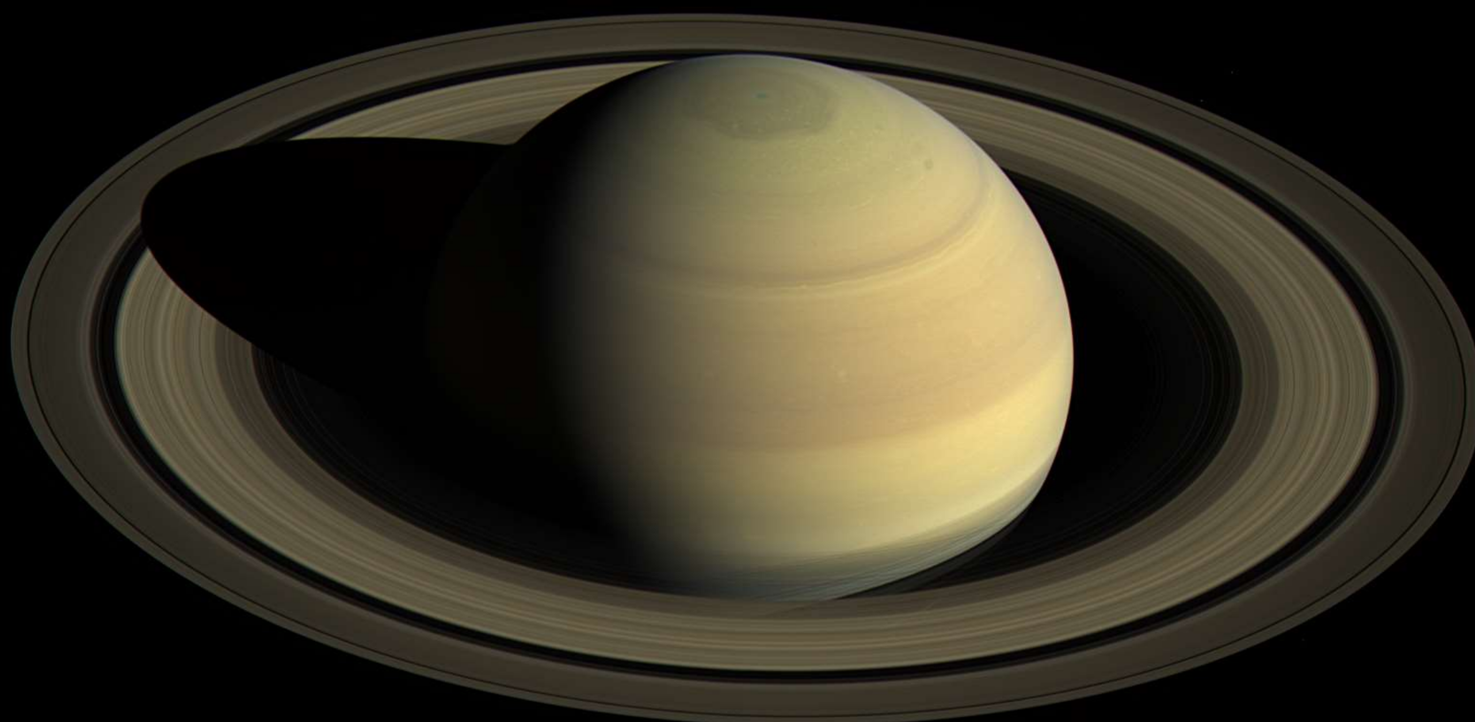
AST 2002
Introduction to Astronomy



A Few Quick Things…

E-mailing me: Must have AST2002 in the subject

Mary Hinkle, Graduate Teaching Assistant:

Office Hours: Mon 1:30-3:00pm. PSB 316

My office hours: Mon 3:00-4:00pm. PSB 308

Tue 3-4 pm. PSB 308

Curved Exam Grades have been Uploaded to Webcourses… this should give a reasonable idea how you are doing in the class… am still uploading extra credit

Scores on Webcourses will not be accurate until near the end of the course. Sorry.

Next Knights Under the Stars Event – Wed 28th Mar 8:30-10:00pm – this Wed

Opportunity to make up the 1% extra credit that was offered (if you haven't been yet, worth 2%) – only 2 more opportunities left (and sometimes doesn't happen!)

What have we covered?

Chapter 11: Our Star

11.1. A Closer Look at the Sun

- Why does the Sun Shine?
- What is the Sun's Structure?

11.2. Nuclear Fusion in the Sun

- How does nuclear fusion occur in the Sun?
- How does the energy from fusion get out of the Sun?
- How do we know what is happening inside the Sun?

11.3. The Sun-Earth Connection

- What causes Solar activity?
- How does solar activity vary with time?

iClicker Question

Which of the following layers of the Sun is the hottest?

A. The convection zone
B. The photosphere
C. The chromosphere
D. The corona
E. The radiation zone

iClicker Question

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A. The convection zone

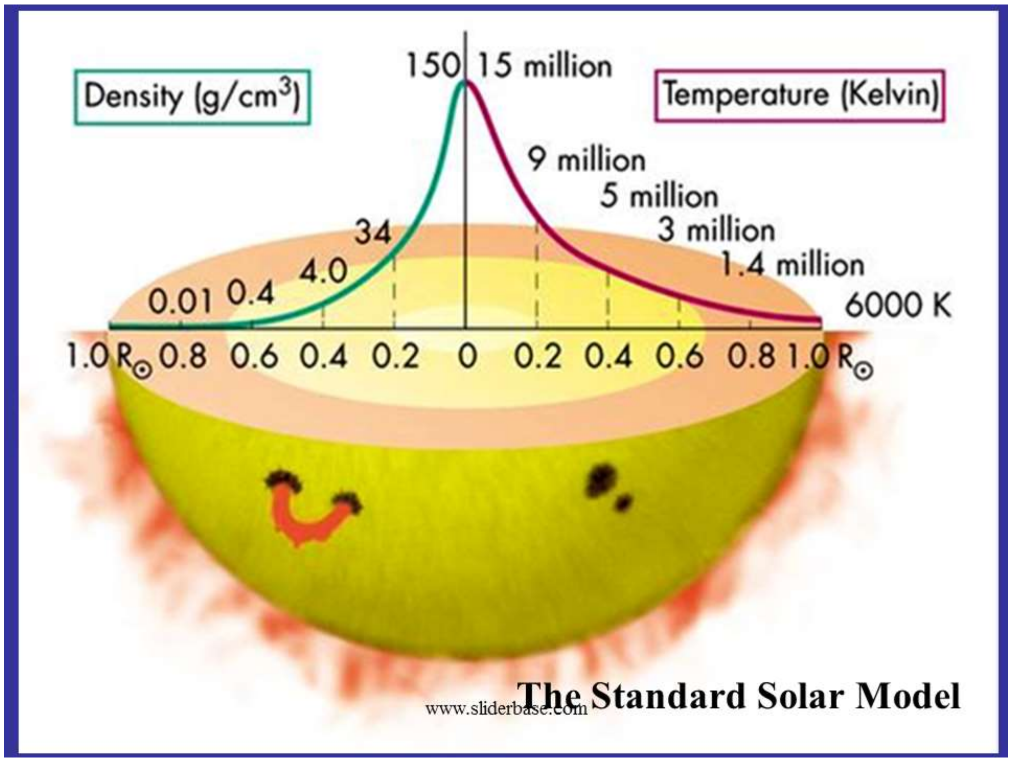
B. The photosphere

C. The chromosphere

D. The corona

E. **The radiation zone**

Pressure and Density of the Sun



Under gravity, the pressure, number density, and temperature will be highest at the Core…

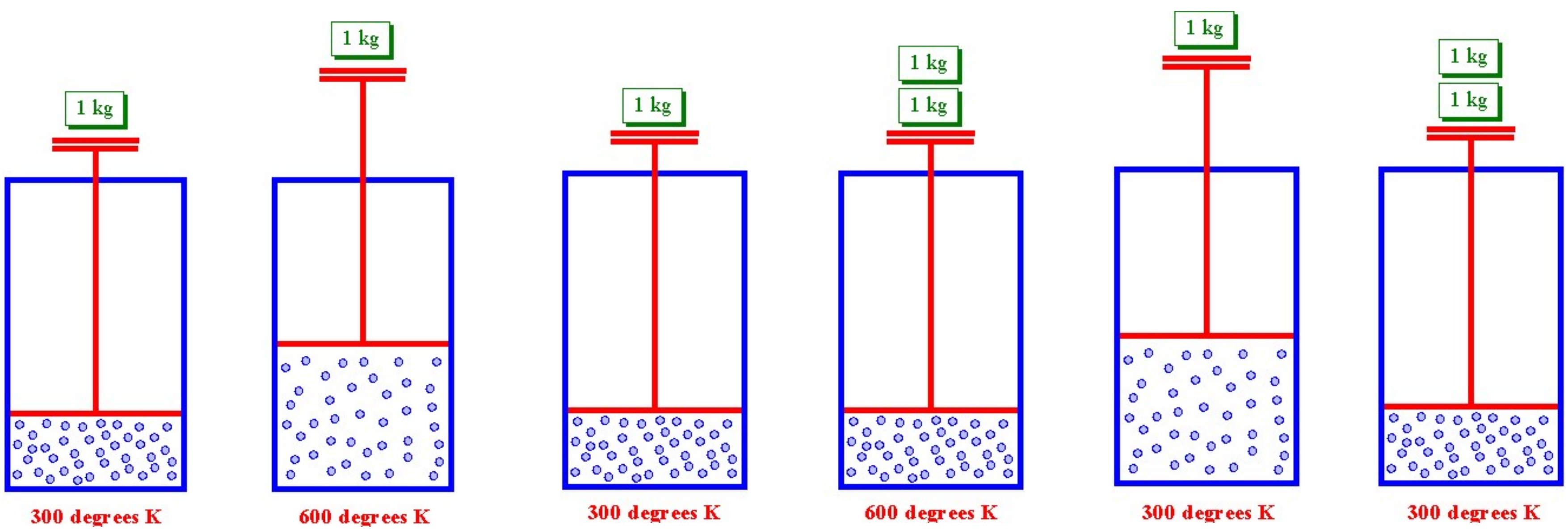
- High pressure and temperature makes fusion possible, and more efficient…
  - More reactions happen per second
  - More chance will have enough velocity to overcome coulombic repulsion
- Fusion outputs energy, generating even more heat
- The heat will generate more pressure…

The Ideal Gas Law

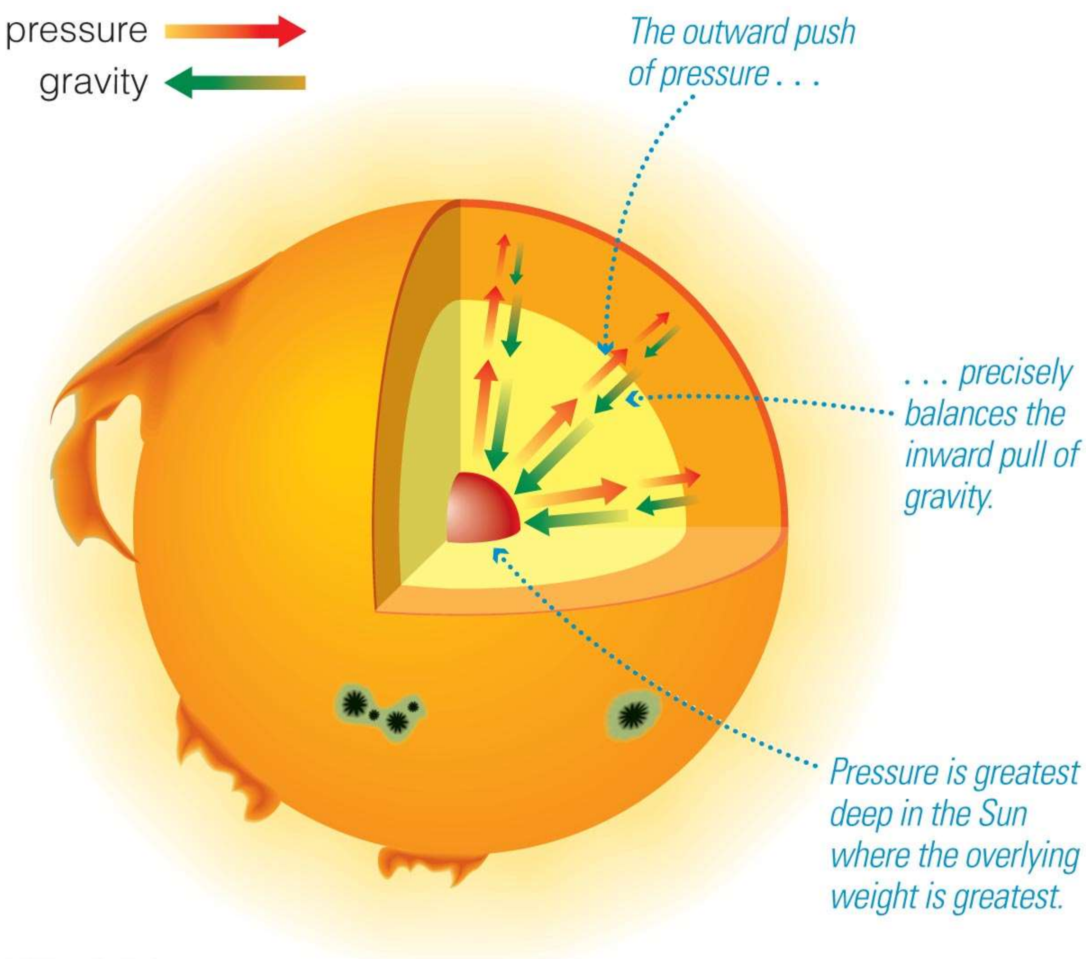
N = number of moles, n = number density
K_B = Boltzmann's constant 1.38 × 10^{-23} J/K
R = Ideal gas constant, 0.082 L atm K^{-1} mol^{-1}

$PV = NRT$ or $\frac{PV}{T} = NR$ $(NR = constant)$ or $\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$ or $P = nk_BT$

- Pressure (P) is related to the force generated by the individual molecules hitting the sides of the walls…
- When the temperature (T) is higher, each atom/molecule is moving faster so hits the walls with more energy, and more frequently, so an increase in temperature results in an increase in pressure
- When the volume (V) is reduced, the atoms/molecules will again hit the walls more frequently, therefore the pressure would be increased.



