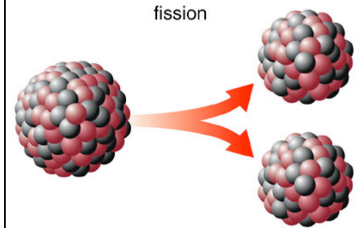
Lecture 8: The HR Diagram and Star Clusters
A2020 Prof. Tom Megeath

Review: How is energy produced in the Sun?



Fission

Big nucleus splits into smaller pieces

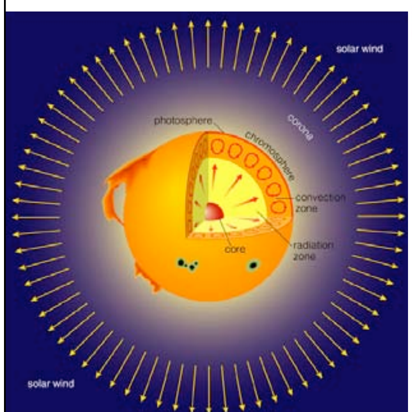
(Nuclear power plants)

Fusion

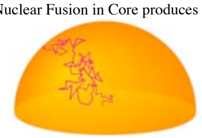
Small nuclei stick together to make a bigger one

(Sun, stars)

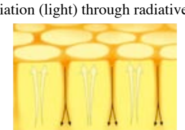
Review of the nearest star



Nuclear Fusion in Core produces energy

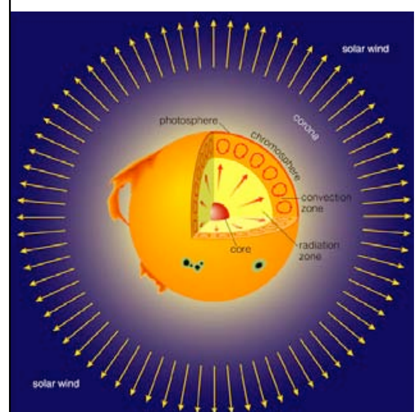


Energy is carried by electromagnetic radiation (light) through radiative zone



Energy is carried by convection through radiative zone

Review of the nearest star



The photosphere is where the light which illuminates the earth is produced.

Outside the photosphere is the tenuous corona where gas is heated to 1 million degrees

Can we use nuclear fusion to generate power on Earth?

Hydrogen is plentiful, this would be a limitless source of power (every water molecule has two hydrogen atoms)

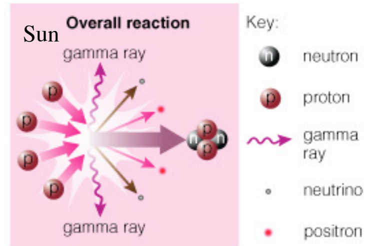
Would not create as much nuclear waste as nuclear fission

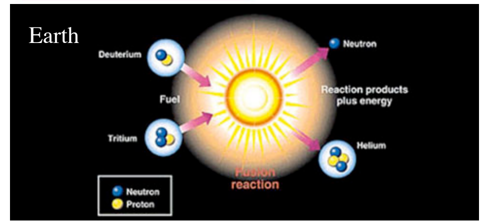
But requires us to generate extreme temperatures and pressures on Earth!!

There have been two approaches to date:

•Tokamaks – now being tried with International Thermonuclear Experimental Reactor (ITER) in France.

•Laser confinement fusion – now being tried at Lawrence Livermore laboratory in California.





https://lasers.llnl.gov/programs/ife/

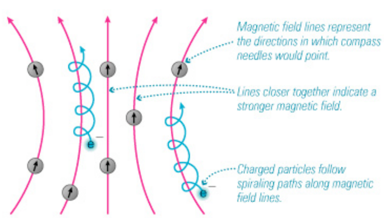
Fusion in the Sun requires a 3 step process starting with normal hydrogen

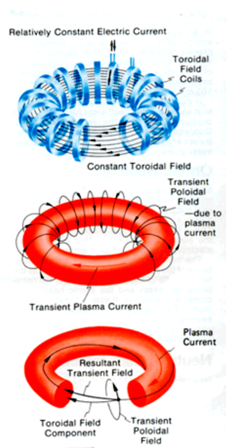
Possible way of generating fusion energy on Earth would be to use two isotopes of hydrogen: deuterium and tritium. By extracting these isotopes of hydrogen from sea water, one gallon of seawater has the energy of 300 gallons of gasoline, 50 cups of water has energy of two tons of coal.

Tokamak:

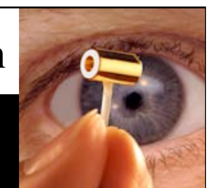
First ionize hydrogen so it forms a plasma, then confine the plasma with magnetic fields, finally heat the plasma with electrical currents.

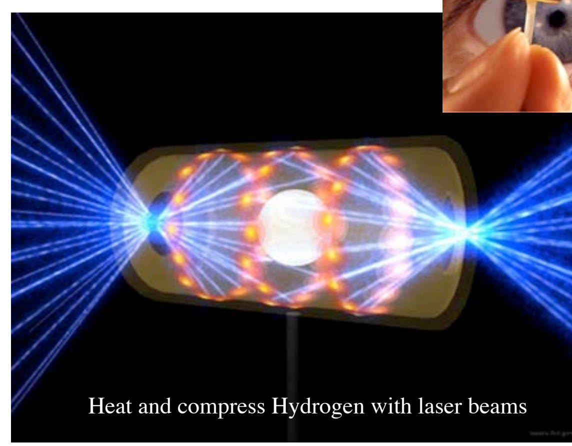
This idea was championed by Lyman Spitzer (born in Toledo) who also was instrumental in promoting space telescopes such as the Hubble.



