Stars

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For thousands of nearby stars we can find:

- the total luminosity
- the temperature (color or spectral type)
- the size (radius)
- the mass

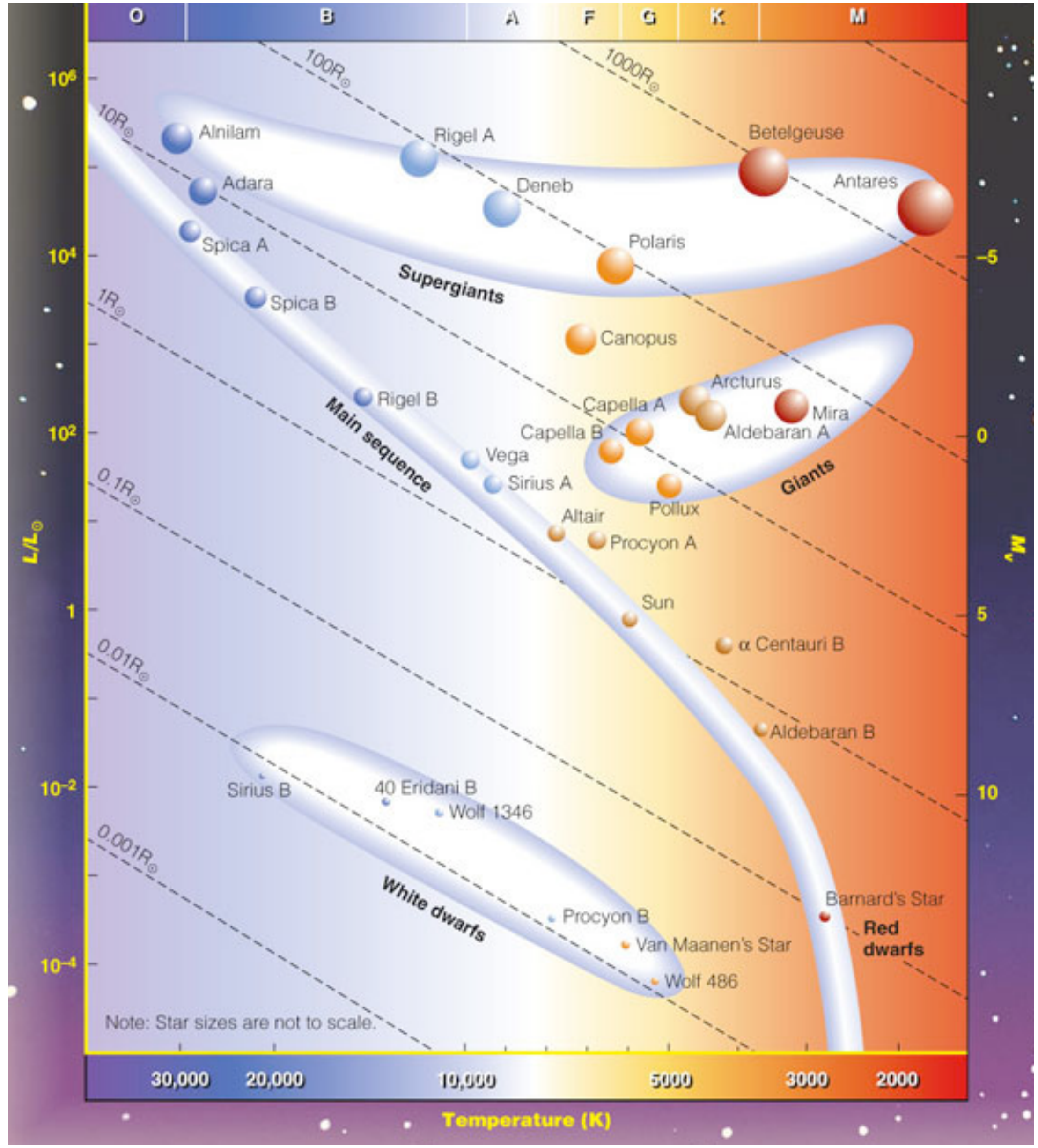
CAN WE FIND ANY RHYME, REASON, OR RELATIONSHIPS?

The H-R Diagram

- done independently by Enjar Hertzsprung and Henry Norris Russell around 1910.
- graph of luminosity (or absolute magnitude) versus temperature (or spectral class)

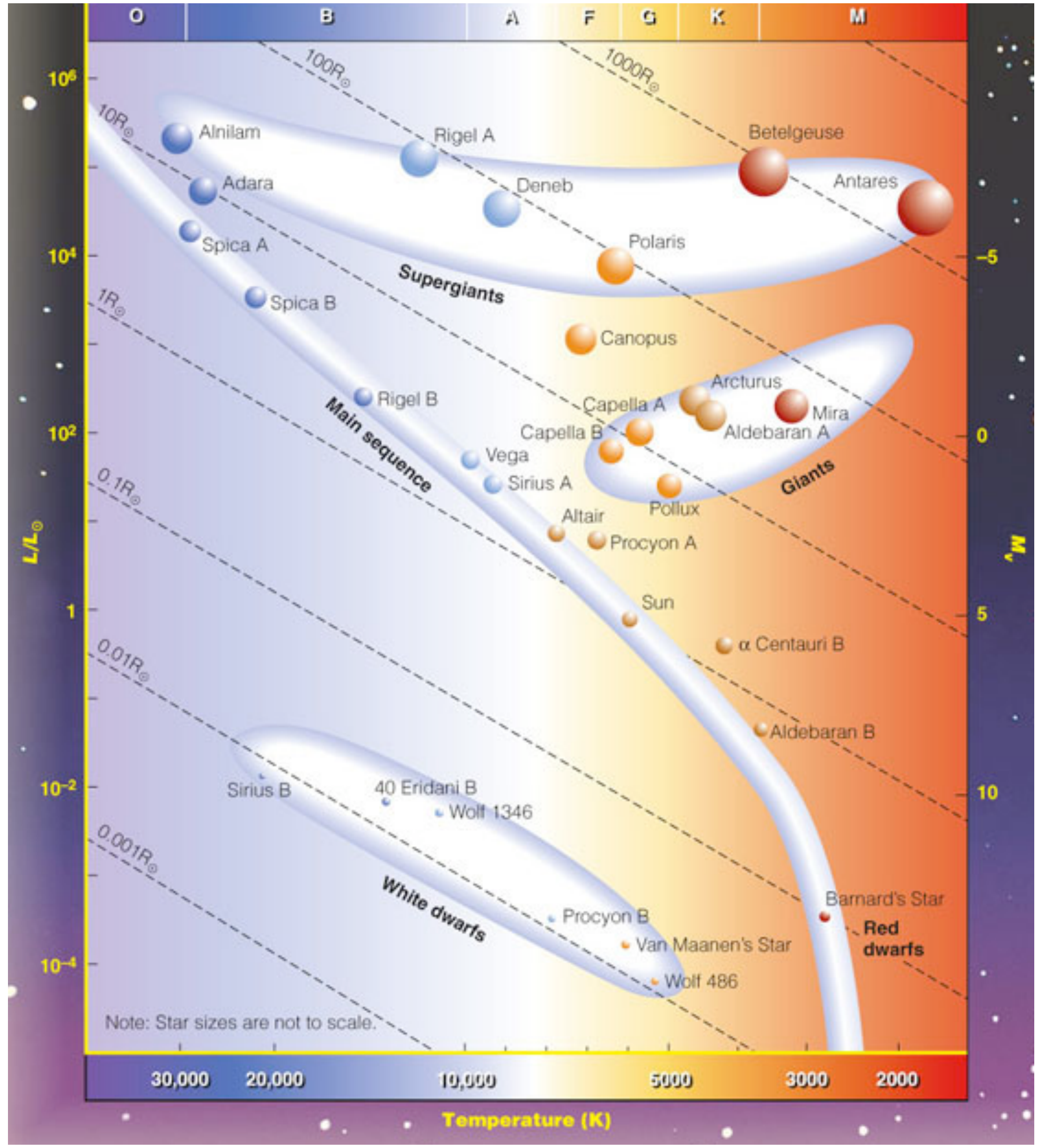
The H-R Diagram

The Hertzprung-Russell (H-R) diagram shows the relationship between luminosity and temperature (absolute magnitude and spectral class) for stars.



The H-R Diagram

The H-R diagram shows that there is a definite relationship between the luminosity (absolute magnitude) of a star and its temperature (spectral class)



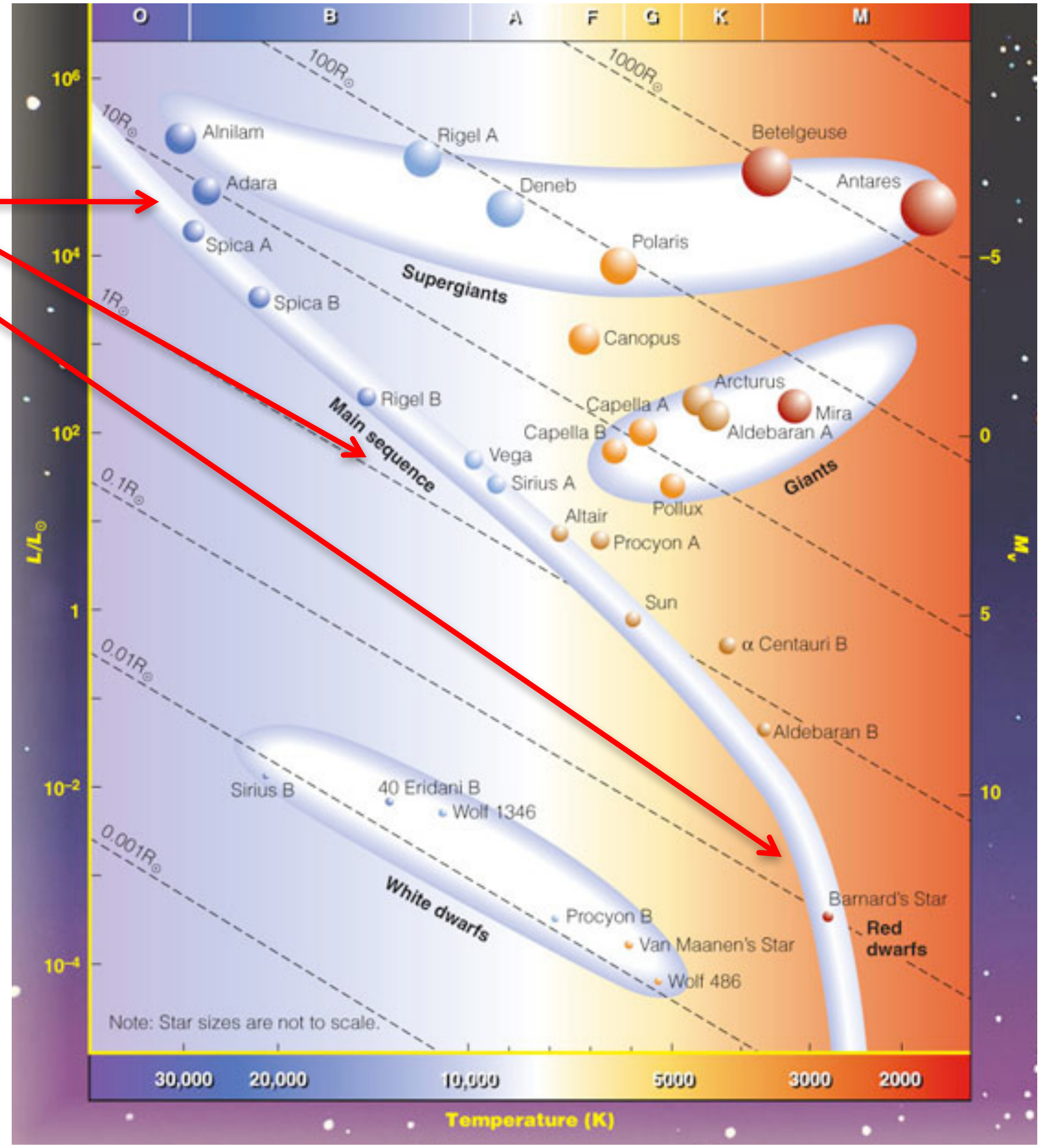
Main Sequence

- Goes from top left (hot and bright) to bottom right (cool and dim).
- 90% of the stars are in the Main Sequence stage of their lives
- Includes our Sun.

Main Sequence

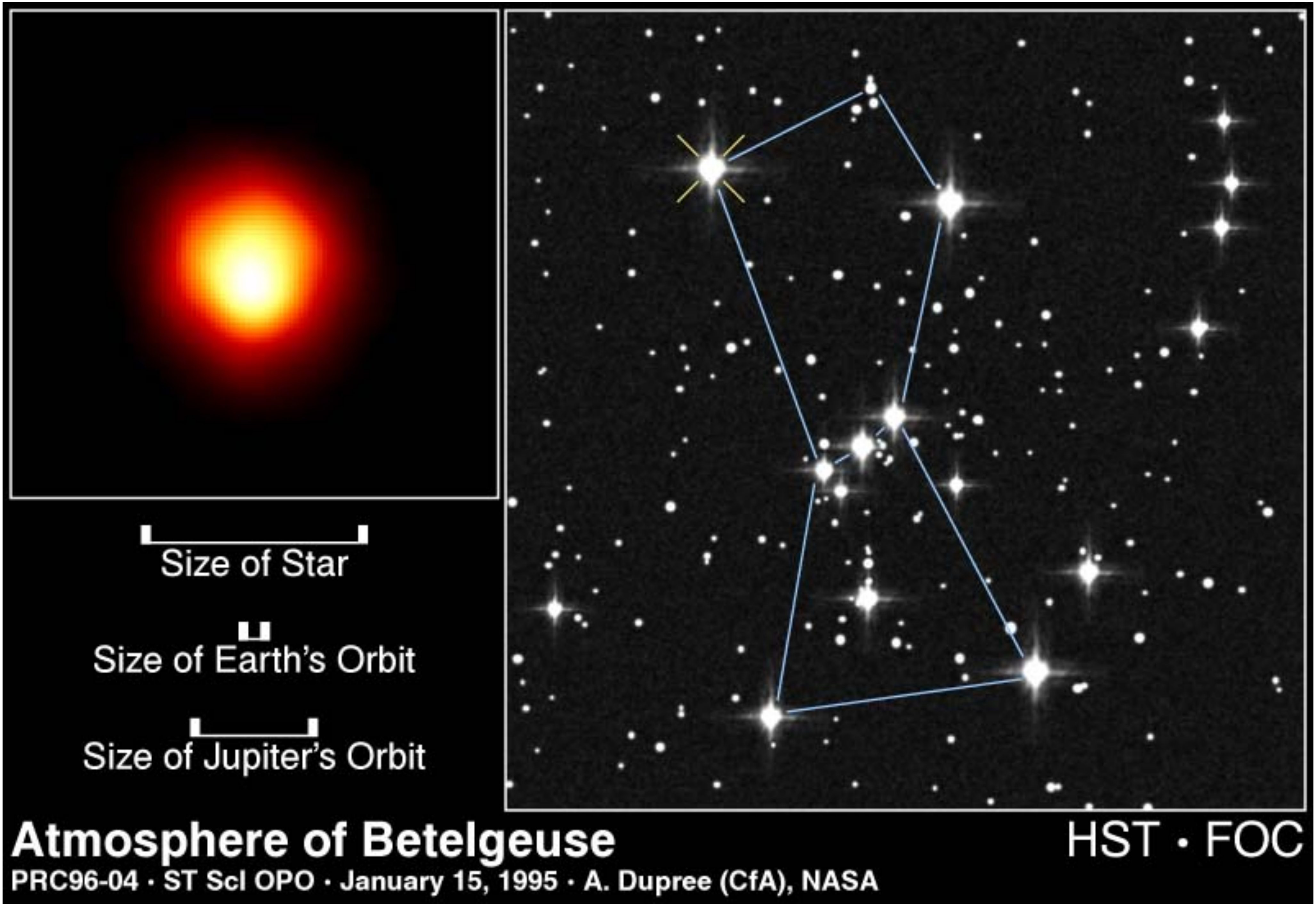
The Main Sequence runs from the lower right to upper left of the H-R diagram.

