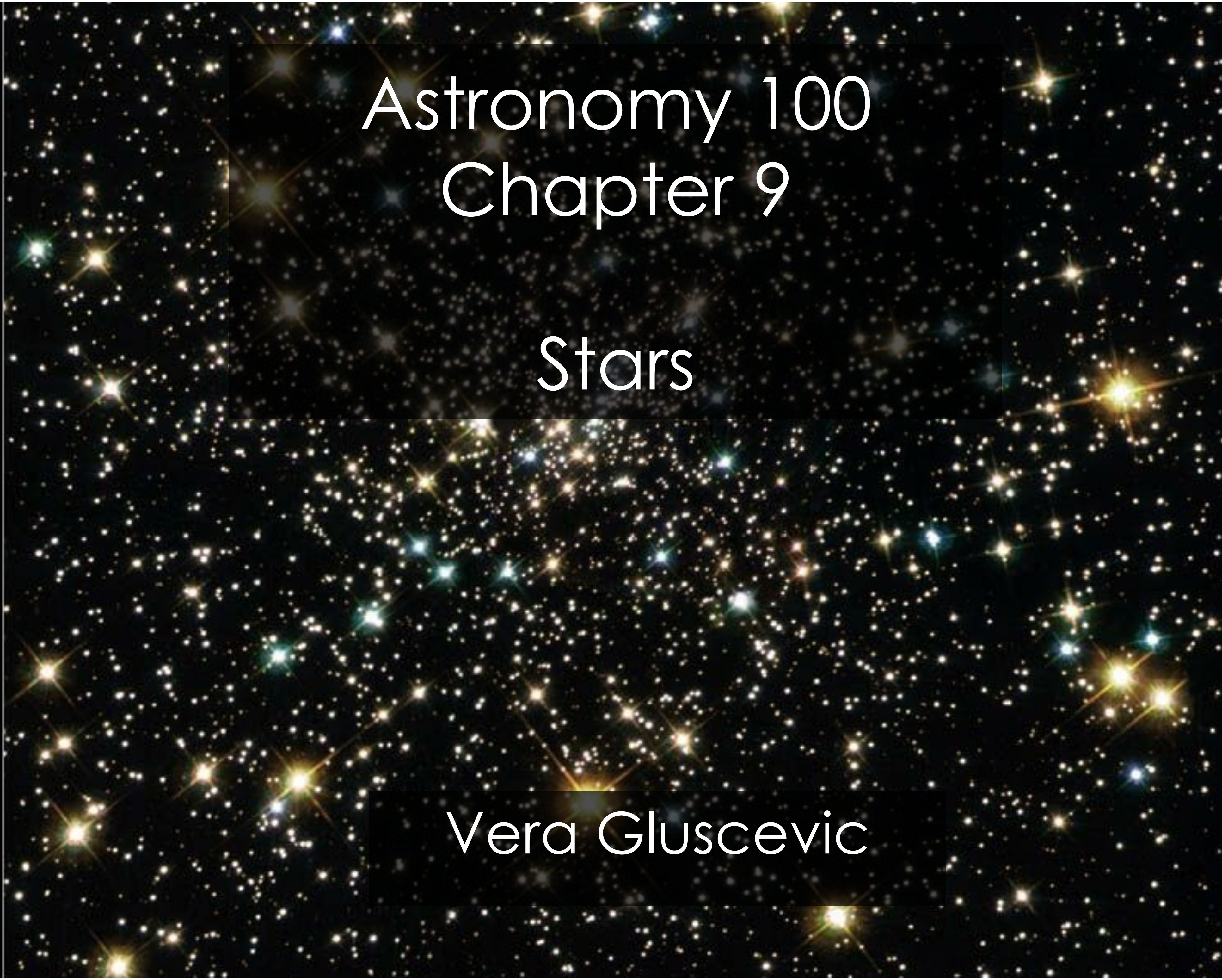
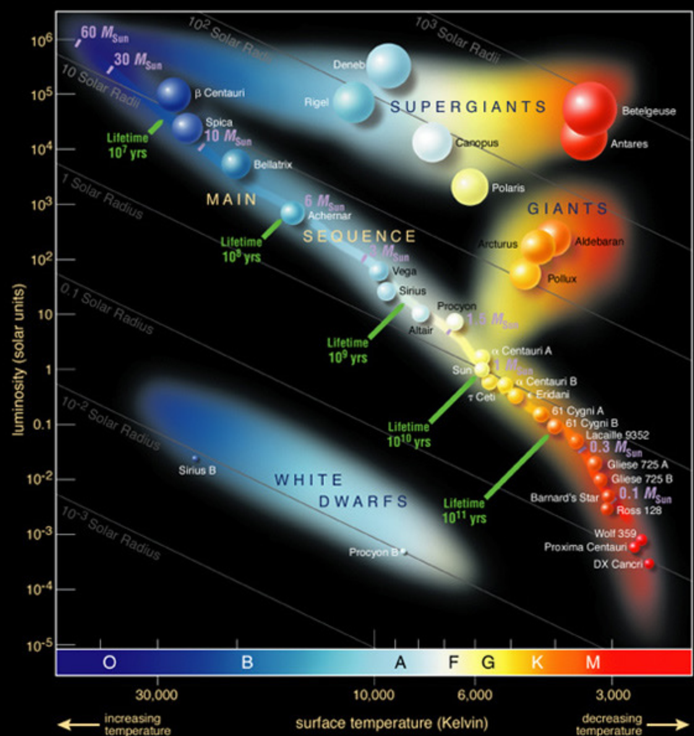
Astronomy 100
Chapter 9

Stars

Vera Gluscevic



Finding order in stars...



1. Brightness
2. Spectrum

→

HR diagram

Luminosity, brightness, magnitude

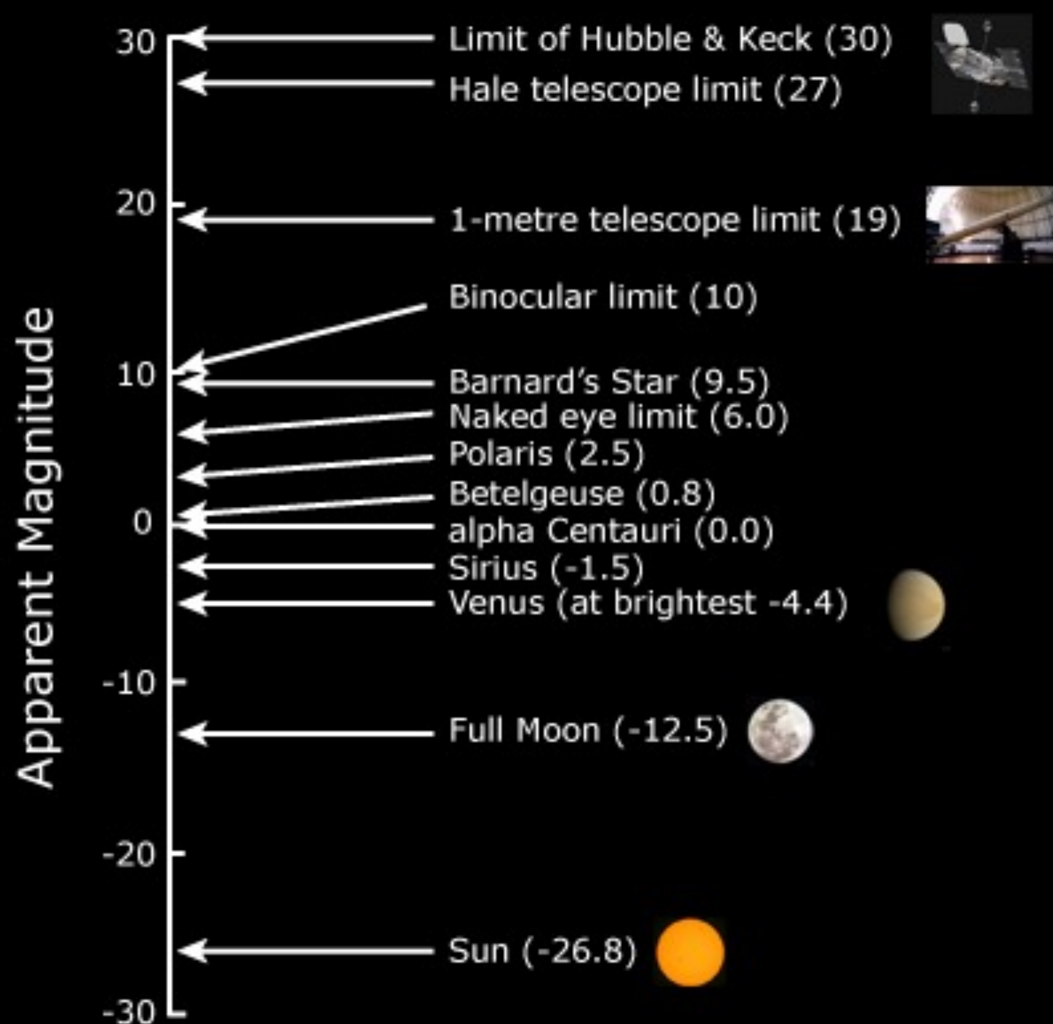
Luminosity = energy output per second

Two kinds of Brightness

1. **Apparent magnitude**: how bright the object appears to us on Earth.
2. **Absolute magnitude**: how bright the object actually is, intrinsically.

Smaller number for magnitude m → brighter object.
Each **five** magnitudes is a factor of 100 change in brightness.

Apparent magnitude



Classification system devised by Hipparchus:

magnitude 1 was brightest, magnitude 6 dimmest star visible.

Image Credit: Ed Prather

Apparent magnitude

- Which would look brighter?
  Vega, m = 0.03
  Antares, m = 1.06

- Which would look brighter?
  Sirius, m = -1.4
  Venus, m = -4.4

Apparent magnitude

- Which would look brighter?

  Vega, m = 0.03

  Antares, m = 1.06

- Which would look brighter?

  Sirius, m = -1.4

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question for you

Star Alpha has an apparent magnitude of +1.1 and an absolute magnitude of +1.1. Star Beta has an apparent magnitude of +3.72 and an absolute magnitude of +6.1. Which star gives off more light?

A. Alpha
B. Beta
C. They give off the same amount of light
D. There is not enough information to determine this

question for you

Star Alpha has an apparent magnitude of +1.1 and an absolute magnitude of +1.1. Star Beta has an apparent magnitude of +3.72 and an absolute magnitude of +6.1. Which star gives off more light?

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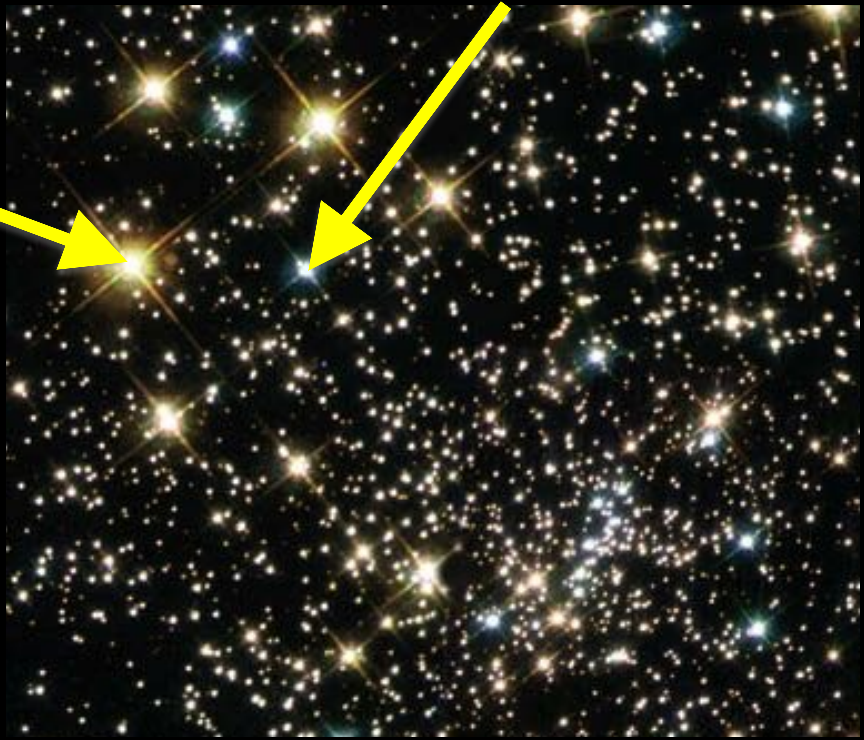
Which star <u>looks</u> like it's giving off more light?

B

A

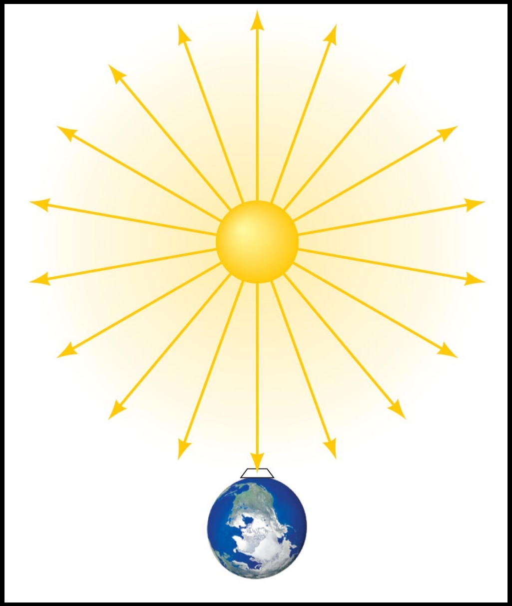


But which one <u>actually</u> gives off more light?

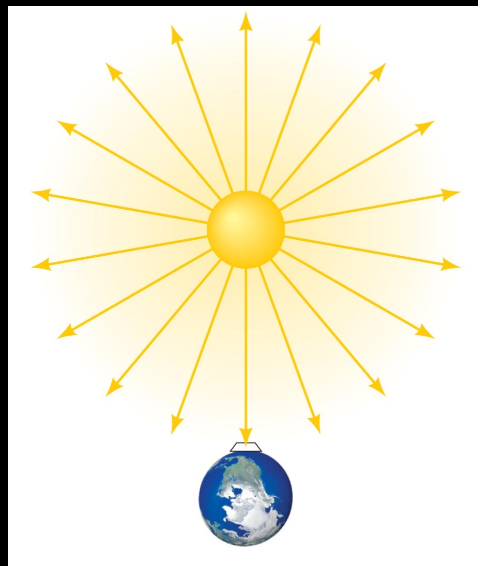
What does m depend on??

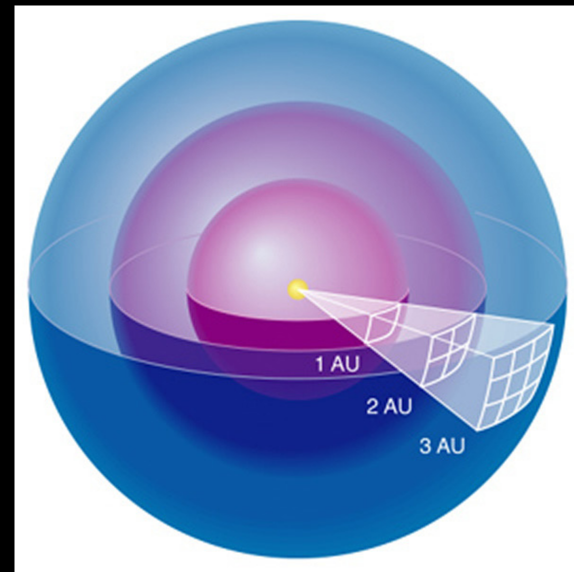
Apparent brightness

- Depends on the **luminosity and distance.**
- Can use watts or L_{SUN} (= 3.85×10^{26} watts) as measure of stellar luminosity (the Earth gets about 1400 W per meter squared from the Sun, a light bulb is ~100 W, for comparison).



Inverse square law



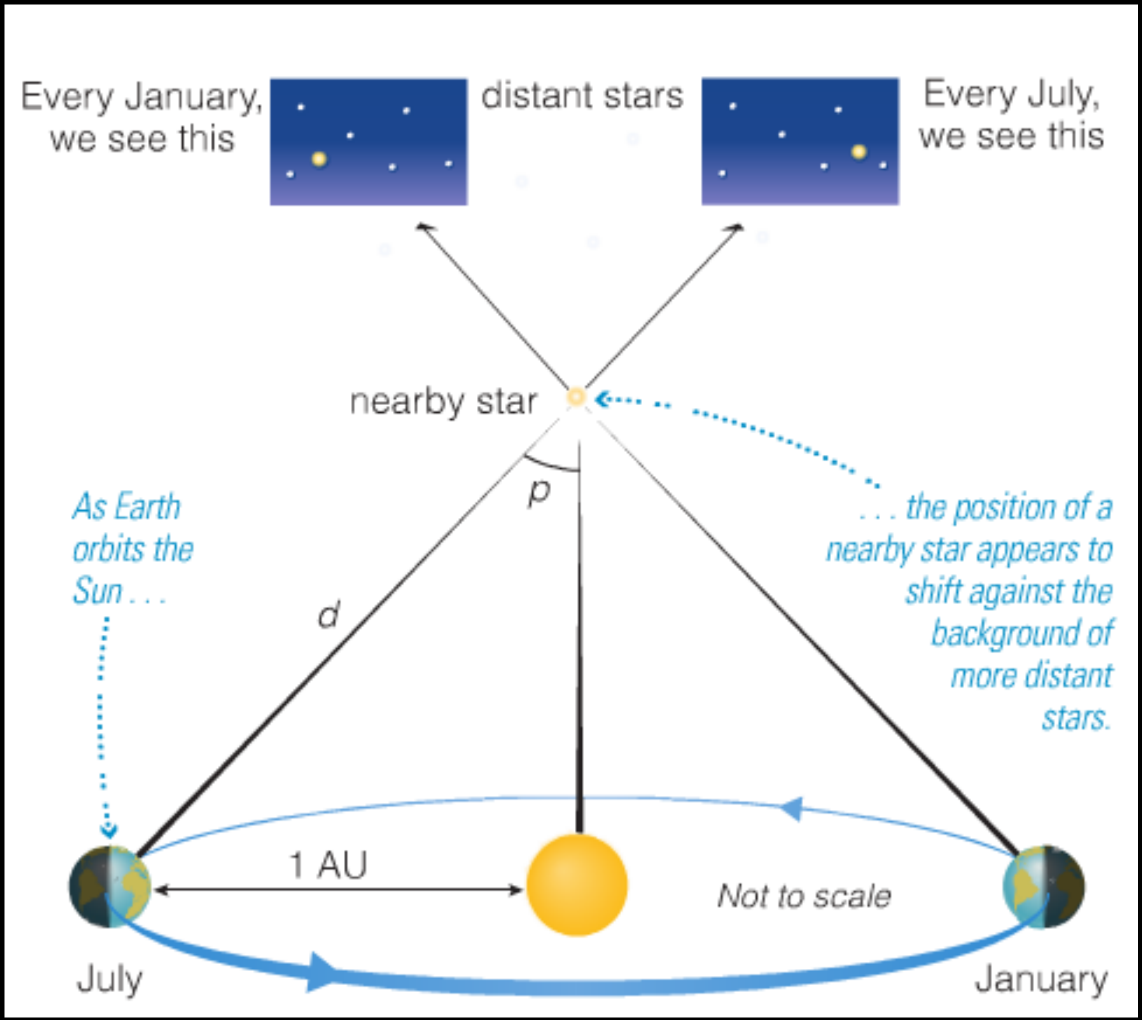


- As we get further from a star, its power output is spread over a larger and larger area, and apparent brightness follows the <u>inverse square law</u>.
- Recall how the force of gravity works

  $$F_{grav} = Gm_1 \times m_2 / r^2$$

- Apparent brightness also decreases as $1/ r^2$.