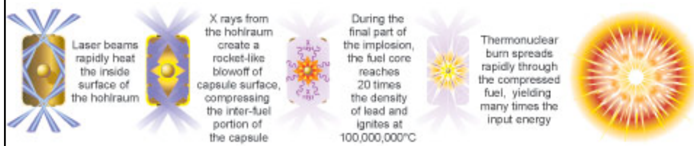


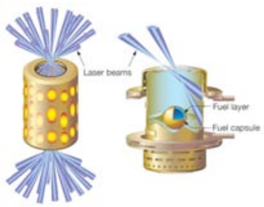
Internal Confinement Fusion





Internal Confinement Fusion



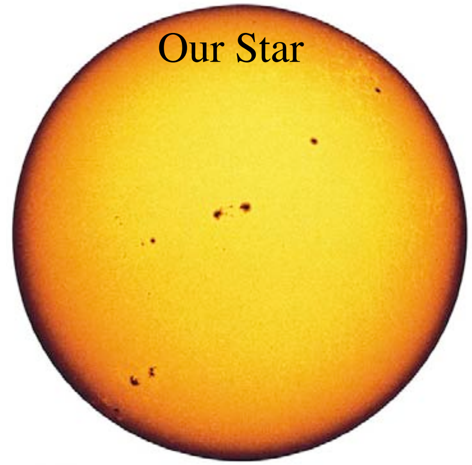


Recently achieved input energy of megajoule (energy generated by 10,000 100-watt bulbs in 1 second) and created temperatures of 3 million Kelvin.

To achieve Fusion, goal is exceed to compress gas 1000 times and achieve a temperatures in the center of sun (100 million Kelvin). This may occur in the next few years.

https://lasers.llnl.gov/

How does the Sun compare to other stars???



Radius:

6.9×10^{8} m

(109 times Earth)

Mass:

2×10^{30} kg

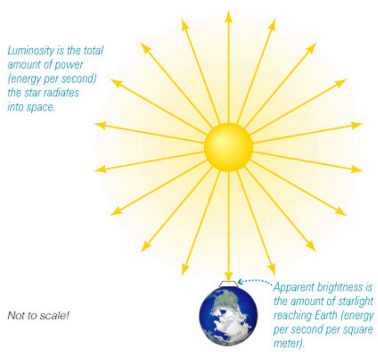
(300,000 Earths)

Luminosity:

3.8×10^{26} watts

Temperature:

5800 K



Luminosity:

Amount of power a star radiates

(energy per second = Watts)

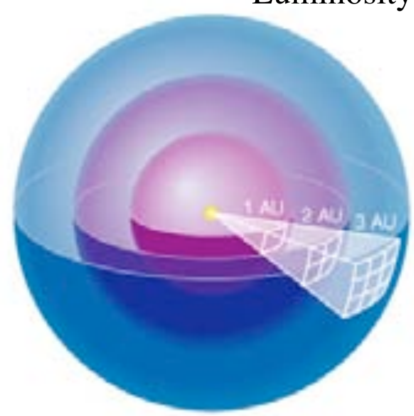
Apparent brightness:

Amount of starlight that reaches Earth

(energy per second per square meter)

How do we find properties of other stars?

Luminosity



Luminosity passing through each sphere is the same

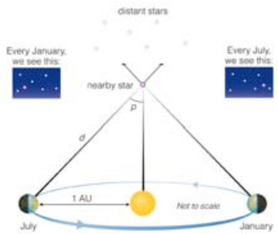
Area of sphere:

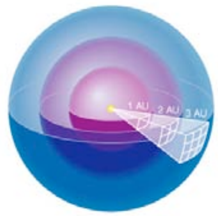
4π (radius)^2

Divide luminosity by area to get brightness

How do we find properties of other stars?

Luminosity





Luminosity = energy per time

Flux = Luminosity / 4 π distance^2

Flux = energy per area per time

The relationship between apparent brightness and luminosity depends on distance:

$$\text{Brightness} = \frac{\text{Luminosity}}{4\pi\ (\text{distance})^2}$$

We can determine a star's luminosity if we can measure its distance and apparent brightness:

$$\text{Luminosity} = 4\pi\ (\text{distance})^2 \times (\text{Brightness})$$

Most luminous stars:

$10^6\ L_{Sun}$

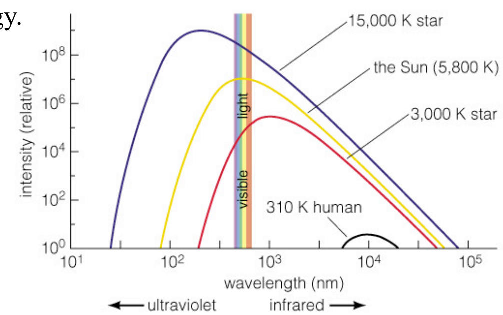
Least luminous stars:

$10^{-4}\ L_{Sun}$

(L_{Sun} is luminosity of Sun)

How do we measure stellar temperatures: I?

1. Hotter objects emit more light per unit area at all frequencies.
2. Hotter objects emit photons with a higher average energy.



How do we measure stellar temperatures: I?