Hotter main sequence stars are brighter.



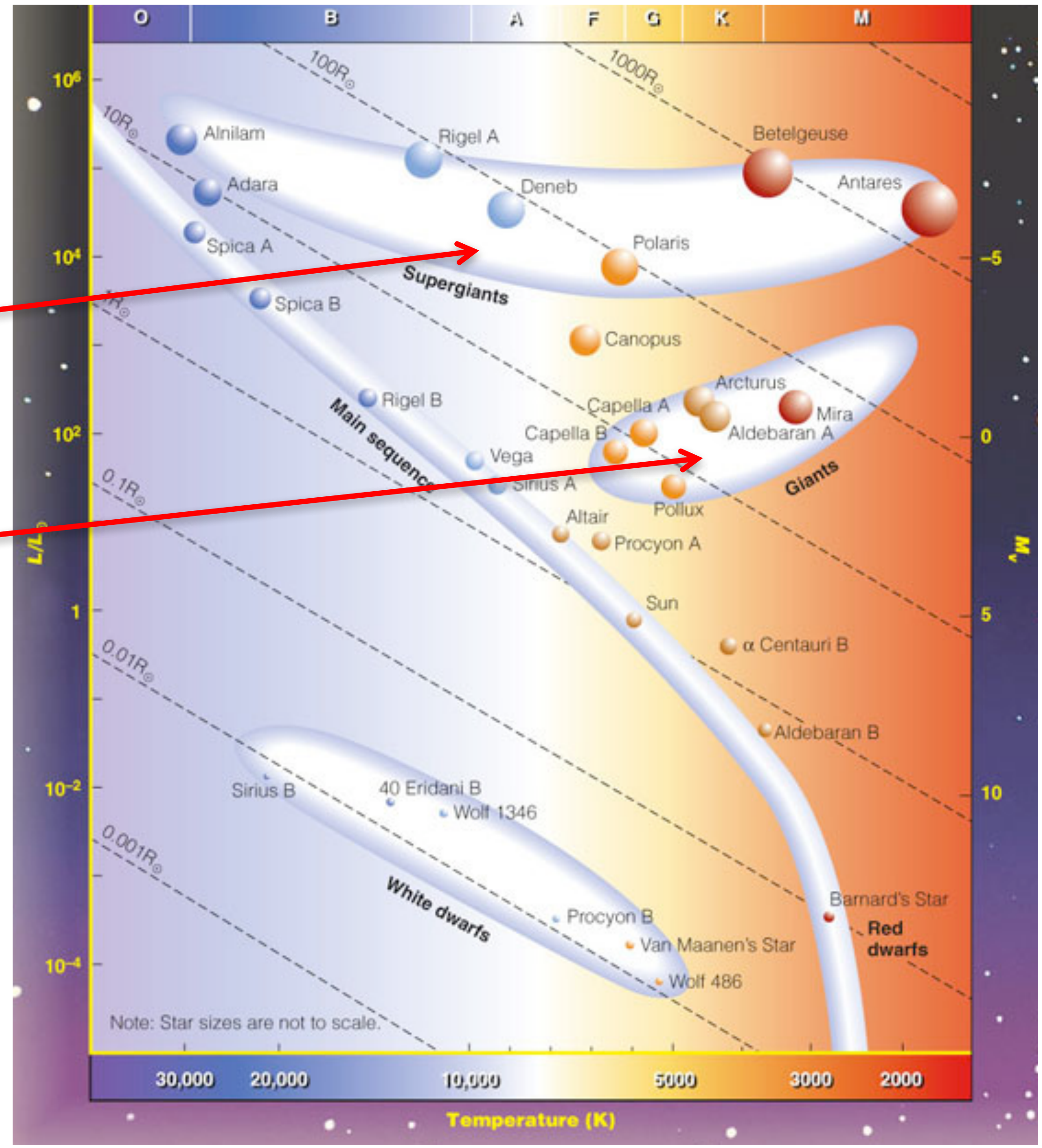
Red Giants

- Really Big, Not Very Hot but VERY BRIGHT!
- Betelgeuse: 3500 K , 100,000 times more luminous than the sun
- radius must be 1000x that of Sun!


Size of Star
Size of Earth's Orbit
Size of Jupiter's Orbit
Atmosphere of Betelgeuse
HST • FOC
PRC96-04 · ST ScI OPO · January 15, 1995 · A. Dupree (CfA), NASA

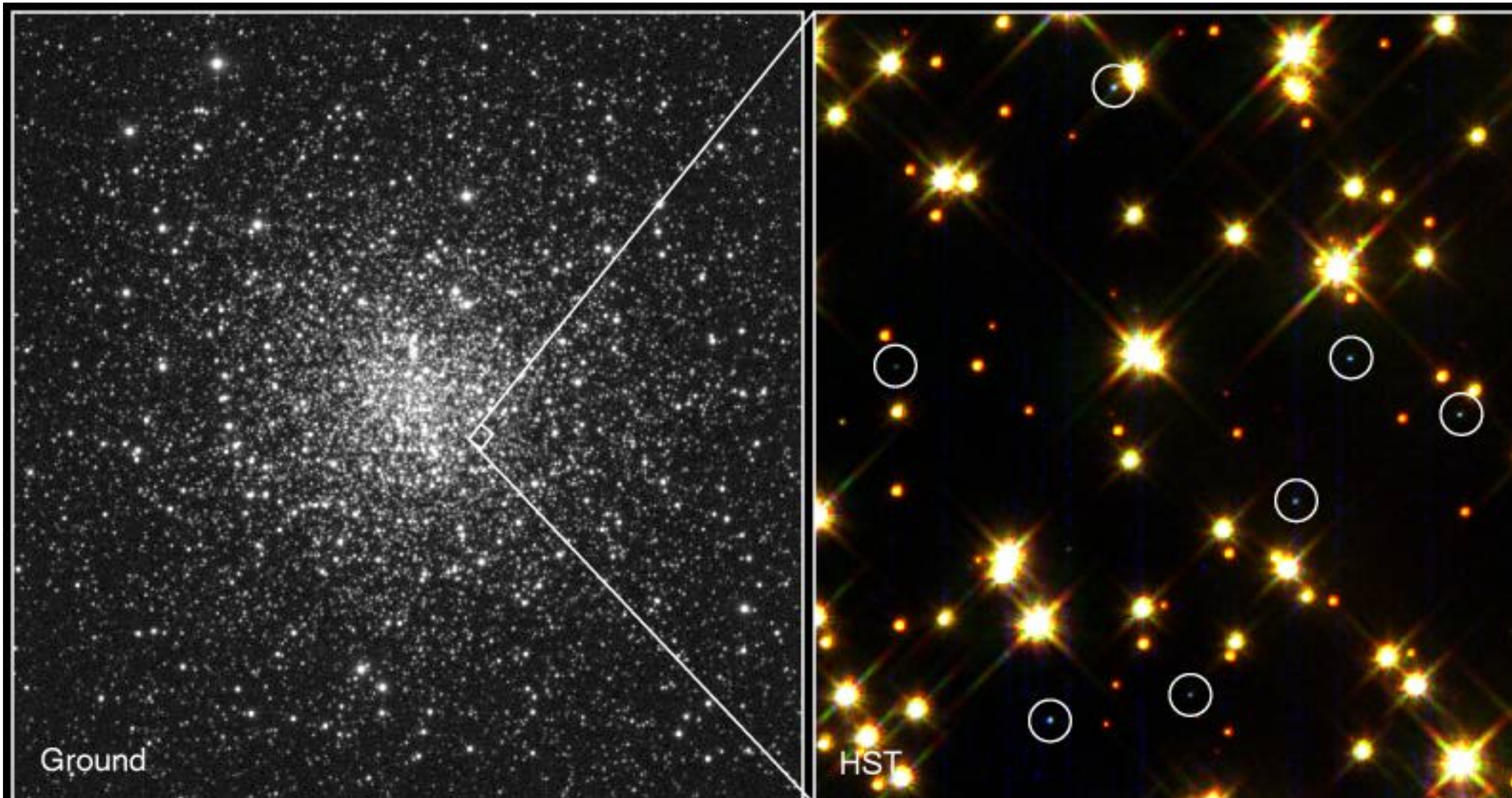
Red Giants

Red Giant and *Supergiant* stars are located above and to the right of the Main Sequence.



White Dwarfs

- Very Small, Very Hot but Not Very Bright
- Sirius B: 27,000 K, but gives off 1000 times less light than the Sun
- 100 times smaller than the Sun