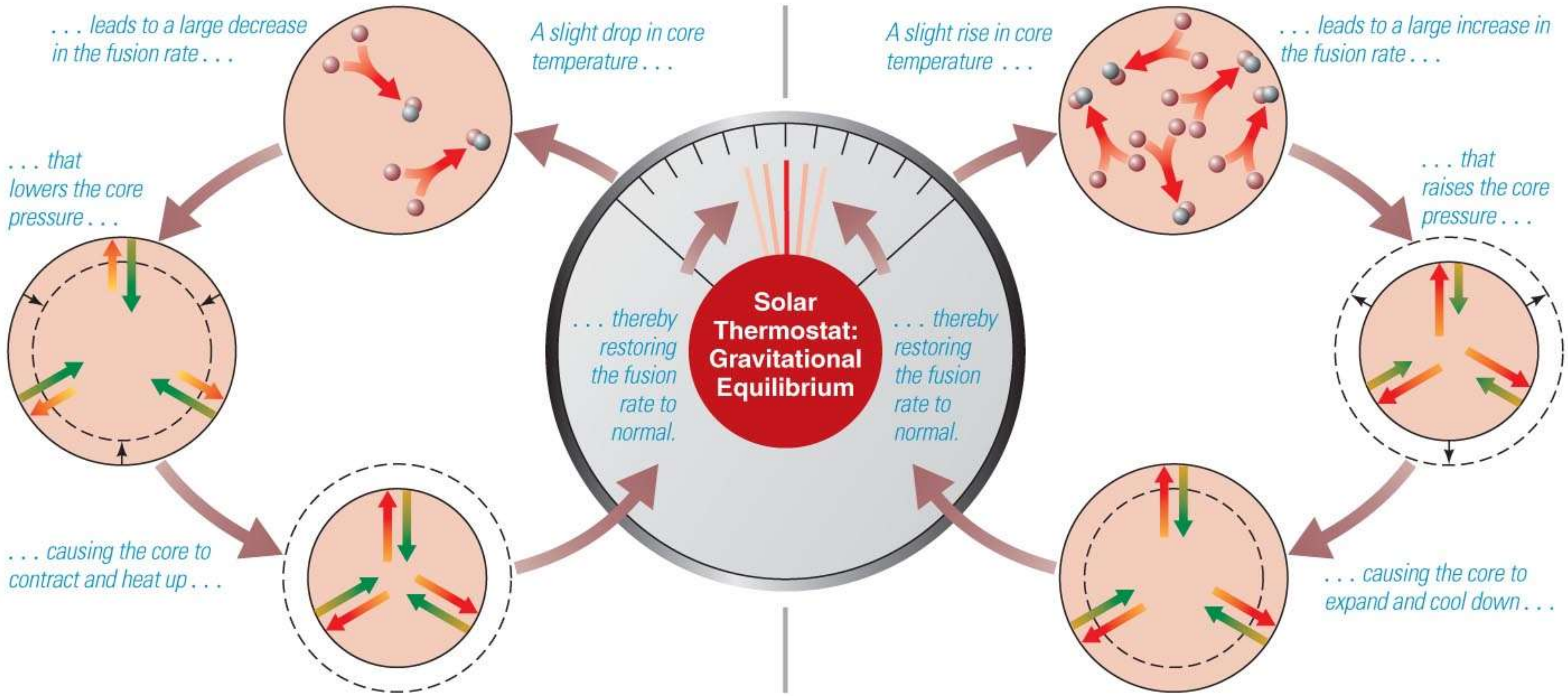
Hydrostatic Equilibrium
(or Gravitational Equilibrium)



Gravitational contraction… provided energy that heated the core as the Sun was forming.

Contraction stopped when fusion started replacing the energy radiated into space.

The Solar Thermostat



Decline in core temperature?

→ Fusion rate in core would drop…

→ Core would contract and heat up

→ Temperature & rate restored…

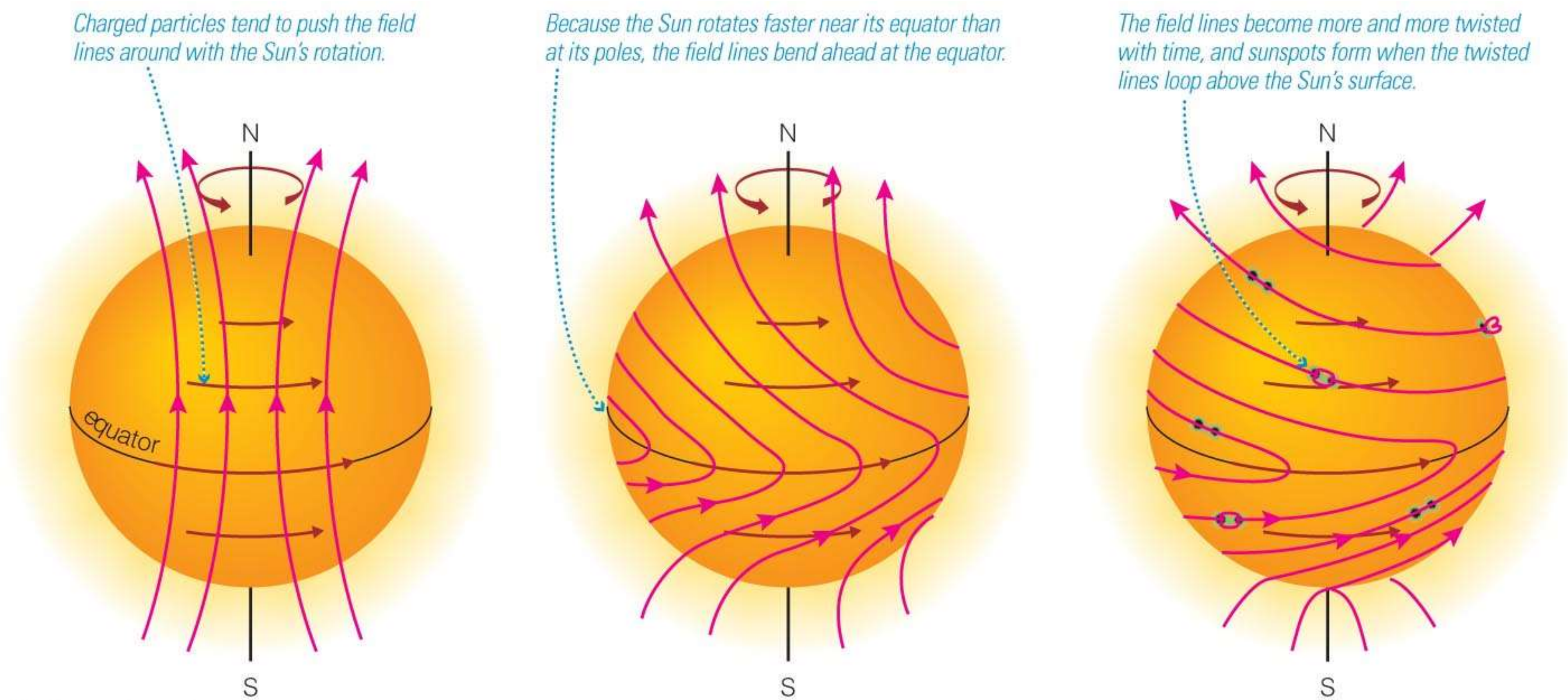
Rise in core temperature?