10^6 K

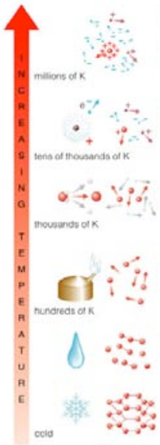
10^5 K

10^4 K

10^3 K

10^2 K

10 K



Ionized Gas (Plasma)

Neutral Gas

Molecules

Solid

Level of ionization also reveals a star's temperature

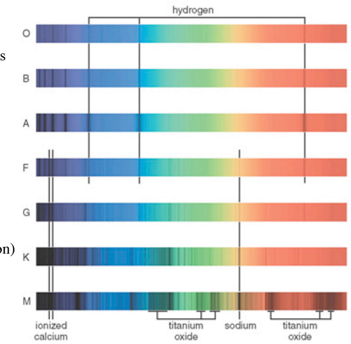
Temperature and Spectral Types

Hydrogen ionized (to hot for hydrogen atoms to exist)

Abundant Hydrogen, sodium and calcium ionized

Abundant sodium and calcium atoms (calcium missing only one electron)

Molecules form



Hot stars

The Sun

Cool stars

Lines in a star's spectrum correspond to a *spectral type* that reveals its temperature

(Hottest) O B A F G K M (Coolest)

- Oh, Be A Fine Girl, Kiss Me
- Only Boys Accepting Feminism Get Kissed Meaningfully

Hottest stars:

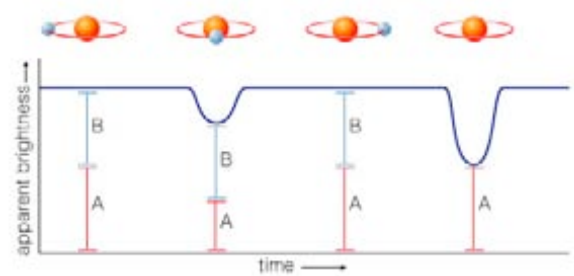
50,000 K (O)

Coolest stars:

3,000 K (M)

(Sun's surface is 5,800 K G)

How do we measure stellar masses?

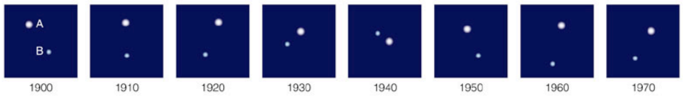


Types of Binary Star Systems

- Visual Binary
- Eclipsing Binary
- Spectroscopic Binary

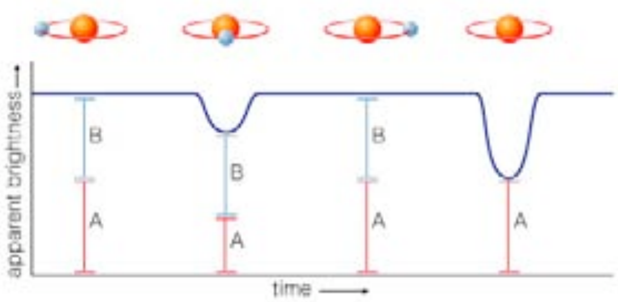
About half of all stars are in binary systems

Visual Binary



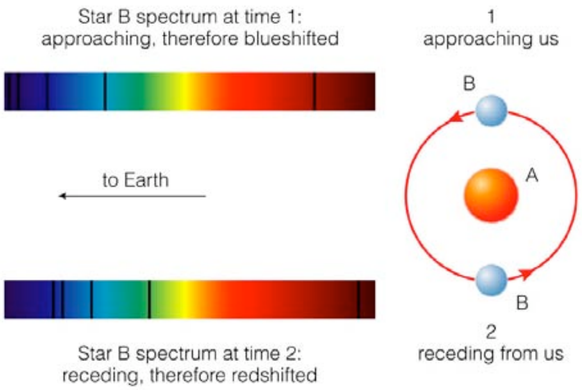
We can directly observe the orbital motions of these stars

Eclipsing Binary



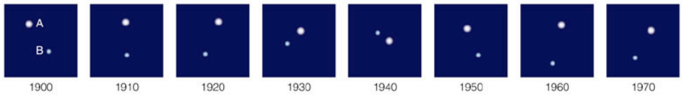
We can measure periodic eclipses

Spectroscopic Binary



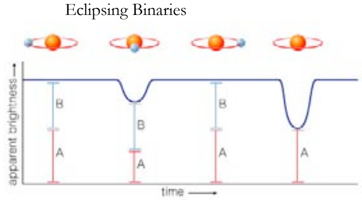
We determine the orbit by measuring Doppler shifts

Stellar Mass

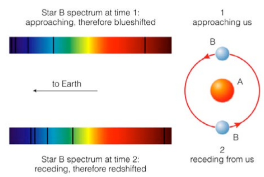


Visual Binaries

Eclipsing Binaries



Spectroscopic Binaries



Measuring mass from binaries

We measure mass using gravity using Newton's law of universal gravity.

p = period (time to complete an orbit)

a = average separation of stars

$$p^2 = \frac{4\pi^2}{G\,(M_1 + M_2)}\, a^3$$

Isaac Newton

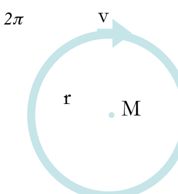
What if we can't measure a, the separation?

For eclipsing, spectroscopic binaries this can be done.

1) Orbital Period (p)
2) Orbital Separation (a = radius)
3) Orbital Velocity (v)

For circular orbits, $v = 2\pi a / p$

Thus $a = vp / 2\pi$



Most massive stars:

$100\ M_{Sun}$

Least massive stars:

$0.08\ M_{Sun}$

(M_{Sun} is the mass of the Sun)

The Properties of Stars

Luminosity, Radius, Temperature and Mass

In the case of Luminosity, Radius, and Temperature we don't need to measure all three.

For blackbodies (good approximation for stars)

Luminosity = 4 π Radius^2 Temperature^4

Thus if we only need to know two of the three values

The Properties of Stars

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In the case of Luminosity, Radius, and Temperature we don't need to measure all three.