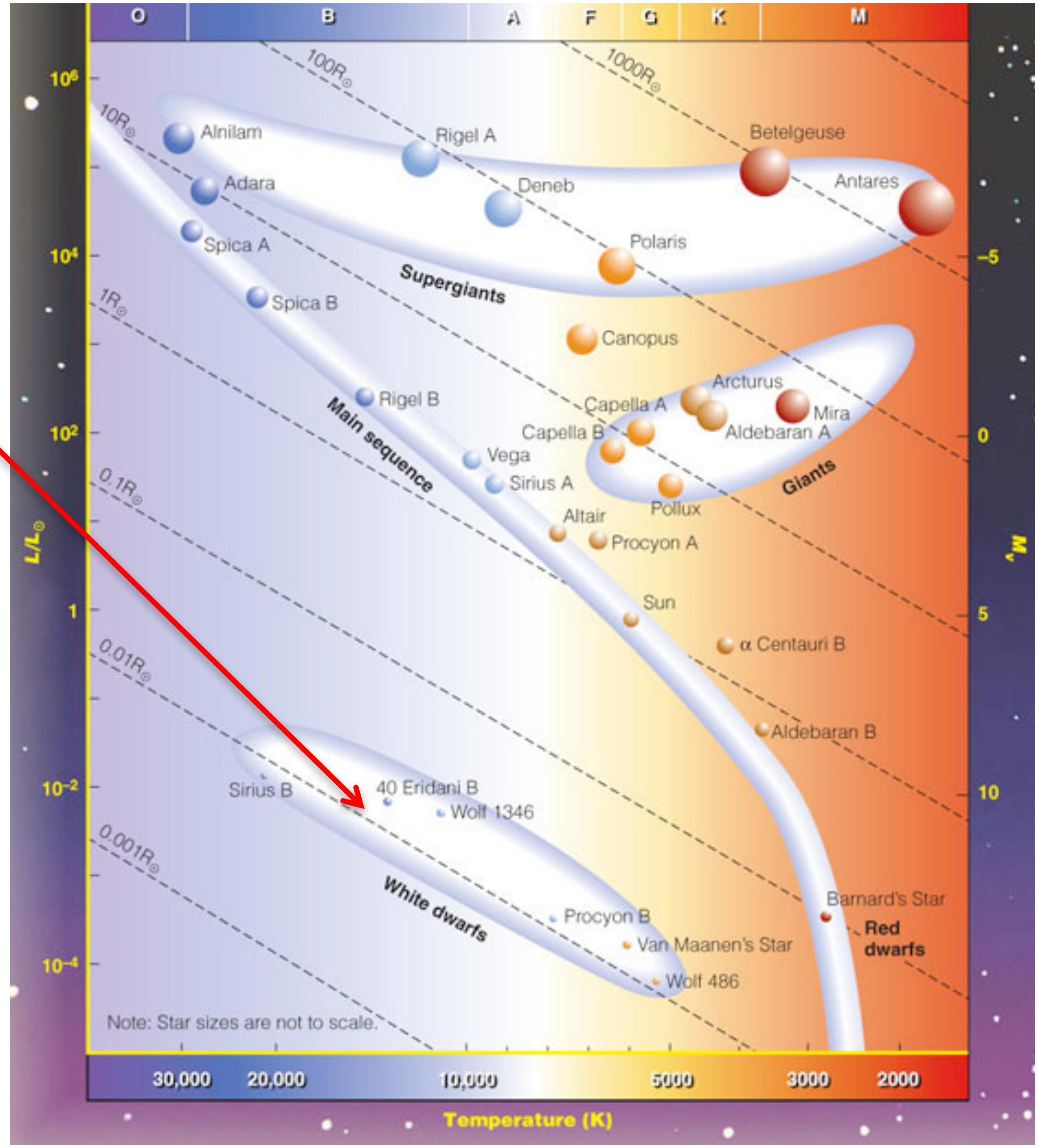
White Dwarf Stars in M4

HST · WFPC2

PRC95-32 · ST ScI OPO · August 28, 1995 · H. Bond (ST ScI), NASA

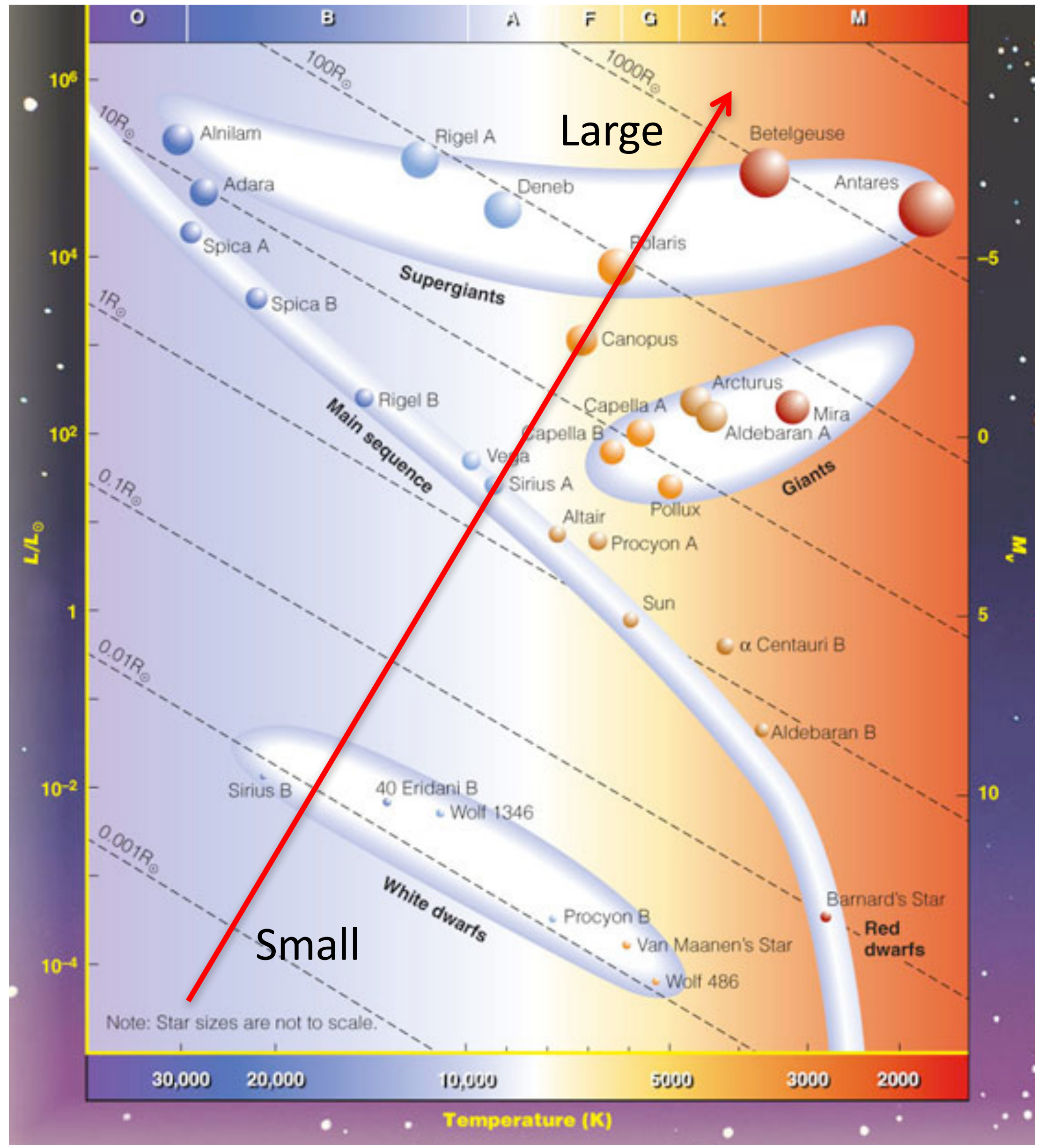
White Dwarfs

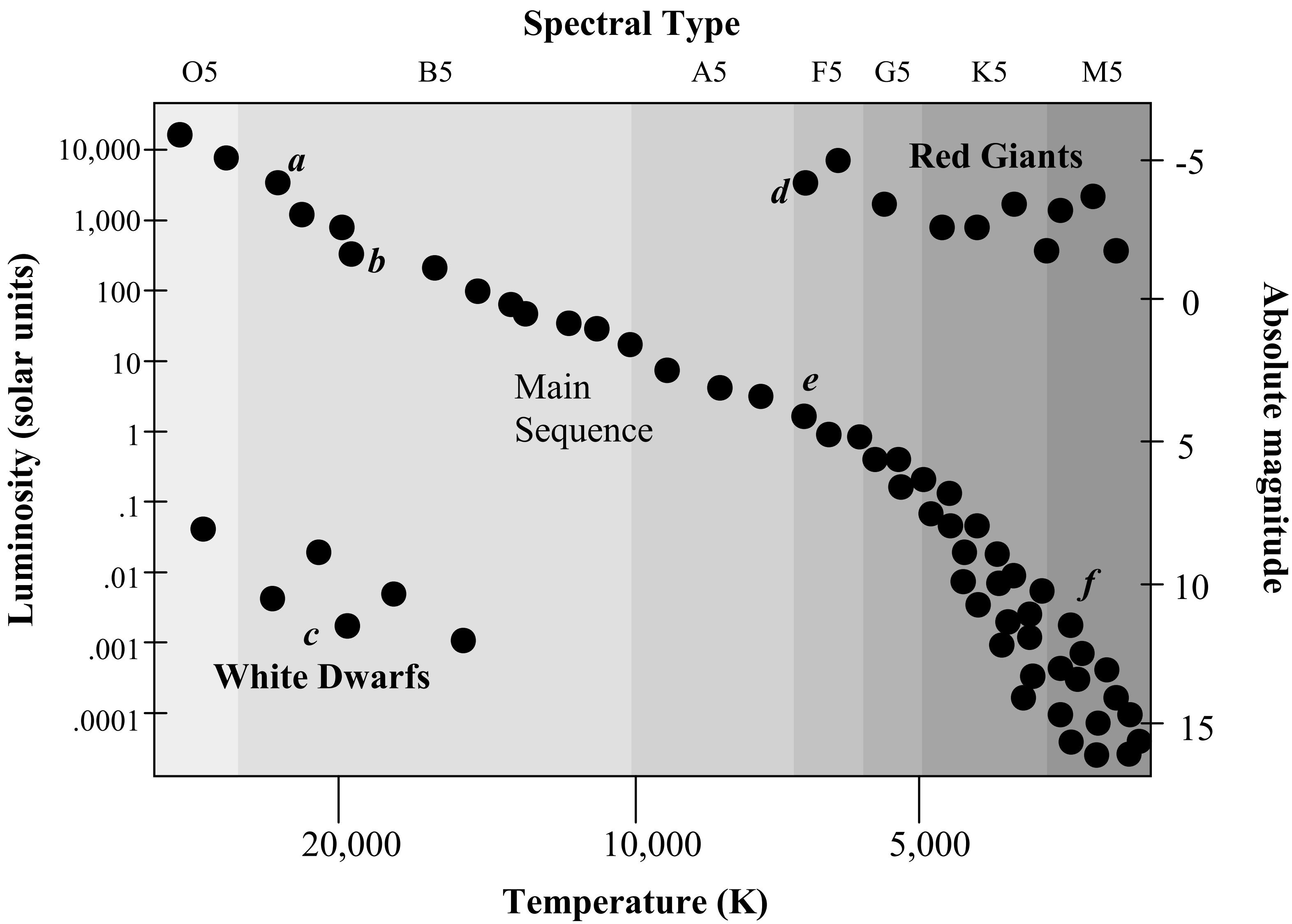
Tiny *white dwarf* stars are located in the bottom left of the H-R diagram



Determining the Sizes of Stars from an HR Diagram

- The Smallest stars are the tiny White Dwarf stars and are found in the lower left corner of the HR diagram
- Main sequence stars span a range of sizes from the small found in the lower right to the large found in the upper left
- The largest stars are the Giant and Supergiant stars which are found in the upper right corner

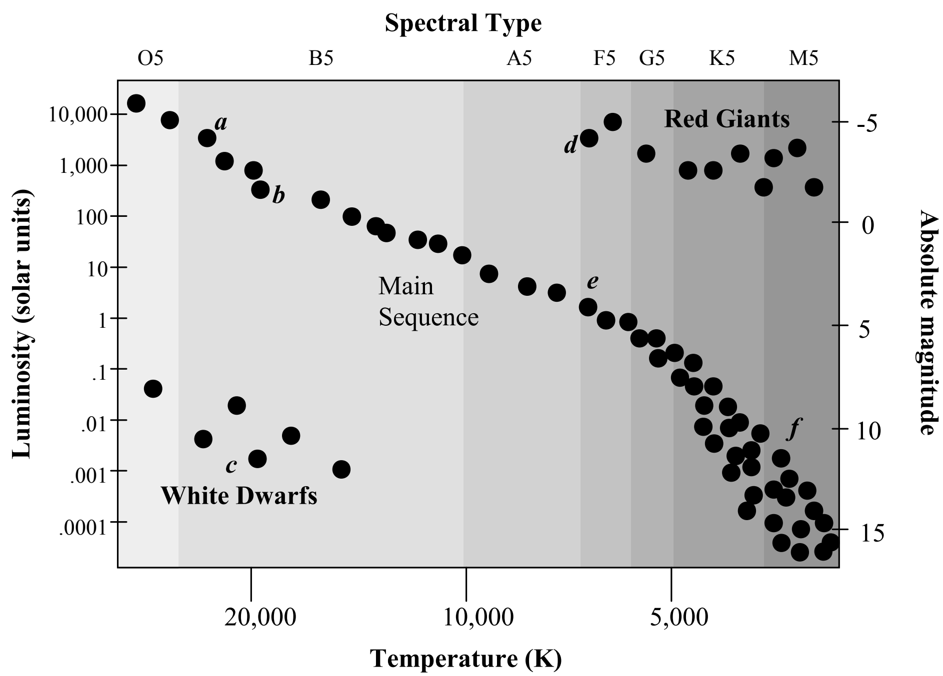




Spectral Type
O5
B5
A5
F5
G5
K5
M5
Red Giants
Main Sequence
White Dwarfs
a
b
c
d
e
f
Luminosity (solar units)
10,000
1,000
100
10
1
.1
.01
.001
.0001
Absolute magnitude
-5
0
5
10
15
20,000
10,000
5,000
Temperature (K)

How does the size of star A compare with star D?

A. Star A is larger
B. Star D is larger
C. They are the same size.
D. There is insufficient information to determine this.

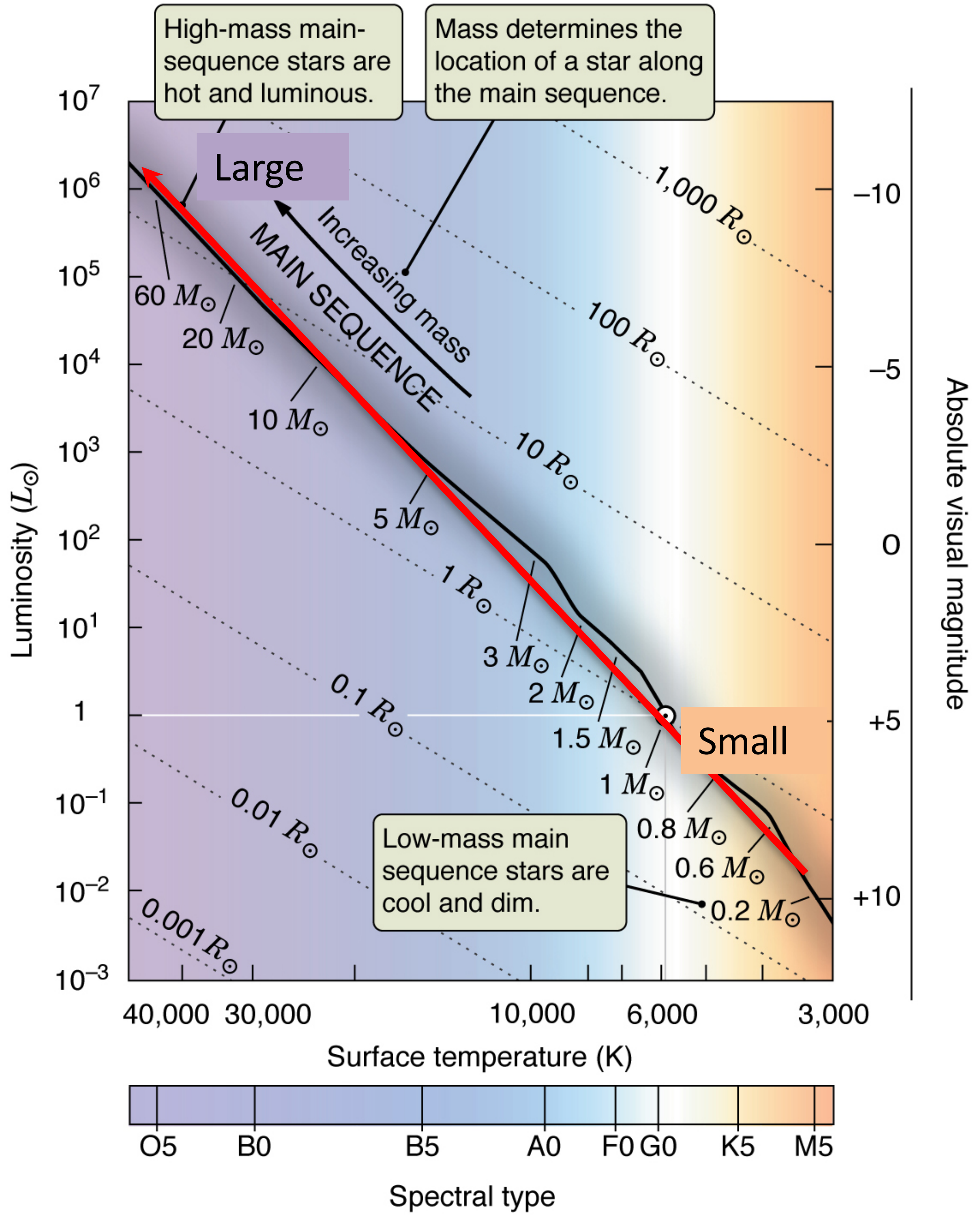


What about stellar masses?

- We can determine the masses of stars if they have companions. These are called *binary stars*.
- We can measure the mass by using Newton’s Laws and Kepler’s Laws, just like in our solar system.