→ Fusion rate in core would rise

→ core would expand and cool

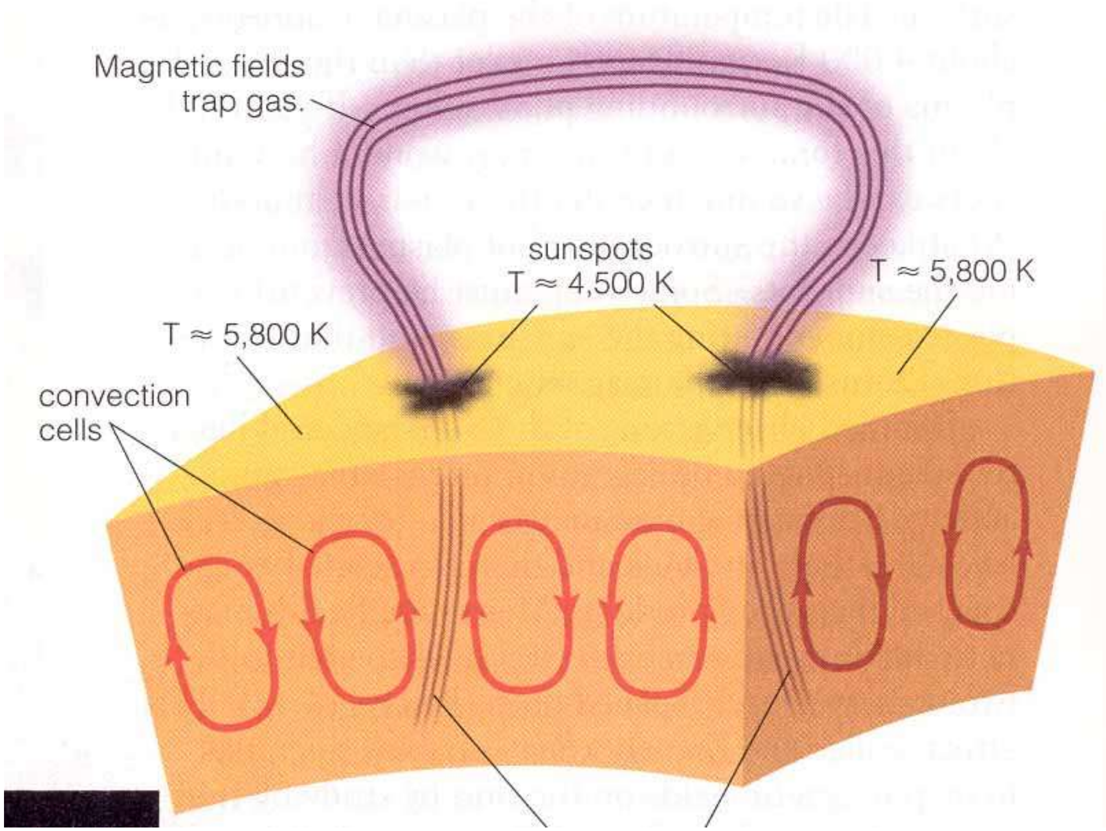
→ Temperature and rate restored

The Suns Differential Rotation



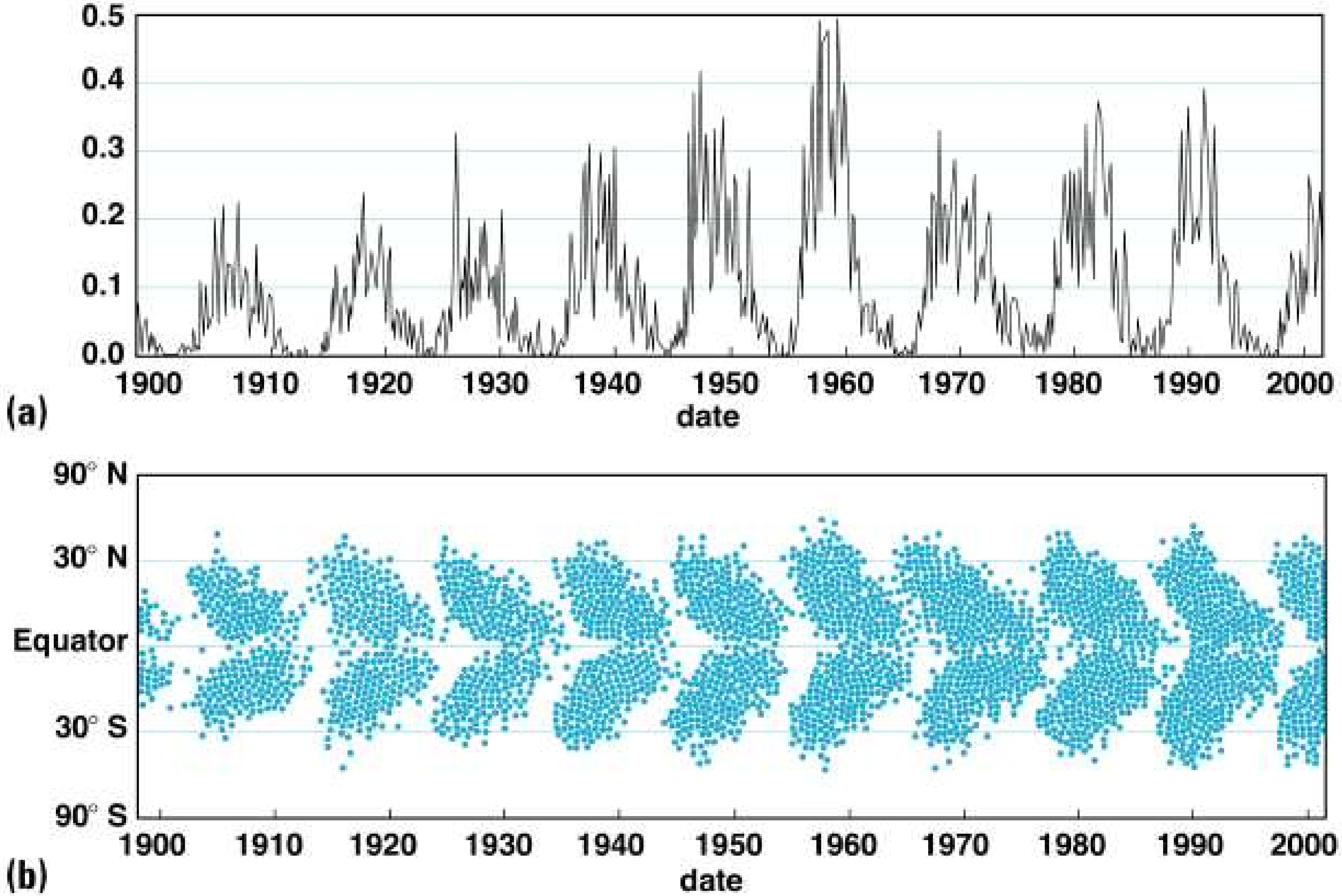
- The Equator rotates every 25 days… the Equator takes 36 days.
- This twists the magnetic field lines more and more throughout an 11-year cycle
- Eventually, the Sun's magnetic field flips (so really it's a 22-year cycle!)

What are sunspots?

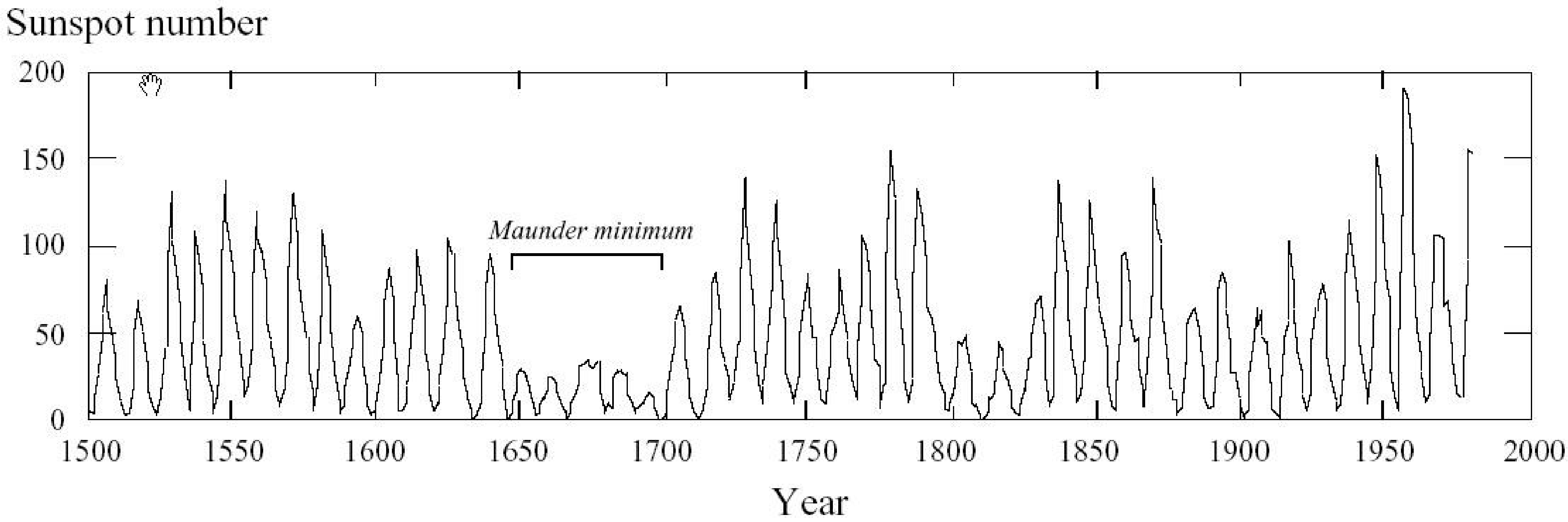


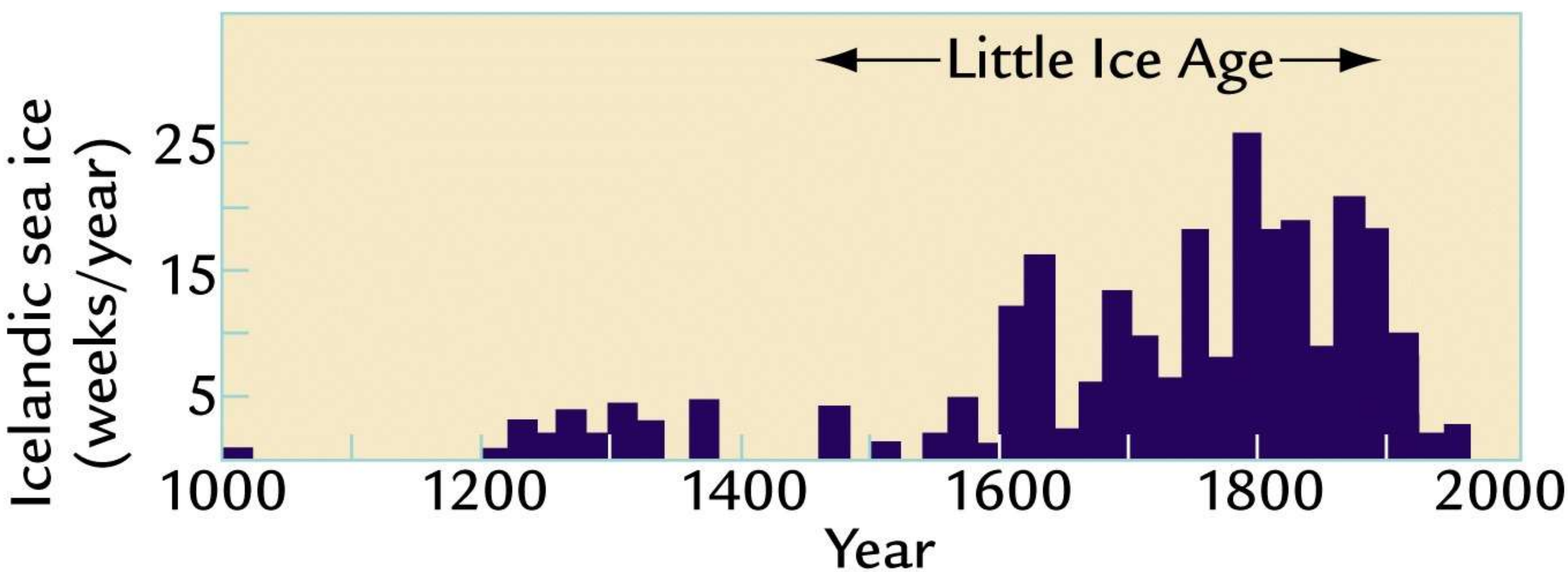
- magnetic field interrupts and slows down convection
- Less heat is transported to surface; so that part of photosphere is cooler (~4000 K *cf.* 5800 K)
- Always appear in pairs…
- More Solar Activity occurs at solar maximum (or shortly after) so seems correlated to Sunspots…

The Sunspot Cycle

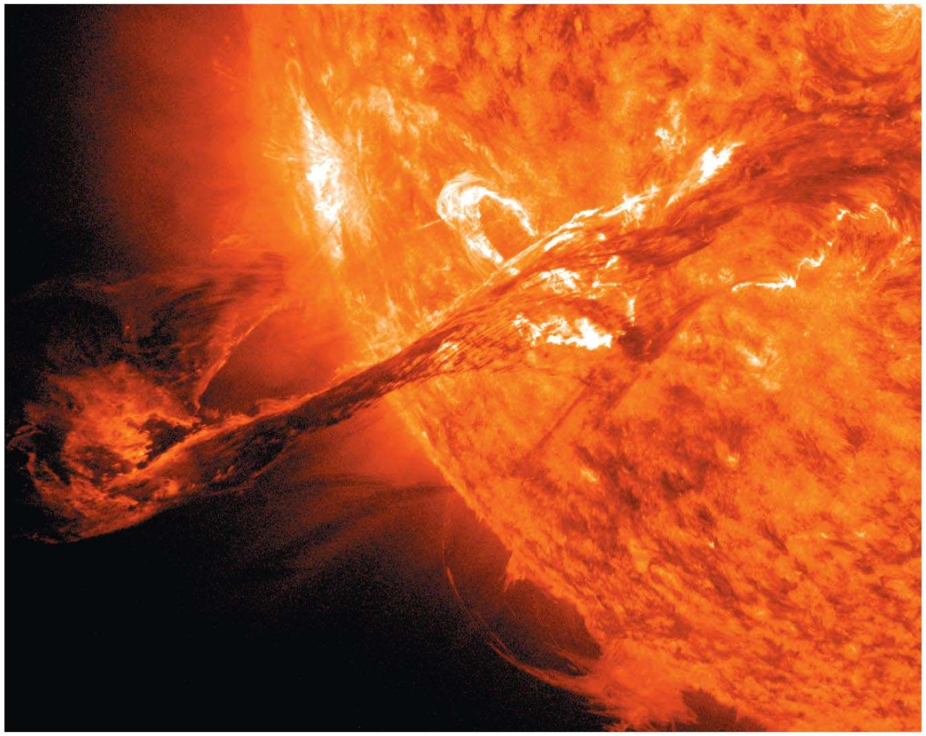


The Butterfly Pattern results because Sunspots appear at higher latitudes early on in the cycle

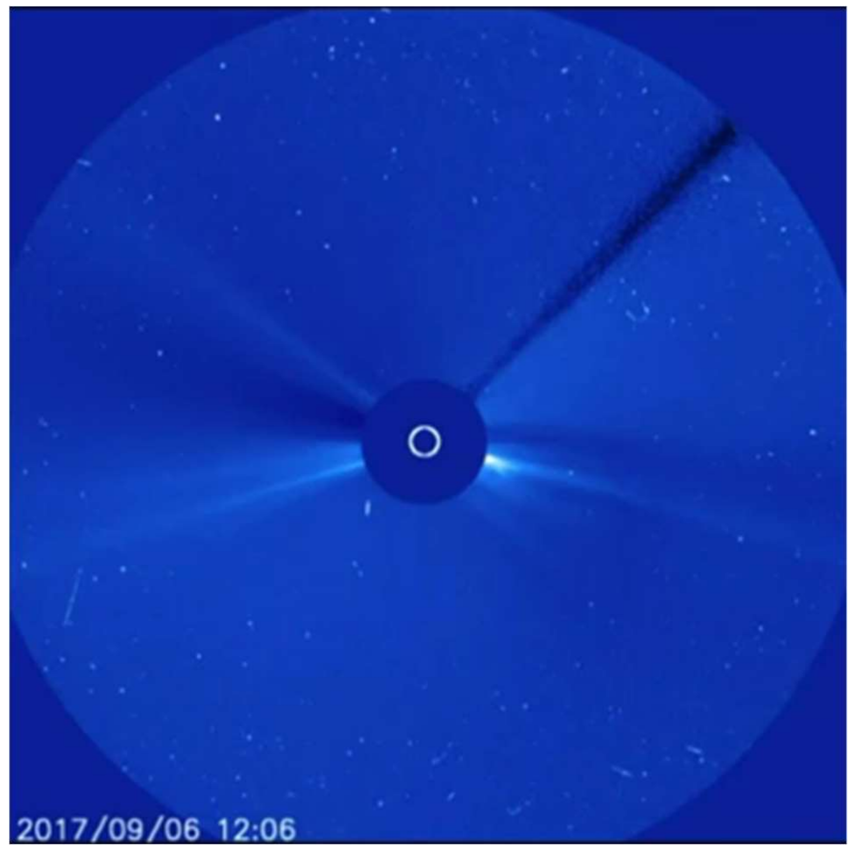

Sunspot number
200
150
100
50
0
Maunder minimum
1500
1550
1600
1650
1700
1750
1800
1850
1900
1950
2000
Year