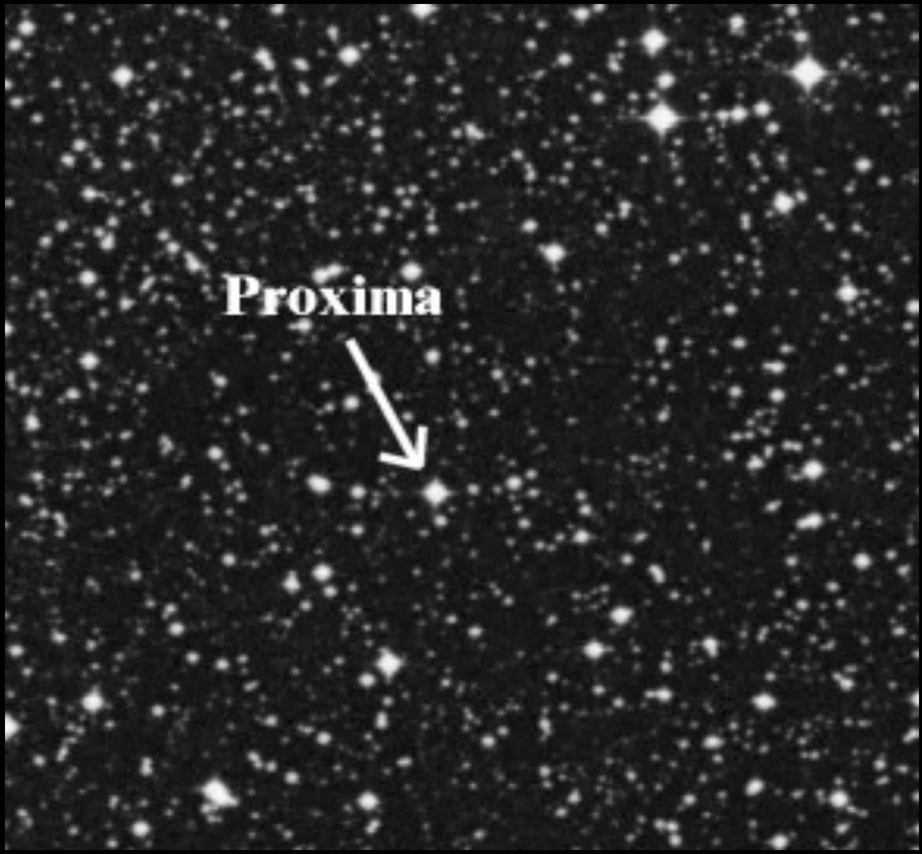
Recall: measuring distances to stars: Parallax



Definition of **parsec** (pc=parallax in arcseconds) is the baseline distance to a star for which the parallax is 1" (one arcsecond).
1 pc = 3.26 ly.

Absolute magnitude

- Absolute magnitude is a measure of how bright a star would appear if it was a distance of 10 parsecs (32.6 ly).
- Sun's absolute magnitude: M=4.8



distance modulus: m - M

- By comparing the apparent (m) and absolute magnitude (M) numbers we can estimate a stars distance from Earth.
- **If m=M, the star is located 10pc away!**

If m<M, the star is farther/closer than 10pc.
If m>M, the star is farther/closer than 10pc.

question for you

Star Alpha has an apparent magnitude of +1.1 and an absolute magnitude of +1.1. Star Beta has an apparent magnitude of +3.72 and an absolute magnitude of +6.1. <u>Which star is closer to Earth?</u>

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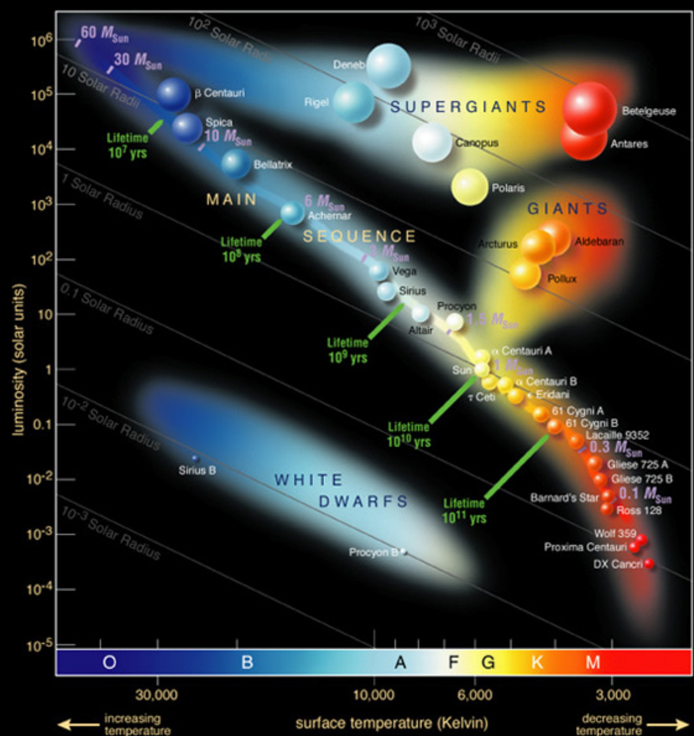
Recap:
Finding order in stars...



1. Brightness

2. Spectrum

→

HR diagram

Recap:

Luminosity is the total energy (light) emitted by an object in each second.

Our Sun has a luminosity of 3.8×10^{26} watts.

Stefan-Boltzmann law:

Luminosity depends on surface area (A) and temperature (T)

Luminosity $= 5.67\times10^{-8} \times \mathbf{A} \times \mathbf{T^4}$

- Big and Hot objects have greater luminosity than small cool objects.

Recap:
Color - when the lights are off!

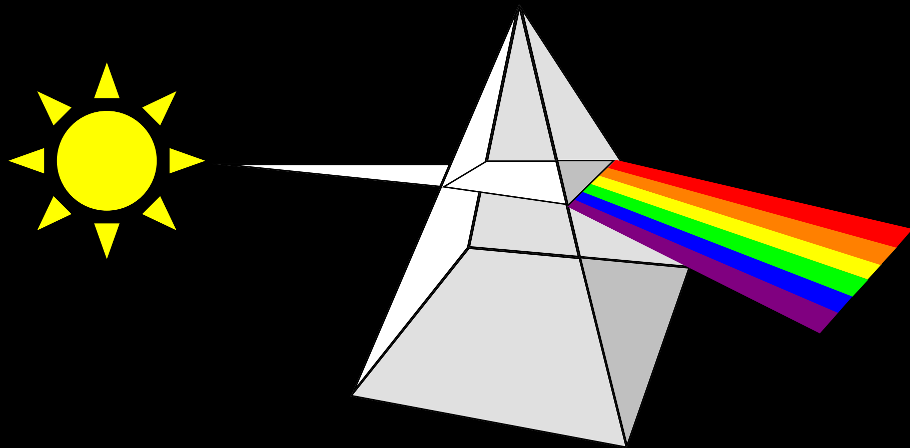
<u>Wein's law:</u>

Relates the temperature of an object to the wavelength of the peak in the black body curve:

$\boldsymbol{\lambda_{peak}} = (2.9 \times 10^{-3}) \;/\; \boldsymbol{T_{kelvin}}$

- Hotter objects have shorter peak wavelength.

Spectral types



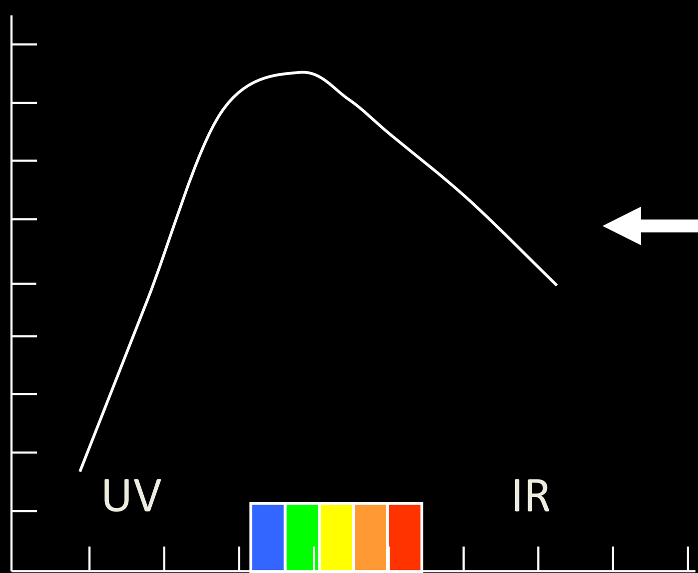
blue 460 nm 81

green 530 nm 85

yellow 580 nm 83

orange 610 nm 78

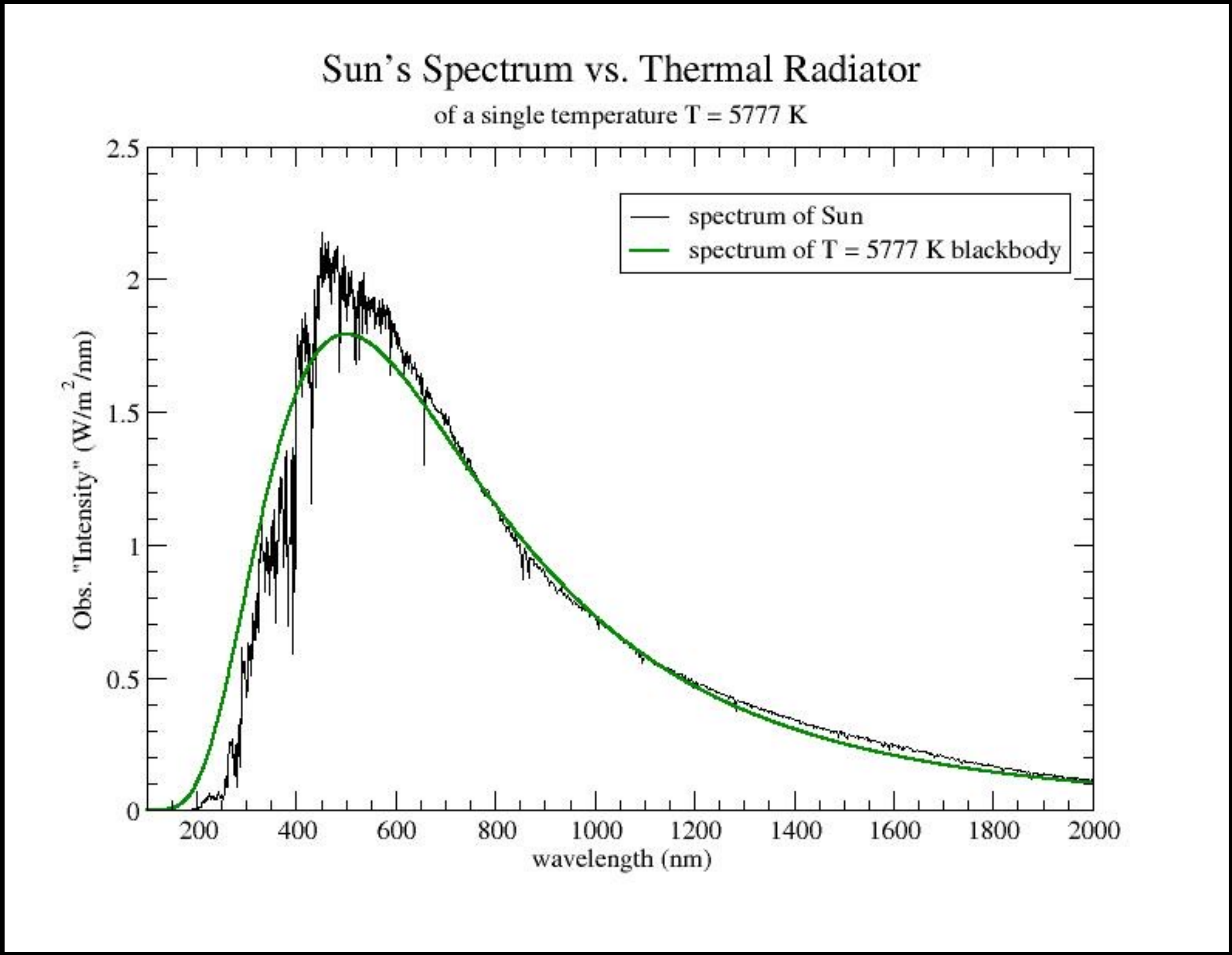
red 660 nm 70



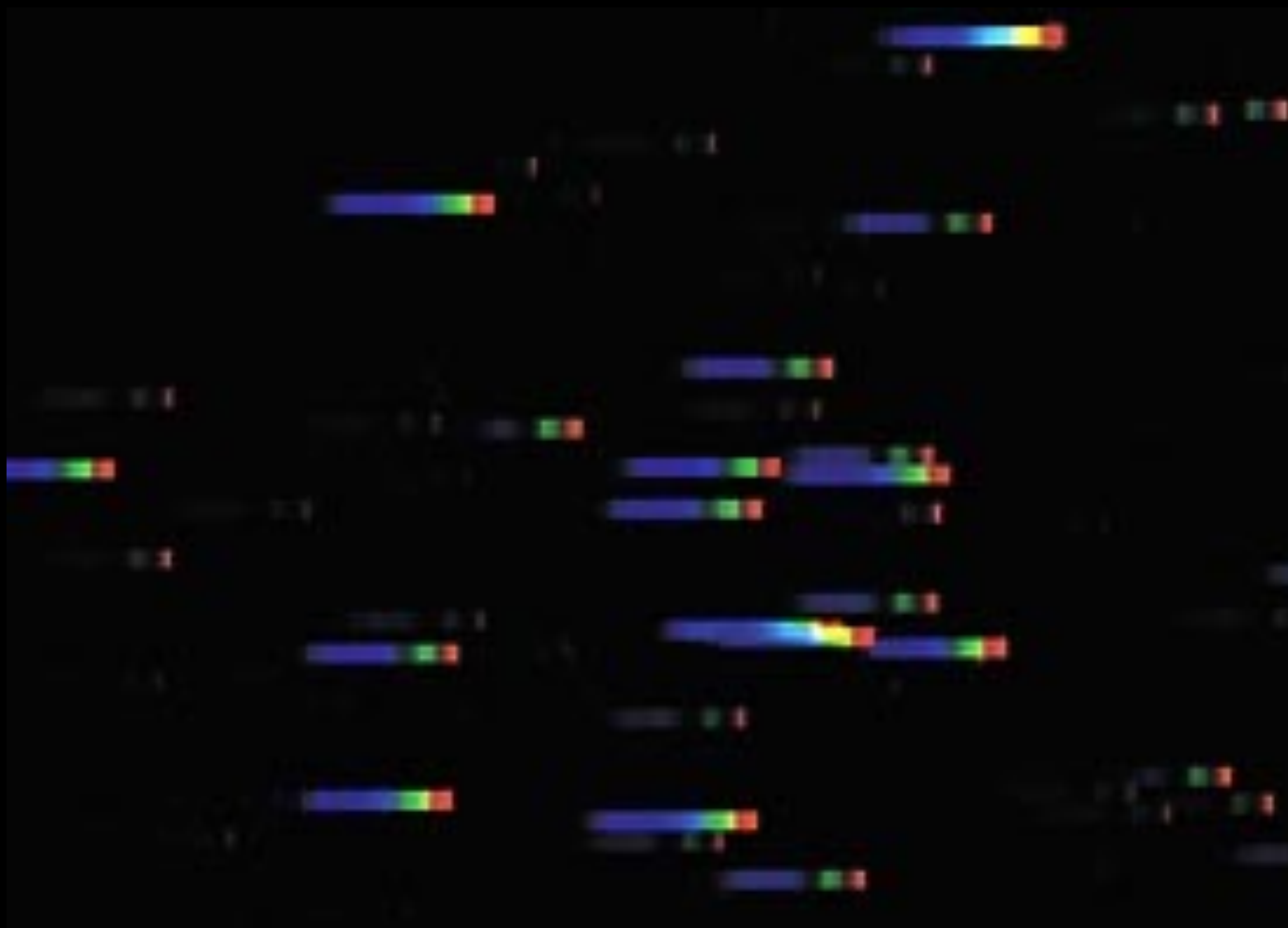
Blackbody Curve - a graph of an object's energy output per wavelength.

The peak of this curve tells us about the object's temperature and color.

Recap: spectrum and black body curve



Spectral Classes



Harvard "computers"

The Origin of Spectral Classes

- In late 19th century, women were hired at the Harvard Observatory (and other institutions) to serve as "computers" and classify stars.
- Williamina **Fleming**, Annie Jump **Cannon**, and Antonia **Maury** have developed a classification system used today.