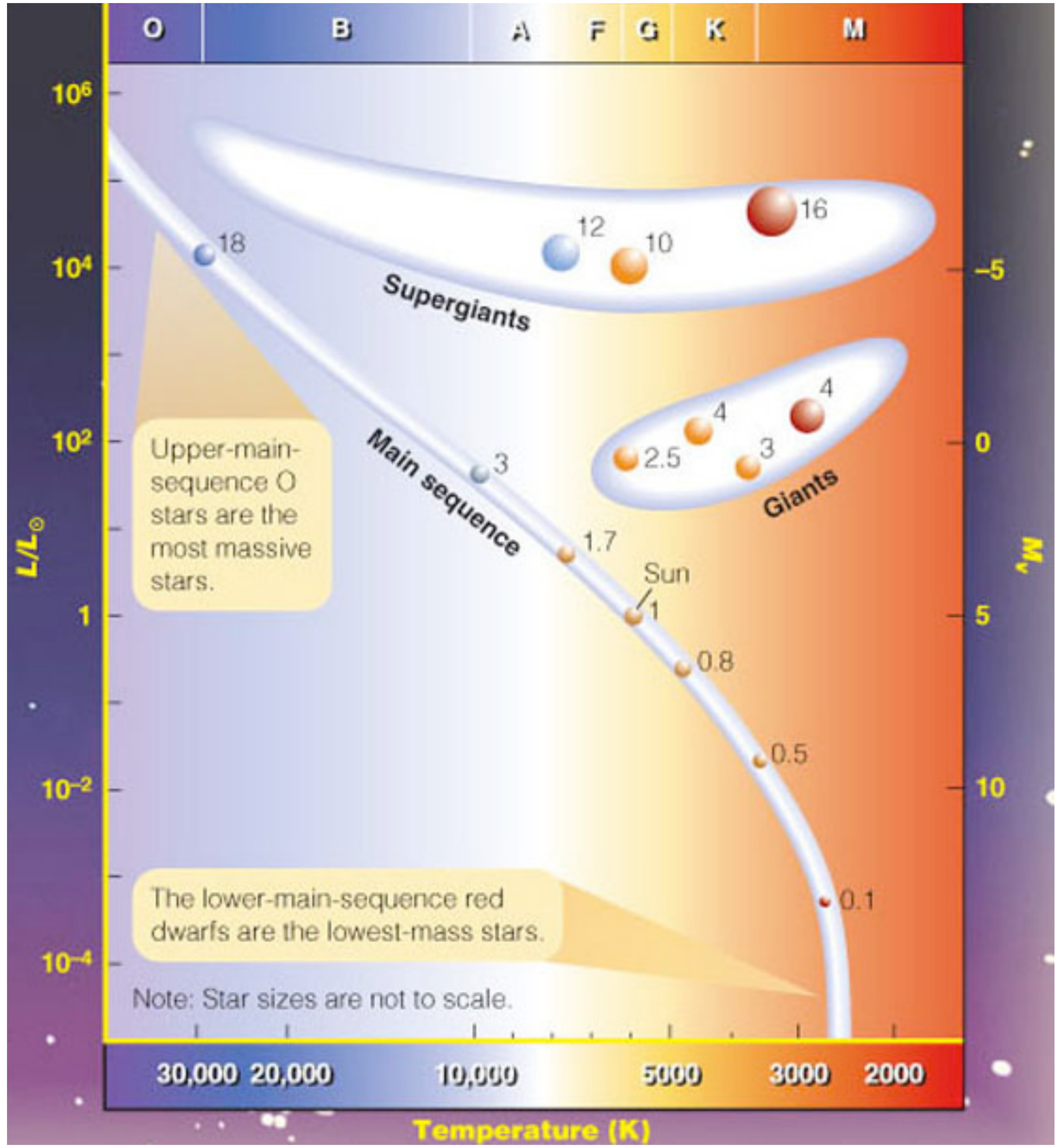
What about masses?

- **Main Sequence** stars range in mass from $0.1M_{\odot}$ to $100M_{\odot}$.
- The masses of **main sequence** stars increase with luminosity, temperature, and size.
- Mass increases from lower right to upper left.



What about masses?

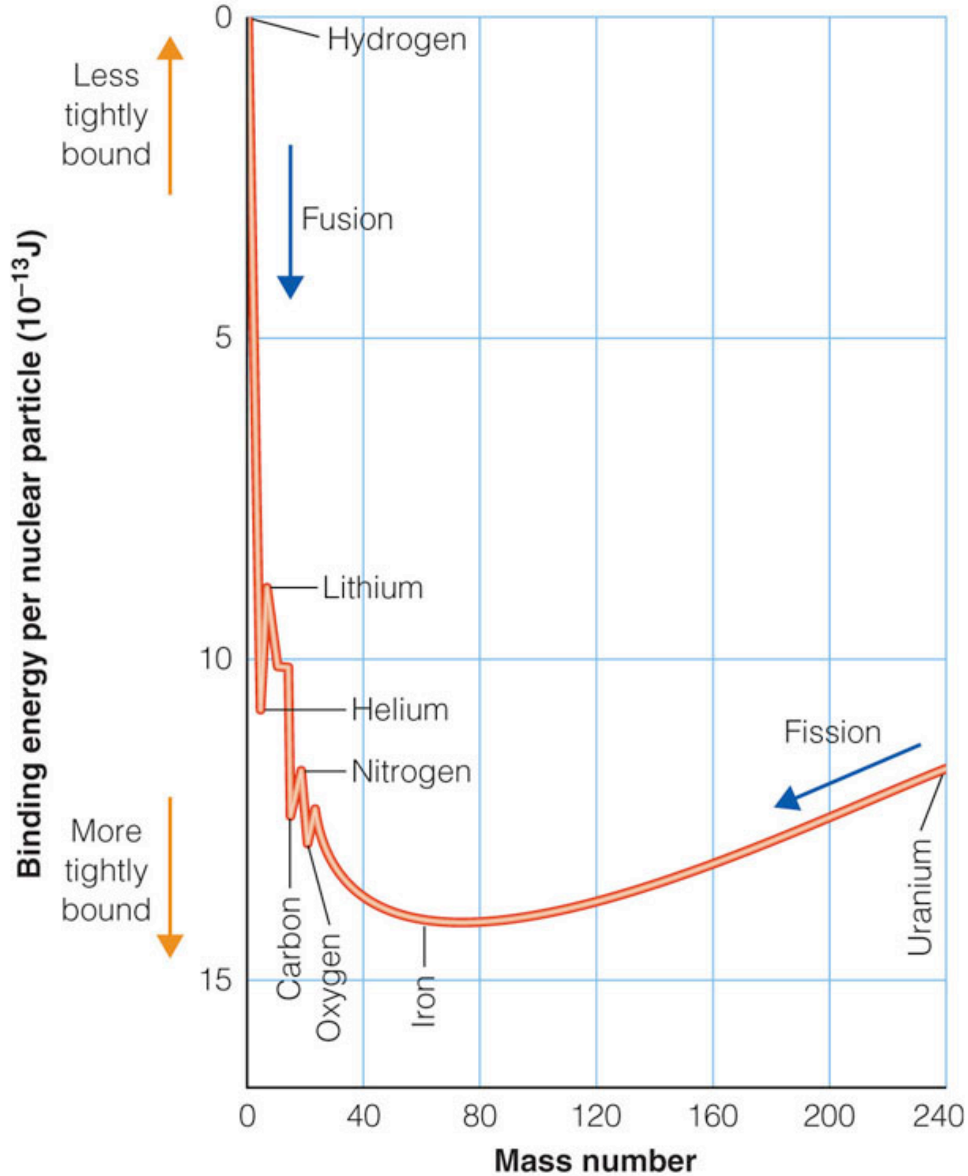
- There is no simple relationship for the masses of non-main sequence stars.
- Red Giants and Supergiants range from about 1 $M_{\odot}$ to 20$M_{\odot}$.
- White Dwarfs are about 1 $M_{\odot}$.



Why is there a Main Sequence?

How to generate energy: Nuclear Fusion vs. Fission

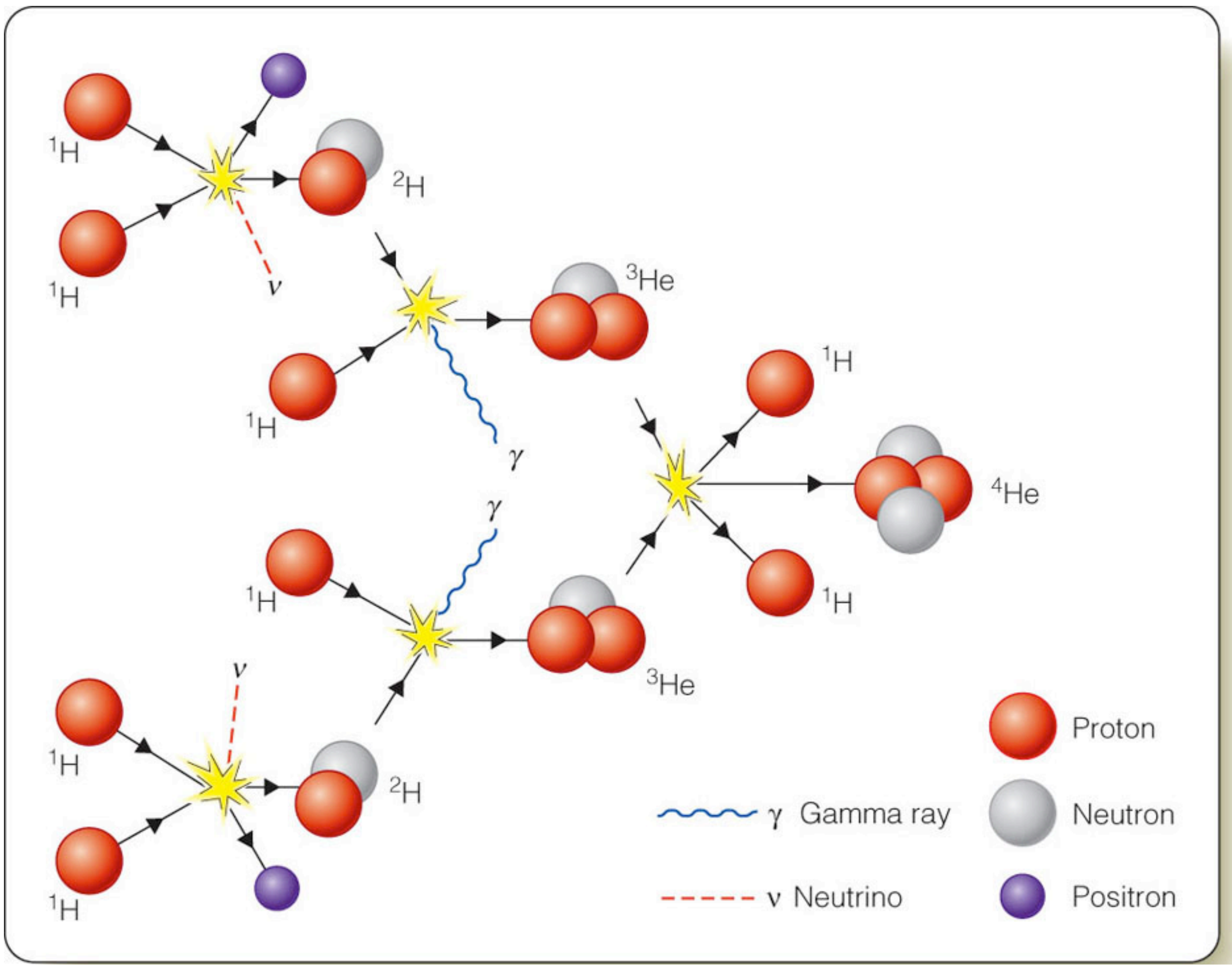
- Nuclear fusion is the *combination* of two atoms to form a more massive atom
- Nuclear fission is the *splitting* of one atom to form two less massive atoms.
- For light atoms, like hydrogen, fusion produces energy. For heavy atoms, it does not.
- For heavy atoms, like uranium, fission releases energy. For light atoms, it does not.



Nuclear Fusion

The centers of stars are hot enough and dense enough to fuse hydrogen into helium.

4 H ➔



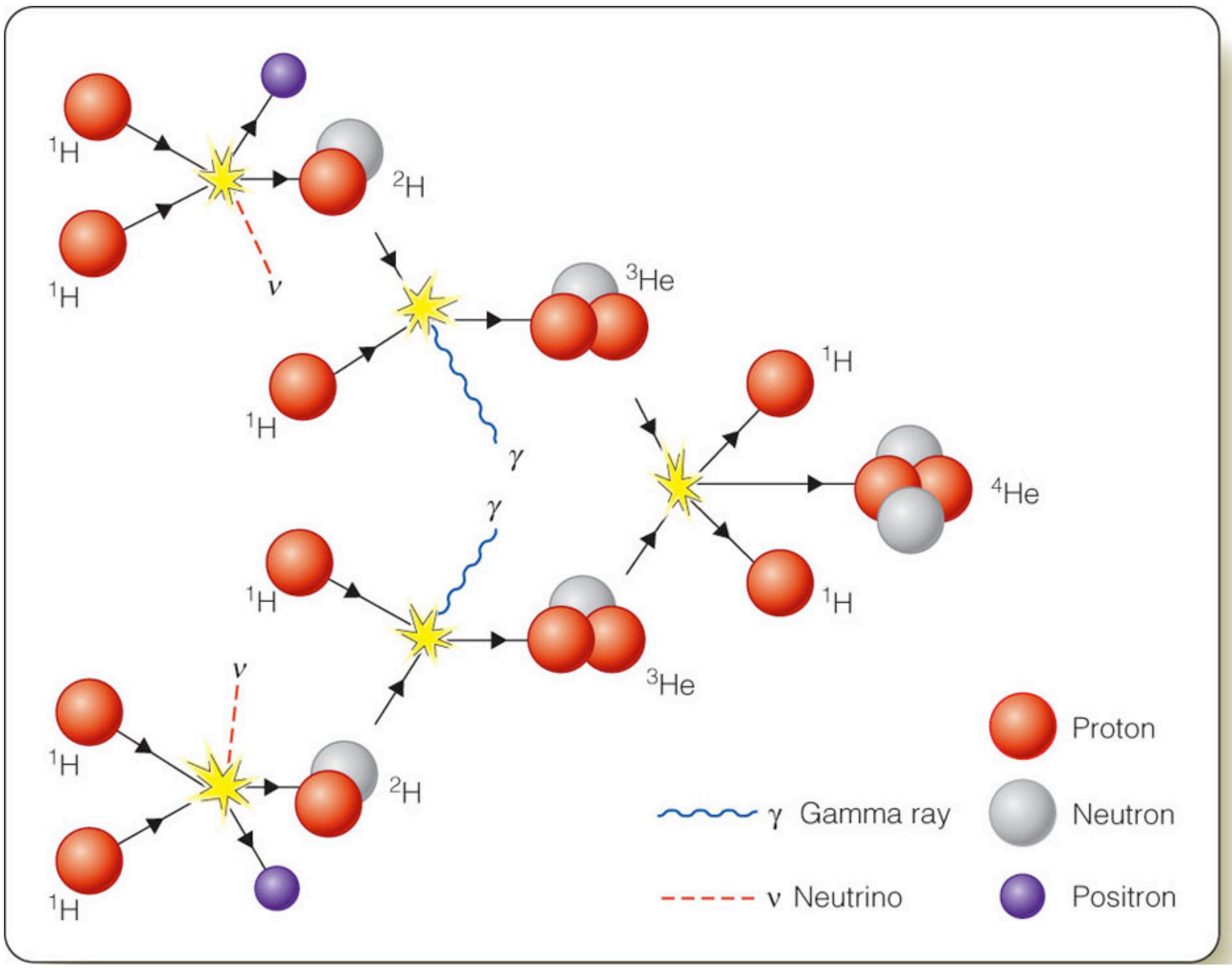
➔ 1 He + Energy!

