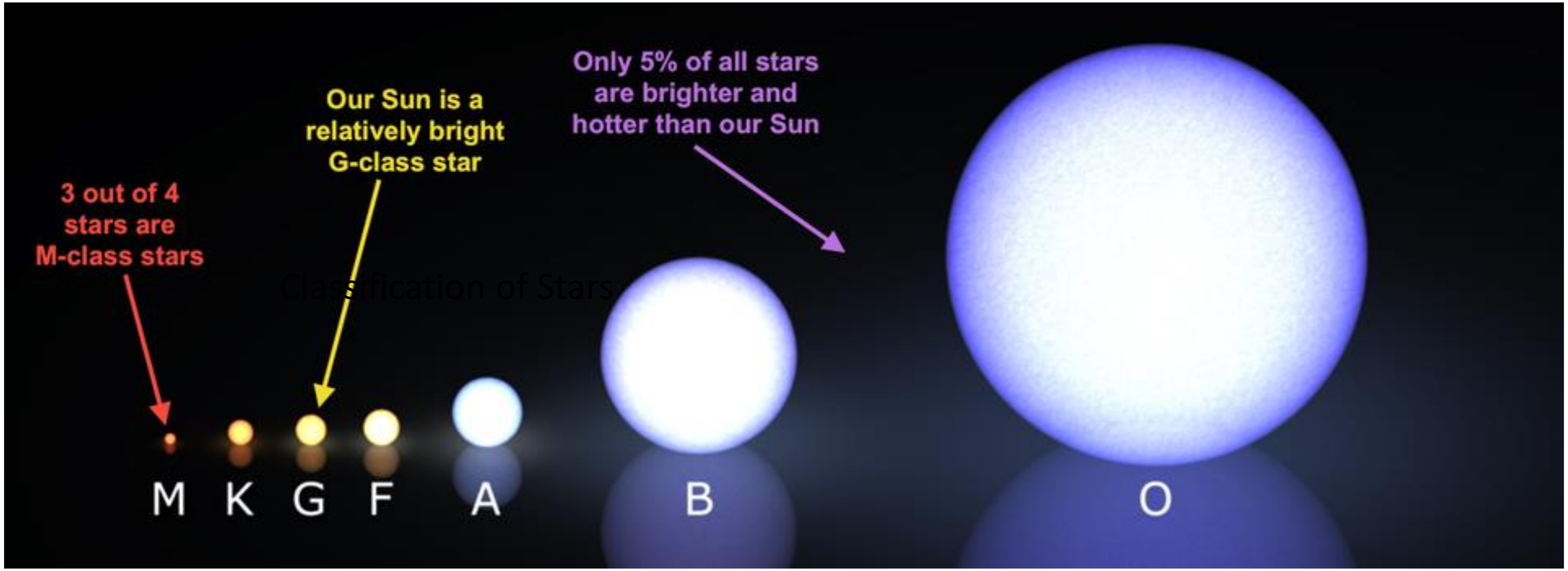
- The **H-R diagram** shows that stars are **not randomly distributed** as far as their luminosities and effective temperatures are concerned
- They can be arranged in groups:
    - The Main Sequence
    - White Dwarfs
    - Giants
    - Super Giants

STAR TYPES AND THEIR TEMPERATURE

Type	Color	Temperature (in K)
O	Bluish	30 000 – 80 000
B	Bluish	10 000 – 30 000
A	Bluish	7 500 – 10 000
F	White	6 000 – 7 500
G	Yellow	5 000 – 6 000
K	Red orange	3 500 – 5 000
M	Reddish	2 000 – 3 500



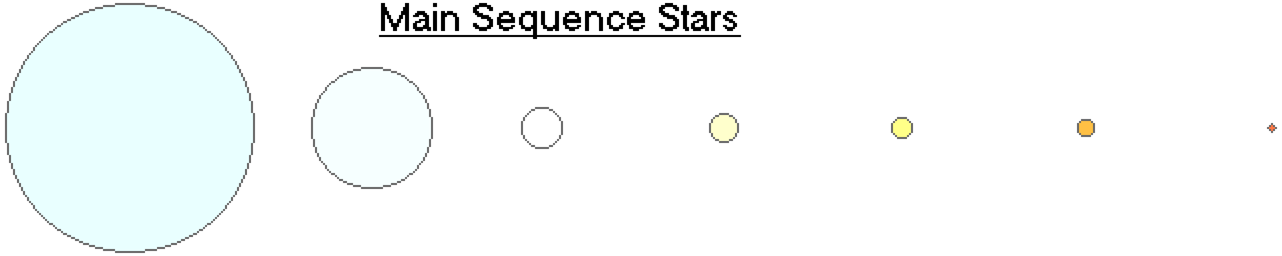
Classification of Stars-Main Spectral Types



Stellar Spectral Classes

Spectral Class	Approximate Surface Temperature (K)	Noteworthy Absorption Lines	Familiar Examples
O	30,000	Ionized helium strong; multiply ionized heavy elements; hydrogen faint	Mintaka (O9)
B	20,000	Neutral helium moderate; singly ionized heavy elements; hydrogen moderate	Rigel (B8)
A	10,000	Neutral helium very faint; singly ionized heavy elements; hydrogen strong	Vega (A0), Sirius (A1)
F	7000	Singly ionized heavy elements; neutral metals; hydrogen moderate	Canopus (F0)
G	6000	Singly ionized heavy elements; neutral metals; hydrogen relatively faint	Sun (G2), Alpha Centauri (G2)
K	4000	Singly ionized heavy elements; neutral metals strong; hydrogen faint	Arcturus (K2), Aldebaran (K5)
M	3000	Neutral atoms strong; molecules moderate; hydrogen very faint	Betelgeuse (M2), Barnard's Star (M5)

Main Sequence Stars



Spectral Type:	O	B	A	F	G	K	M
Temperature:	40 000K	20 000K	8500K	6500K	5700K	4500K	3200K
Radius (Sun=1):	10	5	1.7	1.3	1.0	0.8	0.3
Mass (Sun=1):	50	10	2.0	1.5	1.0	0.7	0.2
Luminosity (Sun=1):	100 000	1000	20	4	1.0	0.2	0.01
Lifetime (million yrs):	10	100	1000	3000	10 000	50 000	200 000
Abundance:	0.00001%	0.1%	0.7%	2%	3.5%	8%	80%

Giant Stars

Low mass stars near the end of their lives.