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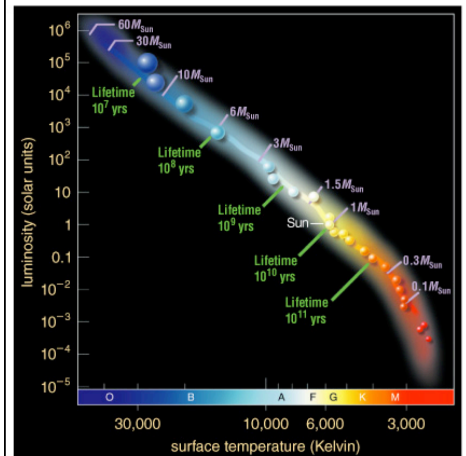
Luminosity = 4 π Radius² Temperature⁴

Thus if we only need to know two of the three values



Main-sequence stars are fusing hydrogen into helium in their cores like the Sun

Luminous main-sequence stars are hot (blue)

Less luminous ones are cooler (yellow or red)

History of Spectral Sequence

1882: Henry Draper' widow makes a large donation to Harvard College Observatory with the goal of continuing his work.

Observatory directory Edward Pickering used give to hire numerous assistants, which he called "calculators".

Most calculators were women who studied astronomy or physics at Radcliffe or Wellsley, but had no opportunity to advance.

Williamina Fleming classified stars with an A, B, C, D, F, G, based on depth of Hydrogen lines.

In 1890, a list of 10,000 stars classified by Fleming were published

Pioneers of Stellar Classification

A better classification scheme was found by Annie Jump Canon, who joined the "computers" in 1896. Found that stars come in a "natural sequence".

The current scheme of O, B, A, F, G, K, M resulted from Canon revising Fleming's work.

Canon went on to classify 400,000 stars, was the first woman awarded an honorary degree by Oxford, and in 1929 was voted one of the 12 greatest living american women by the League of American Women Voters.

The meaning of the spectral lines were discovered by Cecilia Payne-Gaposchkin (1900-1979) another woman working at Harvard Observatory

Used quantum mechanics to understand connection between spectral types and temperatures.

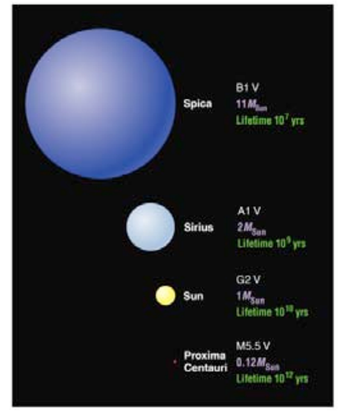
In 1925 she was the first person to earn a Ph.D. in astronomy from Harvard.

Her thesis was later called by Otto Struve the "Undoubted the most brilliant Ph.D. thesis ever written in astronomy"

In 1956 she became the first female tenured professor at Harvard, and later the first female chair.

The reward of the young scientist is the emotional thrill of being the first person in the history of the world to see something or to understand something. Nothing can compare with that experience… The reward of the old scientist is the sense of having seen a vague sketch grow into a masterly landscape.—Cecilia Payne-Gaposchkin (1900-1980)

Main-Sequence Star Summary

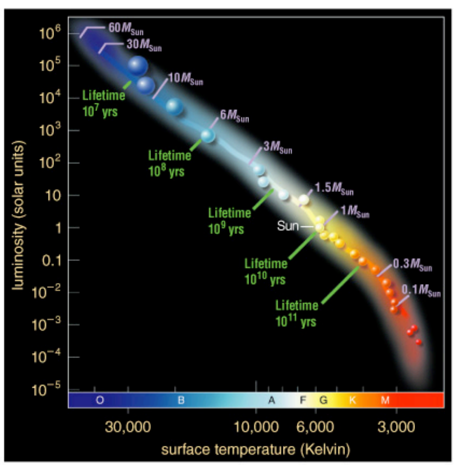


High Mass:

- High Luminosity
- Short-Lived
- Large Radius
- Blue

Low Mass:

- Low Luminosity
- Long-Lived
- Small Radius
- Red



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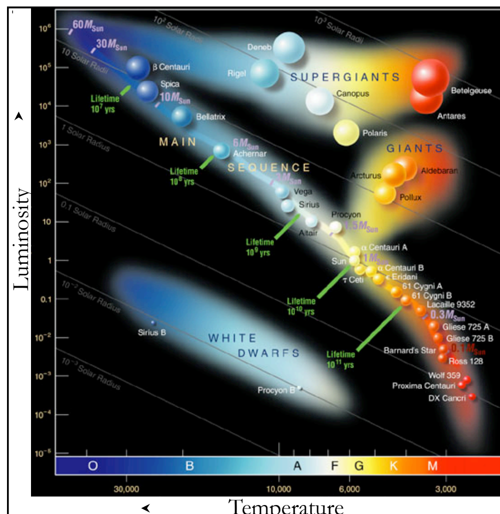
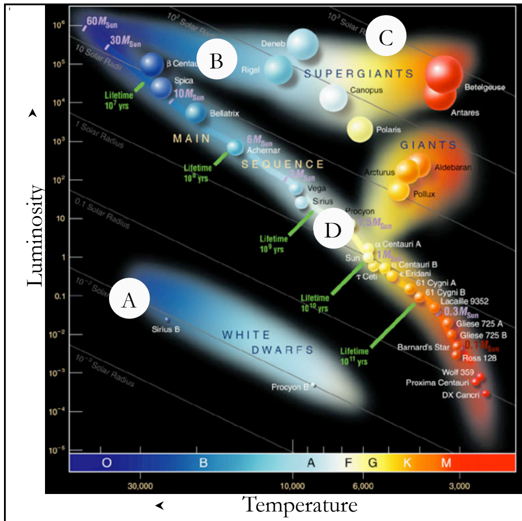
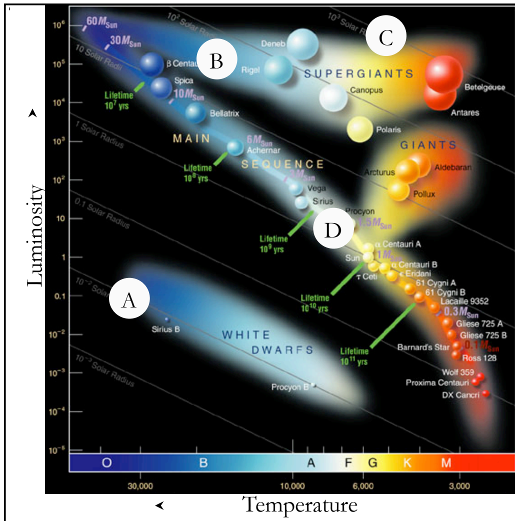