First classification scheme by Fleming (based on strength of H lines)

A

B

C

D

E

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.

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S

New classification scheme by Cannon and Maury (color-based)

O

B

A

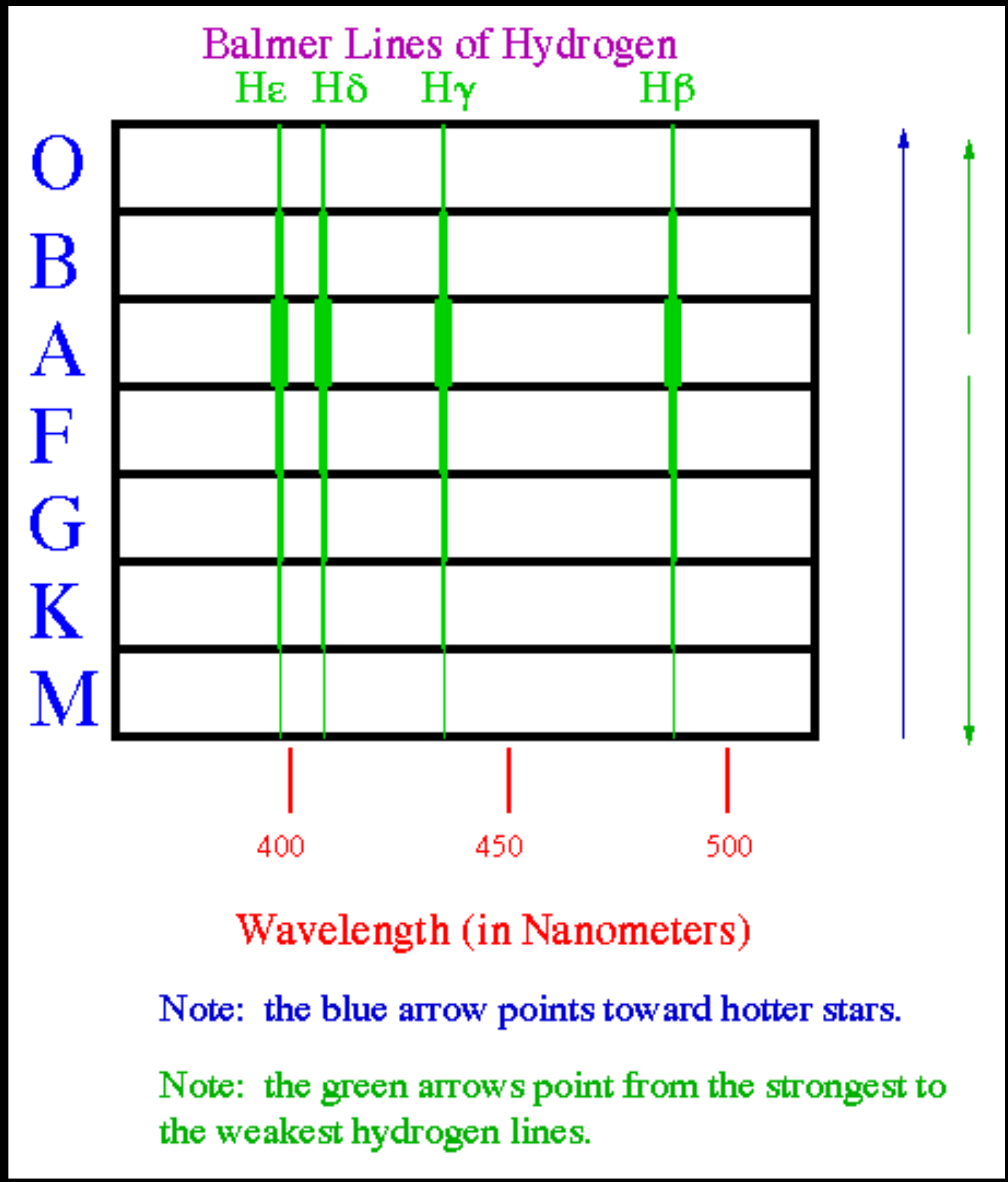
F

G

K

M

Current classification scheme



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Reminder:
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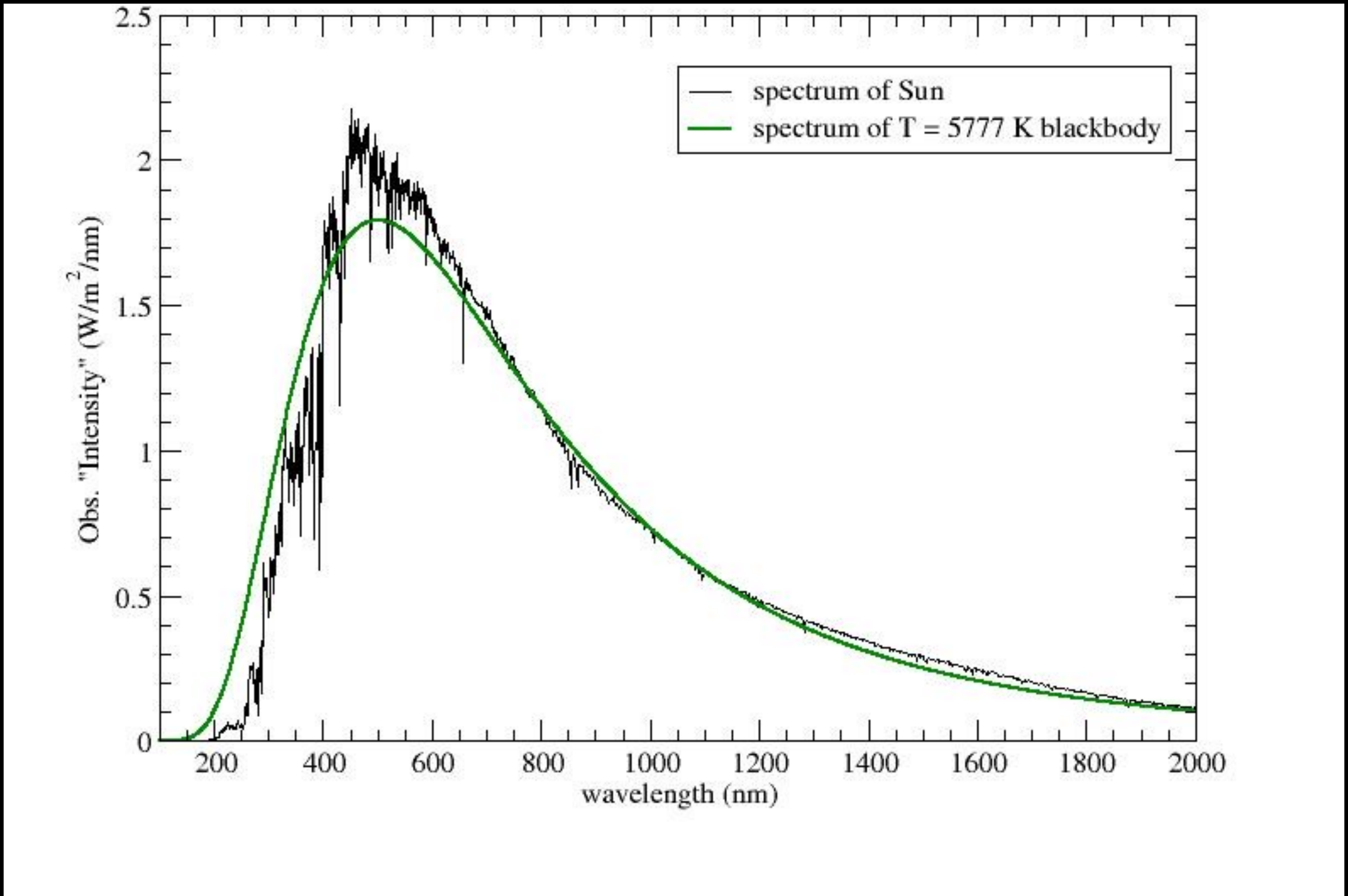
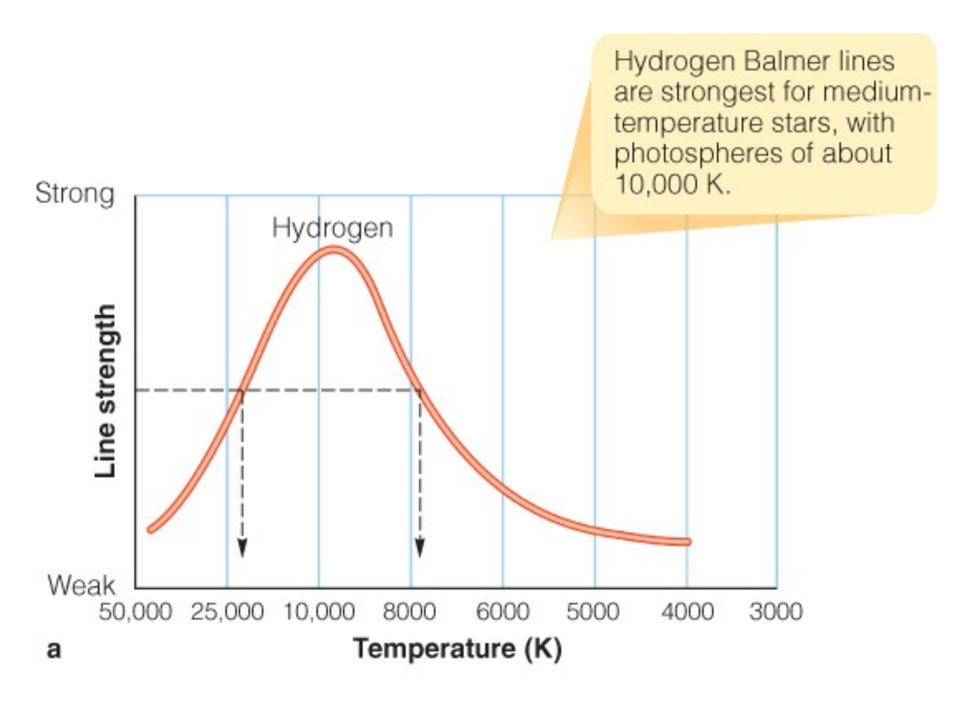
What does the strength of a line depend on?

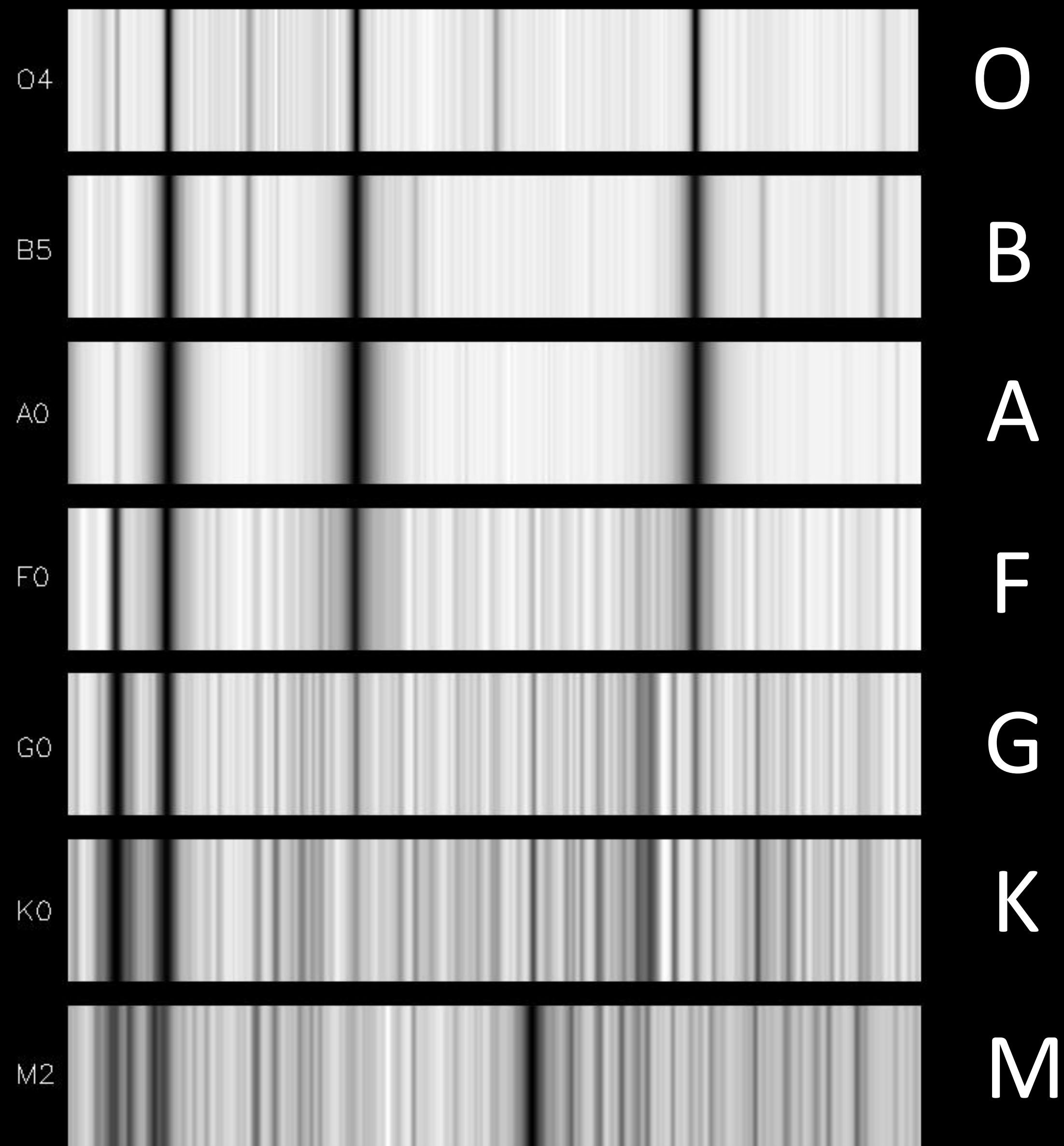


The "Balmer Thermometer"

- Balmer hydrogen line forms due to transitions to/from the first excited state
- Strength ("thickness") of Balmer line is sensitive to temperature.
- Too cold: too few hydrogen atoms excited→ weak Balmer lines.
- Too hot: most hydrogen atoms are ionized→ weak Balmer lines.



Current classification scheme



A Revolution

- Before: most astronomers believed that the differences in spectral lines were due to subtle differences in chemical abundance.
- Meghnad **Saha**: theoretical explanation for Cannon's classification scheme, understanding ionization of atoms in stellar atmospheres and its relationship to stellar spectrum.
- Cecilia **Payne-Gaposhkin**: demonstrated that the O-B-A-F-G-K-M spectral sequence is actually a sequence in <u>temperature</u>.

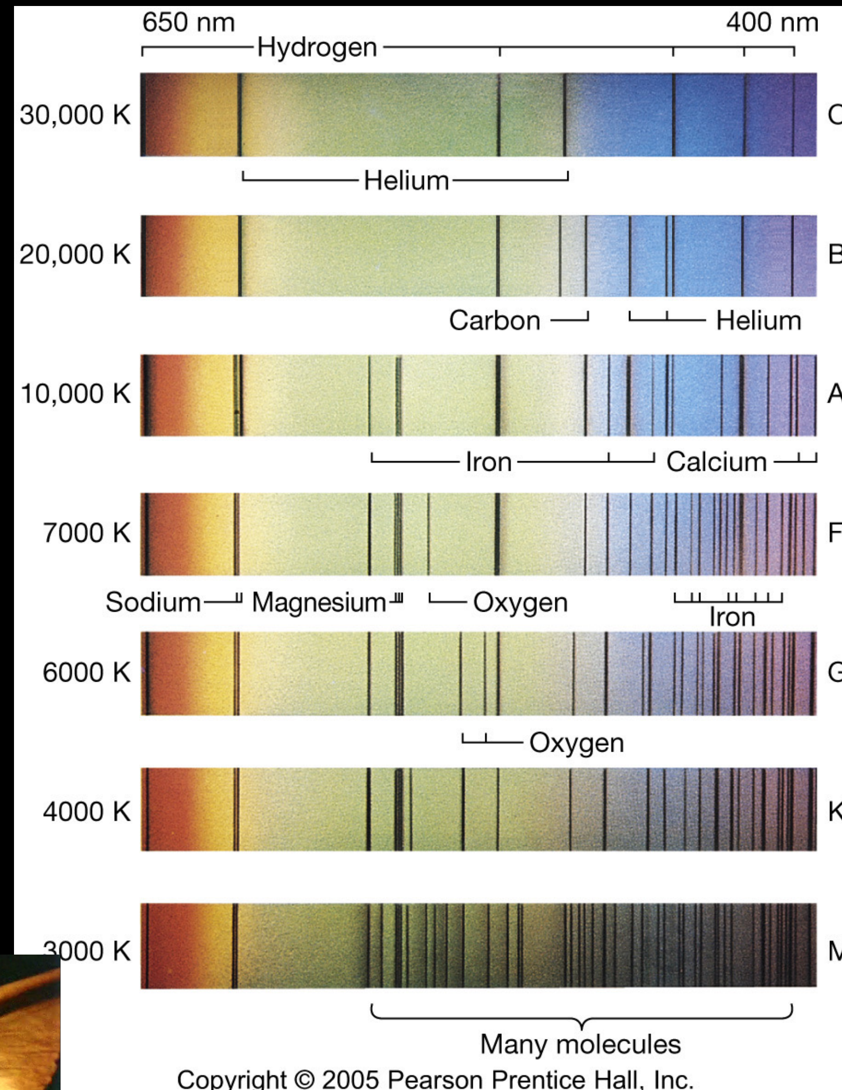
Work by Saha and Payne-Gaposchkin:

- Showed that the differences in spectra (absorption lines) are due to temperature and thermal ionization of atoms---not abundance of elements!
- Provided a evidence that stars are mostly made of hydrogen.