Little Ice Age
Icelandic sea ice (weeks/year)
25
15
5
1000
1200
1400
1600
1800
2000
Year

Coronal Mass Ejections (CMEs)

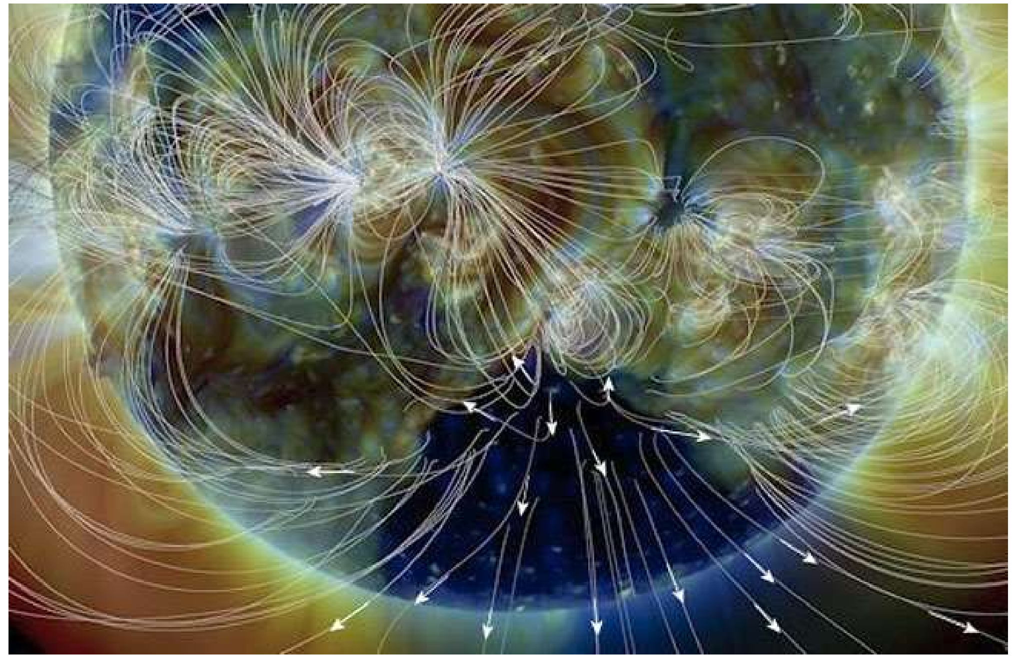


Can occur when a solar Prominence breaks….

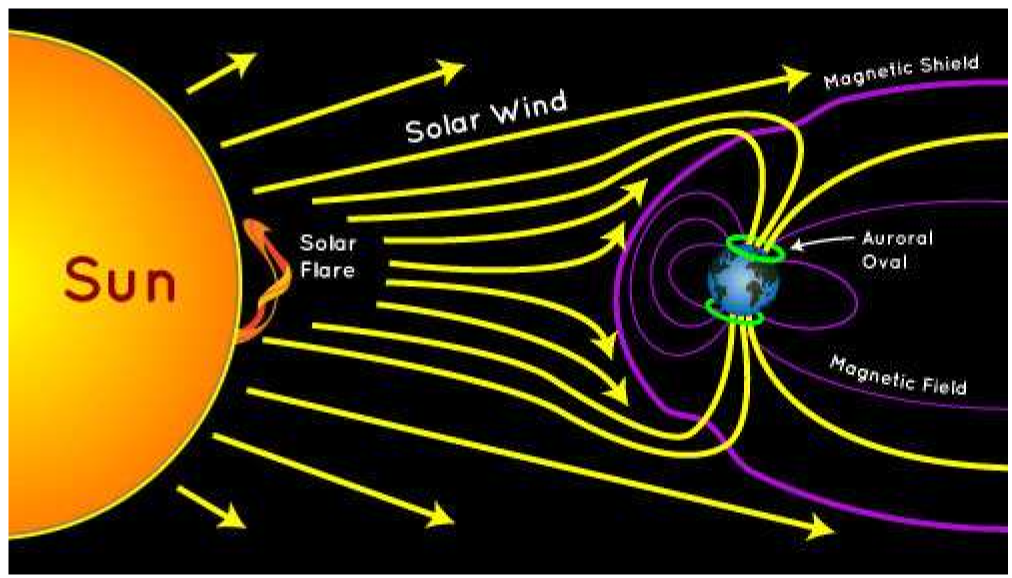


send bursts of energetic charged particles out through the solar system.

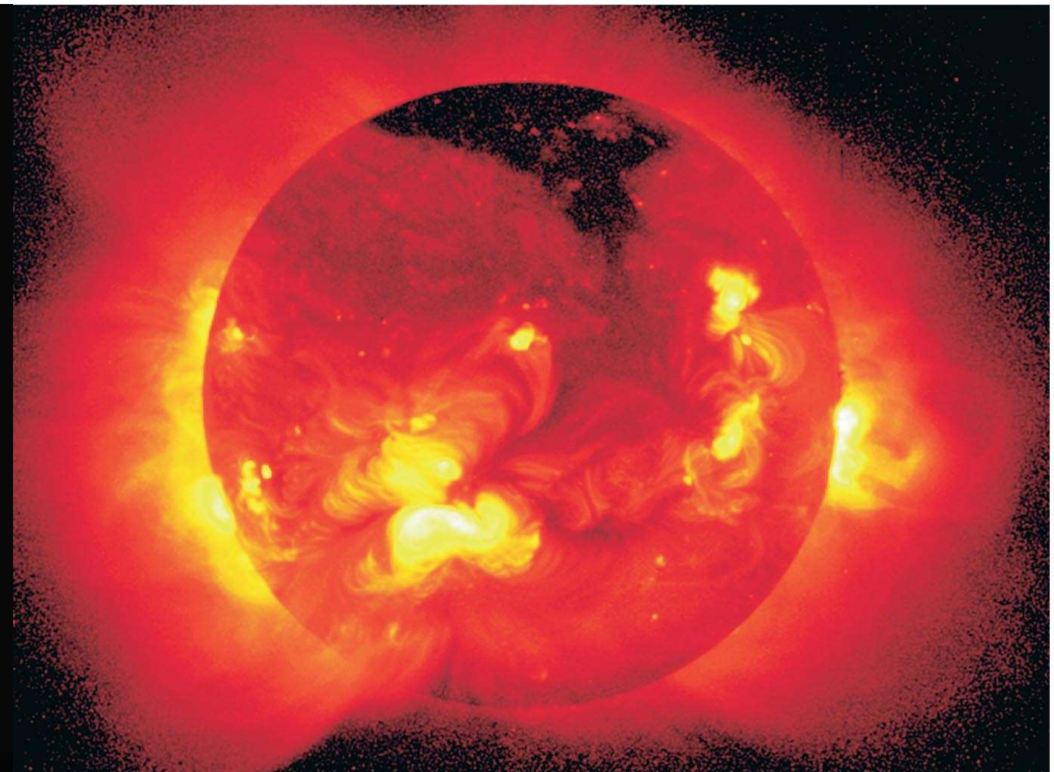
Coronal Holes
&
Solar Wind



- When magnetic field lines break, they release the charged particles into space.
- This so-called **solar wind** escapes through the coronal holes.
- **This is what generates the Aurora's on Earth**



The Solar Corona



- The corona appears bright in X-ray photos in places where magnetic fields trap hot gas.
- Very diffuse, but very hot - ~ 1 million kelvin – source of solar X-rays

iClicker Question

What is the average length of time between consecutive solar maximums?

A. 27 days
B. 8 months
C. 2.5 years
D. 11 years
E. 750 years

iClicker Question

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iClicker Question #2

How much does the total luminosity of the Sun vary between the solar minimum and solar maximum?

A. Less than 0.1%
B. About 1%
C. About 3%
D. About 10%
E. More than 30%

iClicker Question #2

How much does the total luminosity of the Sun vary between the solar minimum and solar maximum?

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What is next?

Chapter 12: Surveying the Stars

12.1. Properties of Stars

- How do we measure stellar luminosities?
- How do we measure stellar temperatures?
- How do we measure stellar masses?

12.2. Patterns Among Stars

- What is the Hertzsprung-Russel diagram?
- What is the significance of the main sequence?
- What are giants, supergiants, and white dwarfs?

12.3. Star Clusters

- What are the two types of star clusters?
- How doe we measure the age of star clusters?

Stellar Diversity

Hubble Space Telescope image of Baede's window towards the galactic center…

Some stars are:

Blue…
White…
Yellow…
Red…

Some stars are:

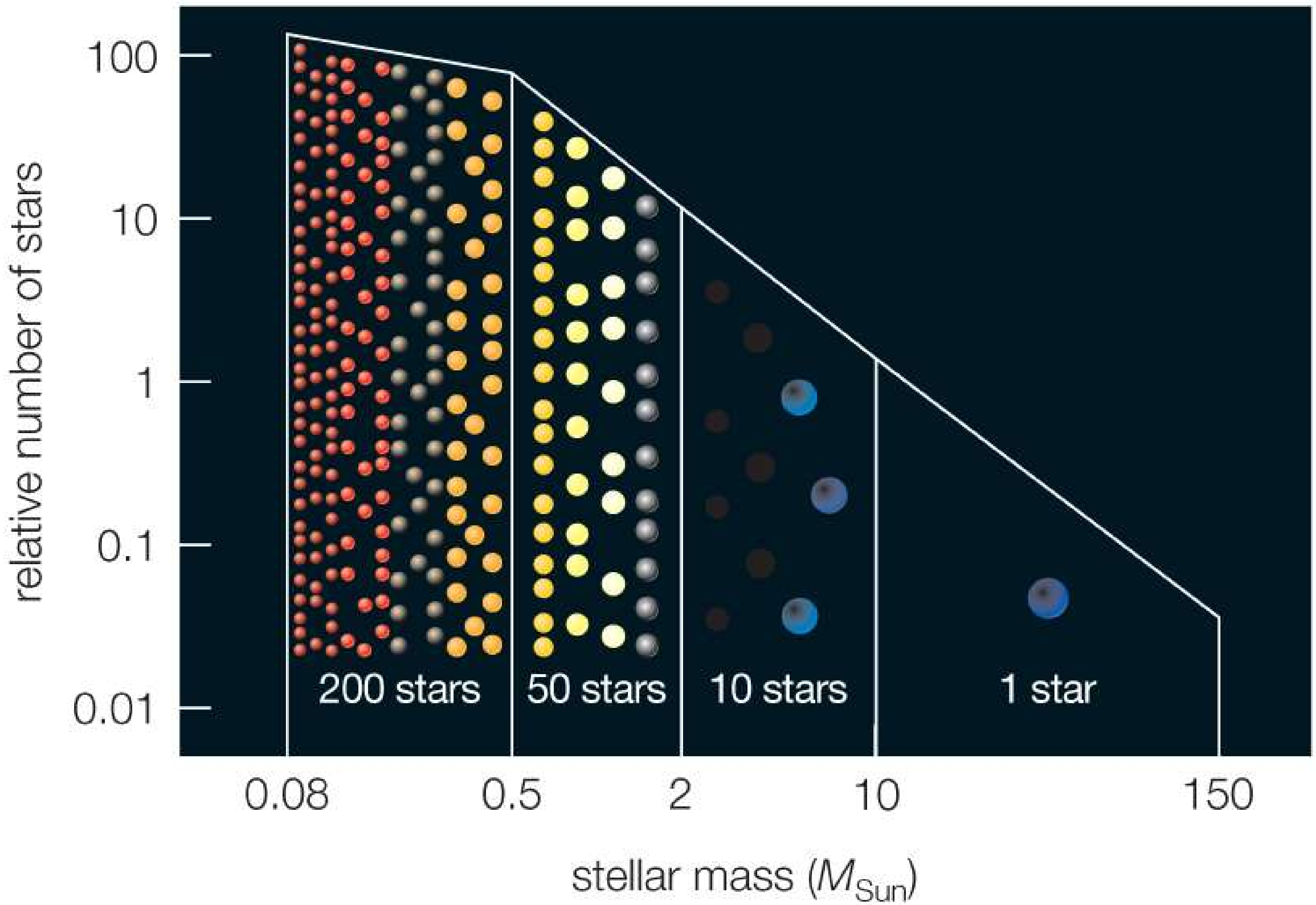
Really bright…
Much dimmer…

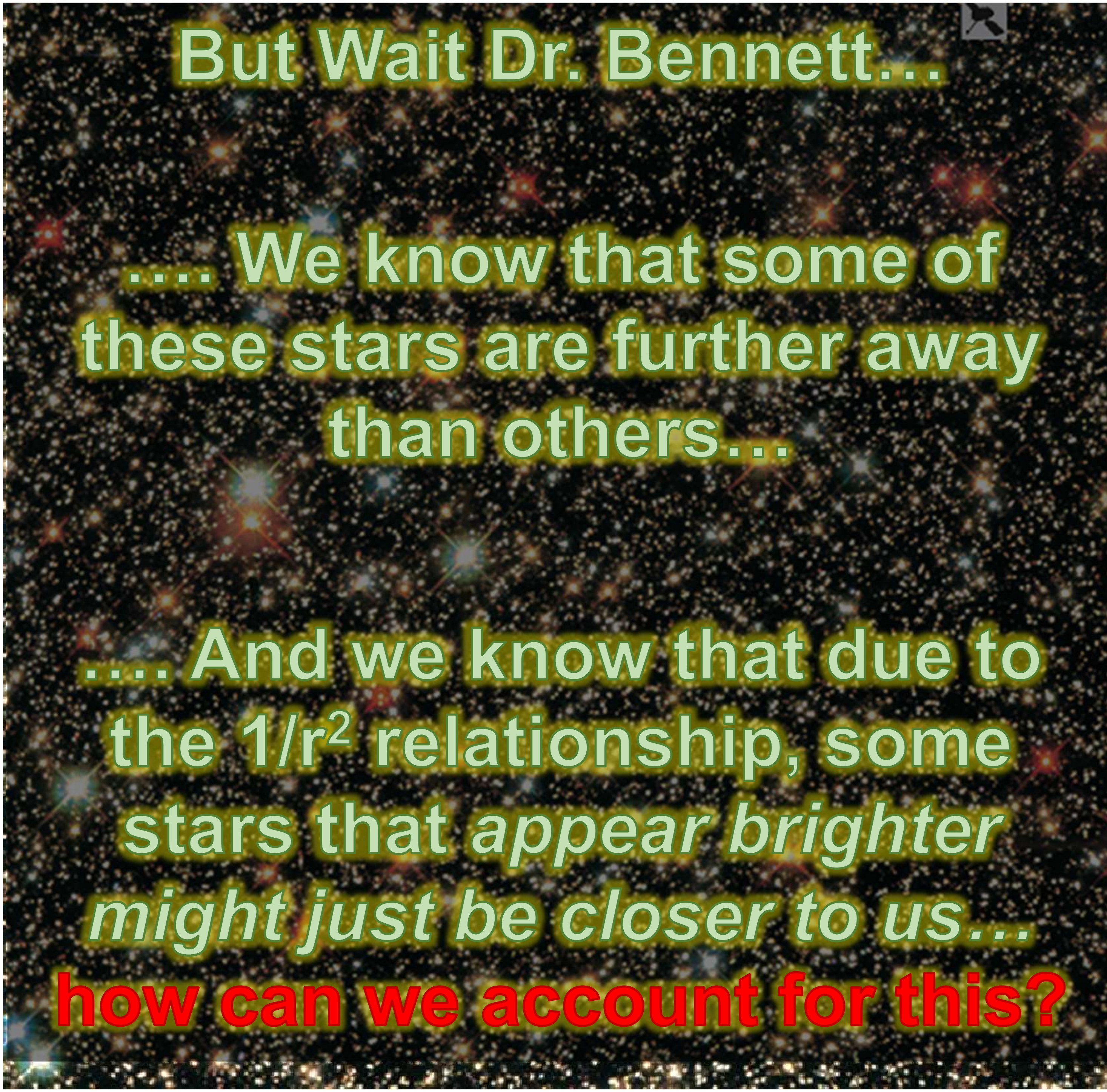
Are there more:

- *blue or red stars?*
- *Brighter or dimmer stars?*

Any dim blue stars?

Stellar Diversity:
Occurrence of Different Colored Stars





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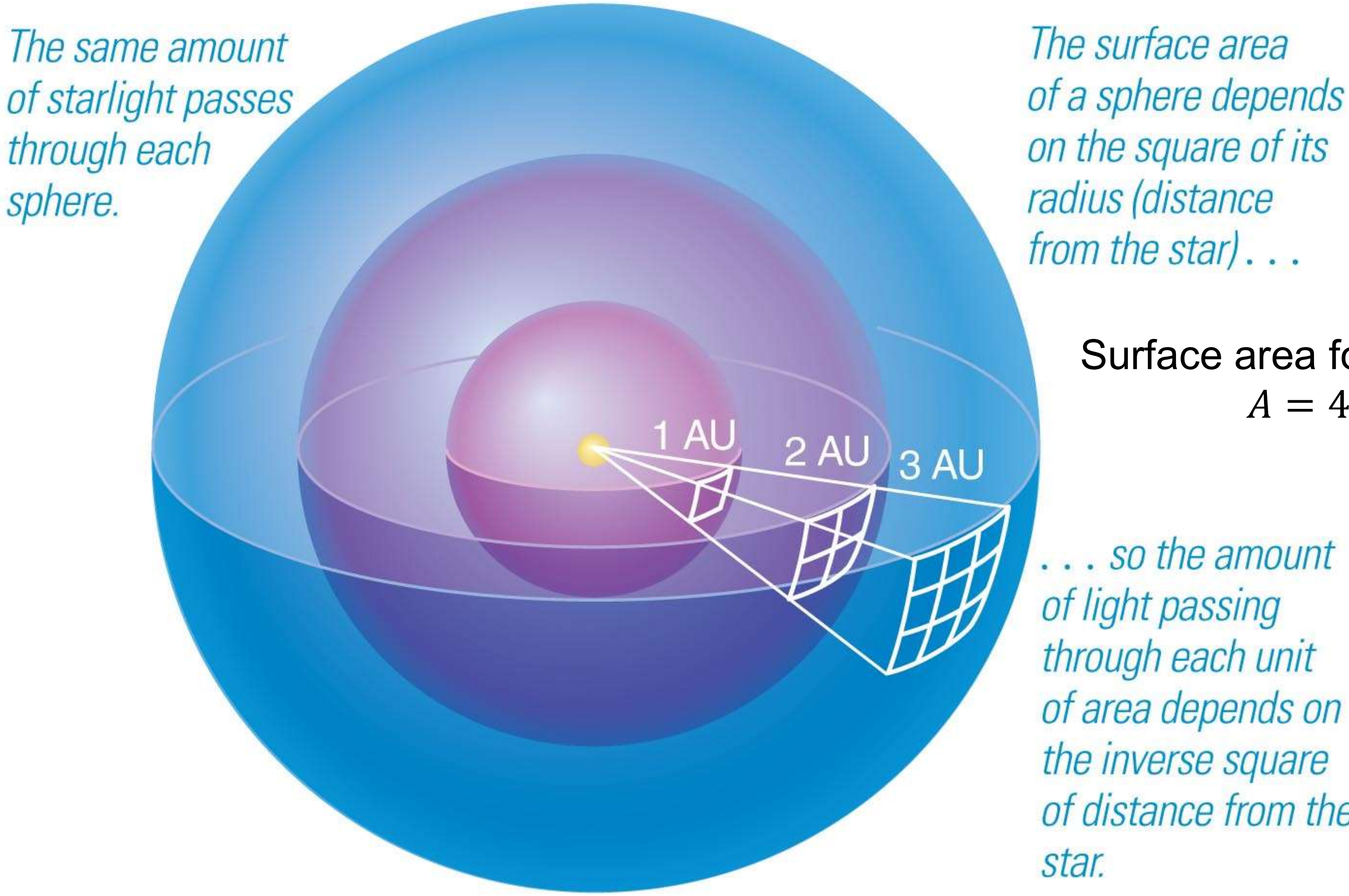
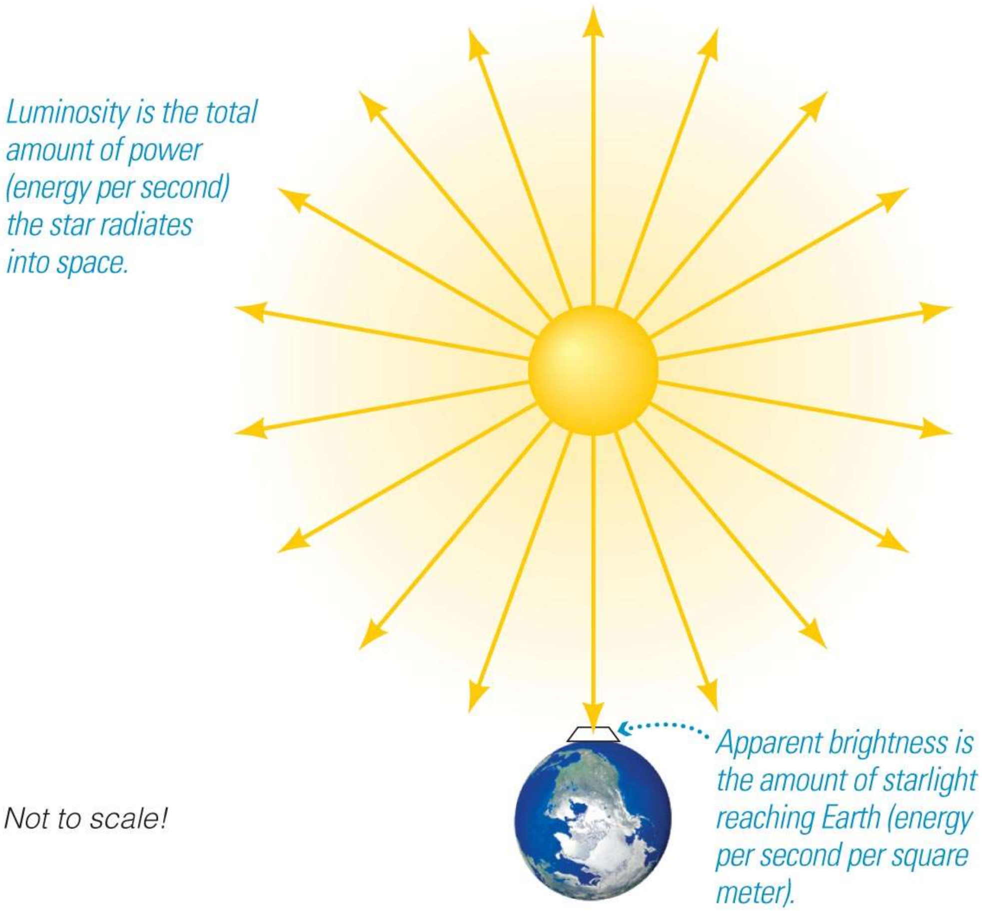
The $1/r^2$ Relationship Revisited…



Surface area for a sphere:

$$A = 4\pi r^2$$

Relationship between Luminosity and Brightness



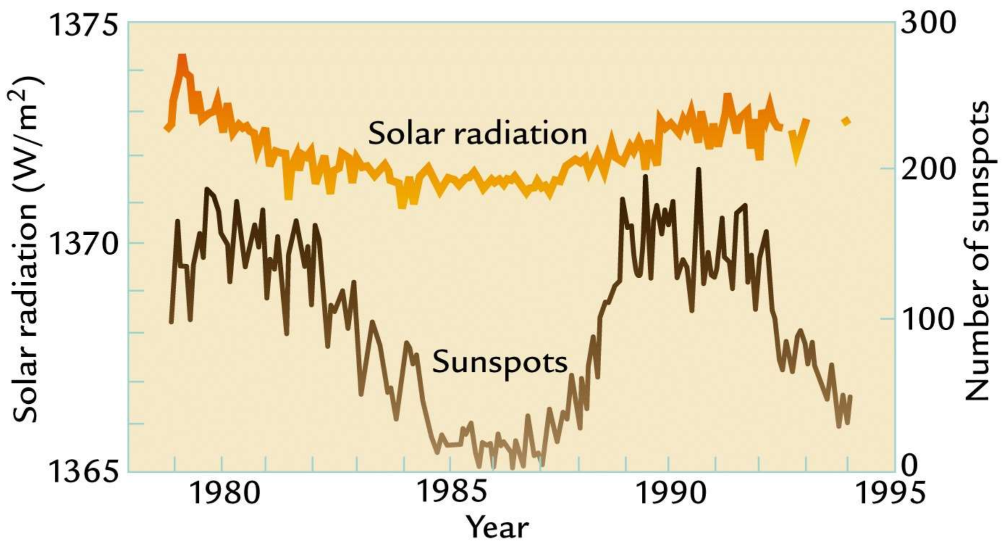
Luminosity:
Amount of power a star radiates (energy per second = watts)

Apparent brightness:
Amount of starlight that reaches Earth (energy per second per square meter)

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

$$Luminosity = 4\pi(distance)^2 \times brightness$$

Example Calculation:



Question: At Earth, the Sun's apparent brightness is recorded to be around 1370 W/m^2. Given that the Earth is approximately 149.6 million km away for the Sun, calculate the Sun's luminosity.

Solution: We just need to put the numbers into the formula…

$$
\begin{aligned}
Luminosity &= 4\pi(distance)^2 \times brightness \\
&= 4\pi \times (149.6 \times 10^9 m)^2 \times 1370\ W/m^2 \\
&= 3.85 \times 10^{26}\ Watts
\end{aligned}
$$

Think about it: *How much Solar Radiation would you receive at the distance of Saturn (~10 AU)?*

Thought Question

How would the apparent brightness of Alpha Centauri change if it were three times farther away?

A. It would be only 1/3 as bright.
B. It would be only 1/6 as bright.
C. It would be only 1/9 as bright.
D. It would be three times as bright.