Nuclear Fusion

The hotter the core, the more fusion that occurs.

This is just one possible fusion process.

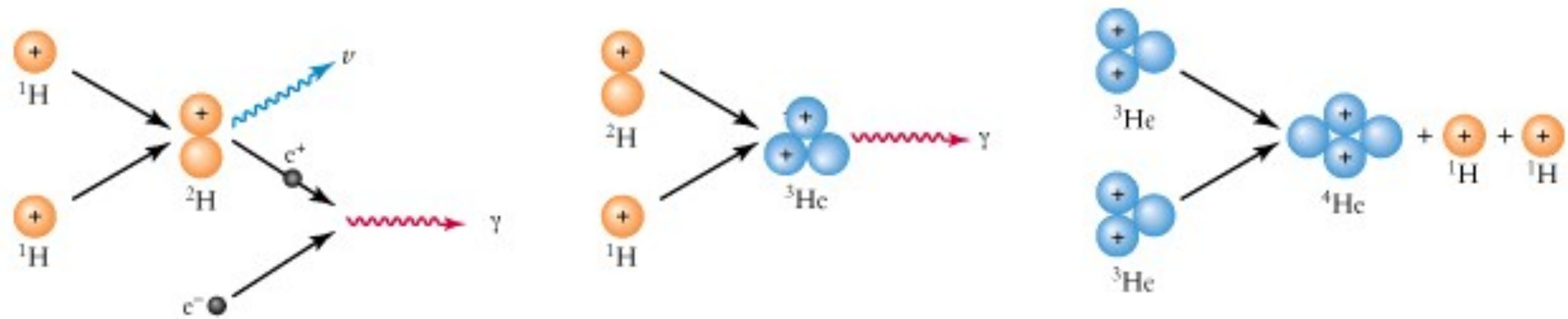
4 H ➔



➔ 1 He + Energy!

Nuclear Fusion

How do we know this happens in the center of the Sun?



Photons (γ) take 10,000 years to escape Sun.

Neutrinos (ν) flow freely from Sun and can be detected on Earth.

Neutrinos

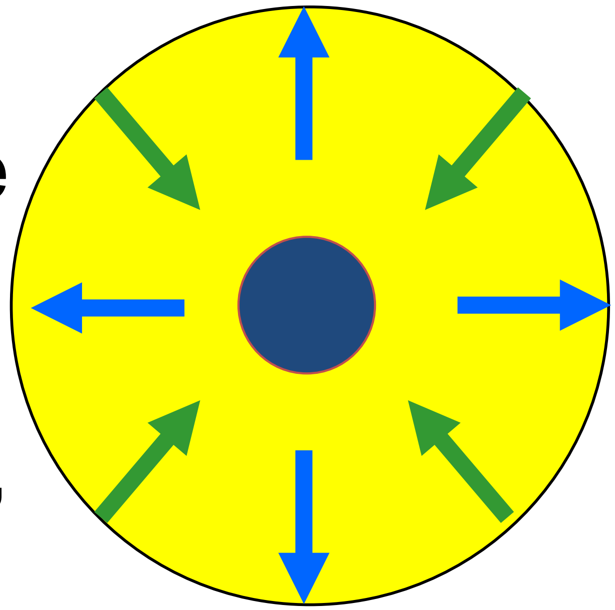
- Neutrinos have almost no mass and no electric charge.
- Neutrinos only weakly interact with matter. They could pass through 1 light-year of lead without interacting with any atoms.
- 65 *billion* solar neutrinos pass through every square centimeter of your body every second.
- The number of solar neutrinos we can detect match what is predicted to come from the reactions in the core of the Sun providing evidence that our models are correct.

Why are stars stable?

- Why don’t they collapse?
- Why don’t they expand?

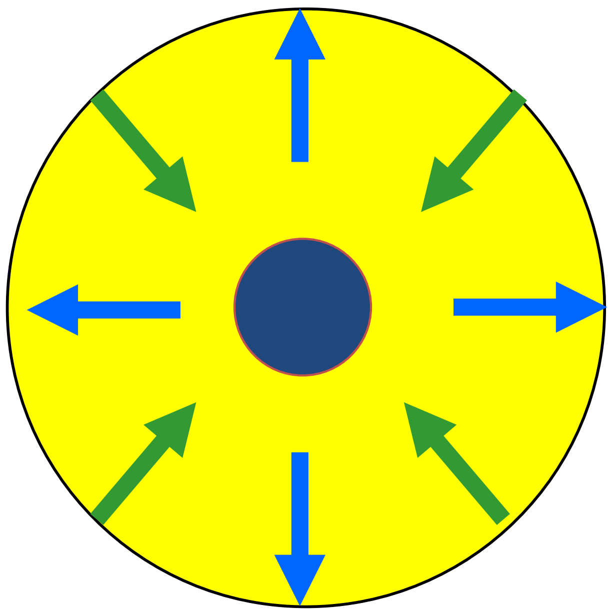
Balance

- All main sequence stars are in *hydrostatic equilibrium.*
- Gravity is pushing the star inward. Light generated in the core generates thermal pressure pushing outwards.
- During hydrostatic equilibrium, these forces are balanced.
- This balance is why the Main Sequence exists.



Balance

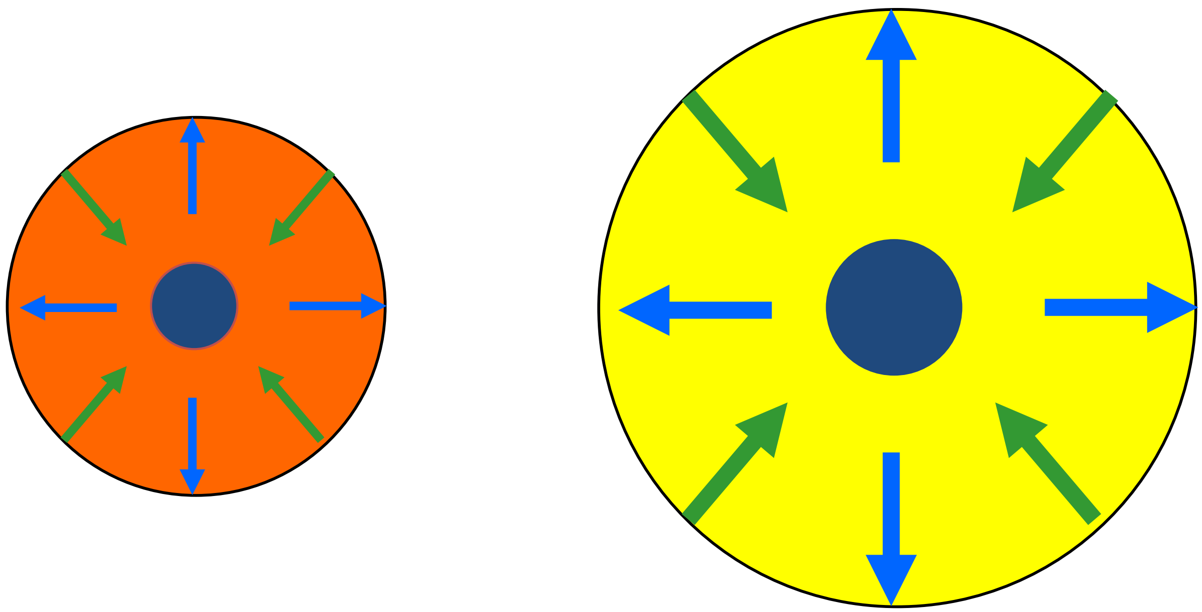
In a main sequence star, the energy generated by nuclear fusion is producing enough outward pressure to balance the inward pressure from the mass of the star.



The more massive a star, the more energy it must produce.

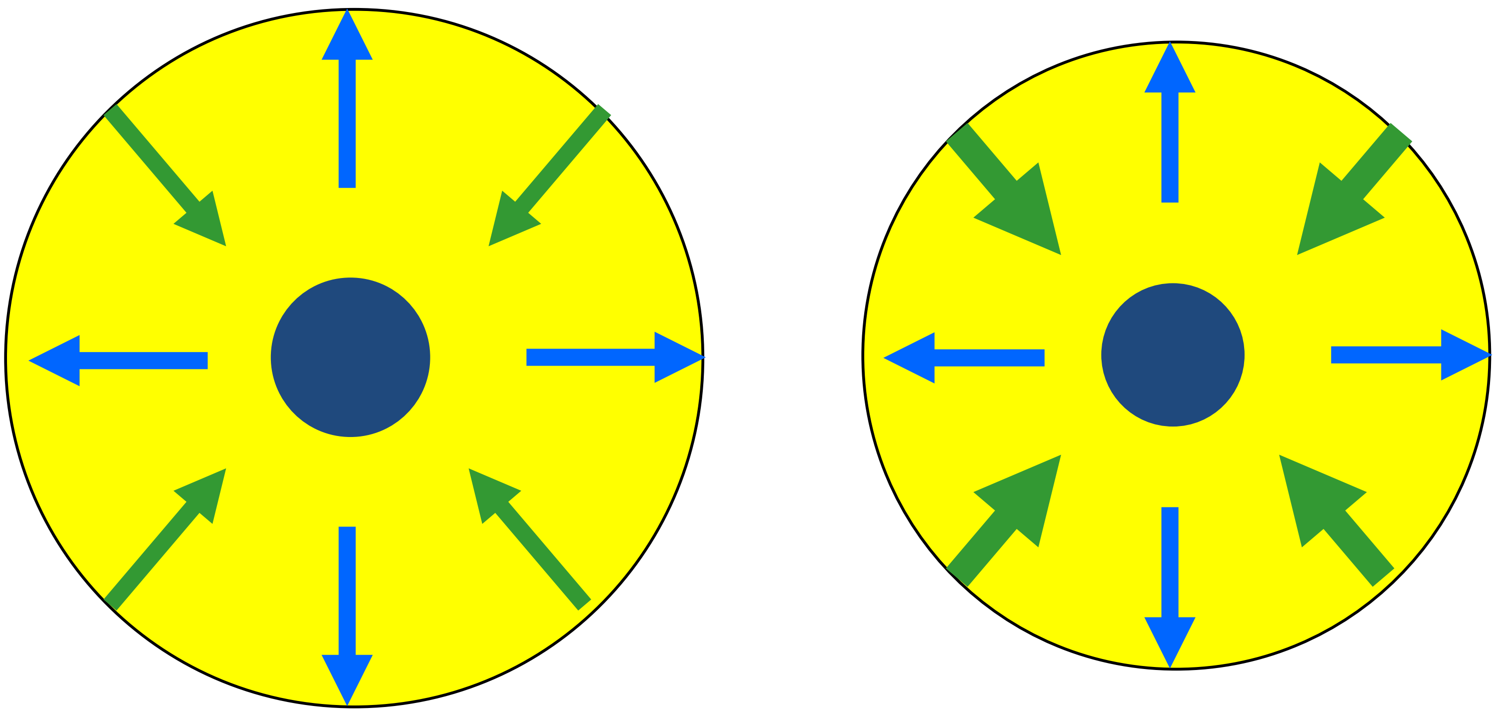
Mass-Luminosity Relation

Because main sequence stars are in hydrostatic equilibrium, **more massive stars are more luminous**.



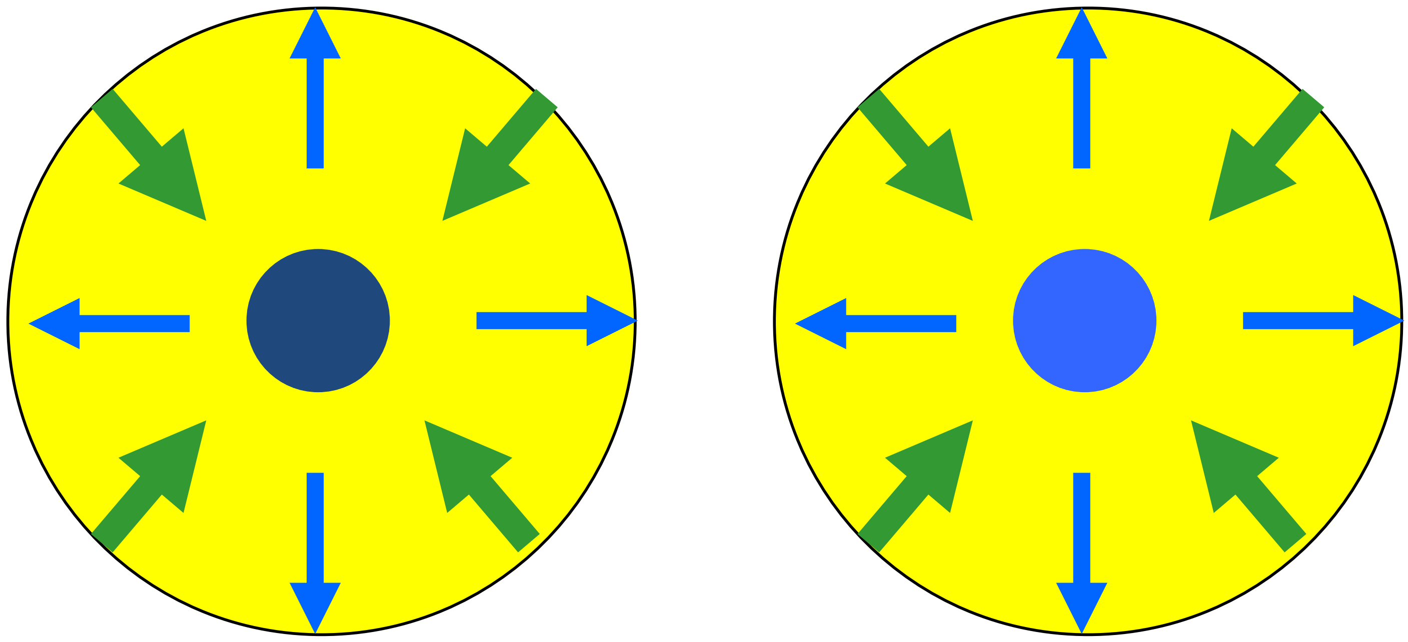
Mass-Luminosity Relation

If you increase the mass of a star, the inward pressure increases.