Spectral Type:	Mainly G, K or M
Temperature:	3000 to 10 000K
Radius (Sun=1):	10 to 50
Mass (Sun=1):	1 to 5
Luminosity (Sun=1):	50 to 1000
Lifetime (million yrs):	1000
Abundance:	0.4%

White Dwarfs

Dying remnant of an imploded star.

Spectral Type:	D
Temperature:	Under 80 000K
Radius (Sun=1):	Under 0.01
Mass (Sun=1):	Under 1.4
Luminosity (Sun=1):	Under 0.01
Lifetime (million yrs):	–
Abundance:	5%

Supergiant Stars

High mass stars near the end of their lives.

Spectral Type:	O, B, A, F, G, K or M
Temperature:	4000 to 40 000K
Radius (Sun=1):	30 to 500
Mass (Sun=1):	10 to 70
Luminosity (Sun=1):	30 000 to 1000 000
Lifetime (million yrs):	10
Abundance:	0.0001%

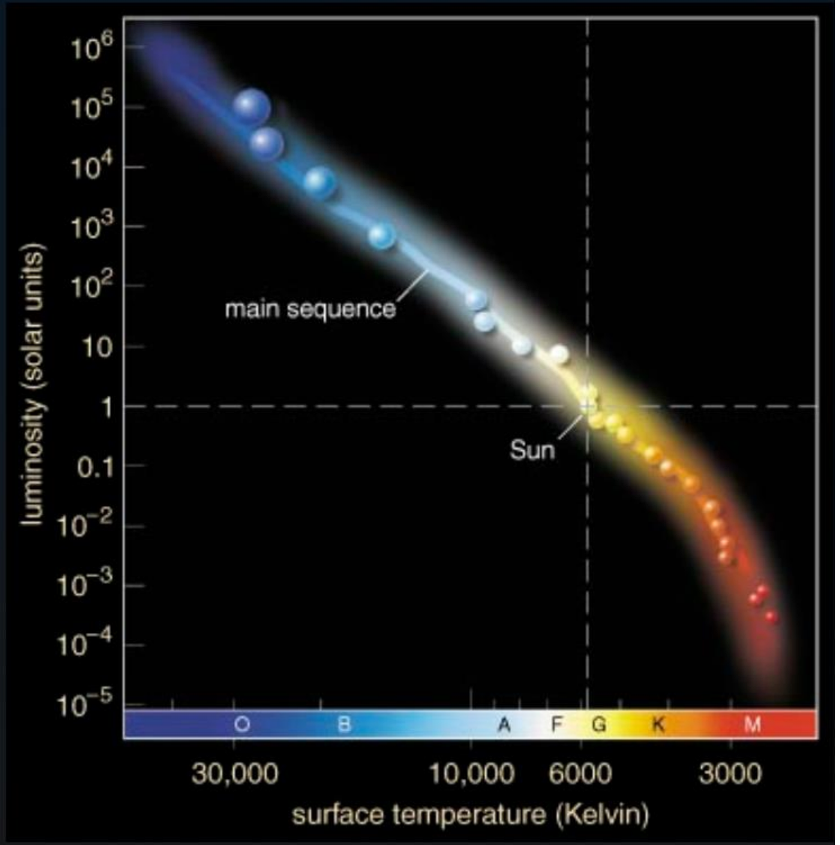
r powell

Classification of Stars- Main Sequence Stars

- The majority of stars in our galaxy are **Main Sequence** stars
- They are also the majority in the Universe
- The **Sun** is a main sequence star, and so are our nearest neighbors, **Sirius** and **Alpha Centauri A**
- Main sequence stars can vary in size, mass and brightness, but they are all converting fusing hydrogen into helium in their cores--releasing a tremendous amount of energy
- A star in the main sequence is in a state of hydrostatic equilibrium
- Gravity is pulling the star inward, and the light pressure from all the fusion reactions in the star are pushing outward
- The inward and outward forces balance one another out, and the star maintains a spherical shape
- Stars in the main sequence will have a size that depends on their mass, which defines the amount of gravity pulling them inward
- The lower mass limit for a main sequence star is about 0.08 times the mass of the Sun, or 80 times the mass of Jupiter
- This is the minimum amount of gravitational pressure you need to ignite hydrogen fusion in the core
- Stars can theoretically grow to more than 100 times the mass of the Sun

The Main Sequence

Most stars in the Sun's neighborhood fall along a roughly diagonal line on an HR diagram.



This line is called the **main sequence**.