Thought Question

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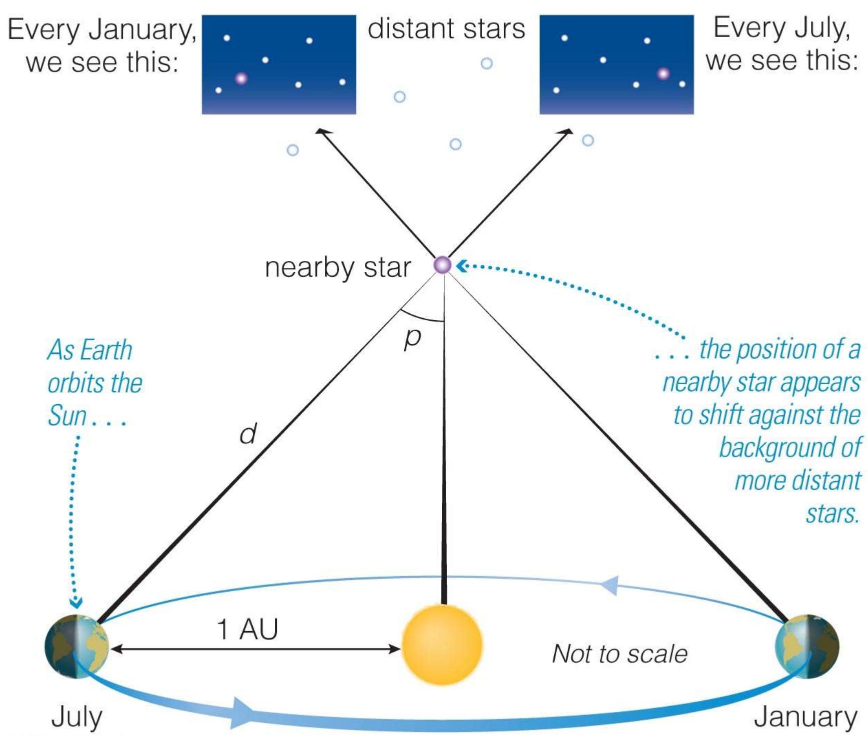
Measuring the Distance of Stars

Stellar Parallax:



If we take a snapshot of the stars 6 months apart, those closest will appear to move more, relative to the further background stars… *(see chapter 2)*

p = parallax angle (in arcseconds)

1 arcsecond = 1/3600 of a degree

$$d\ (in\ parsecs) = \frac{1}{p\ (in\ arcseconds)}$$

$$d(in\ lightyears) = 3.26 \times \frac{1}{p(in\ arcseconds)}$$

Today: the parallax of 100,000 stars up to 1500 lightyears have been measured.

Soon: The GAIA Spacecraft is measuring the parallax of 1 billion stars up to a few 10,000 light years.

Absolute & Apparent Magnitudes

Luminosity ranges of stars:

- **High end:** ~10^6 L_{Sun} (*e.g.*, Betelgeuse is 120,000 L_{Sun})
- **Low end:** ~10^{-4} L_{Sun} (*e.g., Proxima Centauri is 0.0006* L_{Sun})

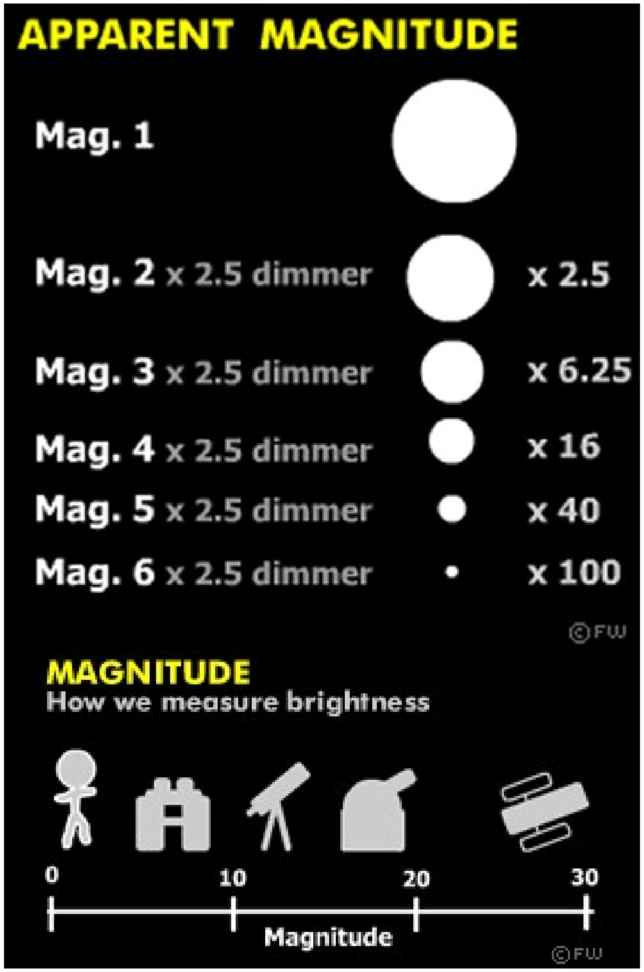
Apparent Magnitude: (Hipparchus; 1-6 scale)

- *Gets 2.5x dimmer per magnitude…*

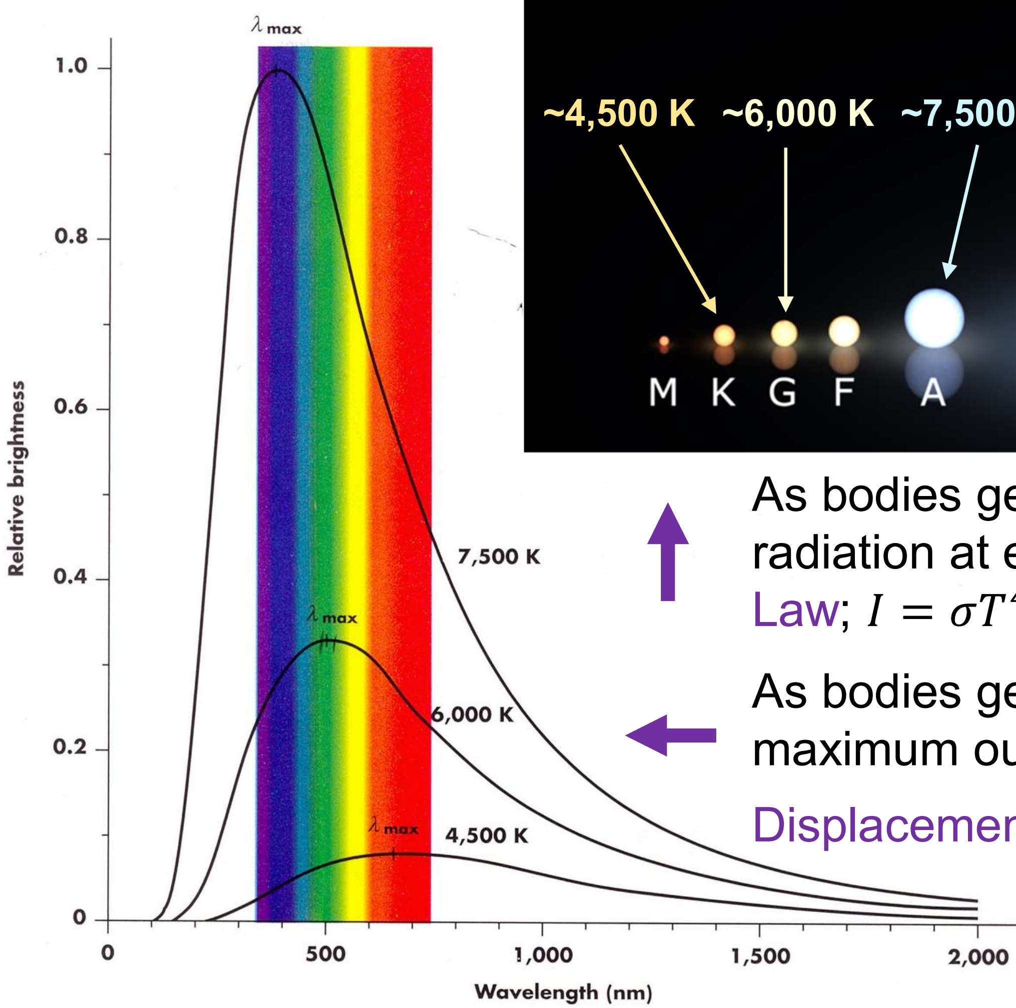
$$\frac{\text{apparent brightness of Star 1}}{\text{apparent brightness of Star 2}} = (100^{1/5})^{m_1 - m_2}$$

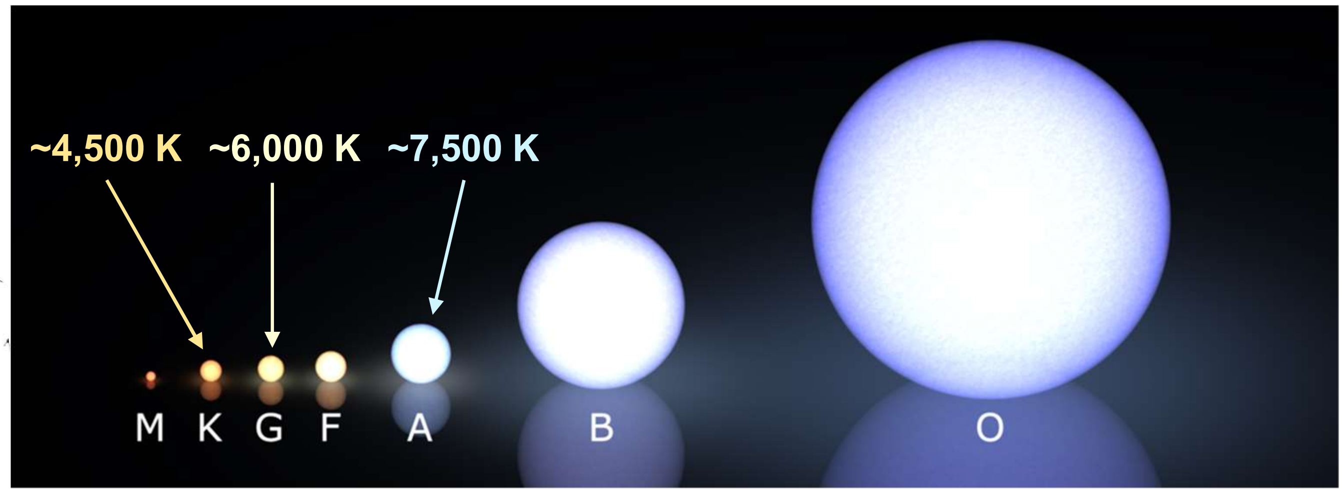
Absolute Magnitude:

- The apparent magnitude that a star would have, if it were at a distance of 10 parsecs (or 32.6 light years).
- For example, our Sun would have an absolute magnitude of 4.8 on this scale