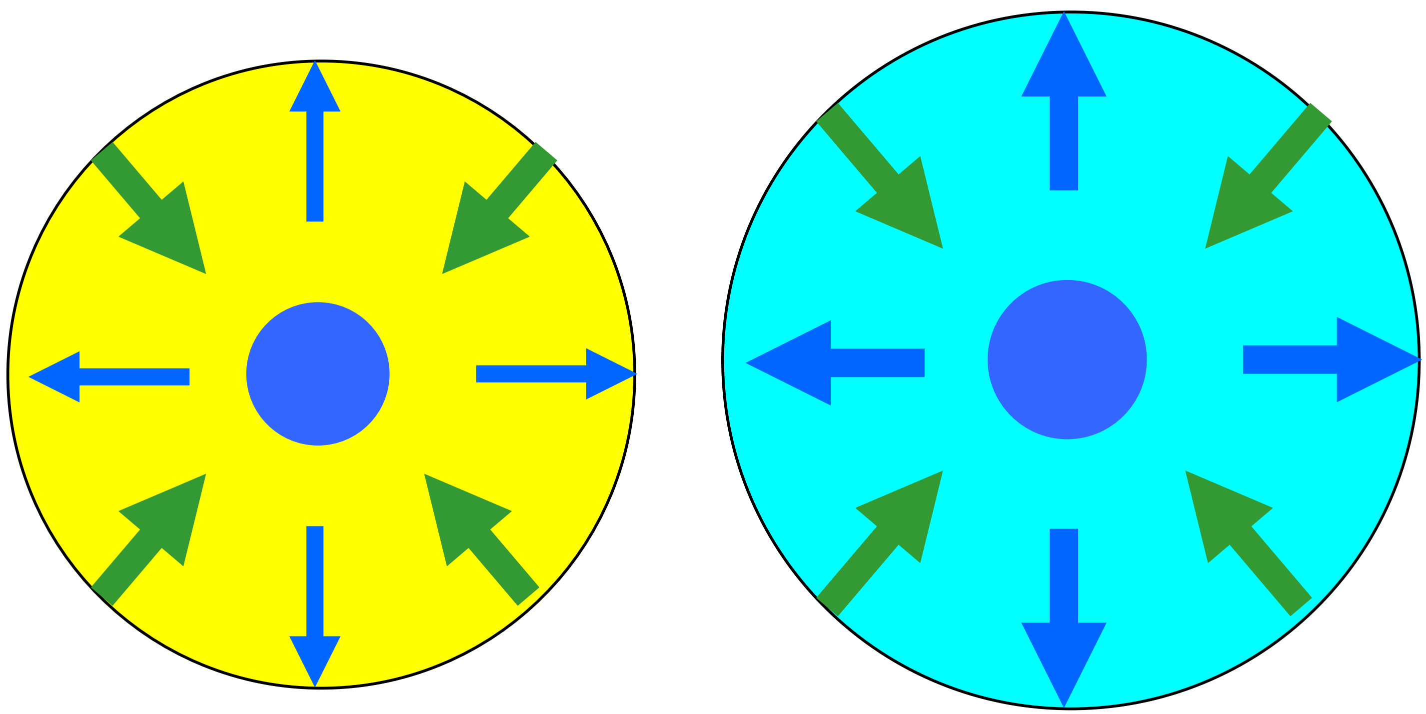
Mass-Luminosity Relation

This causes the core of the star to heat up and produce more energy.



Mass-Luminosity Relation

Which increases the outward pressure, and stabilizes the more luminous star.



Implication of Mass-Luminosity Relation

More mass = More Luminosity = faster rate of fusion

= Shorter lifetime on Main Sequence!

Table 7-2 | Main-Sequence Stars

Spectral Type	Mass (Sun = 1)	Luminosity (Sun = 1)	Approximate Years on Main Sequence
O5	40	405,000	1×10^6
B0	15	13,000	11×10^6
A0	3.5	80	440×10^6
F0	1.7	6.4	3×10^9
G0	1.1	1.4	8×10^9
K0	0.8	0.46	17×10^9
M0	0.5	0.08	56×10^9

Implication of Mass-Luminosity Relation

More mass = More Luminosity = ***Shorter life!***

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O Stars are very massive,
very luminous,
and very short-lived.

Implication of Mass-Luminosity Relation

More mass = More Luminosity = ***Shorter life!***

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G stars (Sun-like) are not very massive, not very luminous, and long-lived.

Implication of Mass-Luminosity Relation

More mass = More Luminosity = ***Shorter life!***

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M stars have very little mass,
are very faint,
and very, very long-lived.

Stellar Evolution

- How do stars form?
- How do stars die?

Stages of Star Formation

1. **The Interstellar medium** – gas and dust
2. A **protostar** forms from the coldest, densest part of the ISM, a **molecular cloud**
3. The protostar gets hot enough for fusion in its center and becomes a **main sequence star**.
4. Lather, Rinse, Repeat.

The Interstellar Medium (ISM)

- 99% Interstellar gas
  75% Hydrogen (by mass)
  24% Helium
  1% everything else
- 1% dust
  mostly Carbon and Silicon

Average density: 1 atom per cubic centimeter vs. 10^{19} per cubic centimeter for air.

Components of the ISM

- Hot Gas (10^6 K) – seen in X-ray light
- Warm Gas (10^4 K) – traced by ionized hydrogen.
- Cool Gas ($<10^4$ K) – traced by neutral, atomic hydrogen.
- Cold Gas (10-300 K) – seen as molecular clouds.

Stars only form in **cold, molecular clouds**

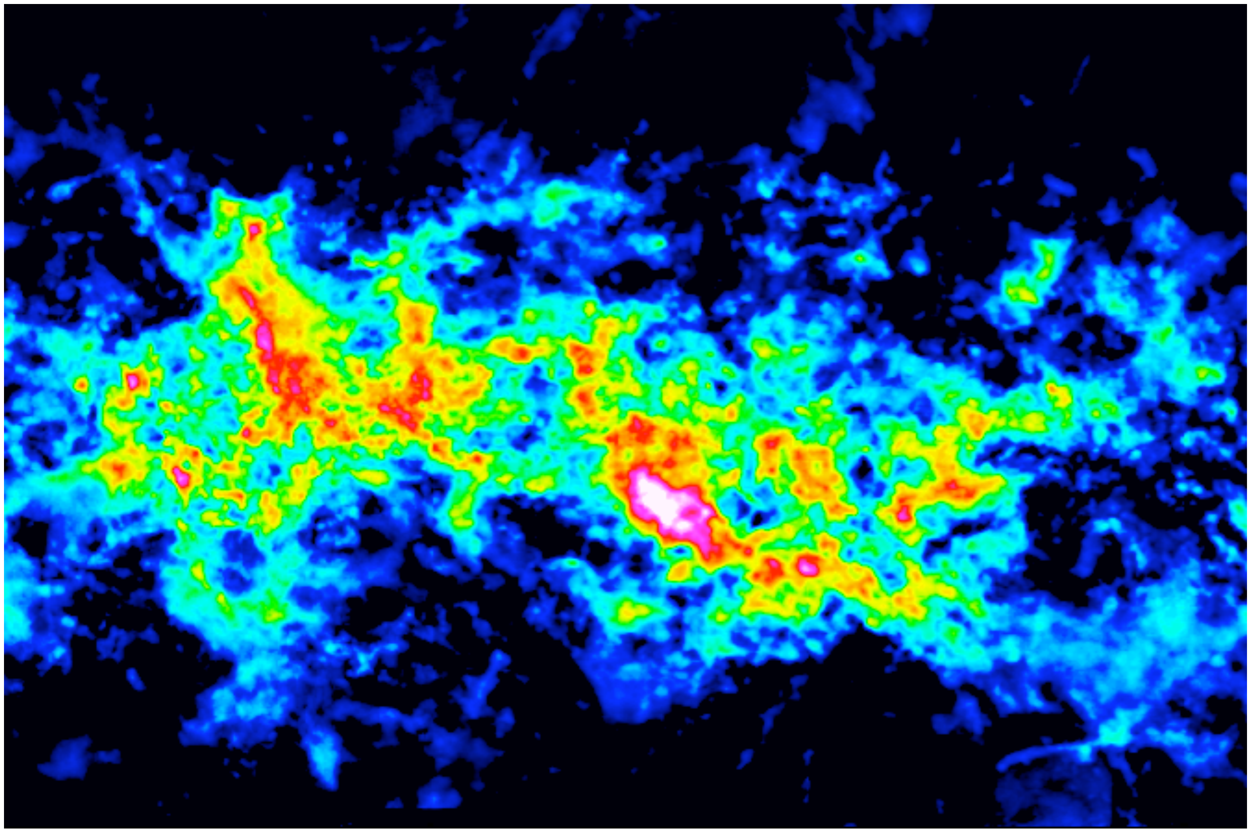
Components of the ISM

- Cold Gas (10-300 K) – molecular clouds seen in dust and gas

Images of dust in molecular clouds blocking star light behind them. **These are dark nebulae.**

Components of the ISM

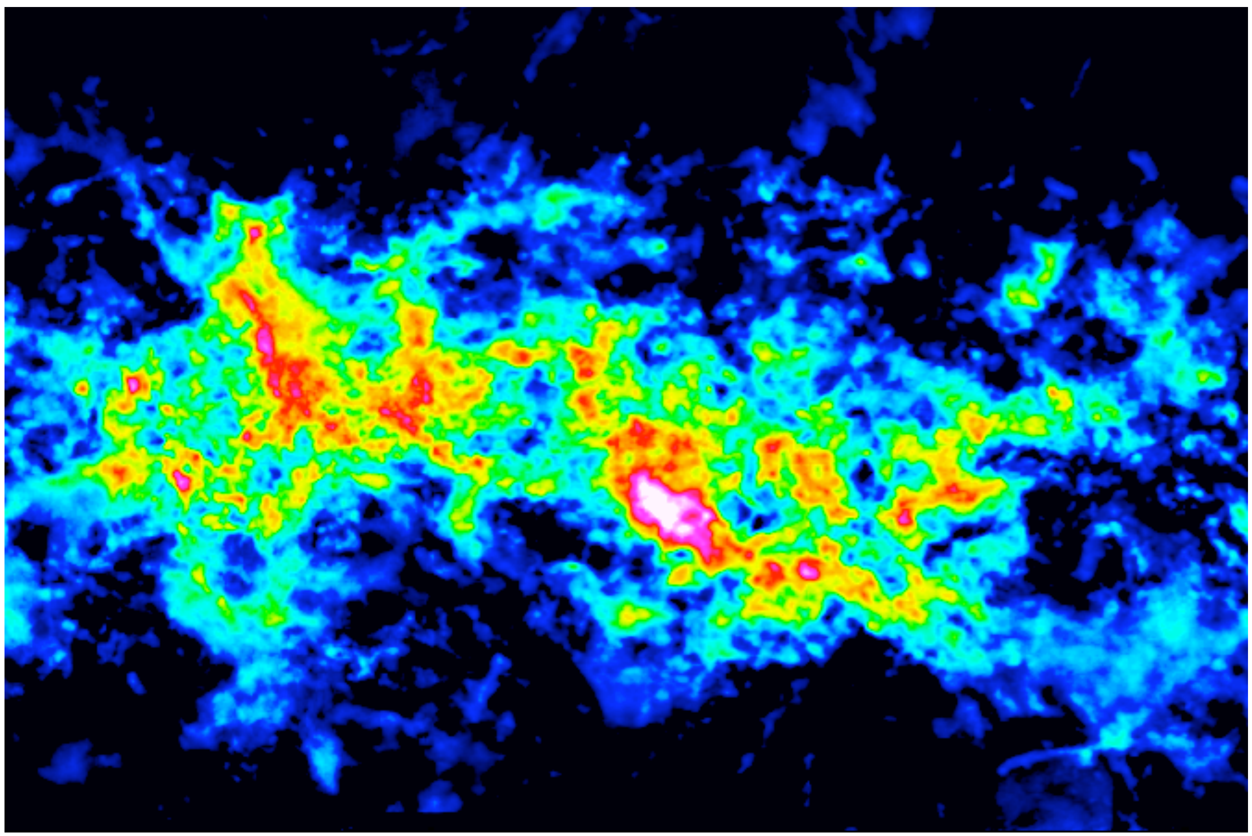
- Cold Gas – molecular clouds seen in dust and gas