Classification of Stars- Main Sequence Stars

- A star's place along the Main Sequence is fixed by its mass
- The Main Sequence is also a sequence of star life-times
- High mass stars must have hotter cores to balance gravity-they use up hydrogen faster
- High-Mass Stars have a very-short life when compared to low-mass and intermediate-mass stars
- In high-mass stars, the fusion process includes heavy elements, the **CNO Cycle**
- **C**arbon- **N**itrogen- **O**xygen: $\mathbf{H_2 \rightarrow He \rightarrow C \rightarrow N \rightarrow O \rightarrow \ldots \rightarrow Fe}$

- Mass is the key property of Main Sequence stars
- Other basic properties are determined by mass

Low mass	**High mass**
Low luminosity	High luminosity
Low temperature	High temperature
Long lifetime	Short lifetime

Main Sequence Lifetimes

- $1\ M_\odot$ star: $L = L_\odot$

  — lifetime: $T_\odot \approx 10^{10}$ yr

- $10\ M_\odot$ star: $L \approx 10^4\ L_\odot$

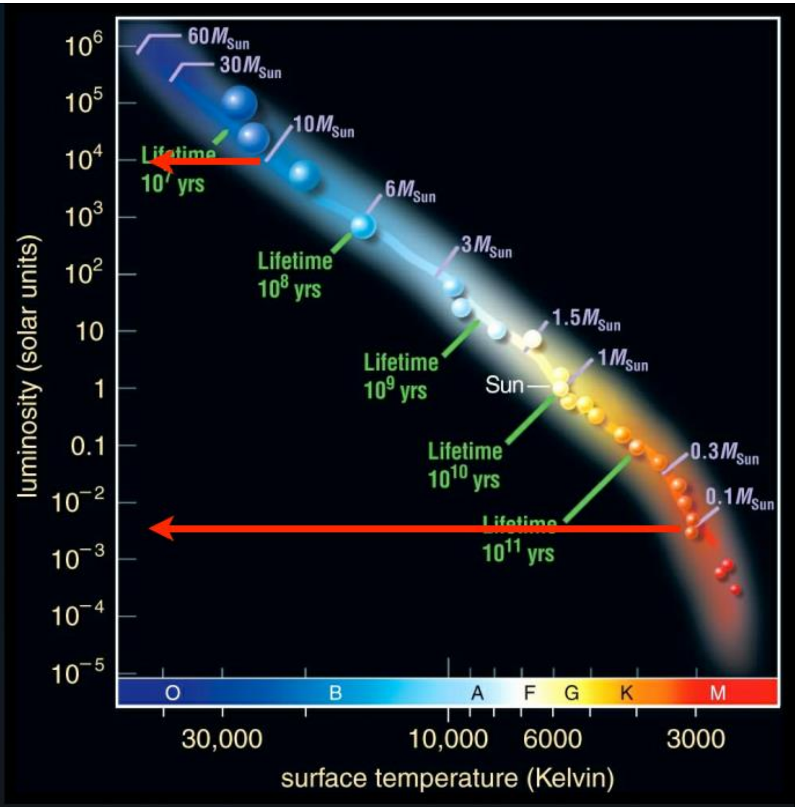
  $10 \times$ fuel; use at $10^4 \times$ rate

  $\Rightarrow T \approx (10/10^4)\ T_\odot \approx 10^7$ yr

- $0.1\ M_\odot$ star: $L \approx 0.003\ L_\odot$

  $0.1 \times$ fuel; use at $0.003 \times$ rate

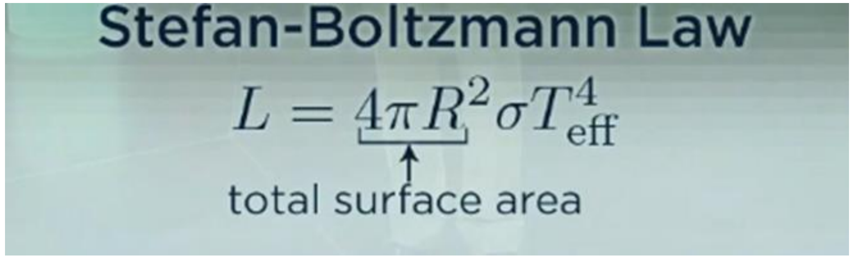
  $\Rightarrow T \approx (0.1/0.003)\ T_\odot \approx 3{\times}10^{11}$ yr