Temperature of Stellar Photospheres: black body radiation revisited

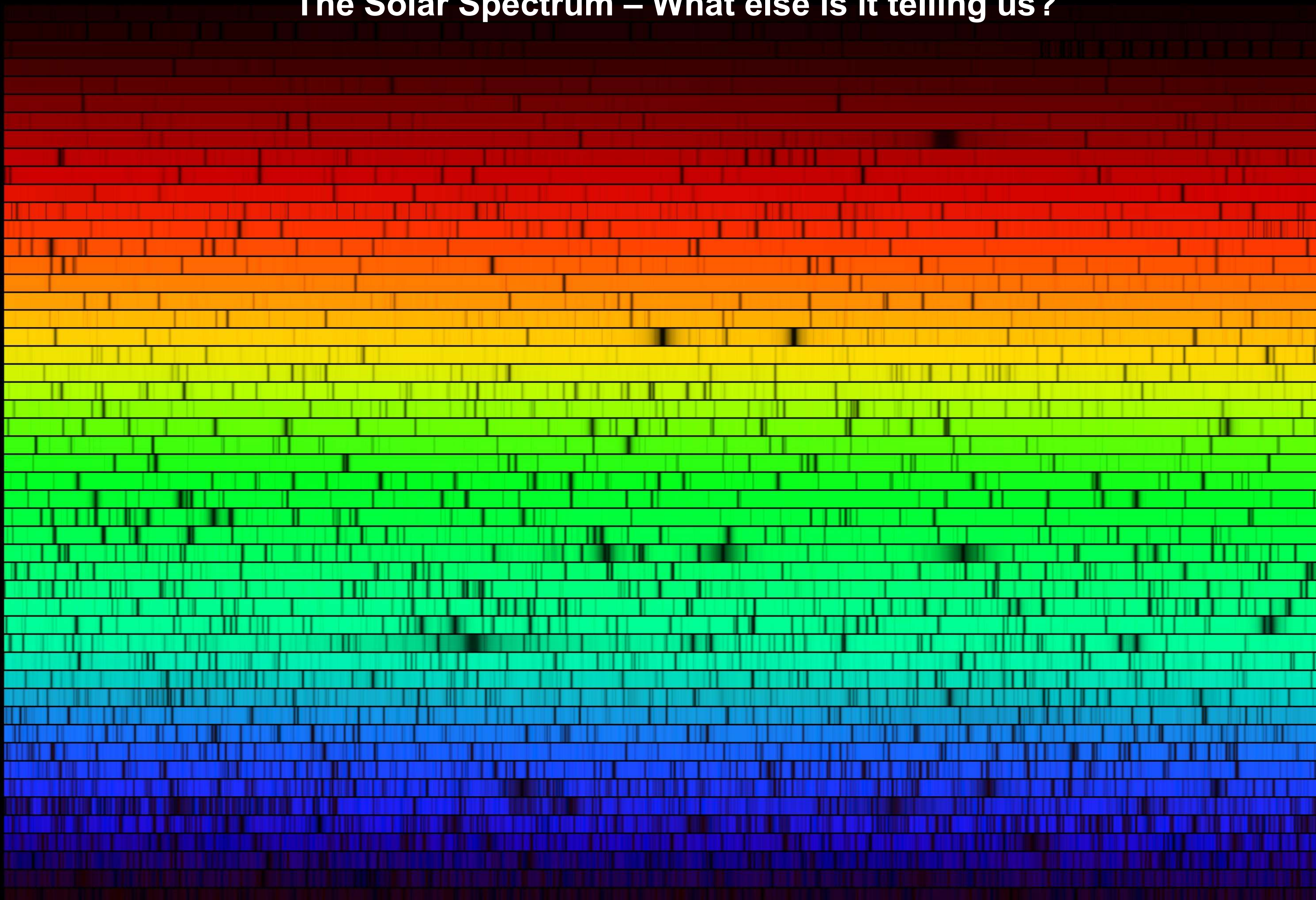




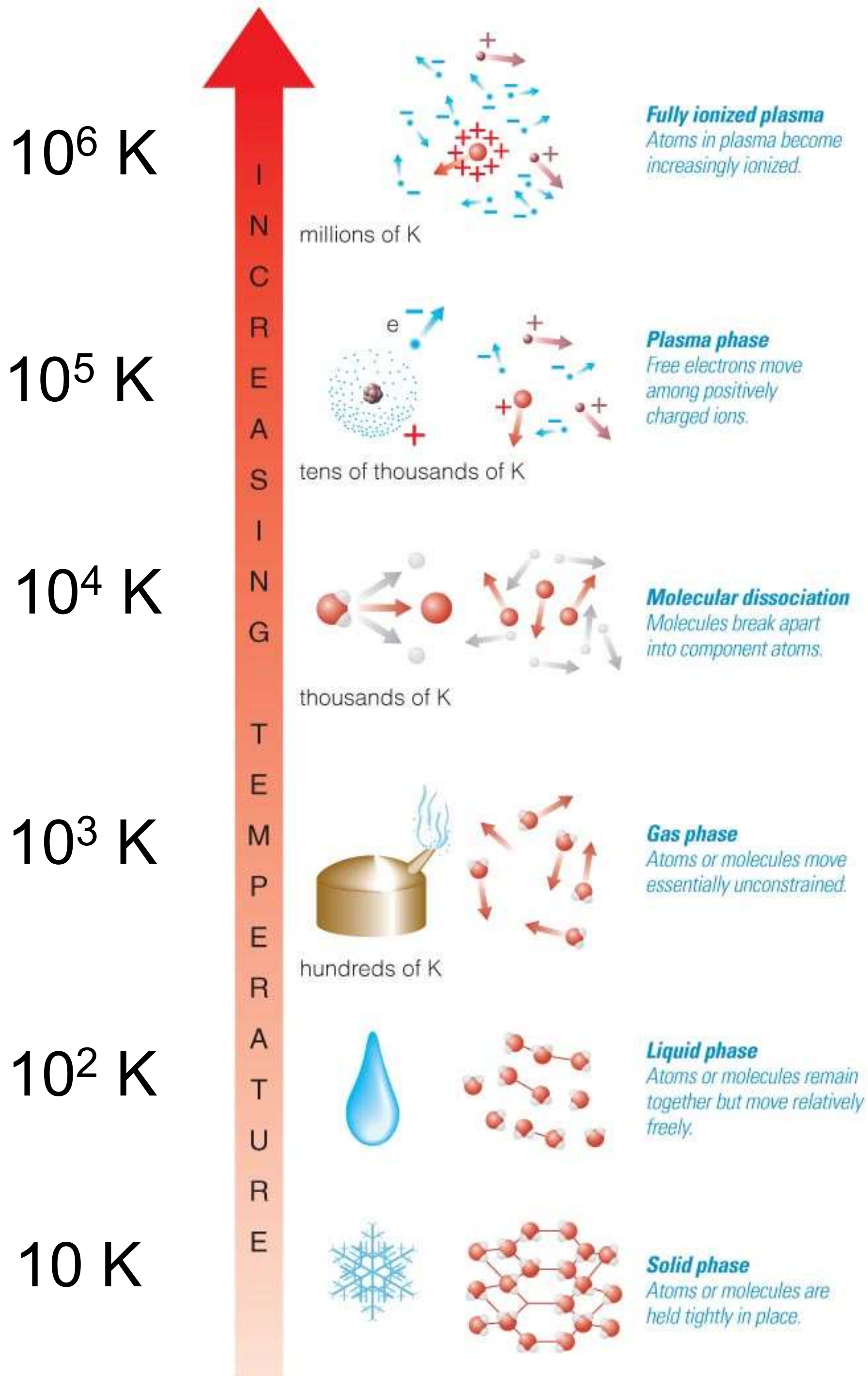
As bodies get warmer, they emit overall more radiation at each wavelength (Stephan-Boltzmann Law; $I = \sigma T^4$ where $\sigma=5.67 \times 10^{8}$ J/m^2K^4)

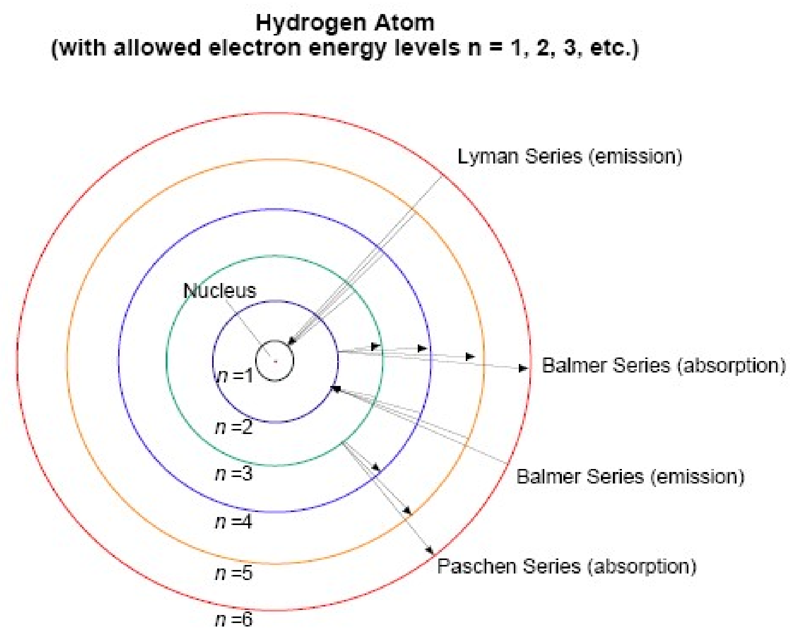
As bodies get warmer, the wavelength where maximum output is shifts to the left (Wien's Displacement Law; $\lambda_{peak}(T) = \frac{2.898\times10^{-3}(m\ K)}{Temperature\ (K)}$

The Solar Spectrum – What else is it telling us?



How Does Star Temperature Alter the Spectrum?



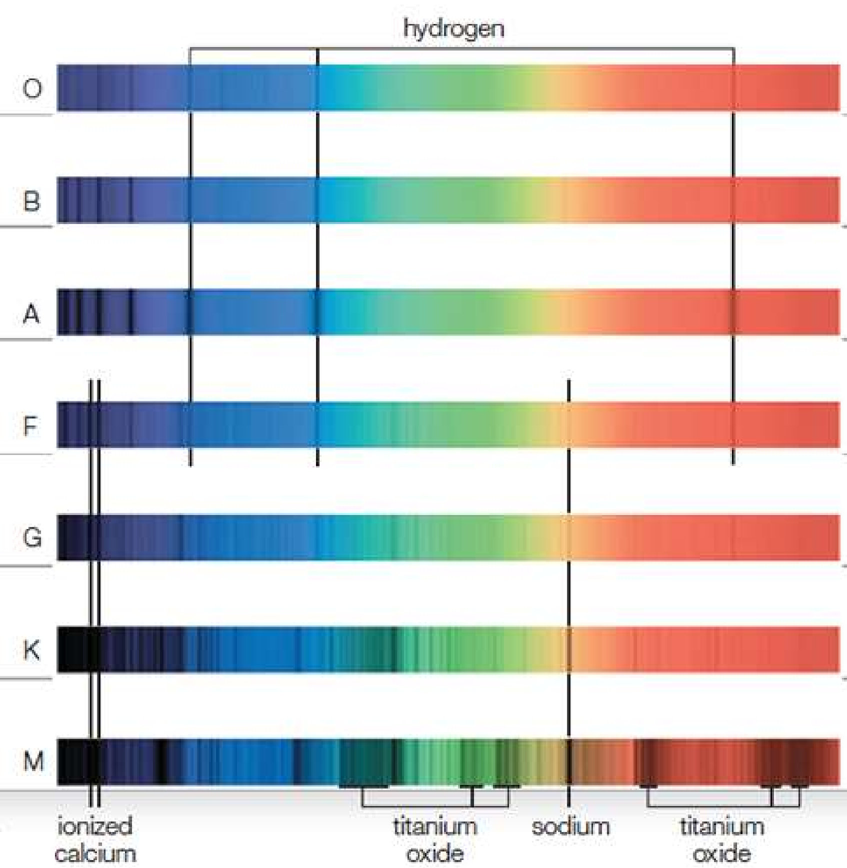


- Hydrogen lines are strongest in Stars around 10,000 K… the ionization energy of hydrogen is 13.6 eV… so when stars get too hot hydrogen is completely ionized and no longer visible…

Stars Based on Spectral Type

Spectral Type	Example(s)	Temperature Range	Key Absorption Line Features	Brightest Wavelength (color)
O	Stars of Orion's Belt	>33,000 K	Lines of ionized helium, weak hydrogen lines	< 89 nm (ultraviolet)*
B	Rigel	33,000 K–10,000 K	Lines of neutral helium, moderate hydrogen lines	89–290 nm (ultraviolet)*
A	Sirius	10,000 K–7500 K	Very strong hydrogen lines	290–390 nm (violet)*
F	Polaris	7500 K–6000 K	Moderate hydrogen lines, moderate lines of ionized calcium	390–480 nm (blue)*
G	Sun, Alpha Centauri A	6000 K–5200 K	Weak hydrogen lines, strong lines of ionized calcium	480–560 nm (yellow)
K	Arcturus	5200 K–3700 K	Lines of neutral and singly ionized metals, some molecules	560–780 nm (red)
M	Betelgeuse, Proxima Centauri	<3700 K	Strong molecular lines	>780 nm (infrared)

Typical Spectrum (selected lines labeled)

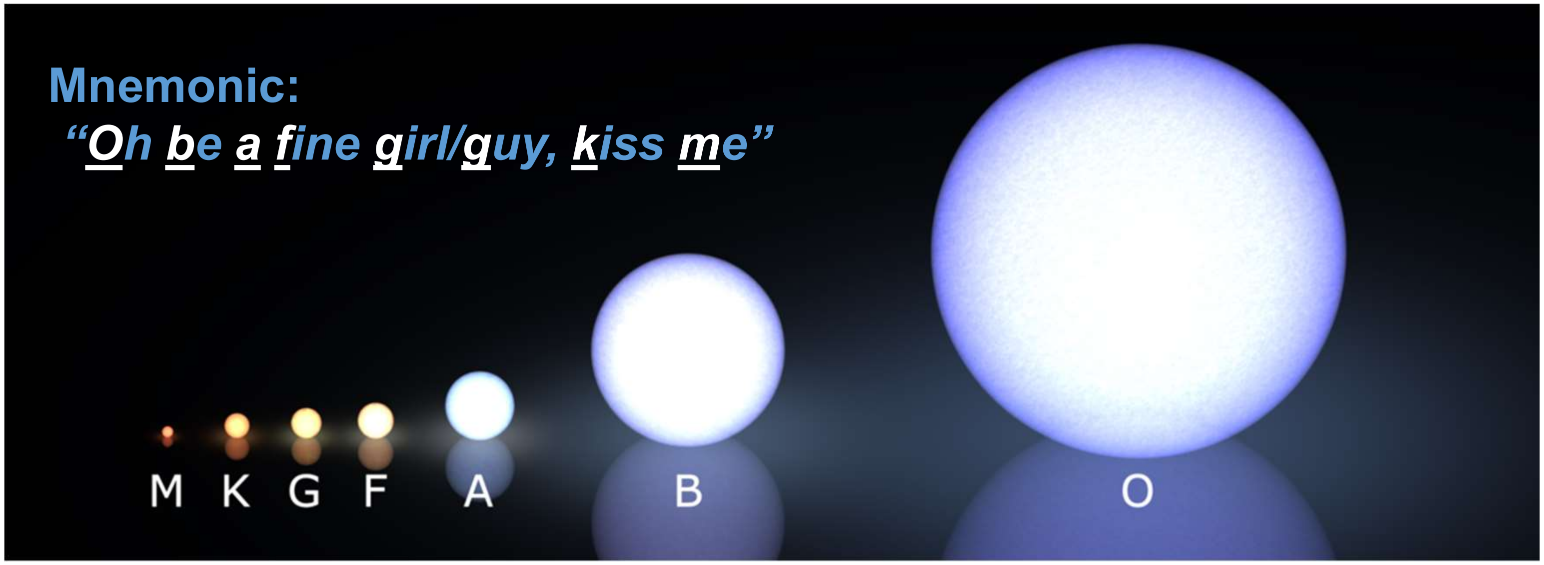


*All stars above 6000 K look more or less white to the human eye because they emit plenty of radiation at all visible wavelengths.