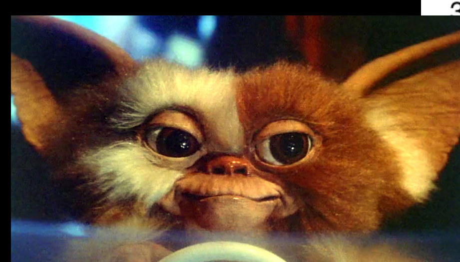
Spectral classes

- The <u>surface temperature</u> of a star can be determined by examining the star's <u>spectrum</u>.
- Star spectra have been classified from hottest to coolest (from blue to red):

  O, B, A, F, G, K, M.
- Each spectral type is subdivided from 0 to 9, with 9 coolest and 0 hottest.
- Roman numeral denotes Luminosity Class, e.g. "V" means "main sequence star."



"<u>O</u>h <u>B</u>rother, <u>A</u> <u>F</u>uzzy <u>G</u>remlin <u>K</u>icked <u>M</u>e!"



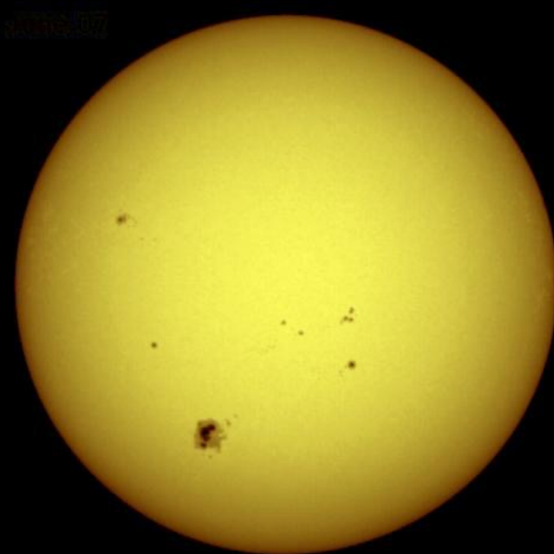
Summary of Spectral Classes

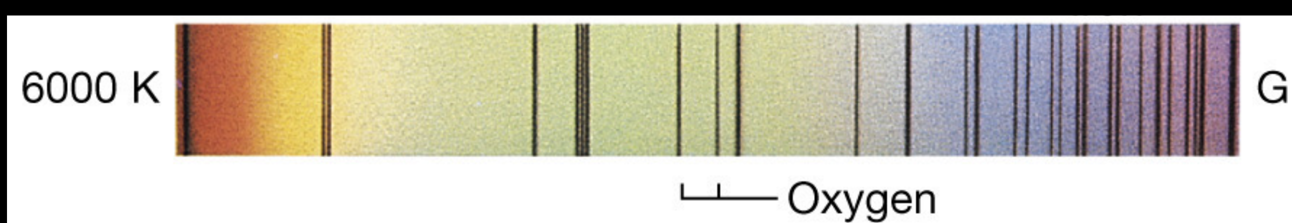
O	**hotter than 25,000 K**
B	**11,000 - 25,000 K**
A	**7500 - 11,000 K**
F	**6000 - 7500 K**
G	**5000 - 6000 K**
K	**3500 - 5000 K**
M	**cooler than 3500 K**

Which spectral class is the Sun?

Spectral classes

- The Sun is a **G2V** star
- Peak wavelength 480 – 560 nm (yellow).





Spectral types, summary

Class	Effective temperature[1][2][3]	Conventional color description[4][nb 1]	Actual apparent color[5][6][7]	Main-sequence mass[1][8] (solar masses)	Main-sequence radius[1][8] (solar radii)	Main-sequence luminosity[1][8] (bolometric)	Hydrogen lines	Fraction of all main-sequence stars[9]
O	≥ 30,000 K	blue	blue	≥ 16 $M_{\odot}$	≥ 6.6 $R_{\odot}$	≥ 30,000 $L_{\odot}$	Weak	~0.00003%
B	10,000–30,000 K	blue white	deep blue white	2.1–16 $M_{\odot}$	1.8–6.6 $R_{\odot}$	25–30,000 $L_{\odot}$	Medium	0.13%
A	7,500–10,000 K	white	blue white	1.4–2.1 $M_{\odot}$	1.4–1.8 $R_{\odot}$	5–25 $L_{\odot}$	Strong	0.6%
F	6,000–7,500 K	yellow white	white	1.04–1.4 $M_{\odot}$	1.15–1.4 $R_{\odot}$	1.5–5 $L_{\odot}$	Medium	3%
G	5,200–6,000 K	yellow	yellowish white	0.8–1.04 $M_{\odot}$	0.96–1.15 $R_{\odot}$	0.6–1.5 $L_{\odot}$	Weak	7.6%
K	3,700–5,200 K	orange	pale yellow orange	0.45–0.8 $M_{\odot}$	0.7–0.96 $R_{\odot}$	0.08–0.6 $L_{\odot}$	Very weak	12.1%
M	2,400–3,700 K	red	light orange red	0.08–0.45 $M_{\odot}$	≤ 0.7 $R_{\odot}$	≤ 0.08 $L_{\odot}$	Very weak	76.45%

The most common stars in the universe are small, cold, red stars.

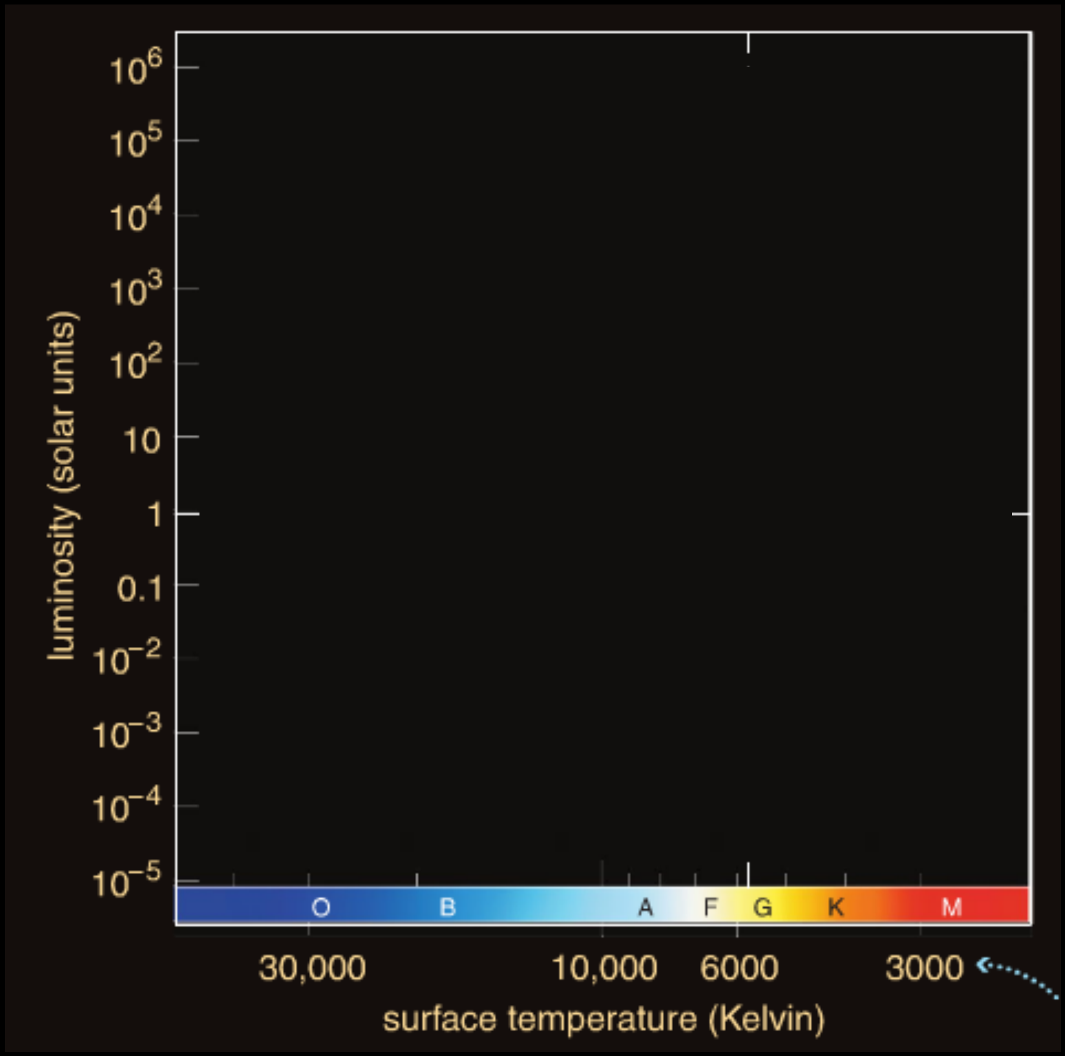
HR diagram

For thousands of nearby stars we can find:

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

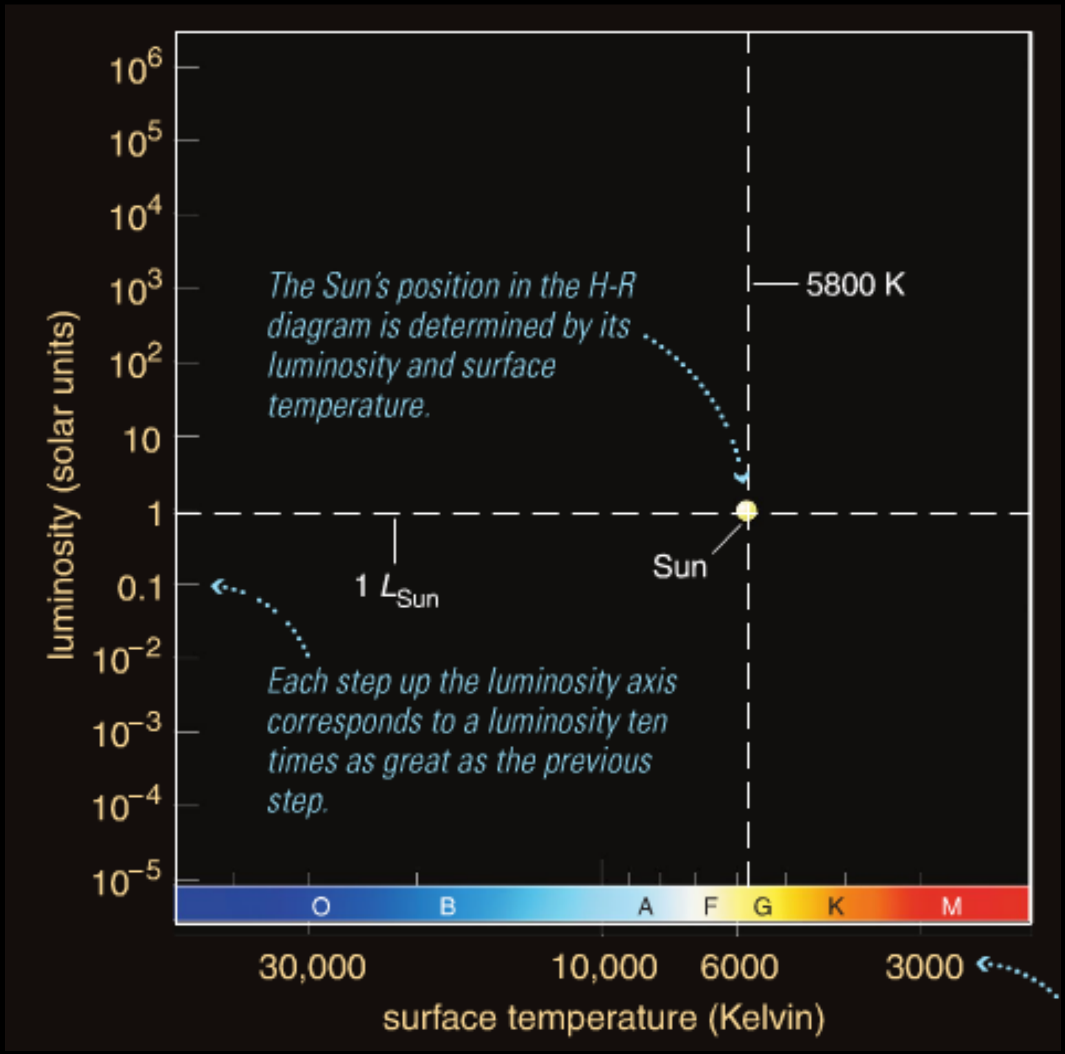
Is there any relationship?
What combinations of these are possible?

Let's make a diagram of stellar characteristics...



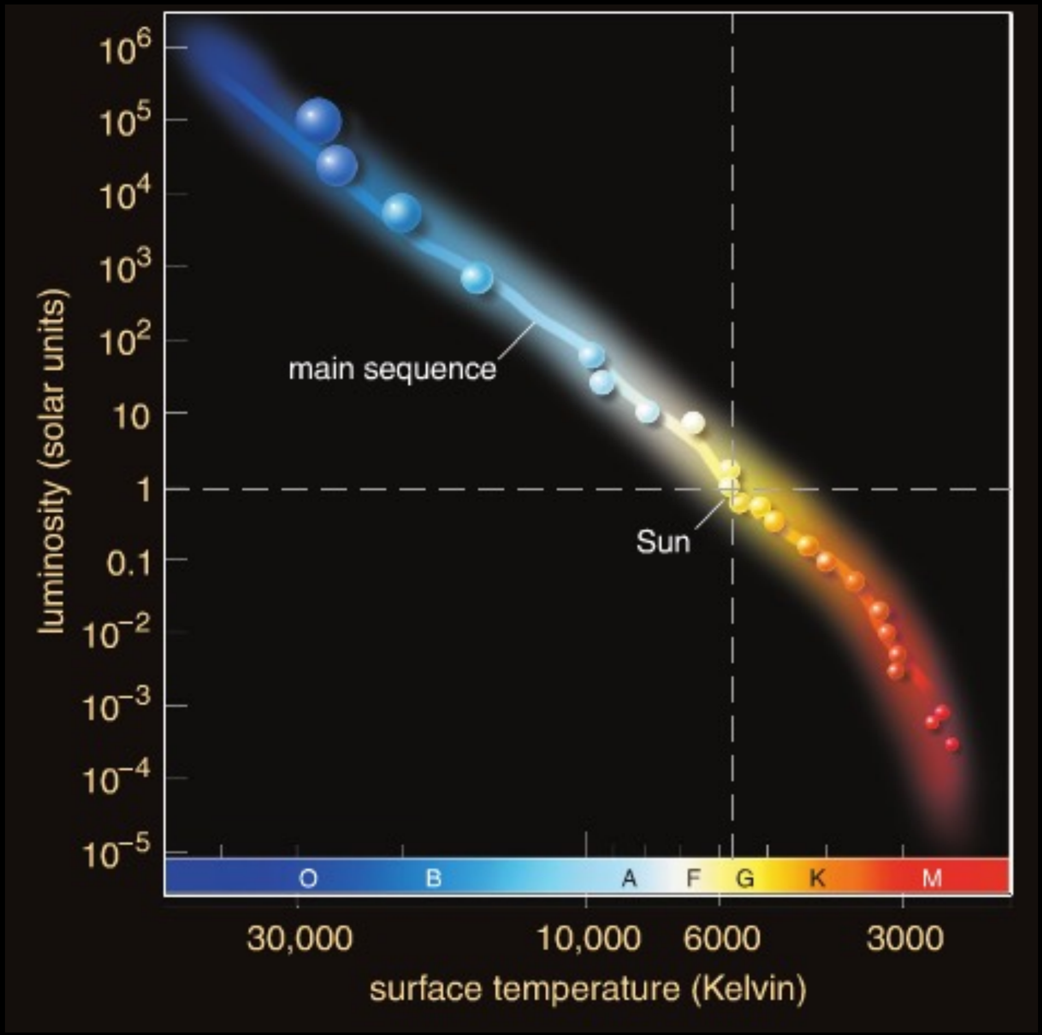
Where is the Sun on this diagram?

Let's make a diagram of stellar characteristics...



Where is the Sun on this diagram?