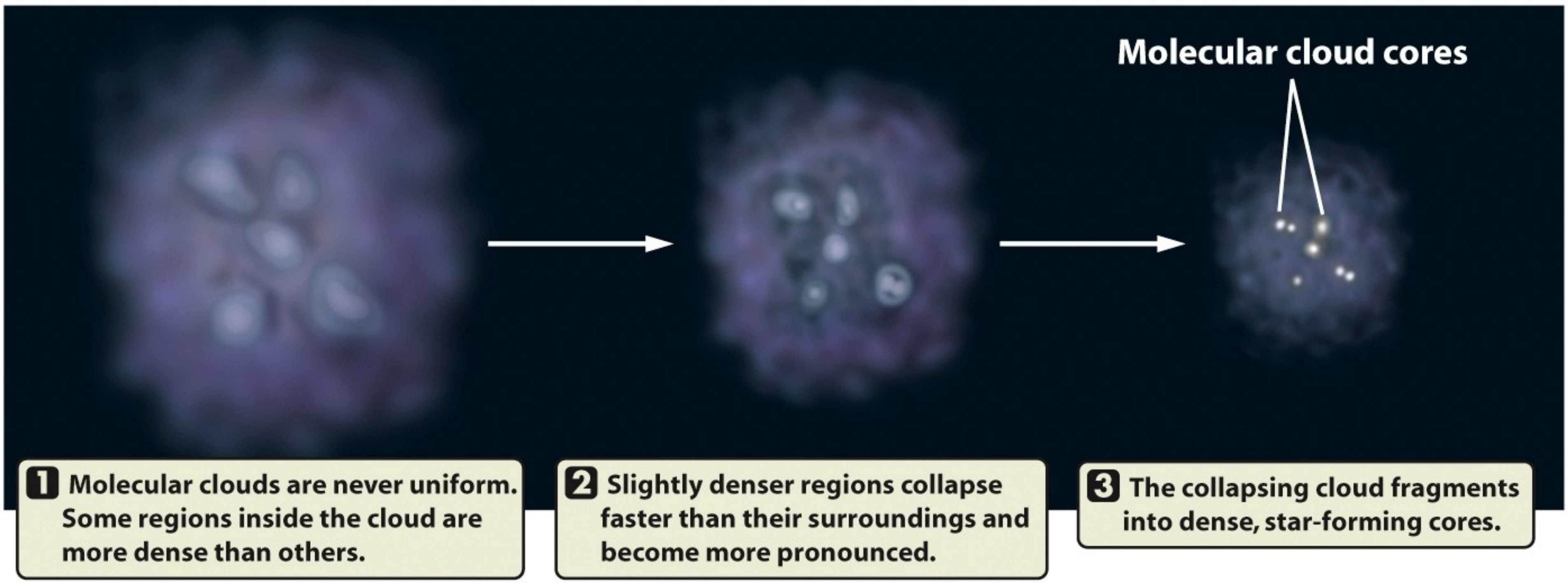
Radio map of molecules in a Giant Molecular Cloud

Molecular Clouds

The coldest and densest regions of the ISM will form molecular clouds when compressed..

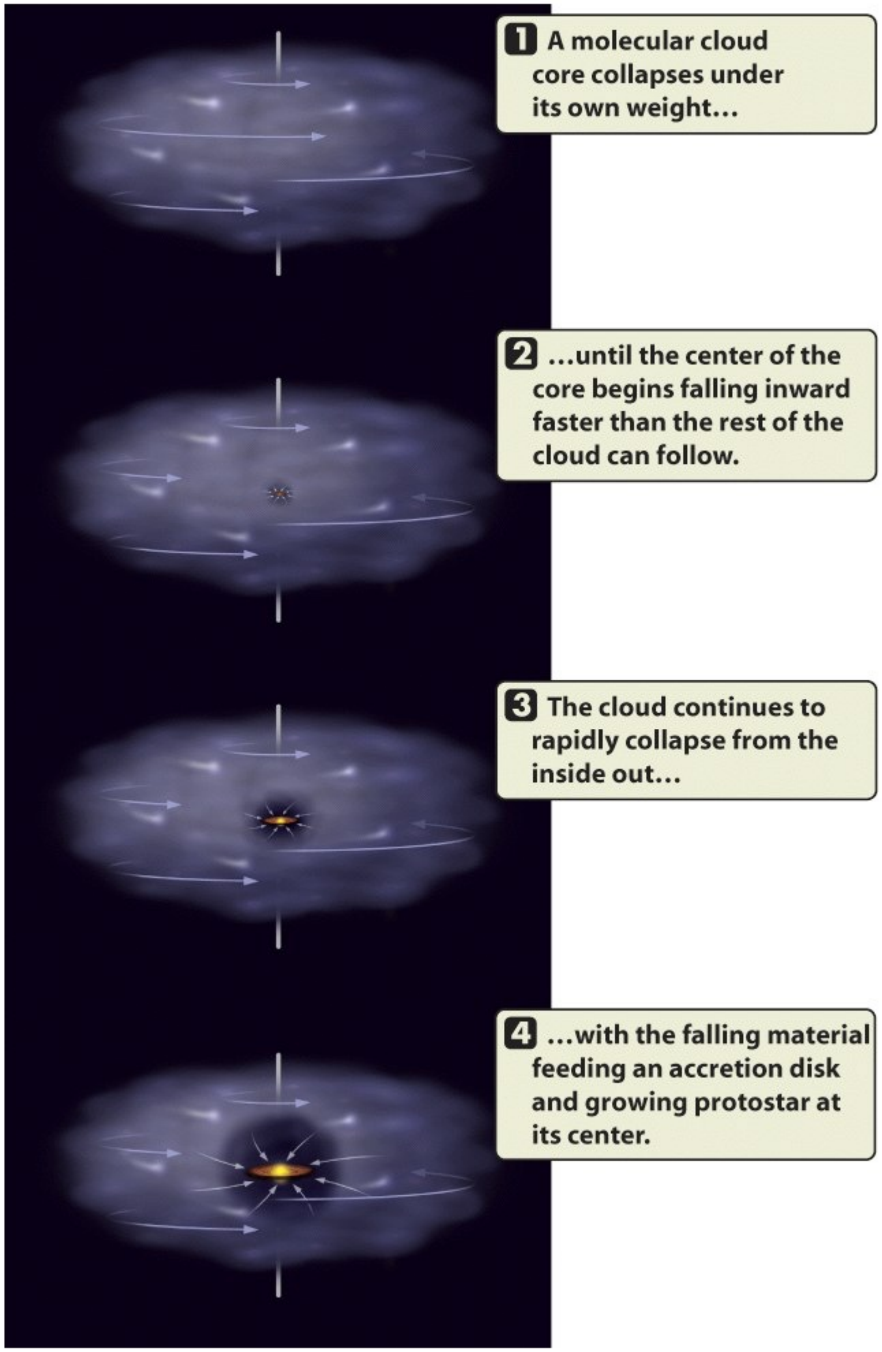


Densest parts of Molecular Cloud continue to collapse.



Each molecular core collapses due to gravity from *its own mass*. These cores are too cold to support their mass, so they continue to collapse and heat up.

As the cores collapse they begin to spin faster, eventually forming a *protostar* surrounded by an *accretion disk* of material.

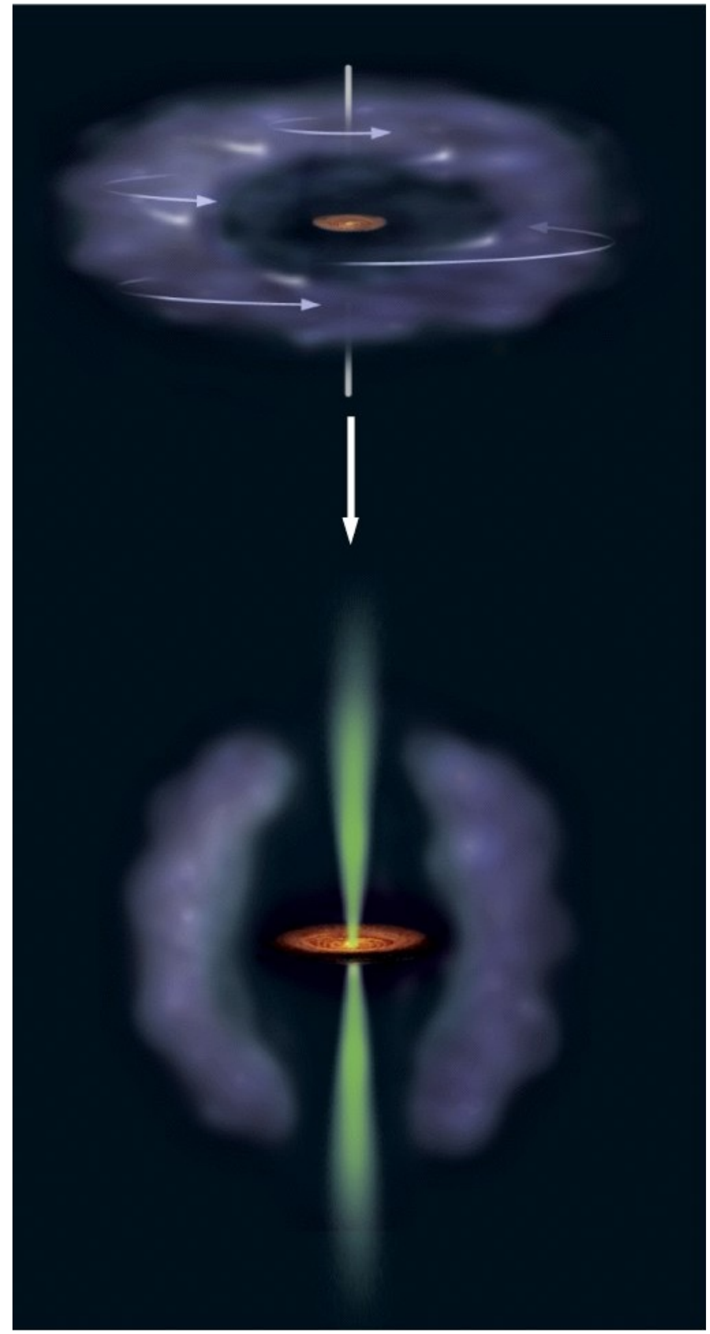


Protostars in Orion Nebula

These are protostars surrounded by cocoons of dust and gas.

After a protostar with an accretion disk forms, material continues to fall onto the “star” from the disk.

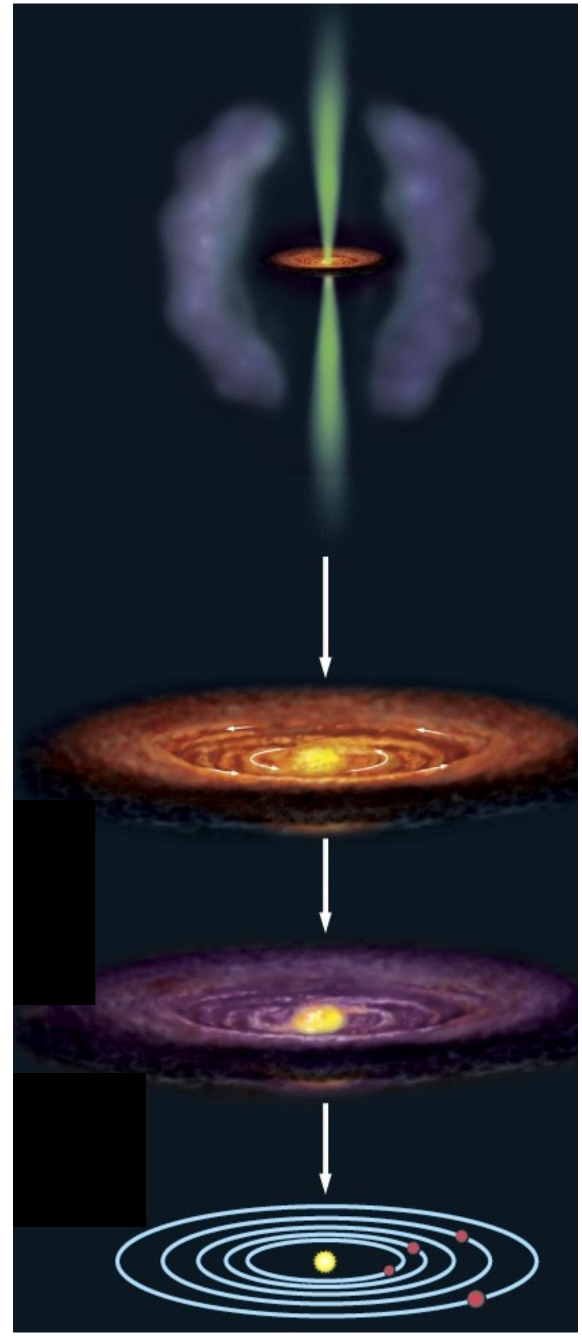
Some material has too much *angular momentum* to fall onto star and is ejected as a *jet.*



The jet blows away the remaining gas and dust surrounding the protostar.

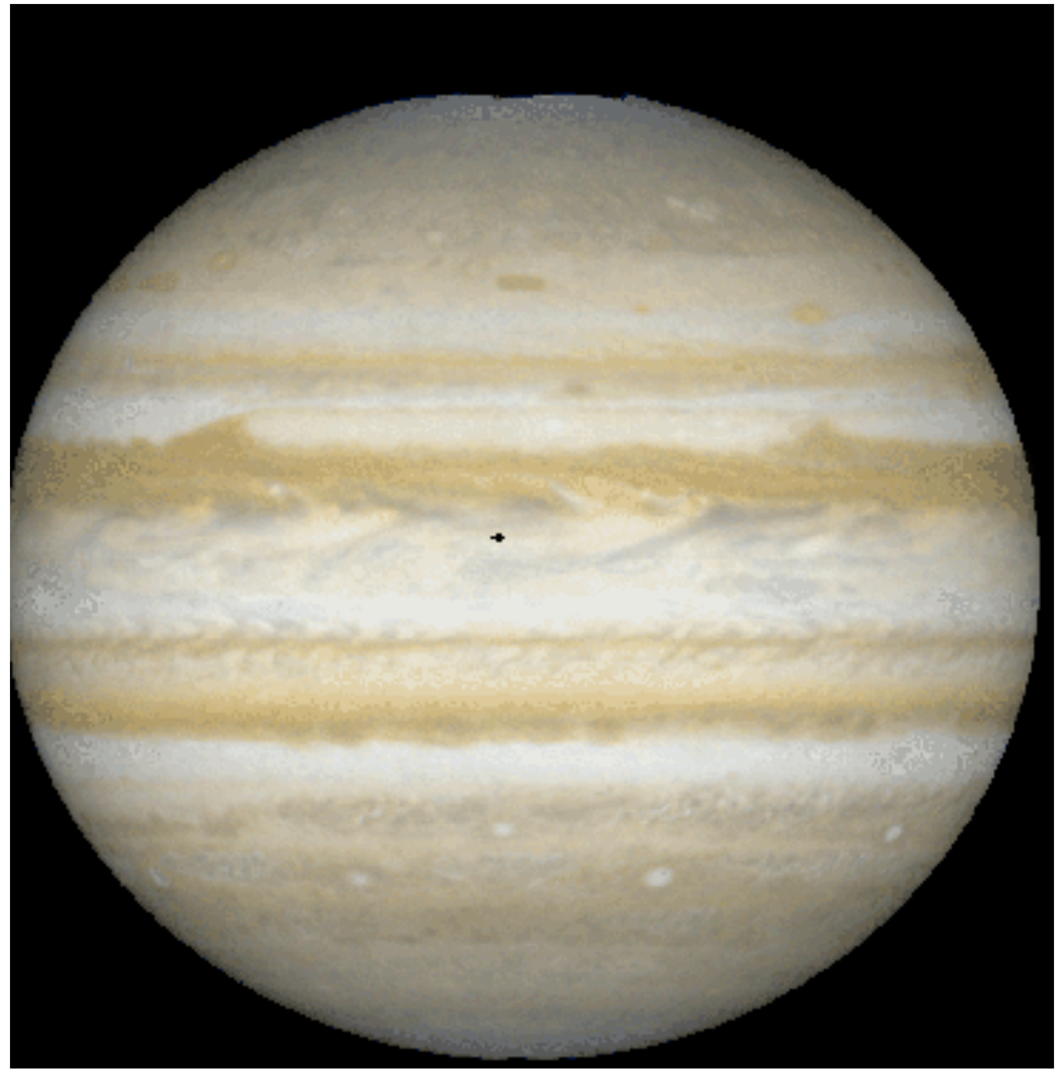
The protostar continues to collapse ***due to gravity*** and heat up.