H-R diagram depicts:

- Temperature
- Color
- Spectral Type
- Luminosity
- Radius

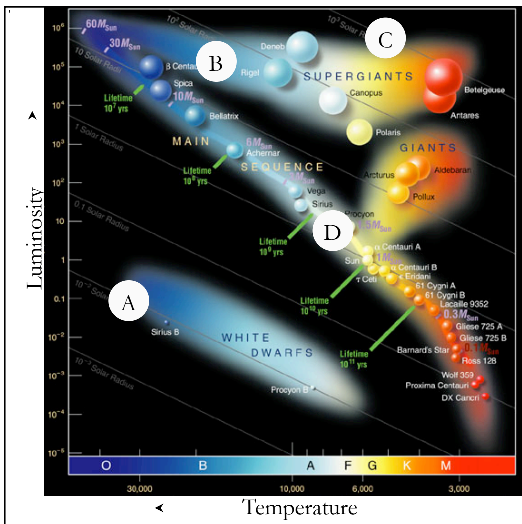


Which star is the hottest?

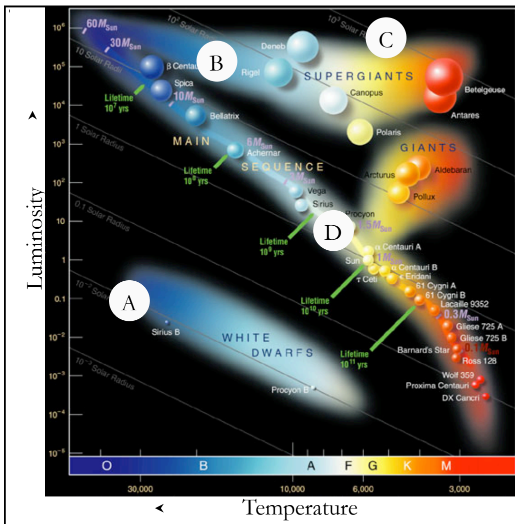


Which star is the hottest?

A

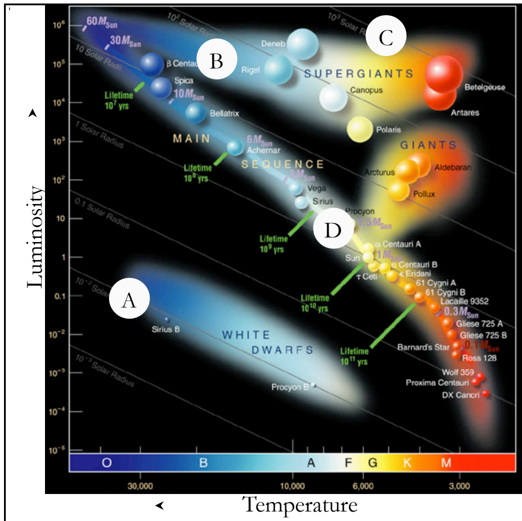


Which star is the most luminous?

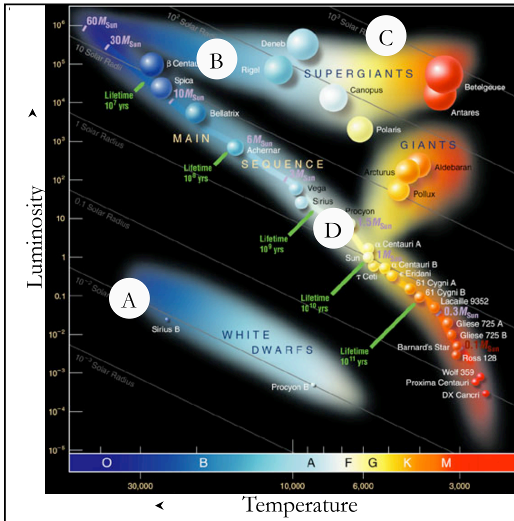


Which star is the most luminous?

C

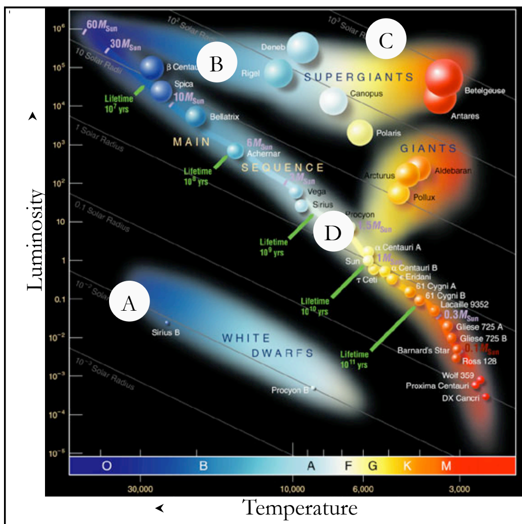


Which star is a main-sequence star?