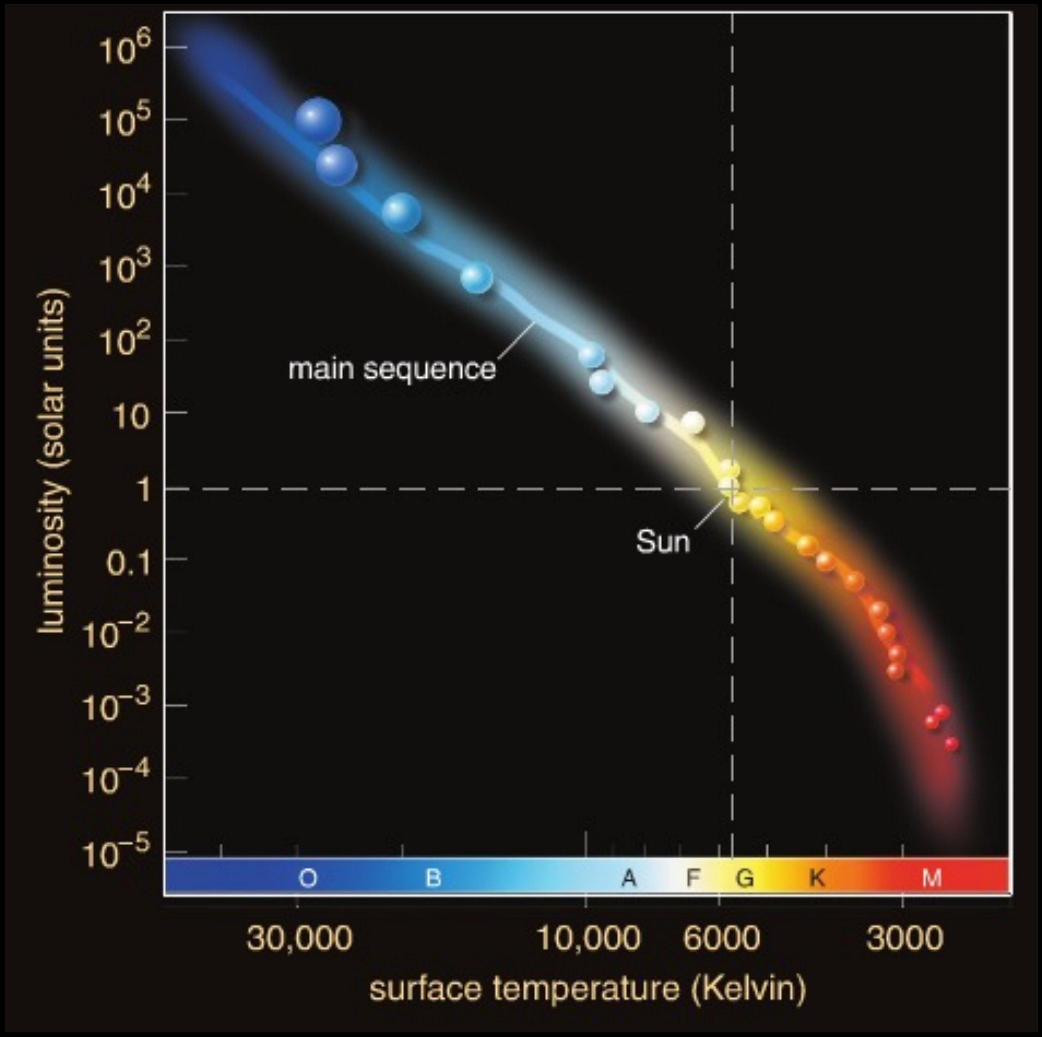
The Hertzsprung-Russell (H-R) diagram



absolute magnitude vs temperature

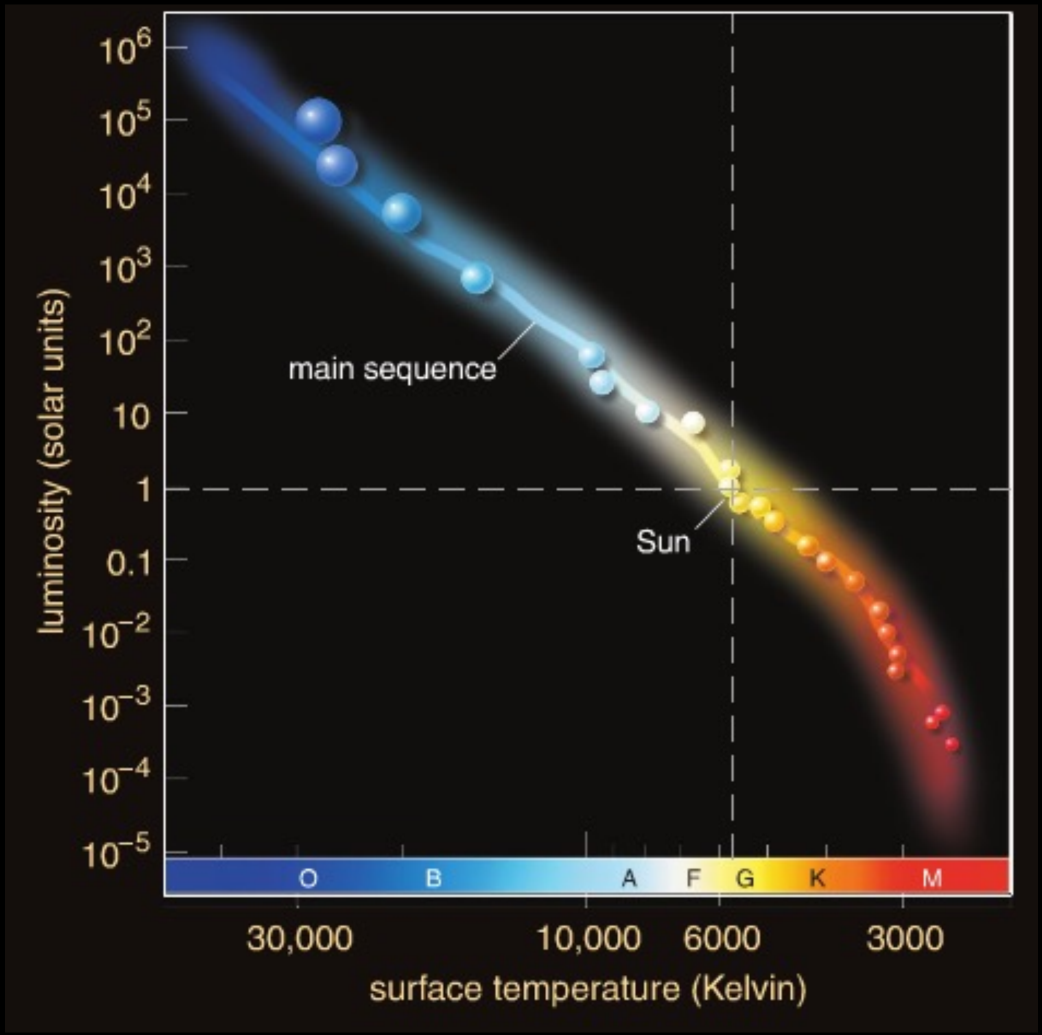
(or luminosity vs spectral type)

The Hertzsprung-Russell (H-R) diagram



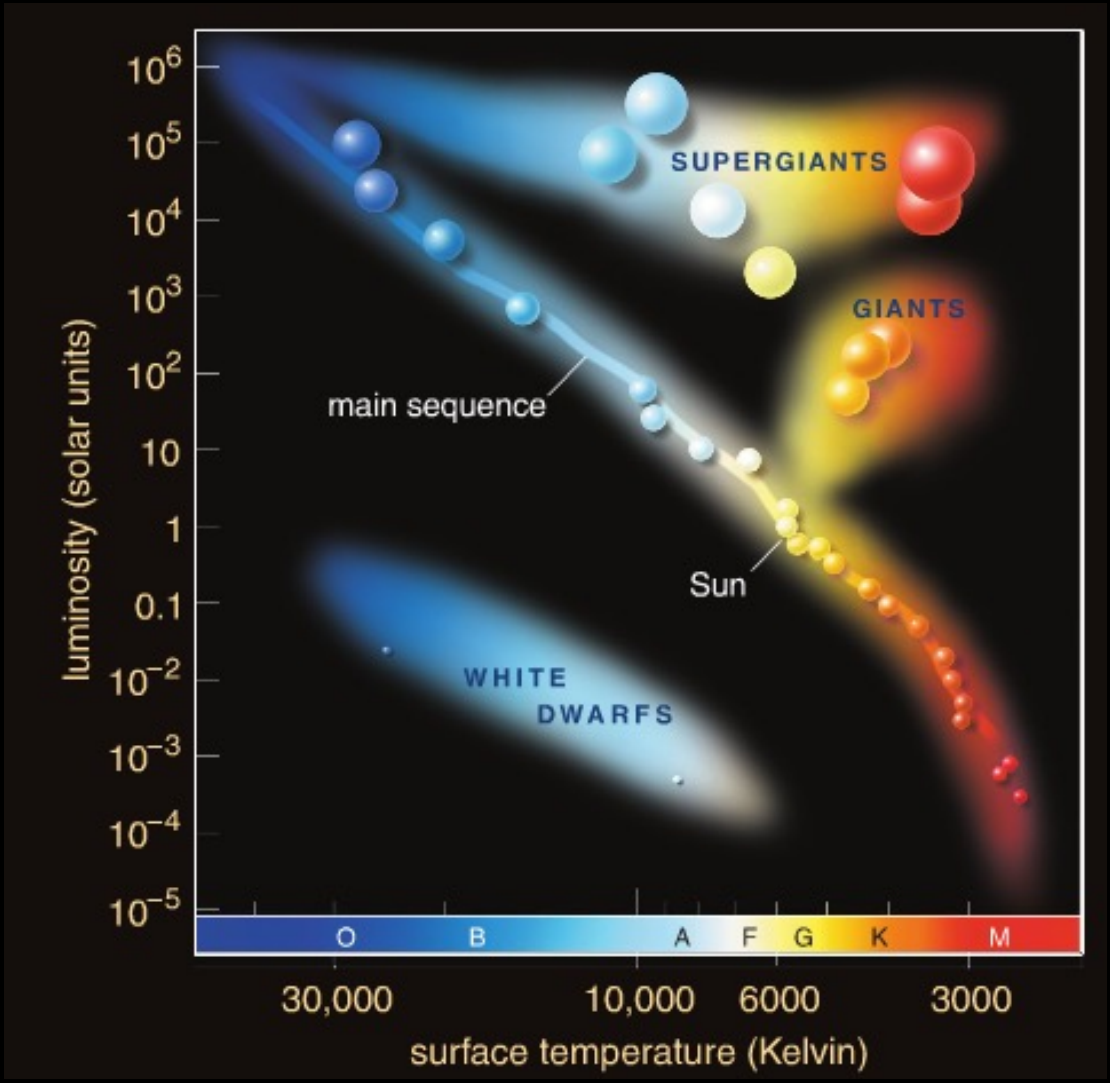
This is the **main sequence.**
All stars that fuse hydrogen in their cores are on it and stay there 90% of their lives.

The Hertzsprung-Russell (H-R) diagram



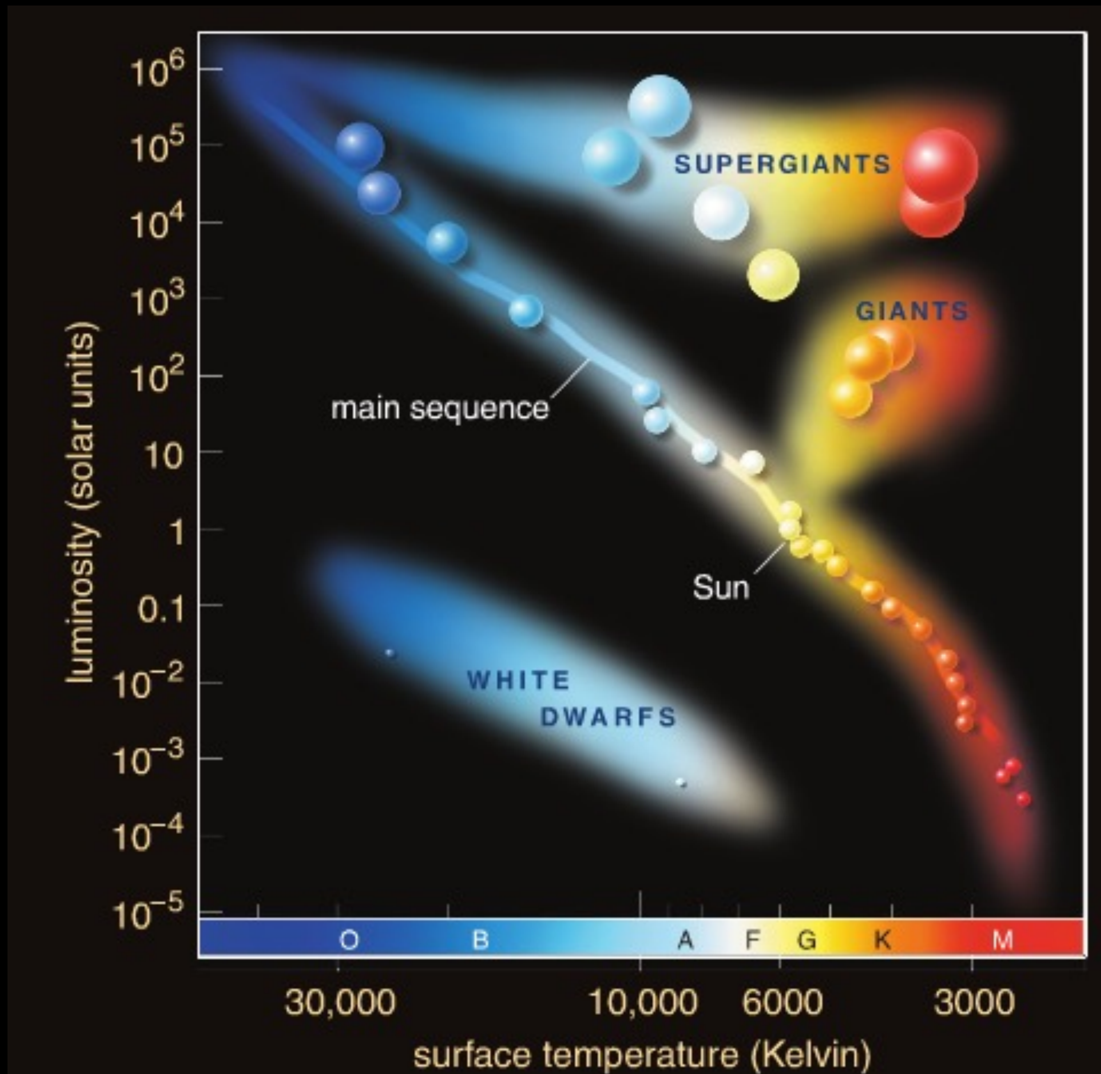
Main sequence goes from top left (hot and bright) to bottom right (cool and dim).

The Hertzsprung-Russell (H-R) diagram

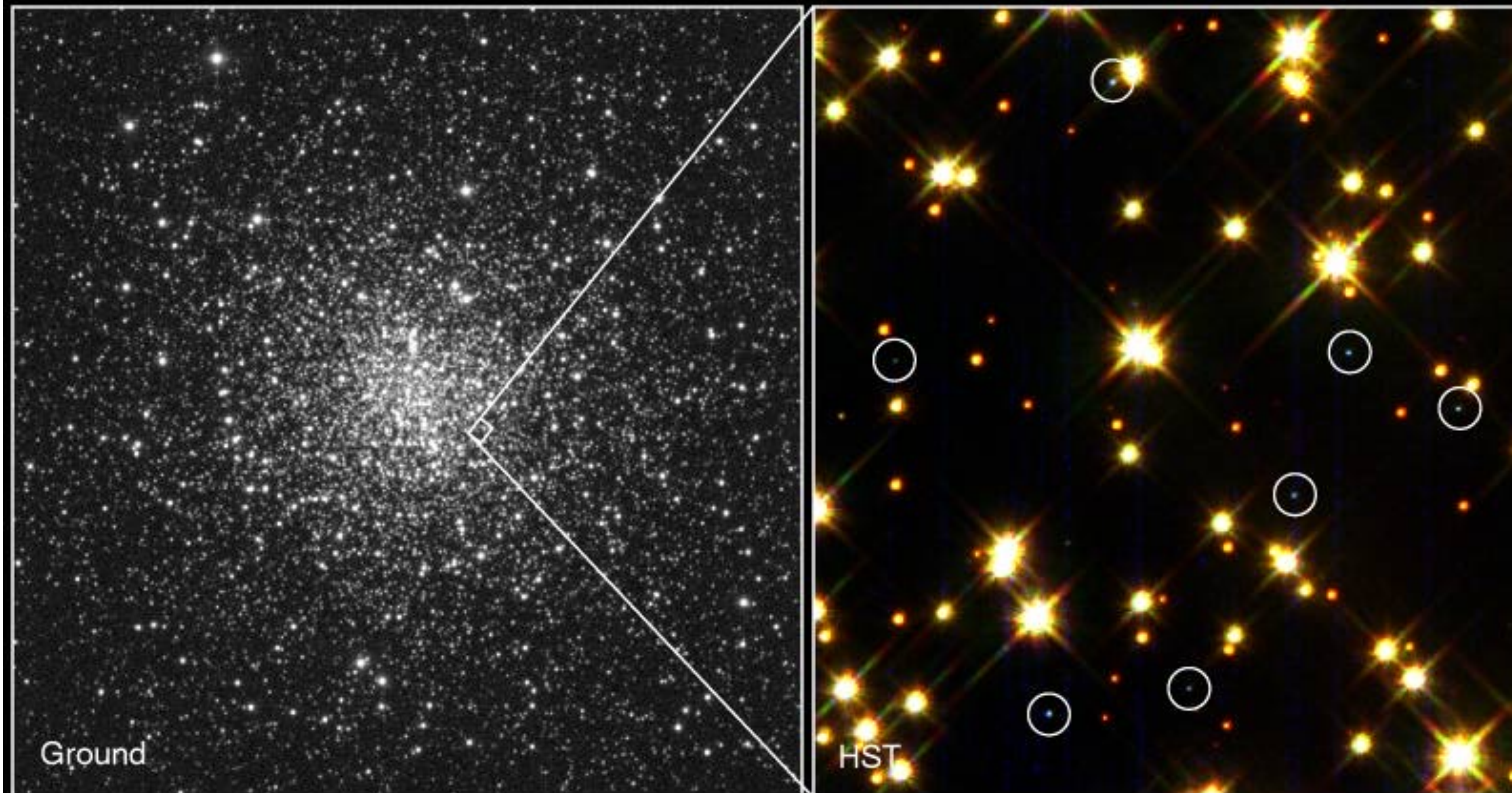


As they evolve, stars change locations on the HR diagram.

The Hertzsprung-Russell (H-R) diagram



Lower portion of HR diagram is populated by **white dwarfs**, which are the last stage in the life cycle of low-mass stars.