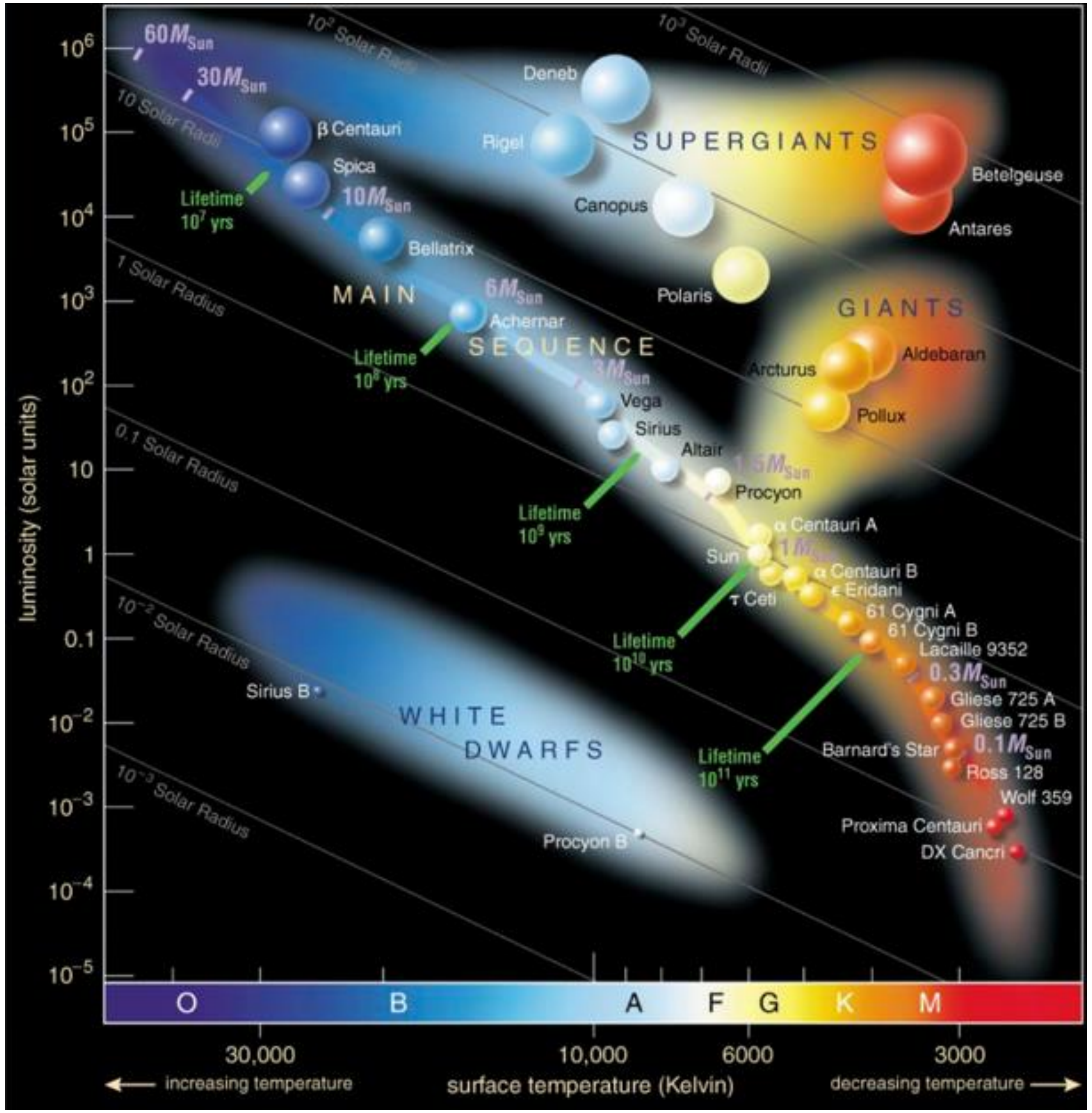


Classification of Stars-Stars not in the Main Sequence

- Some stars are relatively cool but very luminous
- They must have very large radii to give off so much energy
- They are the **Giants** and **Supergiants**

- Other stars are hot but very dim
- They must have very small radii to give off so little energy
- They are the **White Dwarfs**





Classification of Stars-Gravity in Action

- With **no energy released** by fusion in the core, a star having the mass and radius of the Sun would collapse due to its own gravity
  - Mass M
  - Radius R
- An atom on the surface would be accelerated by gravity towards the center of the sphere

$$a(t) = \frac{d^2r}{dt^2} = -\frac{GM}{r^2}$$

$$v_{\text{avg}} = \frac{R}{T}$$

$$\frac{v_{\text{avg}}}{T/2} = \frac{R/T}{T/2} = \frac{2R}{T^2}$$

$$\frac{GM}{(R/2)^2} = \frac{4GM}{R^2}$$

$$\frac{2R}{T^2} \sim \frac{4GM}{R^2}$$

$$R^3 \sim 2GMT^2$$

$$T \sim \sqrt{\frac{R^3}{2GM}} \quad \textbf{estimate}$$

$$T = \frac{\pi}{2}\sqrt{\frac{R^3}{2GM}} \quad \textbf{exact}$$

$$\frac{\pi}{2}\sqrt{\frac{R_\odot^3}{2GM_\odot}} \approx 0.5\,\text{hour}$$

- If gravity were the only force in play, the Sun would collapse into a **black hole** in about 0.5 hours!
- The force opposing the collapse is the force that arises from differences in pressure

Classification of Stars-Central Pressure

- The pressure off a gas is the force per unit area produced by all the microscopic collisions with the gas particles
- A gravity tries to compress a sphere of gas, the particles get closer together increasing the rate of collisions
- The gas is heated , causing more energetic collisions
- Causing the interior pressure to increase, leading to a net outward force that opposes the inward gravitational force of contraction, resulting in a hydrostatic balance
- Halting collapse

- Central pressure for the Sun can be estimated

$$\frac{dP}{dr} = -\rho(r)\,\frac{GM_r}{r^2}$$

$$\downarrow$$

$$\frac{P_c}{R} \sim \rho_{avg}\frac{G(M/2)}{(R/2)^2}$$

$$P_c \sim \rho_{avg}\frac{2GM}{R}$$

$$P_{c,\odot} \sim \rho_\odot\frac{2GM_\odot}{R_\odot} \sim 5\times10^{14}\,\mathrm{N\,m^{-2}}$$

- Central pressure in the Sun is about **5 billion times** Earth atmospheric pressure

Classification of Stars-Central Pressure

- The force that keeps a star, the Sun , from collapsing due to its own gravity is the fusion energy released in the core
- It balances the inward gravitational force with an outward pressure force