Eventually the core of the protostar will be ***dense enough and hot enough*** for fusion to occur and then we have a main sequence star.

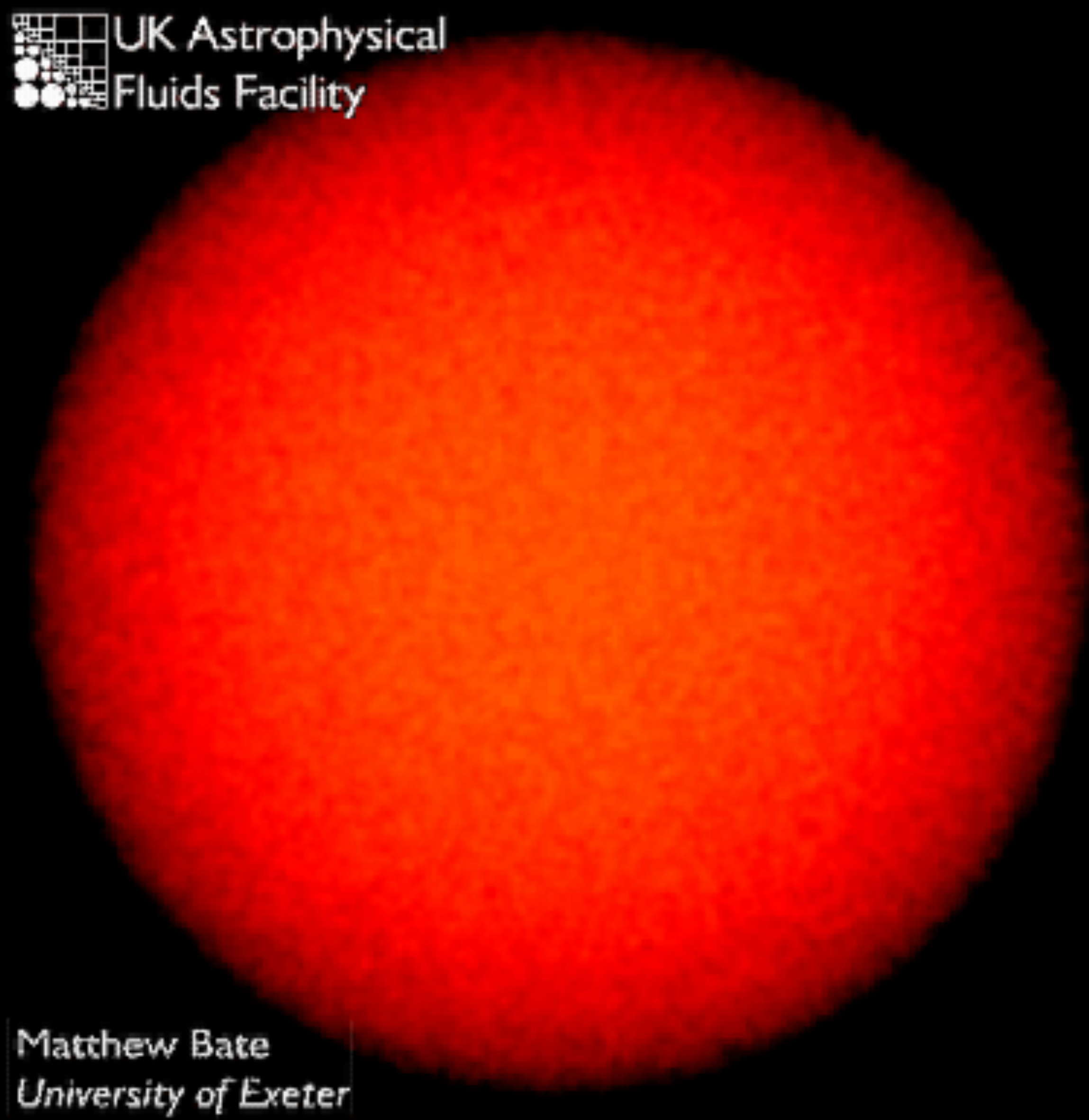


What happens if a protostar never gets hot enough for nuclear fusion?

- Objects with less than 0.08 solar masses will *never* get hot enough for fusion to occur in their cores.
- These are called *brown dwarfs*.
- They glow only from their internal heat from their collapse.
- They have masses greater than Jupiter and less than M dwarfs.

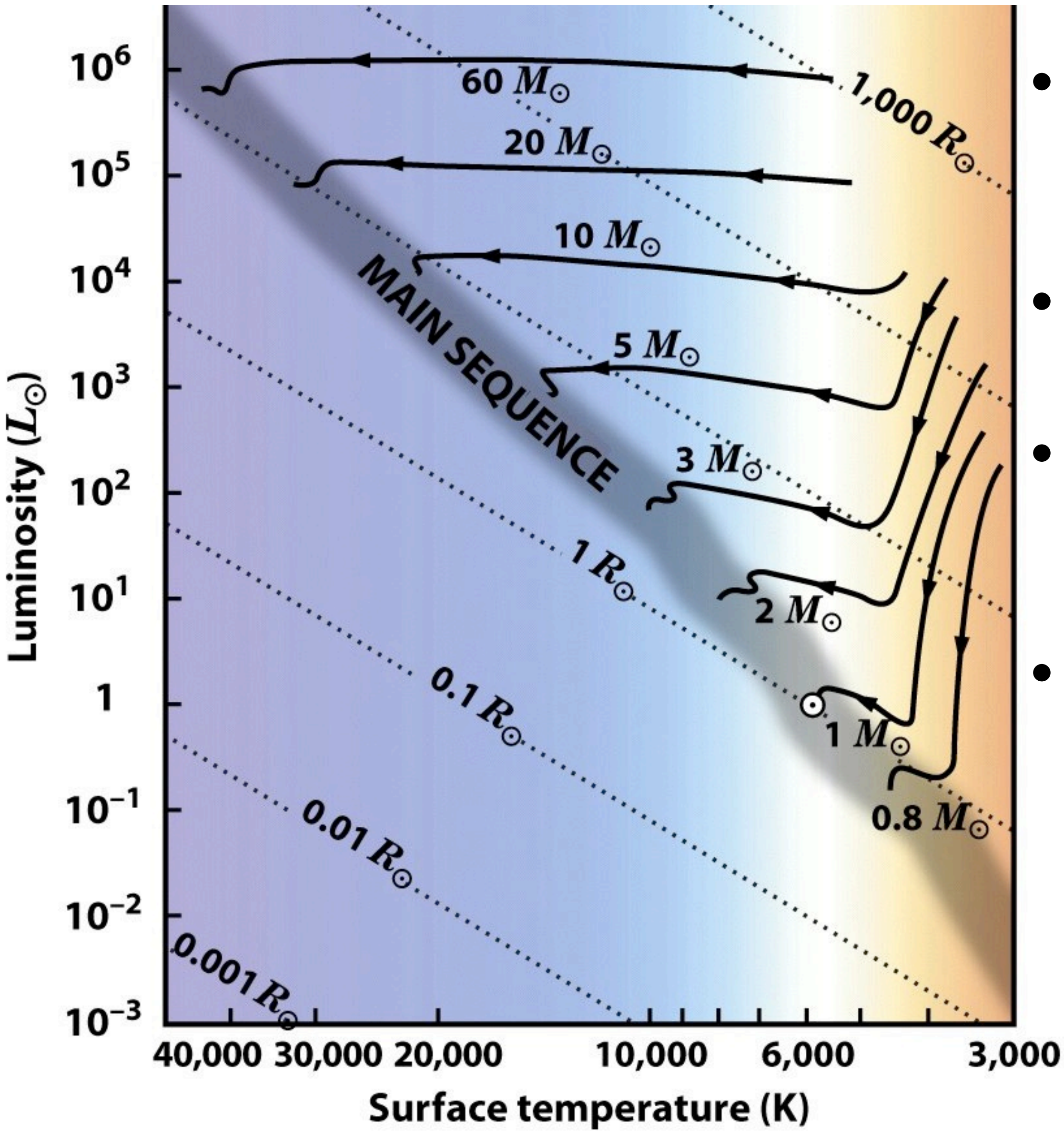


What does star formation look like?



Simulation of stars forming in a cluster from a gas cloud of 50 solar masses.

Protostars on the H-R Diagram



- As stars form they move on the HR diagram.
- The core is always getting hotter.
- High-mass stars remain bright, but heat up as they form.
- Low-mass stars stay at the same temperature (until fusion starts), but get fainter as they form.

Implication of Mass-Luminosity Relation

More mass = More Luminosity = faster rate of fusion

= Shorter lifetime on Main Sequence!

Table 7-2 | Main-Sequence Stars

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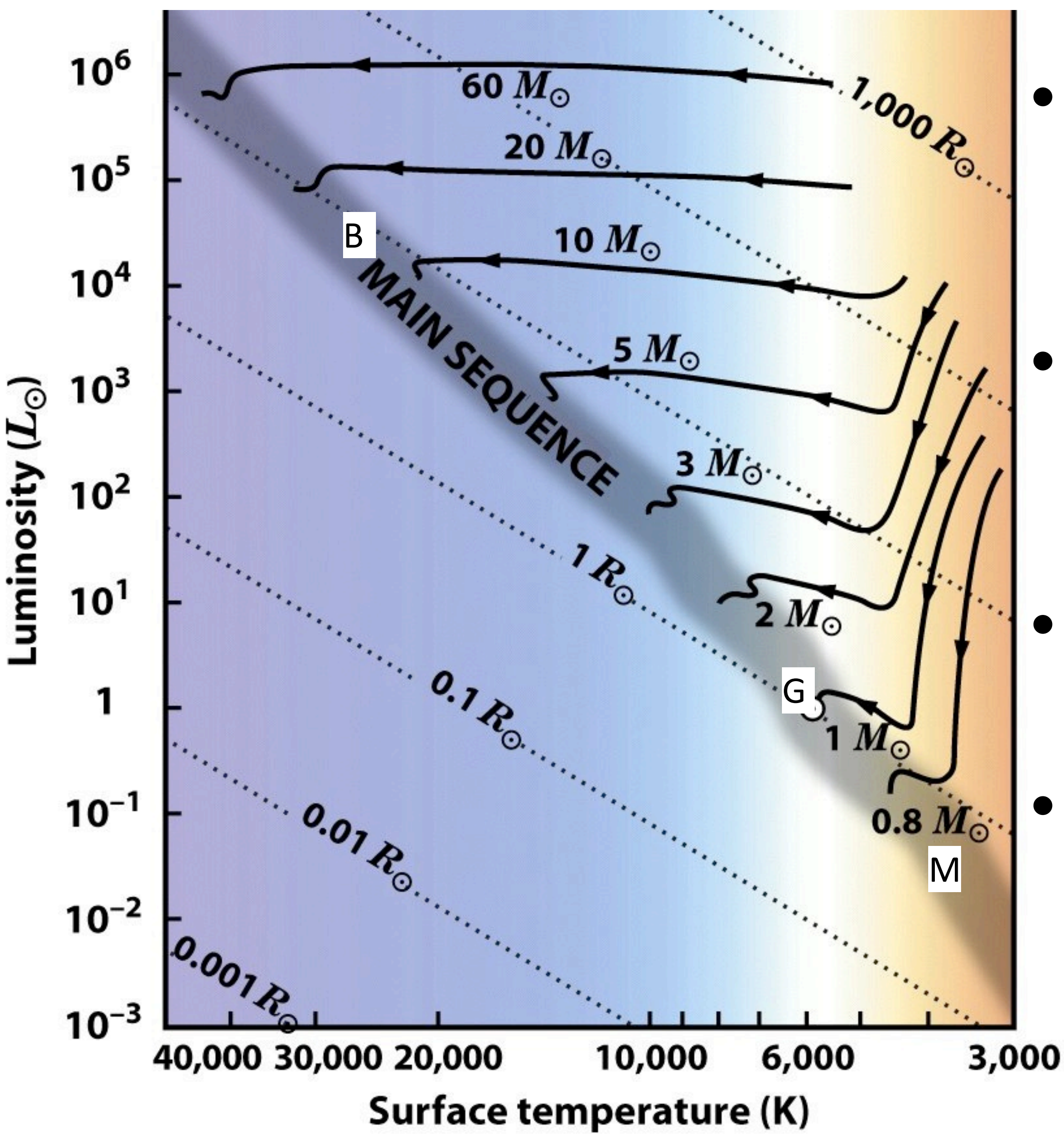
M0	0.5	0.08	56×10^9

O Stars have 40x mass of Sun, live 10,000x shorter.

A stars have 3x mass of Sun, live 20x shorter.

M stars have half the mass of Sun, and live 7x longer.

Formation times



- Just as massive stars have short lifetimes, they also form quickly.
- B stars reach the main sequence in 100,000 years
- G stars form in 30 million years
- M stars can take 1 billion years!