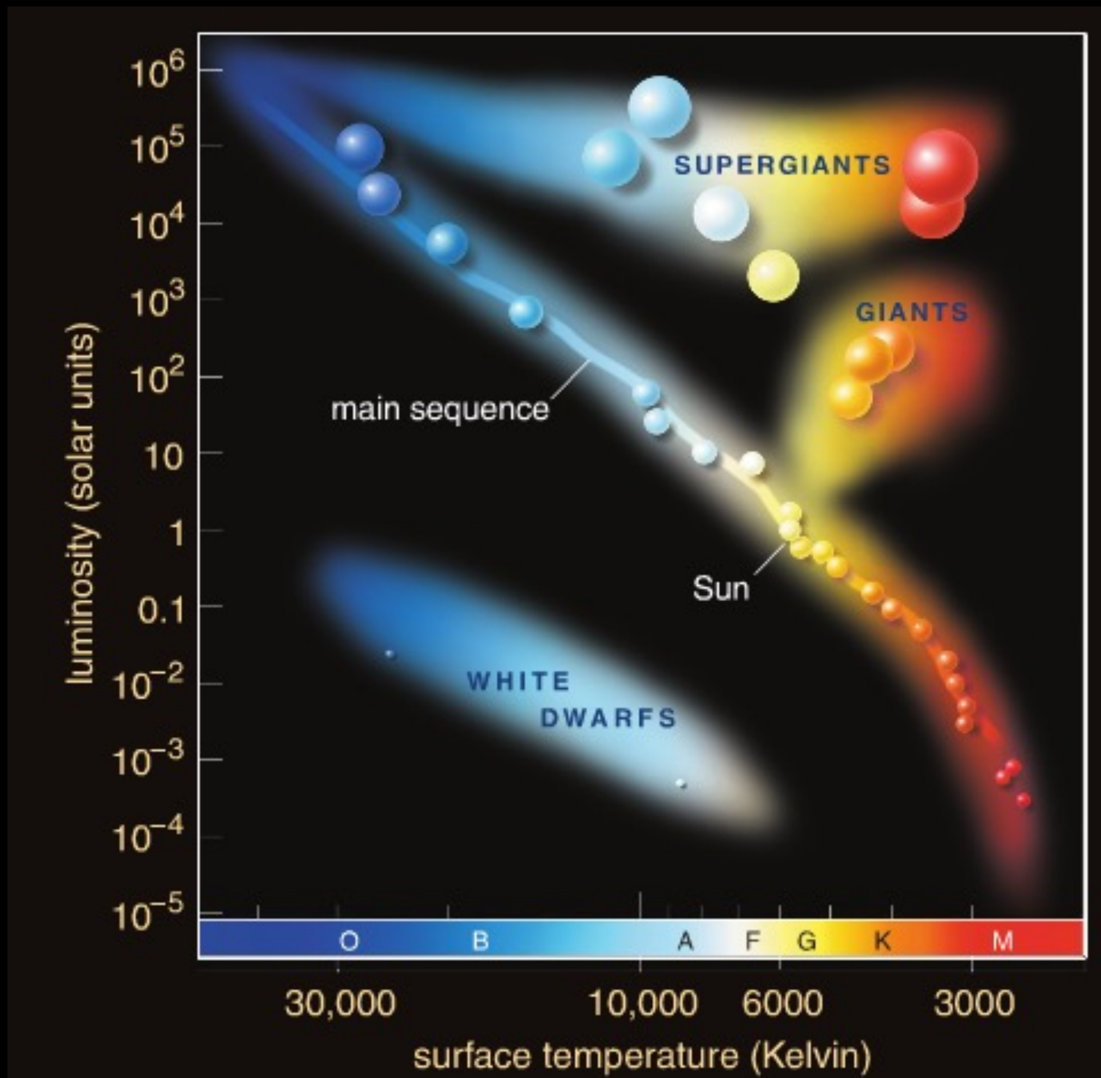


White Dwarf Stars in M4

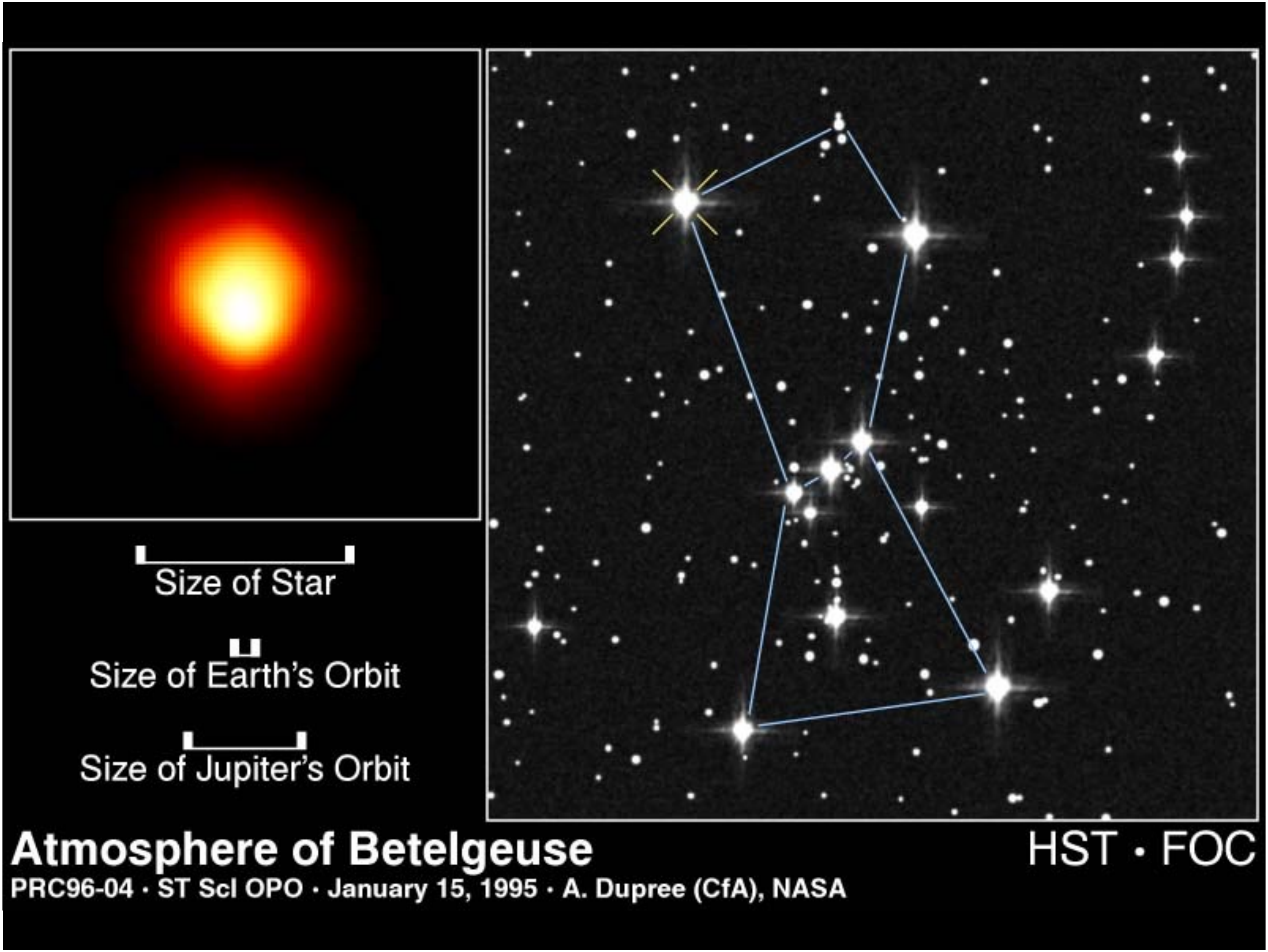
HST • WFPC2

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

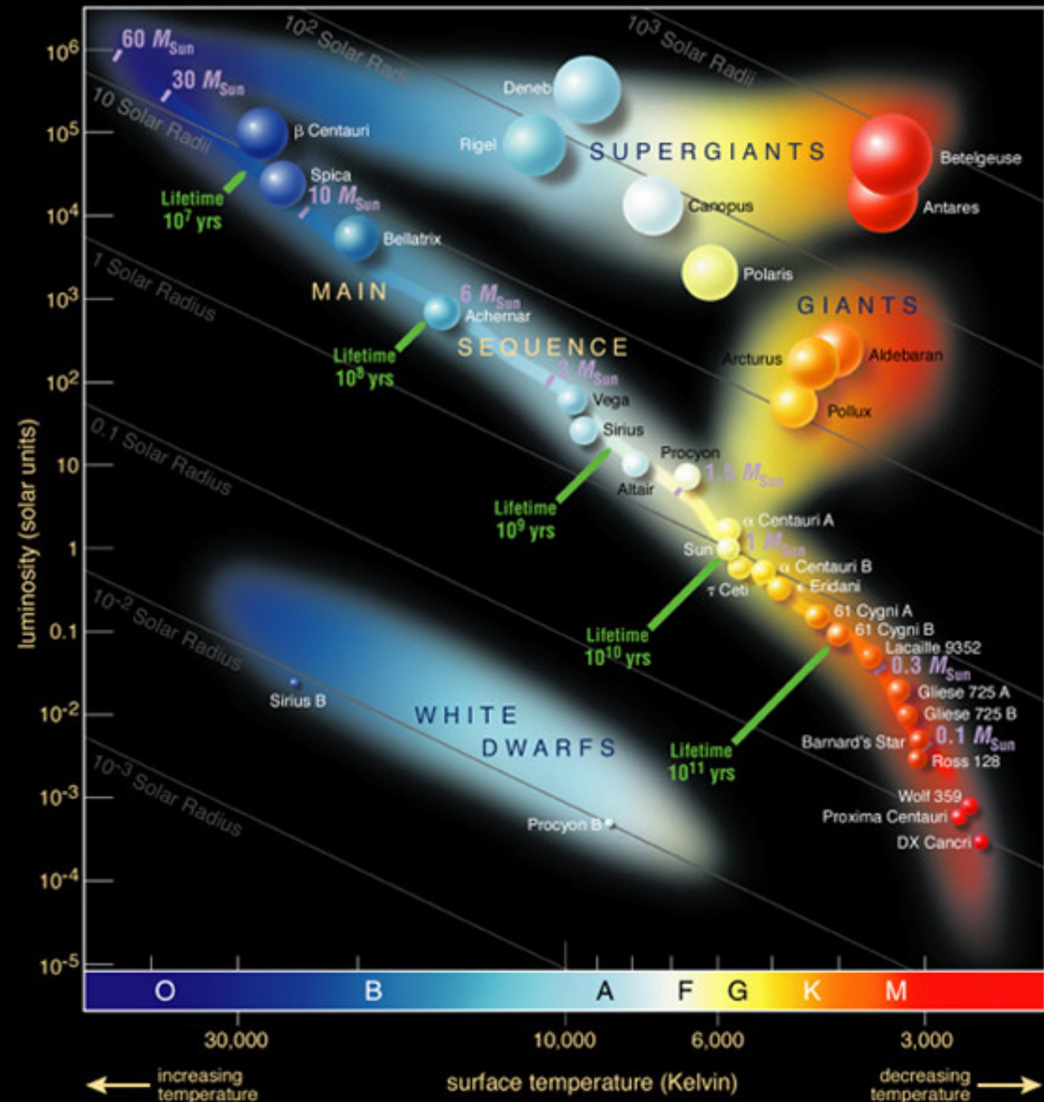
The Hertzsprung-Russell (H-R) diagram



Upper right portion of HR diagram is populated by **red giants and supergiants**.

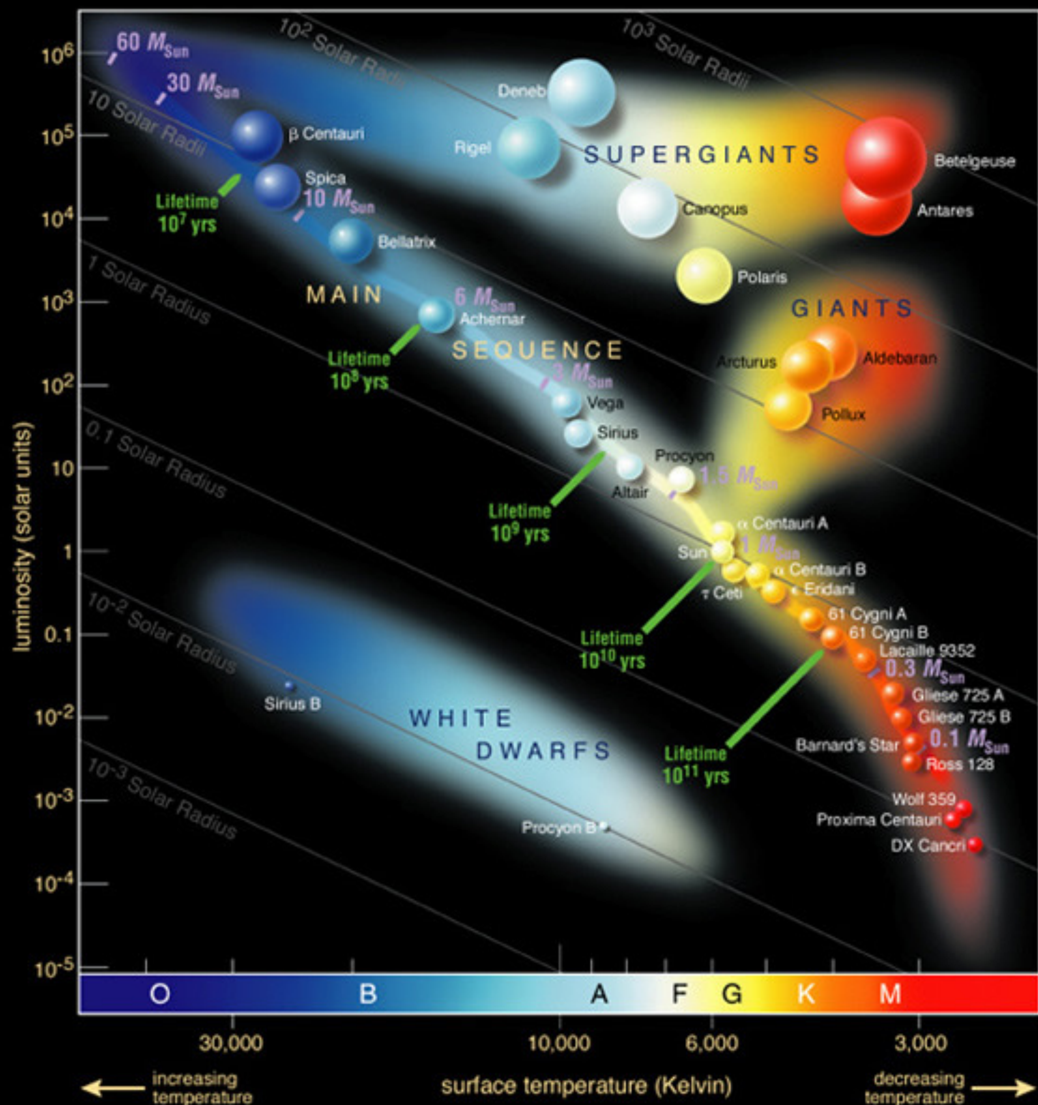

Size of Star
Size of Earth's Orbit
Size of Jupiter's Orbit
Atmosphere of Betelgeuse
HST • FOC
PRC96-04 • ST ScI OPO • January 15, 1995 • A. Dupree (CfA), NASA

The Hertzsprung-Russell (H-R) diagram



Stellar radii <u>increase</u> from lower left to upper right corner.

The Hertzsprung-Russell (H-R) diagram



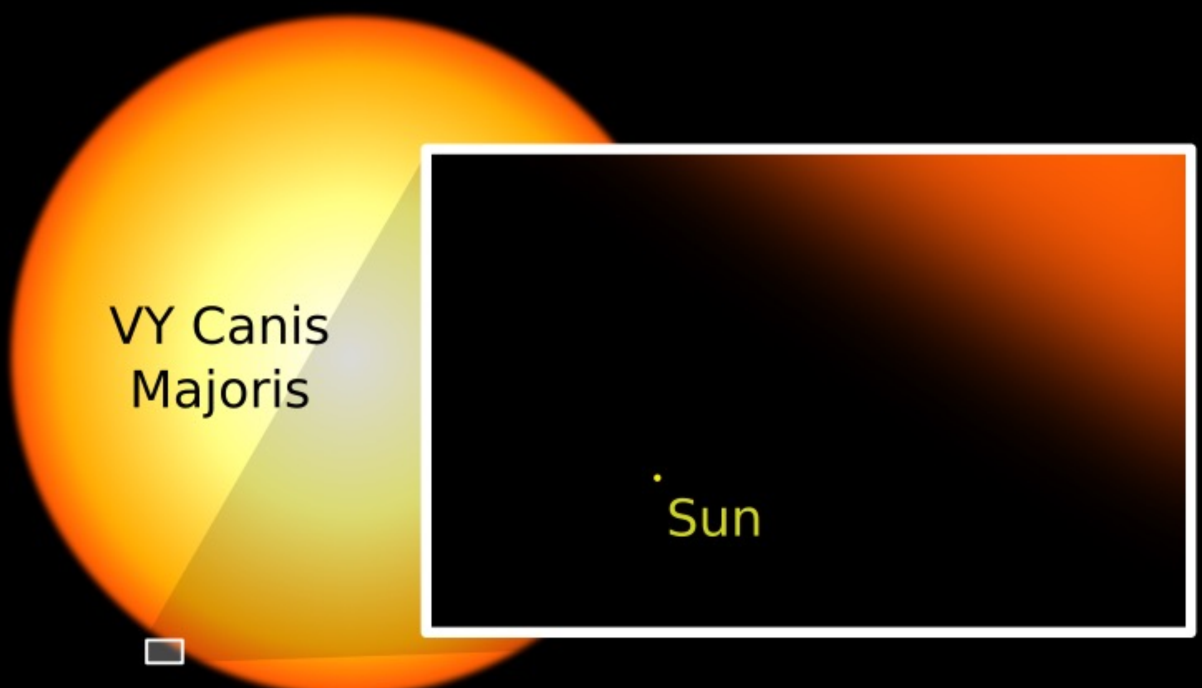
Notice:
Luminosity grows both with <u>temperature</u> and <u>size</u> of the star!

Stellar sizes

Just how big can stars get?