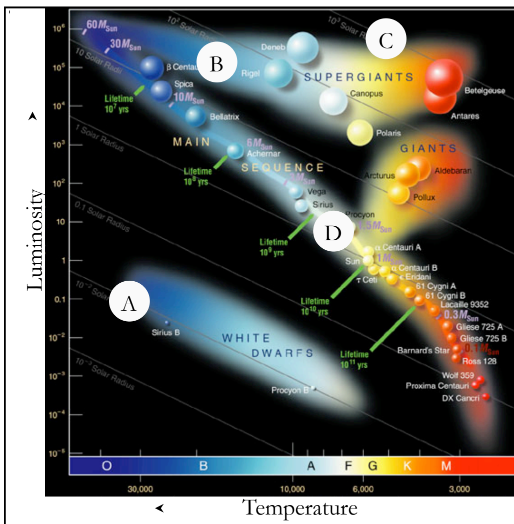


Which star is a main-sequence star?

D

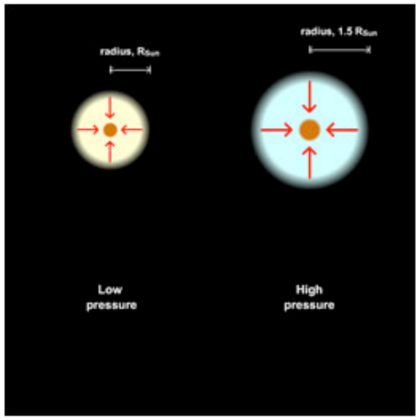


Which star has the largest radius?



Which star has the largest radius?

C



Core pressure and temperature of a higher-mass star need to be larger in order to balance gravity

Higher core temperature boosts fusion rate, leading to larger luminosity

Mass & Lifetime

Sun's life expectancy: 10 billion years

Until core hydrogen (10% of total) is used up

Life expectancy of 10 M_{Sun} star:

10 times as much fuel, uses it 10^4 times as fast

10 million years ~ 10 billion years x $10 / 10^4$

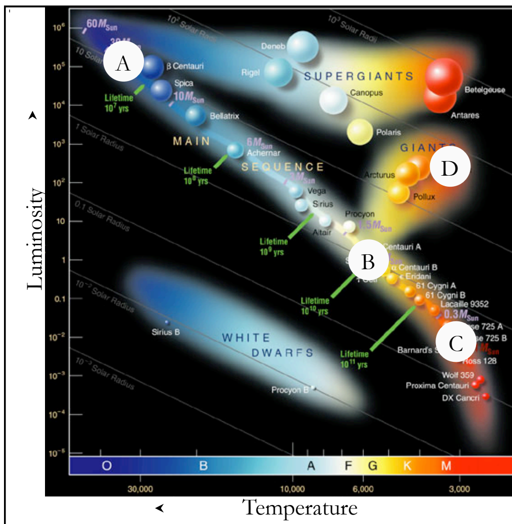
Life expectancy of 0.1 M_{Sun} star:

0.1 times as much fuel, uses it 0.01 times as fast

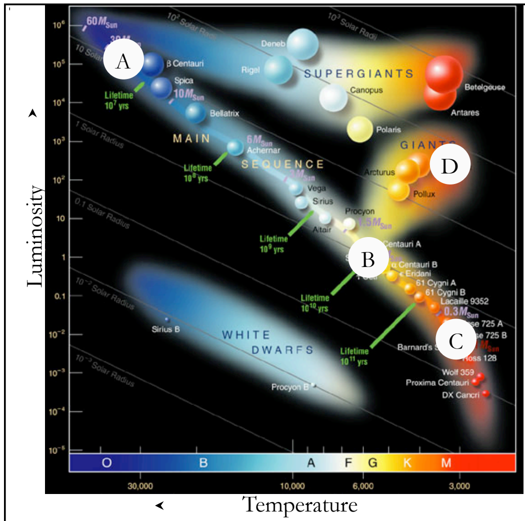
100 billion years ~ 10 billion years x 0.1 / 0.01

Off the Main Sequence

- Stellar properties depend on both mass and age: those that have finished fusing H to He in their cores are no longer on the main sequence
- All stars become larger and redder after exhausting their core hydrogen: **giants** and **supergiants**
- Most stars end up small and white after fusion has ceased: **white dwarfs**

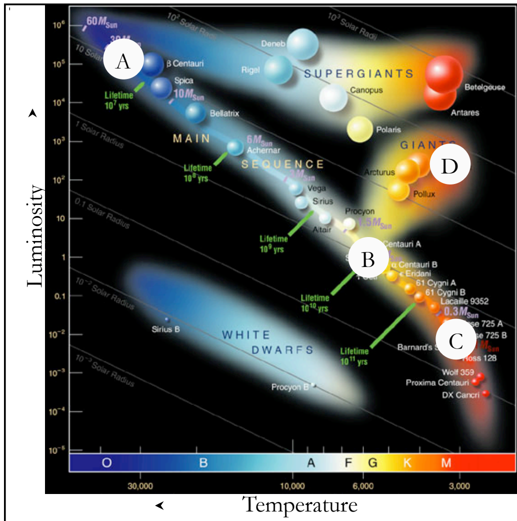


Which star is most like our Sun?