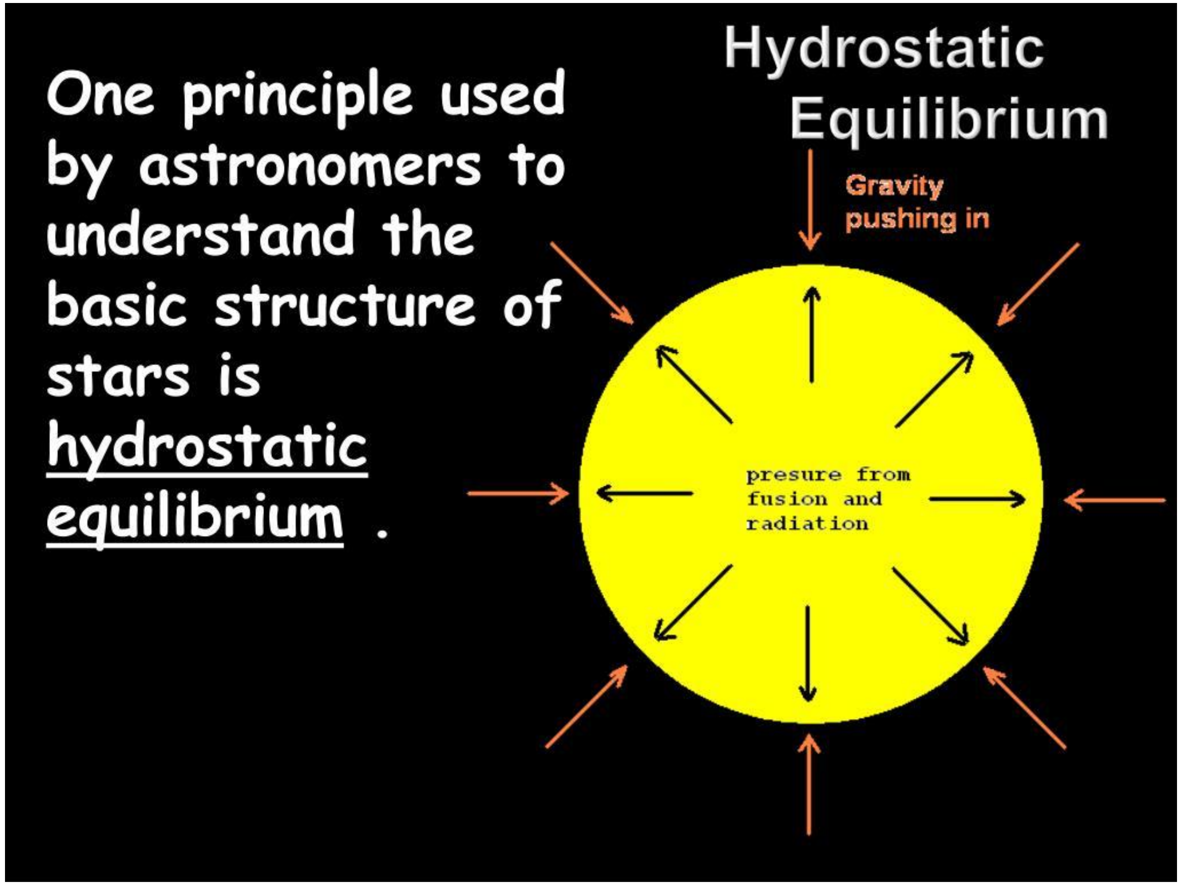
$$\frac{dP}{dr} = -\rho(r)\,\frac{GM_r}{r^2}$$

$$\Downarrow$$

$$\frac{P_c}{R} \sim \rho_{avg}\frac{G(M/2)}{(R/2)^2}$$

$$P_c \sim \rho_{avg}\frac{2GM}{R}$$

$$P_{c,\odot} \sim \rho_\odot \frac{2GM_\odot}{R_\odot} \sim 5\times10^{14}\,\mathrm{N\,m^{-2}}$$



Classification of Stars-Internal Temperature Estimates

- The central pressure in the Sun can be estimated by assuming the **ideal gas law** applies
- Using the estimated central pressure results in an estimated central temperature of

  $\sim 1.2 \times 10^{7}\,\mathrm{K}$

- This the same order of magnitude as the temperature required to ignite hydrogen fusion
  - **15 Million K**

$$P = nkT$$

$$n = \frac{\rho}{m_{\mathrm{avg}}} \longrightarrow P = \frac{\rho k T}{m_{\mathrm{avg}}}$$

hydrostatic balance

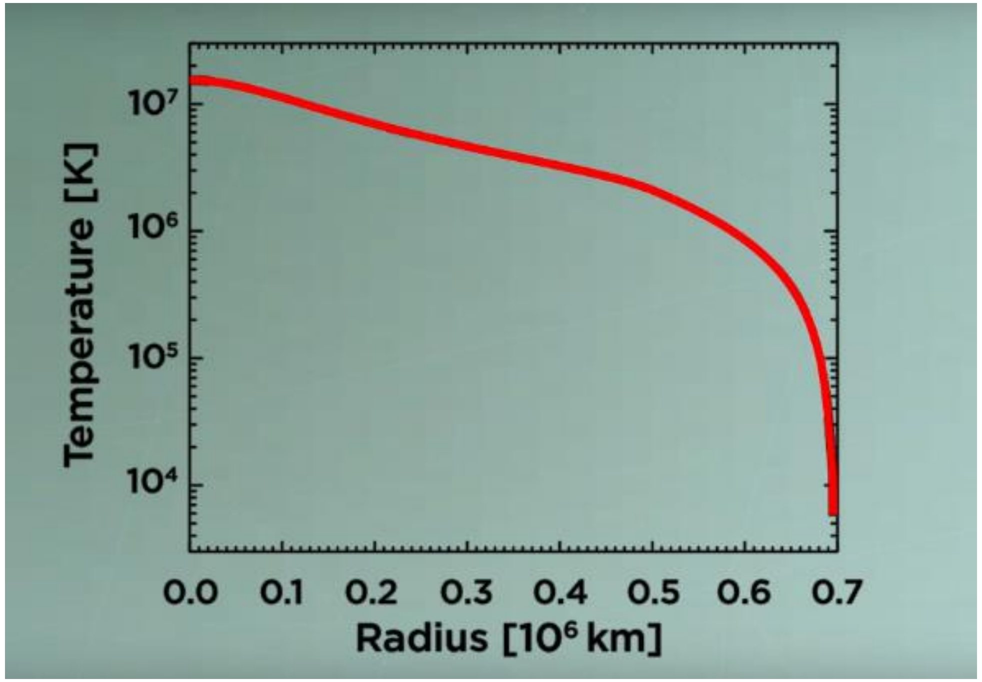
$$P_{\mathrm{c}} = \frac{\rho_{\mathrm{c}} k T_{\mathrm{c}}}{m_{\mathrm{avg}}} \sim \rho_{\mathrm{avg}} \frac{2GM}{R}$$