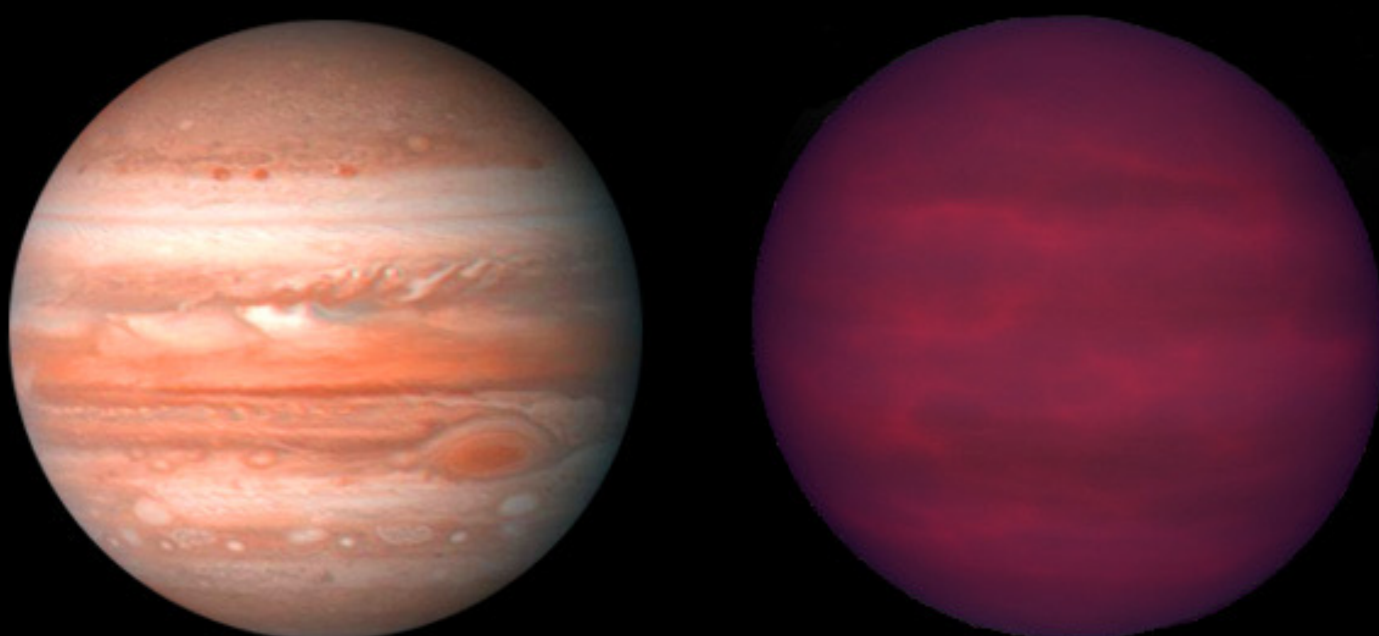
How big and how small?

- In the movie, we saw stars ≥ 10 AU in radius.
- We used to think that stars with masses more than 150 - 200 times the mass of the Sun should blow apart, as the rate of fusion is too great. But, we've found stars that may be up to **300 times the mass of our Sun!**



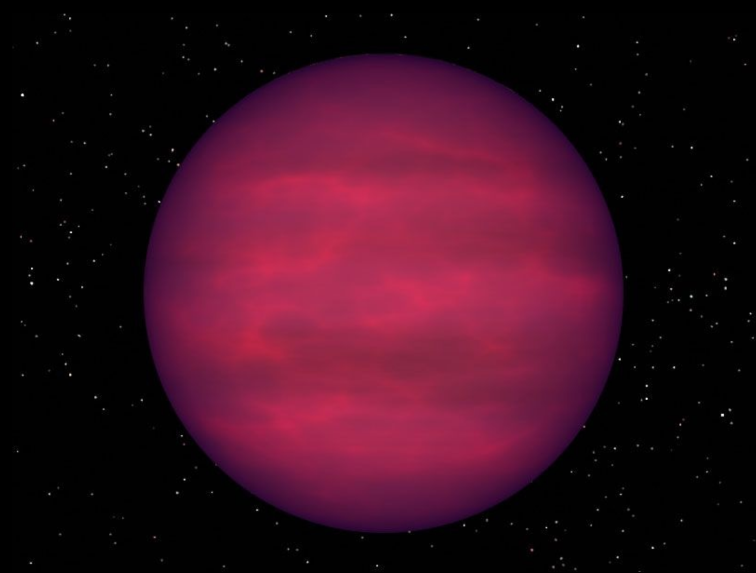
How big and how small?

- If a star is less massive than 8% the mass of the Sun ($50\ M_{JUP}$), it's not large enough to sustain hydrogen fusion, and ends up as a **brown dwarf**.
- Brown dwarfs with masses $5\ M_{JUP}$ to $40\ M_{JUP}$ will have approximately the same size as Jupiter.



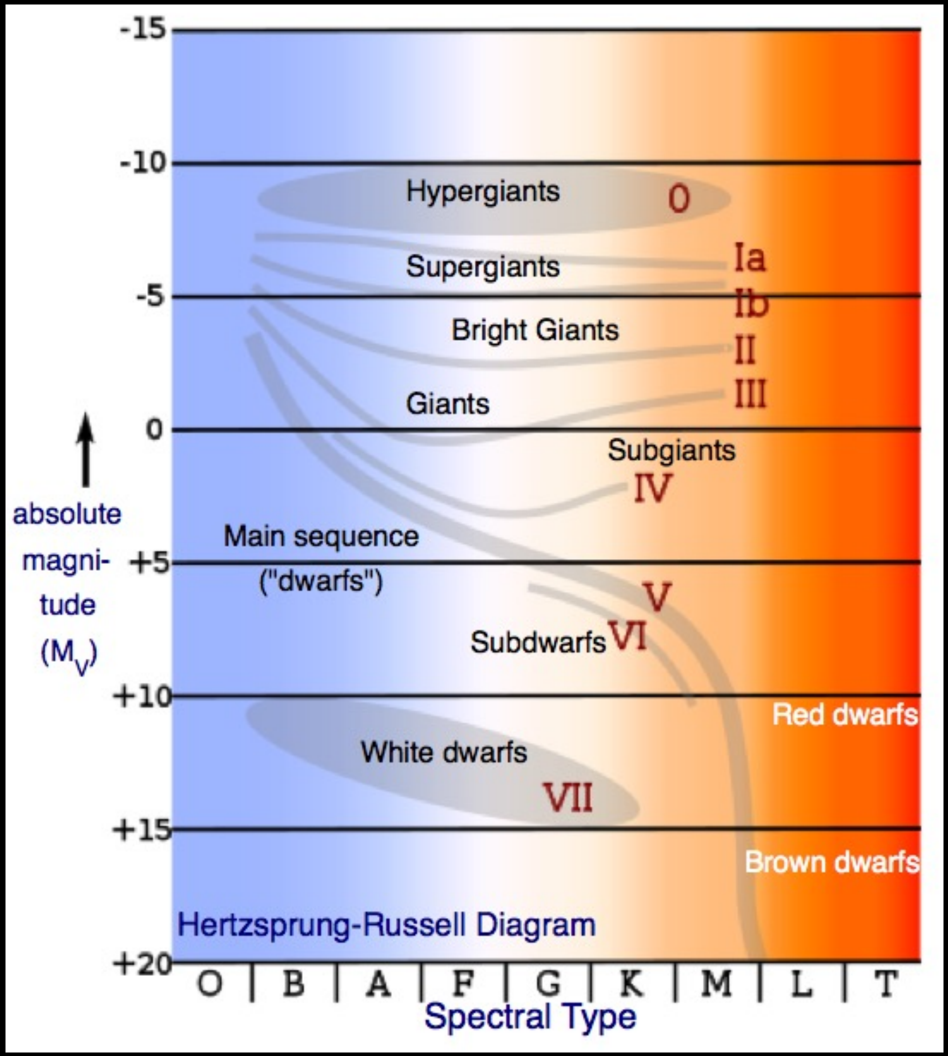
Brown Dwarfs

- Brown dwarfs larger than 13 M_{JUP} can **ignite deuterium** (heavy hydrogen) to obtain a modest amount of energy output.
- Three new spectral classes, (L, T, Y) were created to account for spectra observed from cool red and brown dwarfs.
- The coolest brown dwarfs' surfaces are at room temperature!
- Their cores are supported by electron degeneracy pressure.

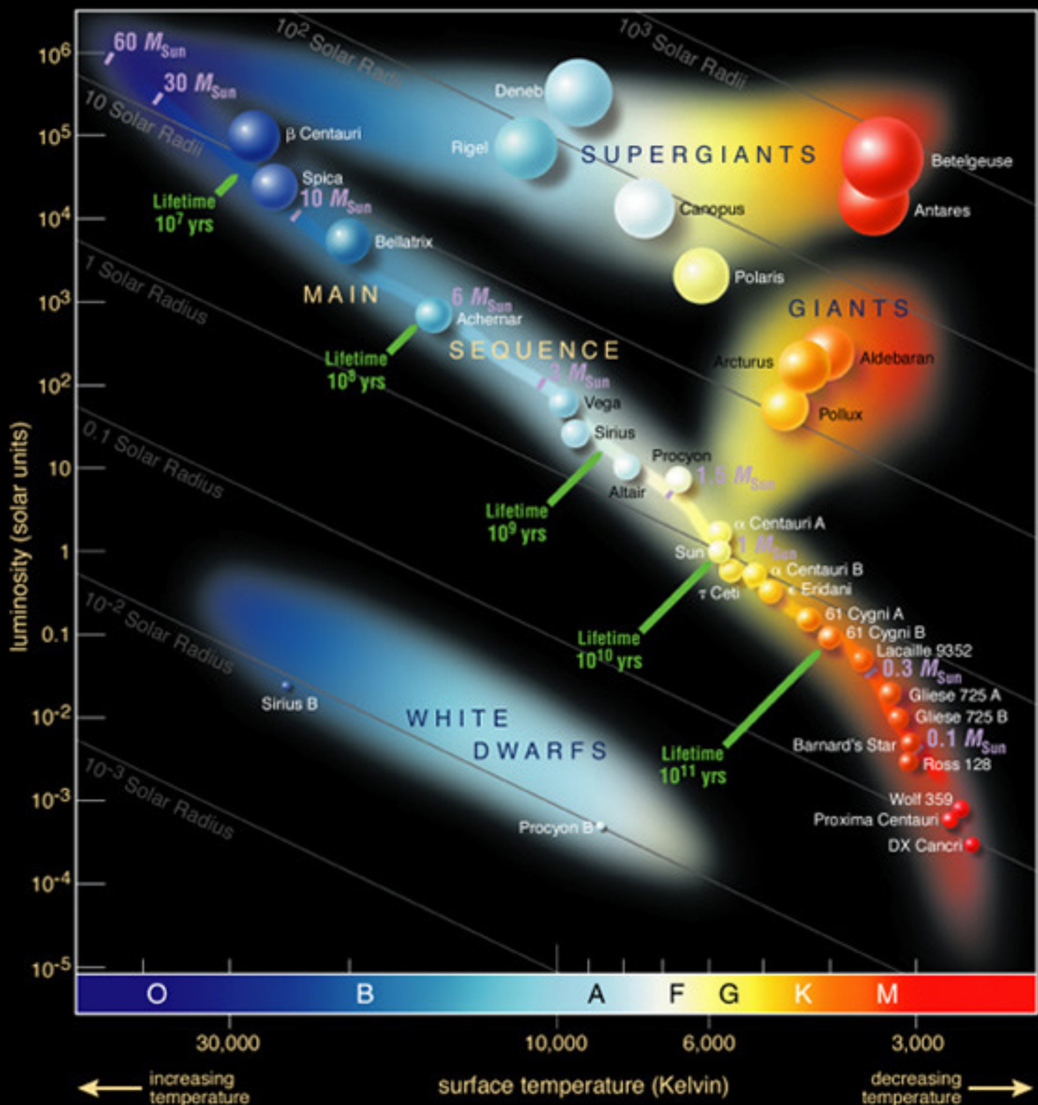


The Hertzsprung-Russell (H-R) diagram

- 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



Stellar masses

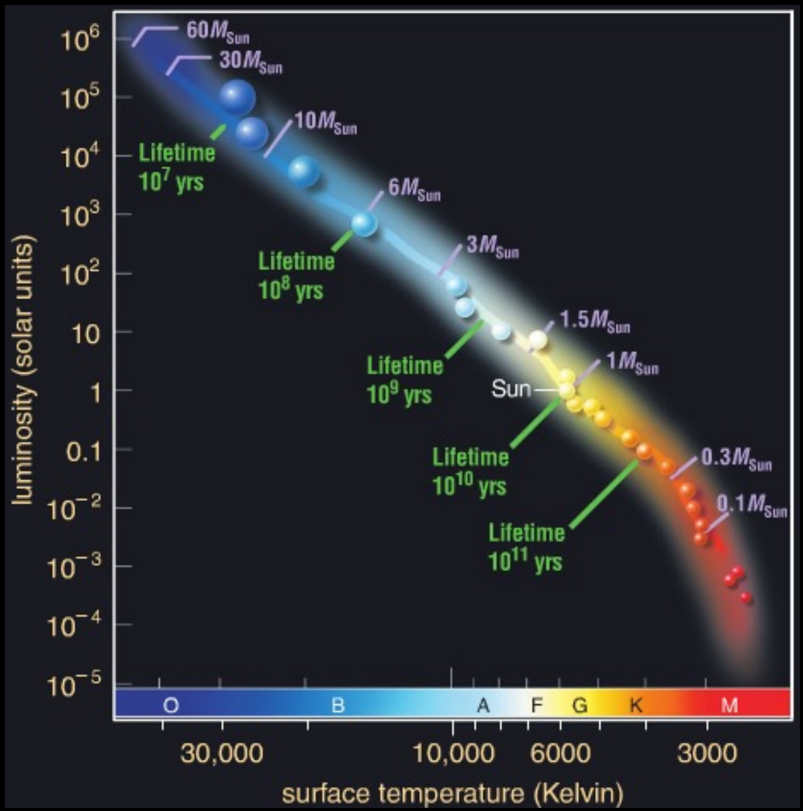


There is a relationship between mass and luminosity for Main Sequence stars.

Bigger (more massive) is brighter and hotter!

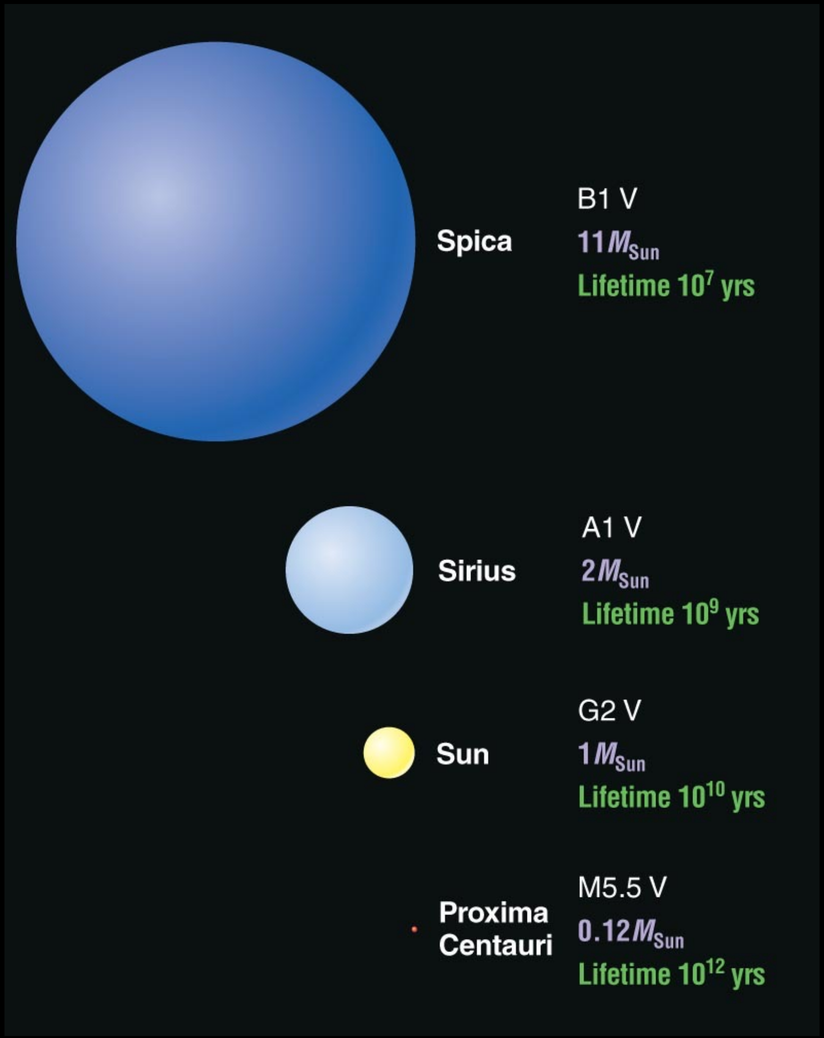
Mass and lifetime of stars

- Mass and lifetime go hand-in-hand: the higher the mass, the shorter the lifetime of the star!
- Divide mass by luminosity (in solar units) to obtain lifetime (in solar units).
- The Sun is halfway through its 10 billion year lifetime.



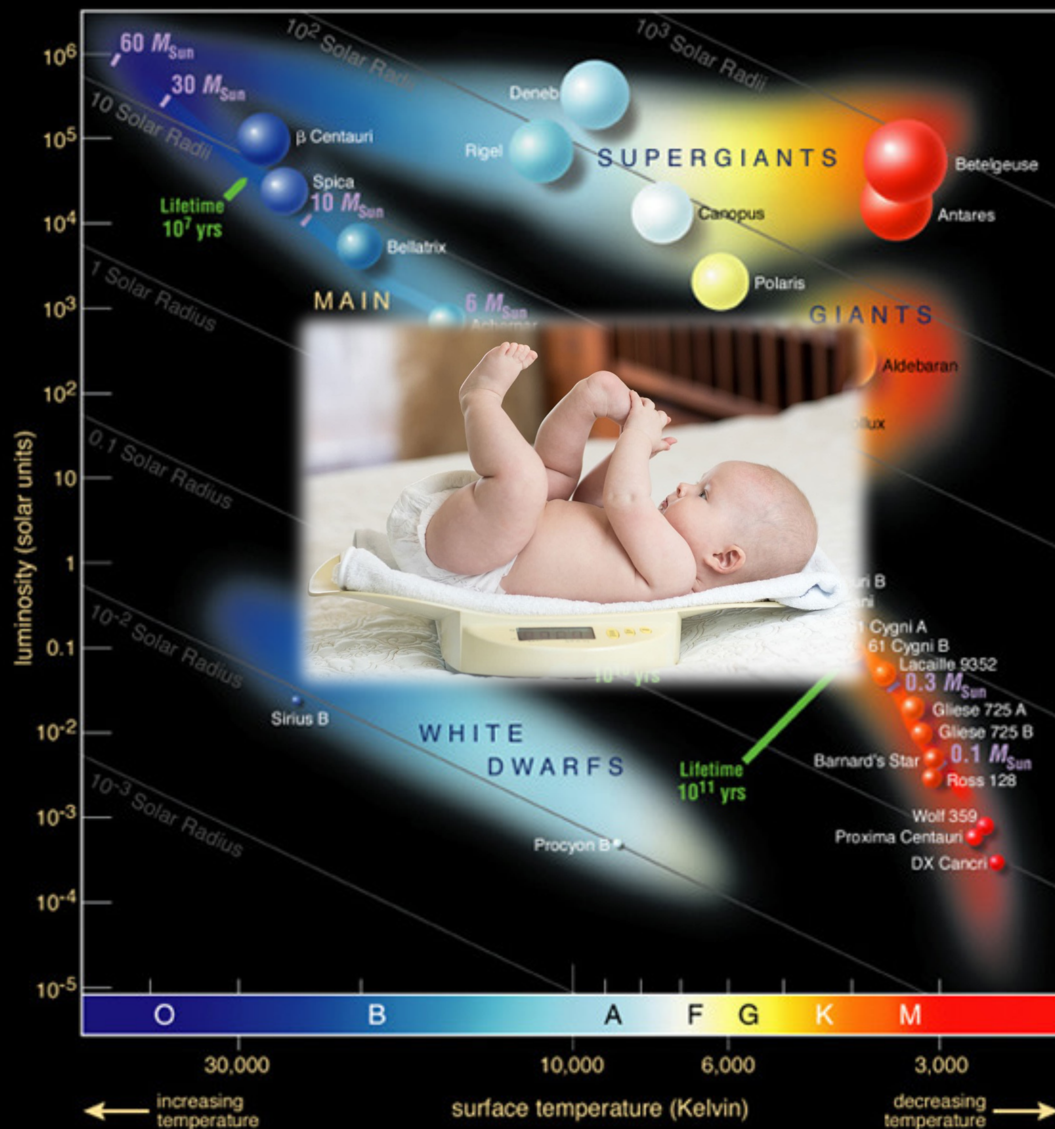
Mass and Lifetime of Stars

- A star with twice the mass of the Sun (Sirius) has a lifetime of 1 billion years, or one tenth the lifetime of the Sun.
- A star with more than 10 times the mass of the Sun (Spica) has a lifetime of only 10 million years (1000 times shorter than the Sun!).