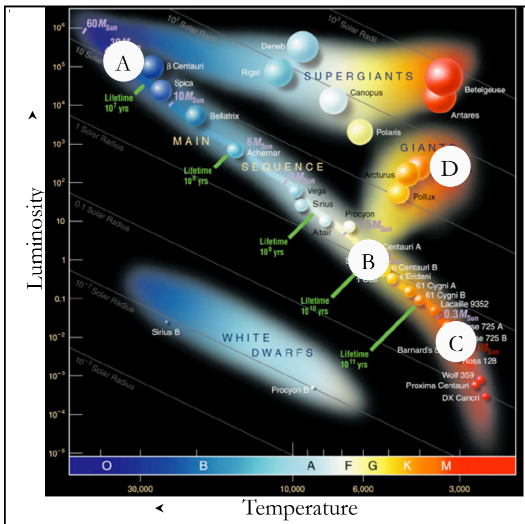


Which star is most like our Sun?

B

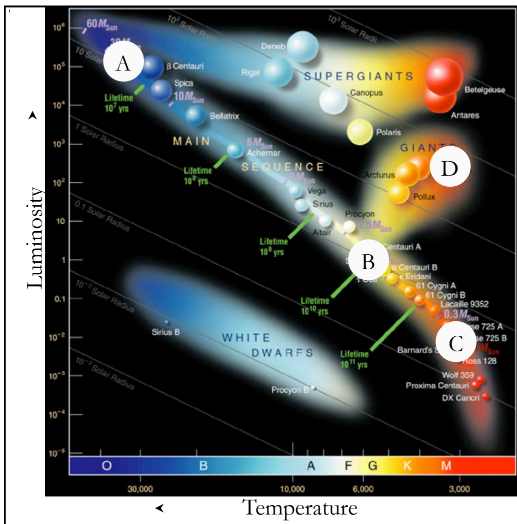


Which of these stars will have changed the least 10 billion years from now?

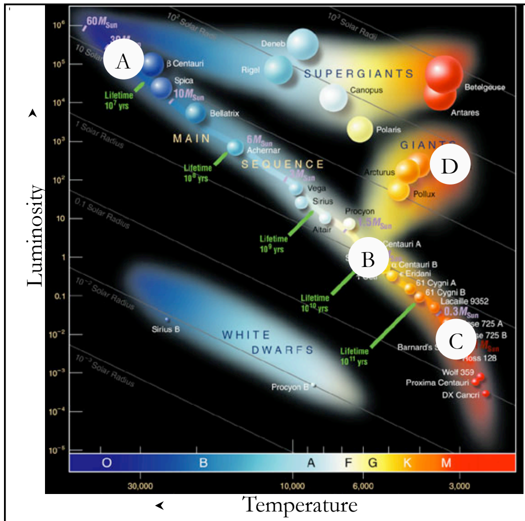


Which of these stars will have changed the least 10 billion years from now?

C



Which of these stars can be no more than 10 million years old?



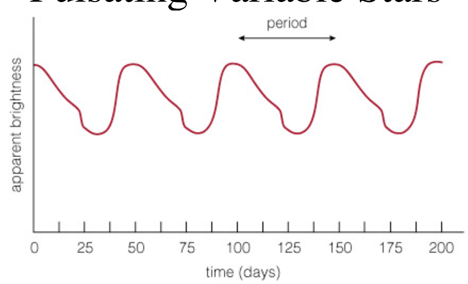
Which of these stars can be no more than 10 million years old?

A

Variable Stars

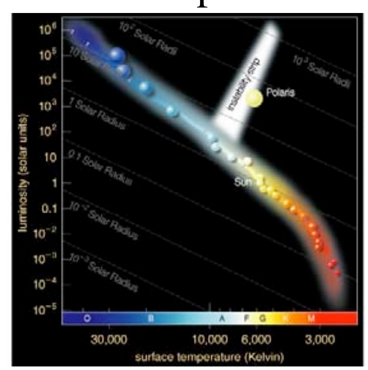
- Any star that varies significantly in brightness with time is called a *variable star*
- Some stars vary in brightness because they cannot achieve proper balance between power welling up from the core and power radiated from the surface
- Such a star alternately expands and contracts, varying in brightness as it tries to find a balance

Pulsating Variable Stars



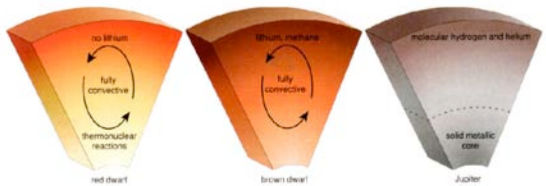
- The light curve of this *pulsating variable star* shows that its brightness alternately rises and falls over a 50-day period

Cepheid Variable Stars



- Most pulsating variable stars inhabit an *instability strip* on the H-R diagram
- The most luminous ones are known as *Cepheid variables*

Brown Dwarfs



M star
0.3-0.08 Msun
Fusion in center,
Convective zone
surrounding core
Cool photosphere
(3000K)

Brown Dwarf
Mass < 0.08 Msun
Core never reaches
densities and
temperature for fusion
to occur.
Made of metallic
hydrogen.

Jupiter
0.001 Msun
Largest planet in our
solar system, mass is
320 times the mass of
the Earth. Metallic
hydrogen core.