$$\rho_{\mathrm{c}} \stackrel{?}{=} 2\rho_{\mathrm{avg}} \longrightarrow \frac{2\rho_{\mathrm{avg}} k T_{\mathrm{c}}}{m_{\mathrm{avg}}} \sim \rho_{\mathrm{avg}} \frac{2GM}{R}$$

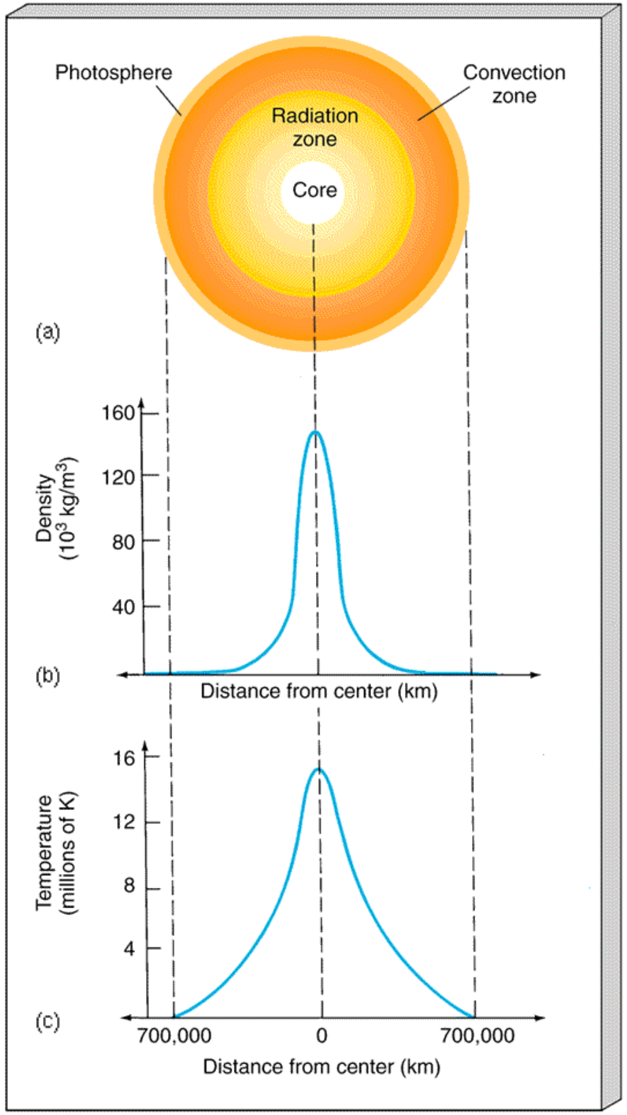
$$T_{\mathrm{c}} \sim \frac{GM m_{\mathrm{avg}}}{kR}$$

$$m_{\mathrm{avg}} \approx 0.5\, m_{\mathrm{p}} \longrightarrow T_{\mathrm{c},\odot} \sim \frac{GM_{\odot}(m_{\mathrm{p}}/2)}{kR_{\odot}} \sim 1.2 \times 10^{7}\,\mathrm{K}$$