Recap

- **HR diagram** shows the luminosity vs. color of stars.
- Finding the luminosity of stars isn't trivial: we need to know their apparent brightness AND their distance.
- Luminosity of stars, and their lifetime, is determined by the **mass** they are born with.



question for you

Star Alpha has an apparent magnitude of +1.1 and an absolute magnitude of +1.1. Star Beta has an apparent magnitude of +3.72 and an absolute magnitude of +6.1. If both are main sequence stars, which star is hotter?

A. Alpha
B. Beta
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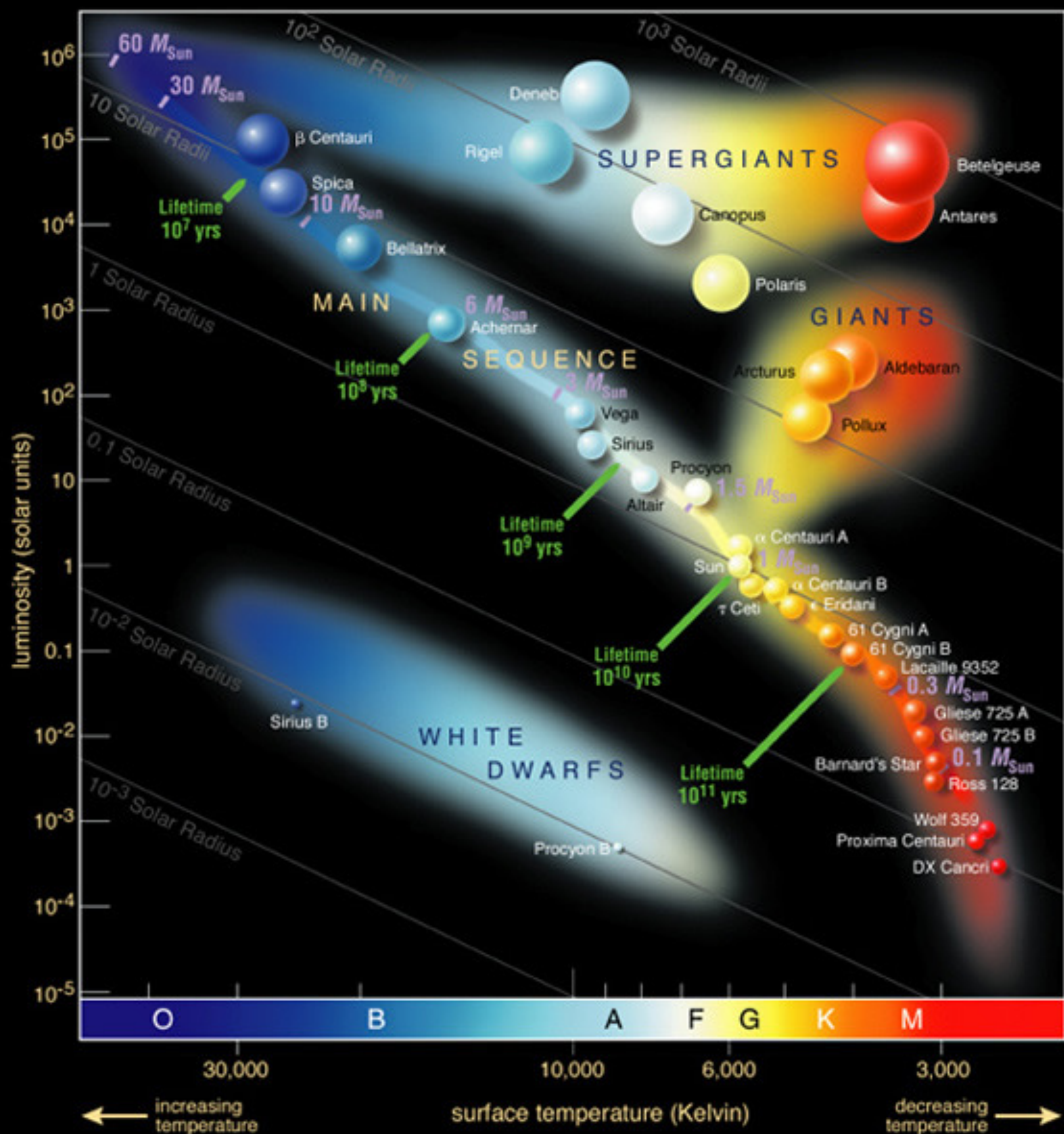
HR diagram

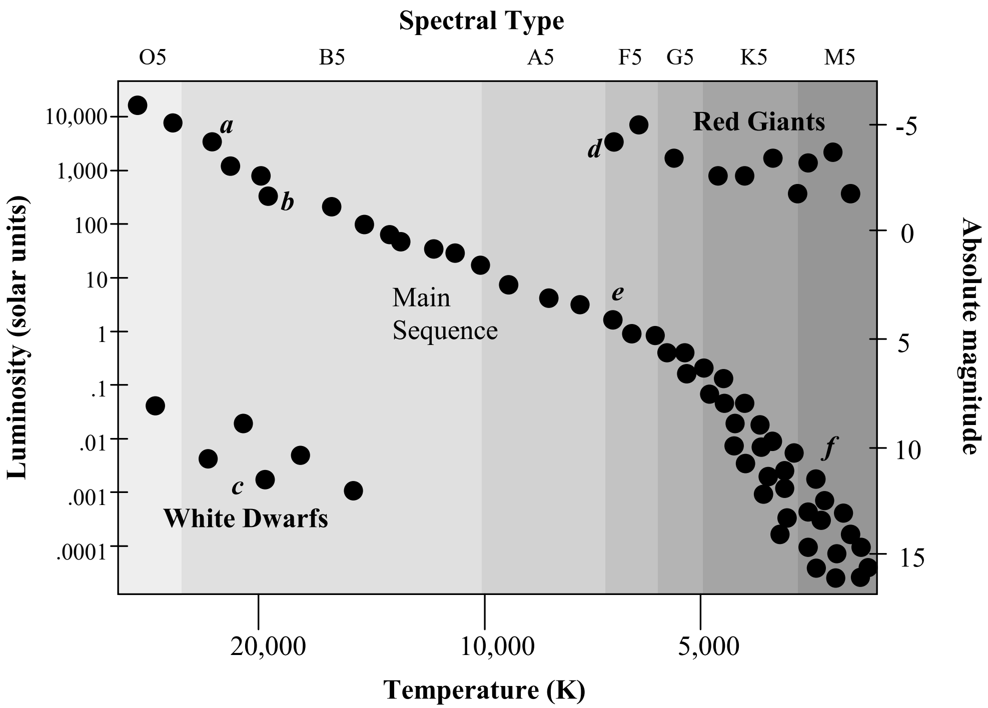


luminosity (solar units)
surface temperature (Kelvin)
increasing temperature
decreasing temperature
SUPERGIANTS
GIANTS
MAIN
SEQUENCE
WHITE
DWARFS
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
Deneb
Rigel
Betelgeuse
Antares
Canopus
Polaris
Arcturus
Aldebaran
Pollux
β Centauri
Spica
Bellatrix
Achernar
Vega
Sirius
Procyon
Altair
α Centauri A
Sun
α Centauri B
τ Ceti
ε Eridani
61 Cygni A
61 Cygni B
Lacaille 9352
Gliese 725 A
Gliese 725 B
Barnard's Star
Ross 128
Wolf 359
Proxima Centauri
DX Cancri
Sirius B
Procyon B
10 Solar Radii
1 Solar Radius
0.1 Solar Radius

question for you

How does the size of a star near the top left of the H-R diagram compare with a star of the same luminosity near the top right of the H-R diagram?

A. They are the same size.
B. The star near the top left is larger.
C. The star near the top right is larger.
D. There is insufficient information to determine this.



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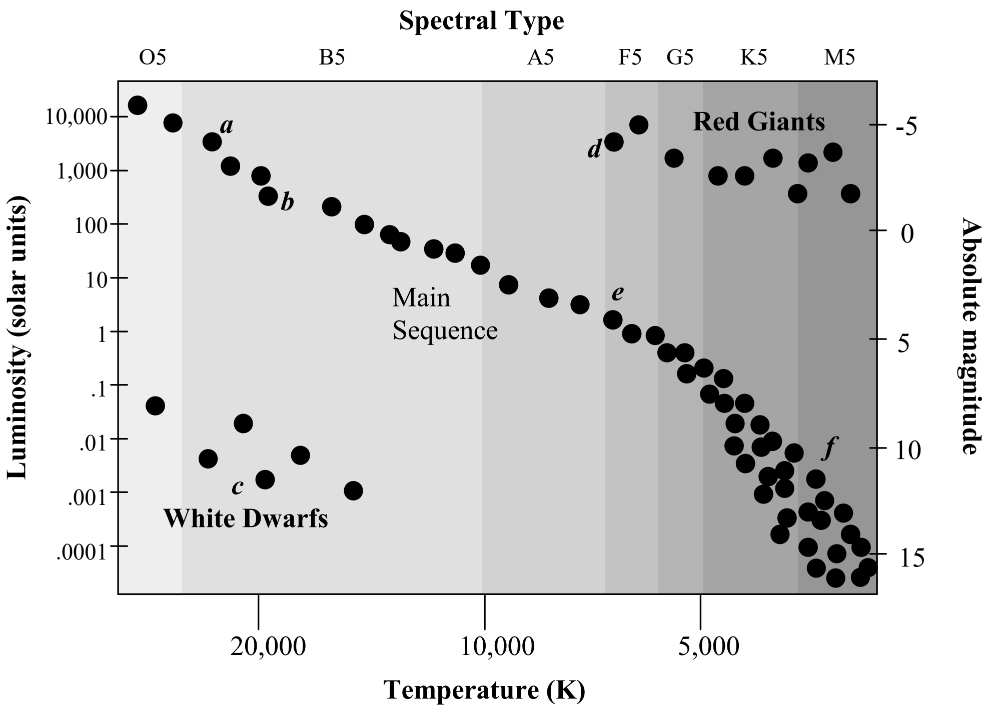

question for you

The star Rigel is about 100,000 times brighter than the Sun and belongs to spectral type B8. The star Sirius B is about 3000 times dimmer than the Sun and also belongs to spectral type B8. Which star has the greatest surface temperature?

A. Rigel
B. Sirius B
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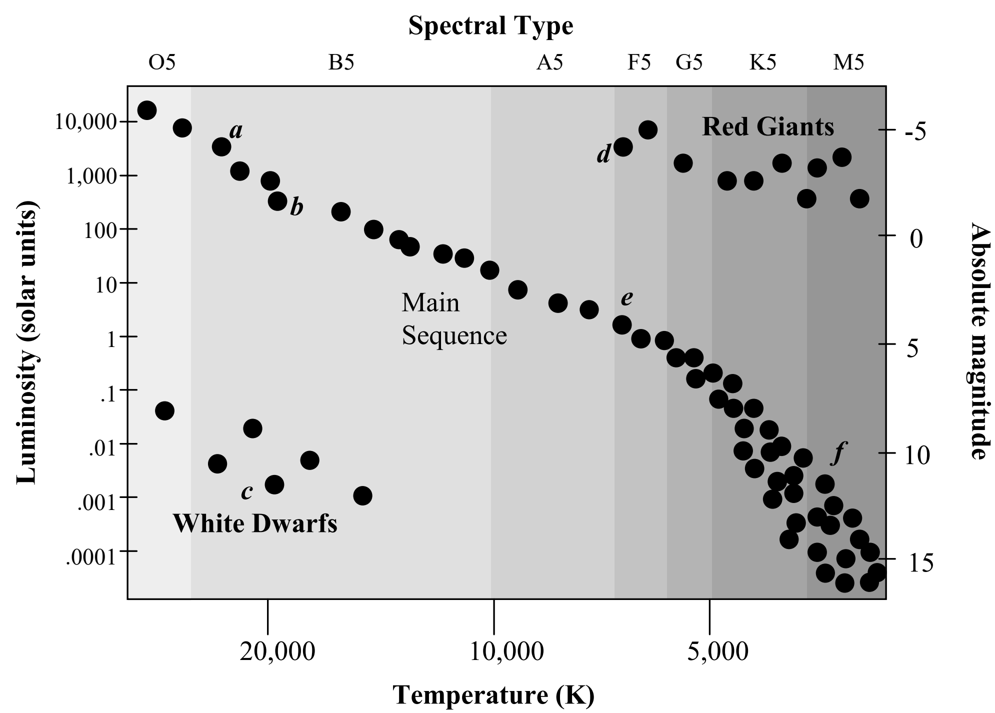

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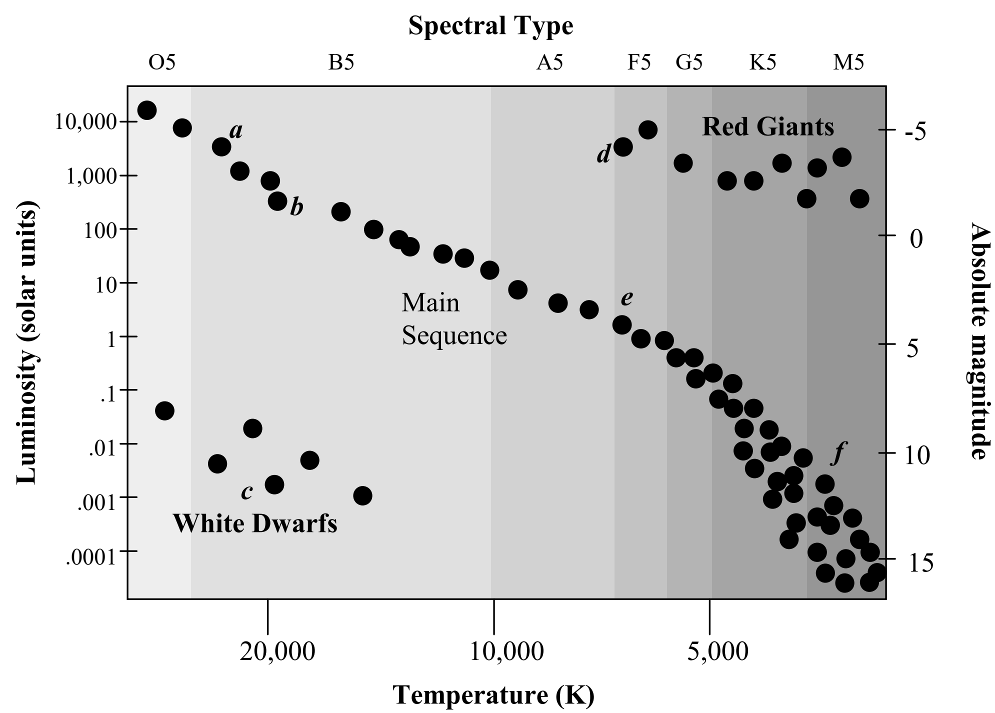

What did we learn in Chapter 9?

- A star's luminosity is the amount of power it generates (which is equal to the amount of power it radiates to space).
- Apparent brightness is how bright we perceive a star to be, and can be affected by both the star's luminosity and its distance from us.
- The magnitude system in use today was first devised by Hipparchus, then modified so that each five magnitudes is a factor of 100 change in brightness. Lower (and negative) numbers are brighter objects.
- Absolute magnitude is the brightness of a star if viewed from exactly 10 parsecs away.
- A star's spectral class has three parts:
  - O, B, A, F, G, K, M denotes the spectral class
  - Number 0 – 9 is a subdivision within each class.
  - Roman numeral indicates where the star is in its life cycle.
- Our Sun is spectral class G2V, with V (Roman numeral 5) denoting the main sequence.

What did we learn in Chapter 9?

- The minimum mass for a star is 0.08 times the Sun's mass.
- More and more brown dwarfs are being detected, and may outnumber stars! Three new spectral classes, L, T, and Y have been created for brown dwarfs.
- Brown dwarfs don't collapse under the force of gravity due to electron degeneracy pressure.
- Binary stars are used to find stellar masses, which in turn give us the mass-luminosity relationship.
- The Hertzsprung-Russell (HR) diagram has spectral class (or surface temperature) on the horizontal axis and luminosity (or absolute magnitude) on the vertical axis.
- The HR diagram organizes stars and is useful for determining a star's position in its life cycle and for comparing the radii, masses, and lifetimes of stars.
- The more massive a star, the greater its luminosity, and the shorter its lifetime.