Brown Dwarfs: The Failed Stars

0.08 Solar Masses

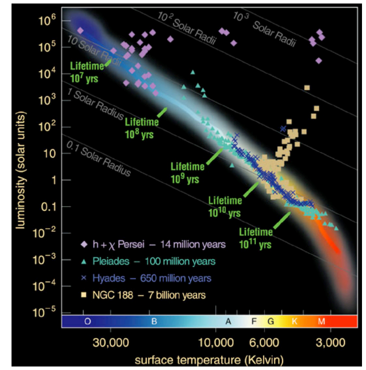
Hurt/SSC

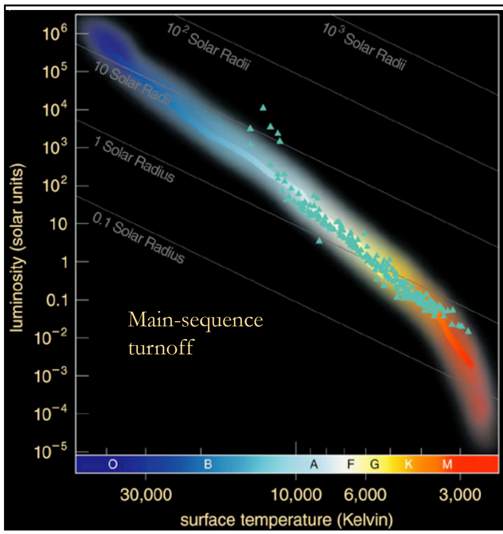
What are the two types of star clusters?

Open cluster: A few thousand loosely packed stars

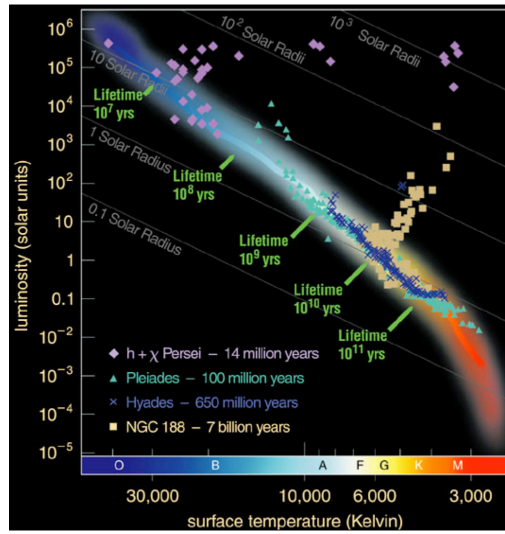
Globular cluster: Up to a million or more stars in a dense ball bound together by gravity

How do we measure the age of a star cluster?

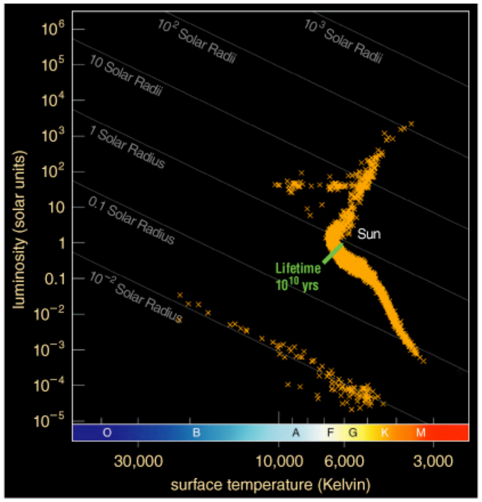




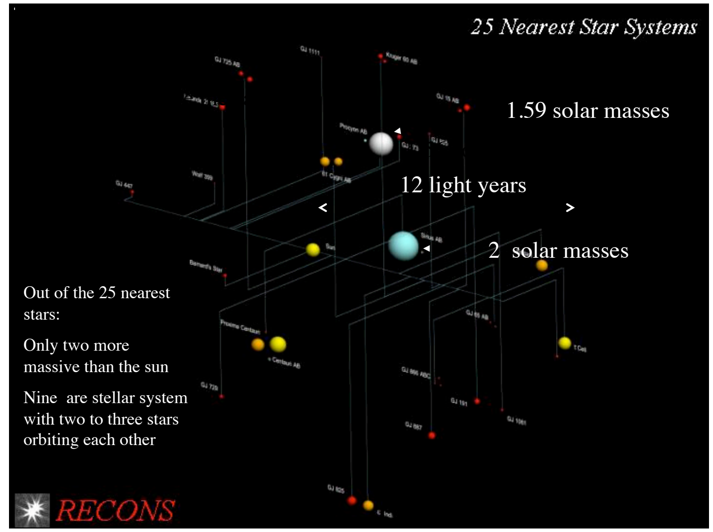
Pleiades now has no stars with life expectancy less than around 100 million years



Main-sequence turnoff point of a cluster tells us its age



Detailed modeling of the oldest globular clusters reveals that they are about 13 billion years old



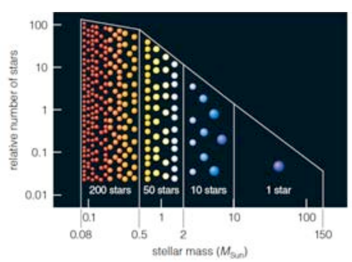
The nearest stars

Out to a distance of 4 pc, 12 light, from the Sun, there are 30 stars.

The brightest is Sirius, which can be seen in the night sky.

Only 10 are bright enough to see with the naked eye.

The rest have been discovered through telescopic surveys of the sky.



Most stars in the sky are cool M-stars

Summary

Stars spend most of their lives on the main sequence

The properties of main sequence stars depend largely on its mass

•High mass stars are very luminous, hot and have short lives

•Cool stars are faint, cool and have very long lives

Hertzsprung Russel (HR) diagram is the key to understand stars and stellar evolution.

Stars are often found in clusters:

•Open clusters with thousands of stars

•Globular clusters with millions of stars

The age of a cluster can be measured with an HR diagram.

•Open clusters are often "young" (100 million years)

• Globular clusters are always old (13 billion years)

Most stars are low mass M-stars (about 0.5 the mass of our Sun)

Summary

Stars spend most of their lives on the main sequence

The properties of a star depend largely on its mass

High mass stars are very luminous, hot and have short lives

Cool stars are faint, cool and have very long lives

Hertzsprung Russel (HR) diagram is the key to understand stars and stellar evolution.