Classification of Stars- Temperature Density Estimates for the Sun

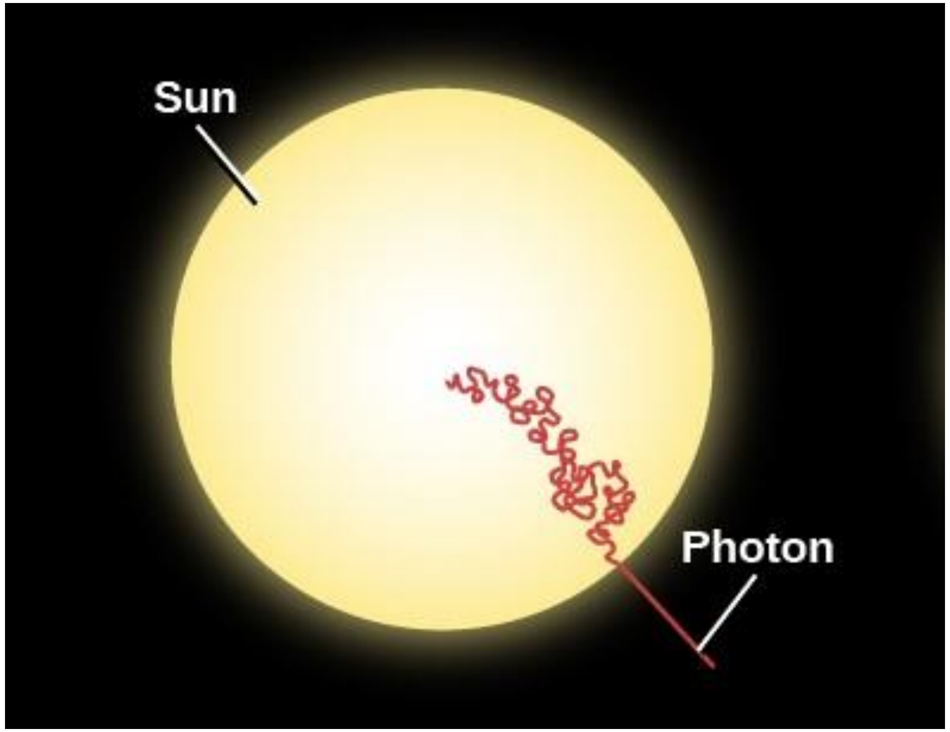


- Energy created In the core is "spread out" throughout the star's total volume
- For the Sun temperature drops from ~ 15 million K in the core to ~5.8 million K at the surface



Classification of Stars-

- Temperature is not constant throughout a star
- The core is super hot and above the photosphere is the cold vacuum of space
- The energy flow is a function of temperature gradient
- The energy is being transferred from the core to the surface by gamma ray **photons**
- If the star were "**optically thin**" the photons traveling at the speed of light would reach the Sun's surface in about 2.3 seconds
    - **Neutrinos** very weak interactions with matter
- Stars are "**optically thick**" so photons collide with particles and fly off in random directions as they leave the core
- Each gamma photon is converted during scattering into several million light (UV to IR) photons before escaping into space
- It takes ~50,000 years for a photon to go from the core to the surface



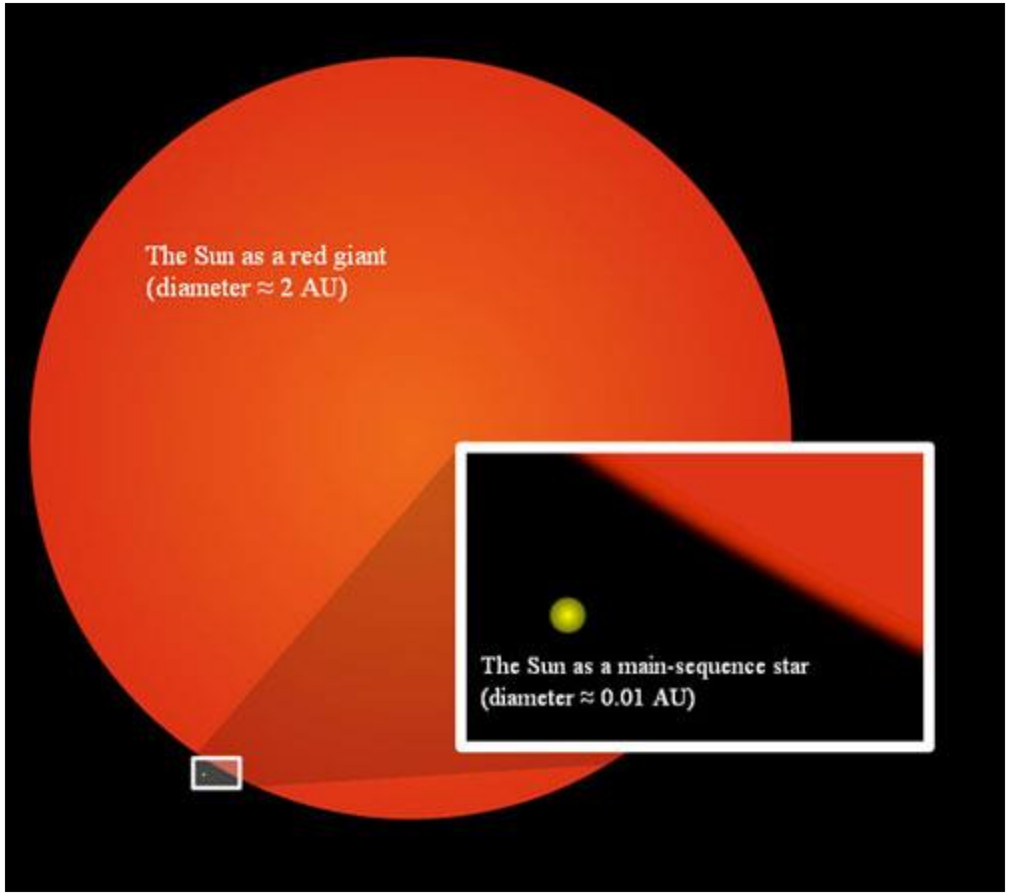
Classification of Stars-

- **Protostar** is what you have before a star forms
- It is a collection of gas that has collapsed down from a giant molecular cloud
- The protostar phase of stellar evolution lasts about 100,000 years
- Over time, gravity and pressure increase, forcing the protostar to collapse down
- All of the energy release by the protostar comes only from the heating caused by the gravitational energy – nuclear fusion reactions haven't started yet-not hot enough

- **T Tauri** star is a stage in a star's formation and evolution right before it becomes a main sequence star
- It occurs at the end of the protostar phase, when the gravitational pressure holding the star together is the source of all its energy
- T Tauri stars don't have enough pressure and temperature at their cores to generate nuclear fusion, but they do resemble main sequence stars; they're about the same temperature but brighter because they're a larger
- T Tauri stars can have large areas of sunspot coverage , and have intense X-ray flares and extremely powerful stellar winds
- Stars will remain in the T Tauri stage for about 100 million years

Classification of Stars- Red Giant Stars

- When a star has consumed its stock of hydrogen in its core, fusion stops and the star no longer generates an outward pressure to counteract the inward pressure pulling it together
- A shell of hydrogen around the core ignites continuing the life of the star, but causes it to increase in size dramatically
- The aging star has become a red giant star, and can be 100 times larger than it was in its main sequence phase
- When this hydrogen fuel is used up, further shells of helium and even heavier elements can be consumed in fusion reactions
- The red giant phase of a star's life will only last a few hundred million years before it runs out of fuel completely and becomes a white dwarf



Classification of Stars-

- When a star has completely run out of hydrogen fuel in its core and it lacks the mass to force higher elements into fusion reaction, it becomes a **white dwarf** star
- The outward light pressure from the fusion reaction stops and the star collapses inward under its own gravity
- A white dwarf shines because it was a hot star once, but there's **no fusion** reactions happening any more
- A white dwarf will just cool down until it becomes the background temperature of the Universe
- This process will take hundreds of billions of years, so no white dwarfs have actually cooled down that far yet

- **Red dwarf** stars are the most common kind of stars in the Universe
- These are main sequence stars but they have such low mass that they're much cooler than stars like the Sun
- Red dwarf stars are able to keep the hydrogen fuel mixing into their core, and so they can conserve their fuel for much longer than other stars
- Astronomers estimate that some red dwarf stars will burn for up to 10 trillion years
  - The age of the universe is estimated at 13.8 billion years
- The smallest red dwarfs are 0.075 times the mass of the Sun, and they can have a mass of up to half of the Sun

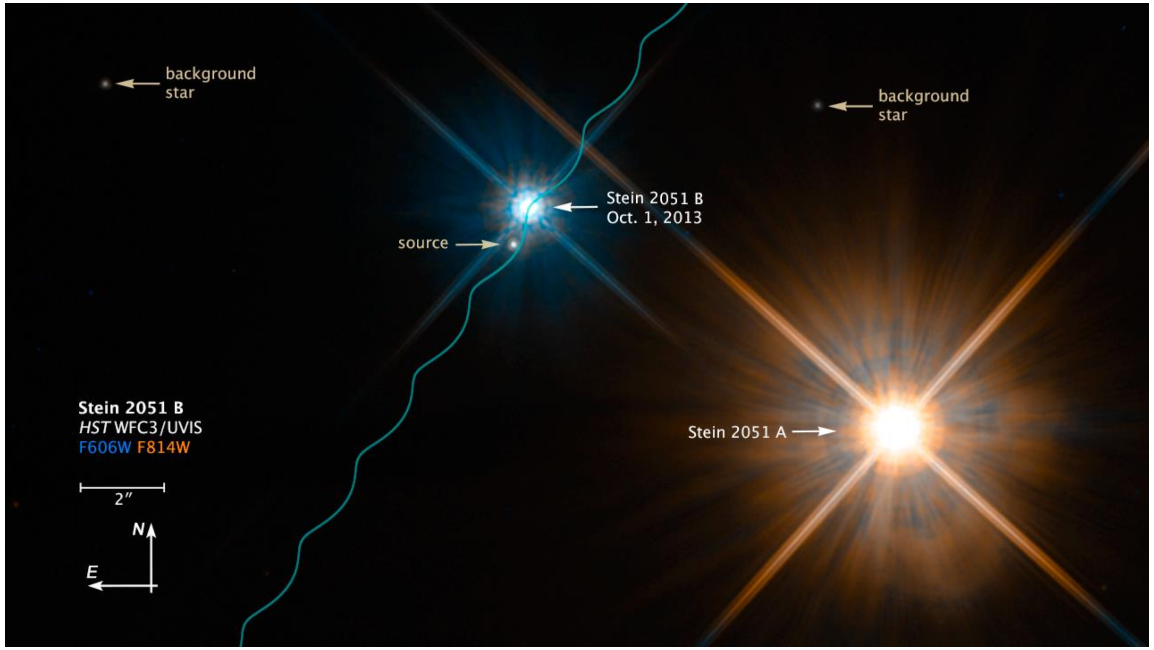
Classification of Stars-

- If a star has between 1.35 and 2.1 times the mass of the Sun, it doesn’t form a white dwarf when it dies
- Instead, the star dies in a catastrophic supernova explosion, and the remaining core becomes a **neutron star**
- As its name implies, a neutron star is an exotic type of star that is composed entirely of neutrons
- This is because the intense gravity of the neutron star crushes protons and electrons together to form neutrons
- A Neutron star is characterized by incredible density
- A single teaspoon of neutron star would weigh as much as a mountain
- If stars are even more massive, they will become **black holes** instead of neutron stars after the supernova goes off

- The largest stars in the Universe are **supergiant** stars
- These are monsters with dozens of times the mass of the Sun
- Supergiants are consuming hydrogen fuel at an enormous rate and will consume all the fuel in their cores within just a few million years
- Supergiant stars live fast and die young, detonating as supernovae- completely disintegrating themselves in the process

Classification of Stars-

- A **Binary star** is actually a star system made up of usually two stars that orbit around one center of mass – where the mass is most concentrated
- Astrophysicists find binary systems to be quite useful in determining the mass of the individual stars involved
- When two objects orbit one another, their mass can be calculated very precisely by using Newton's calculations for gravity
- The data collected from binary stars allows astrophysicists to extrapolate the relative mass of similar single stars



Hubble Space Telescope image shows the binary star system Stein 2051 on October 1, 2013, consisting of the brighter, redder "A" component at lower right and the fainter, bluer "B" component near the center, a white dwarf star

Next Session

- Formation of stars