Lines in a star's spectrum correspond to a temperature & ***spectral type:***

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

Stellar Classification System



- Annie Jump Cannon's stellar classification system adopted since 1910
  - Originally classified due to strength of hydrogen lines (A is strongest)
- Subdivided into subclasses from 0-9 (0 being hottest, 9 being coolest)
  - Our Sun is a G2-type star from this classification system.
- There are additional types L, T, and Y which are cooler objects (e.g., red/brown dwarfs … these are failed or dying stars)

Binary Systems and Stellar Masses

If you remember (from Newton's formulation of Kepler's 3rd law), binary systems allow us a method to determine the mass. From the relationship for circular orbits, $v = 2\pi r / p$, *we need two of the following:*

1. Orbital period (p)
2. Orbital separation (a or r = radius)
3. Orbital velocity (v)

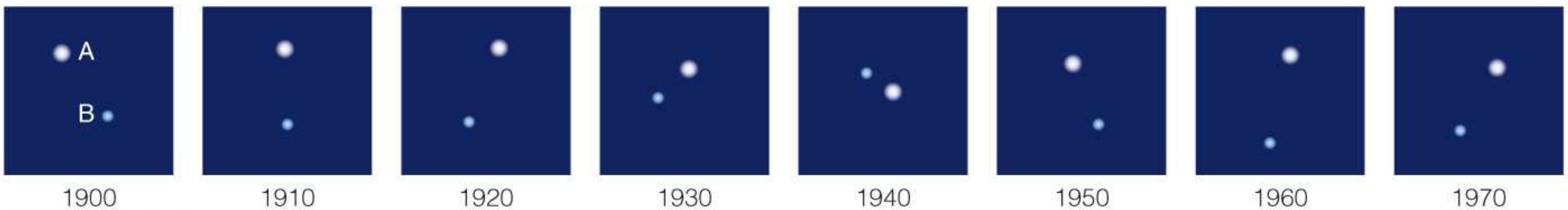
$\rightarrow$ Fortunately, approximately half of all stars are in binary systems.

How can we determine these properties?

- Transits…
- Doppler Shifts…
- Astrometry…

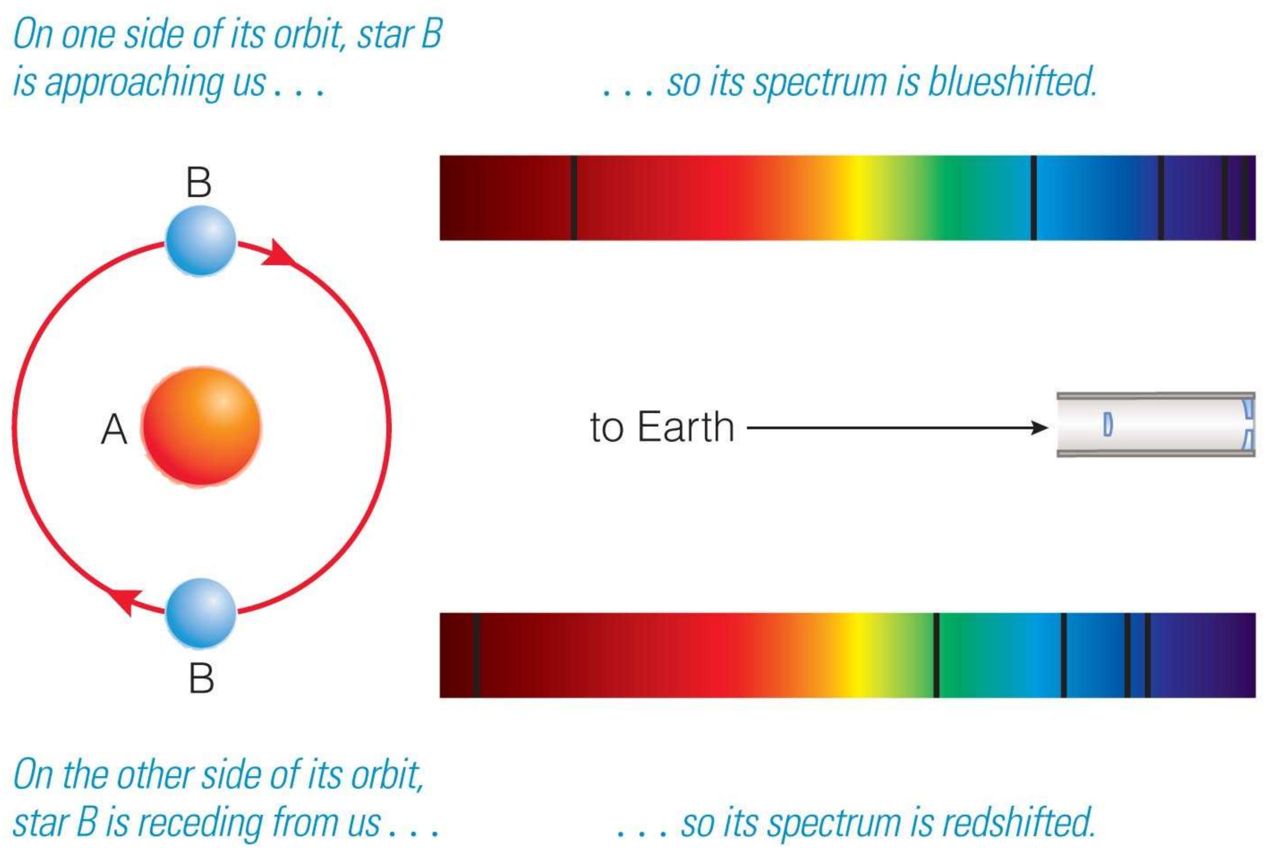
i.e. using the same techniques used for detecting exoplanets

Example of a Visual Binary



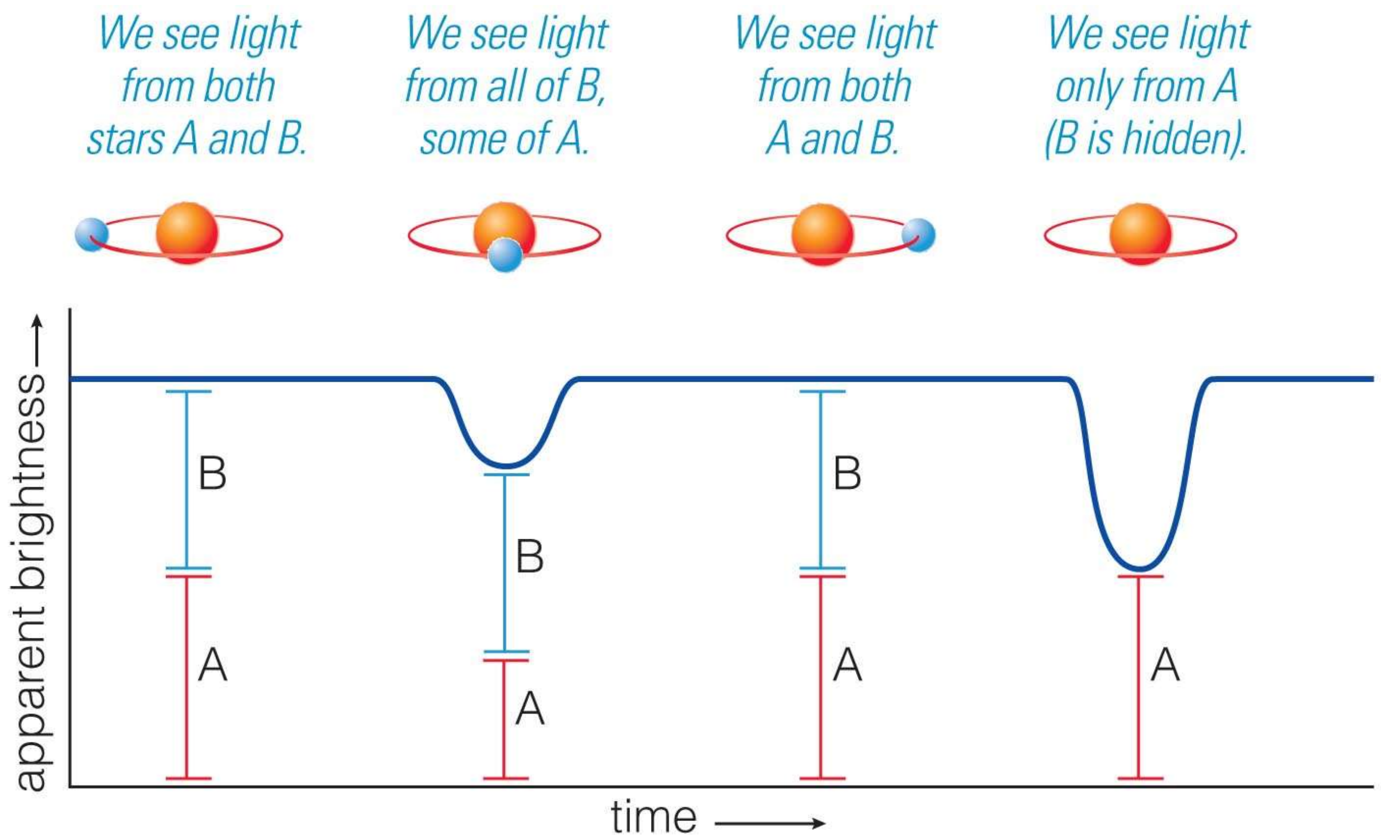
We can directly observe the orbital motions of some stars, here, Sirius A and Sirius B have an orbital separation of around 20 AU.

Spectroscopic Binary



→ We can determine the orbital properties by measuring Doppler shifts.

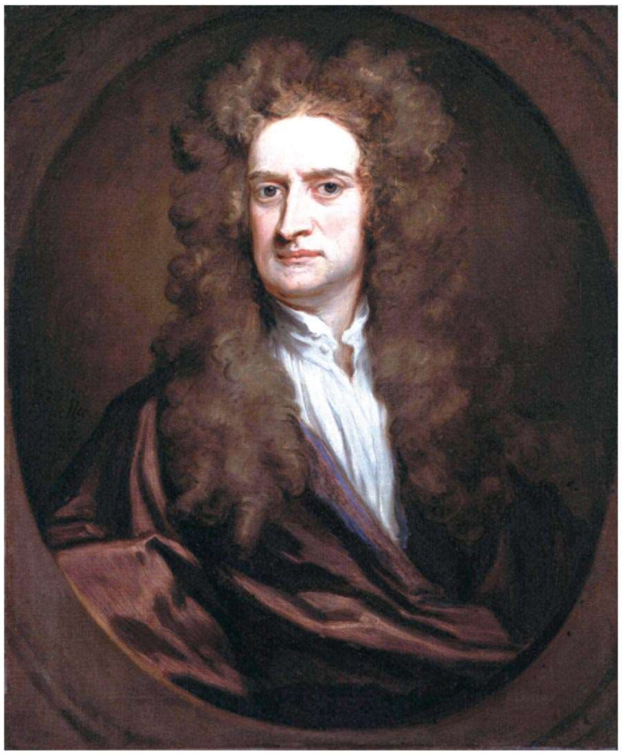
Eclipsing Binaries



- We can measure periodic eclipses much easier than for exoplanets
- This technique can also provide information of a Stars radius…

Determination of Mass in Binary Systems

http://www.austincc.edu/jheath/Solar/Hand/NVK3L/nvk3l.htm



Isaac Newton

We measure mass using gravity, and Newton's version of Kepler's 3rd law:

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

p = period

a = average separation

G = Universal Gravitational Constant ($6.67408 \times 10^{-11}\ m^3\ kg^{-1}\ s^{-2}$)

M1 and M2 are the masses of the stars in the system

- Direct mass measurements are only possible for stars in binary star systems.
- But they can provide a framework for us to calculate the masses of other stars.

Radius of a Star

- From the Stefan-Boltzmann Law, we know the energy given out per unit area for a black body source.
- The total Luminosity must be equal to the energy per unit area given out over the entire surface area of a sphere ($4\pi r^2$)

Therefore: $L = 4\pi r^2 \times \sigma T^4$

Which can be rearranged as: $r = \sqrt{\frac{L}{4\pi\sigma T^4}}$

Example: The star Betelgeuse has a surface temperature of around 3650 K and a luminosity of 120,000 L_{Sun}, which is about 4.6×10^{31} watts. What is it's radius?

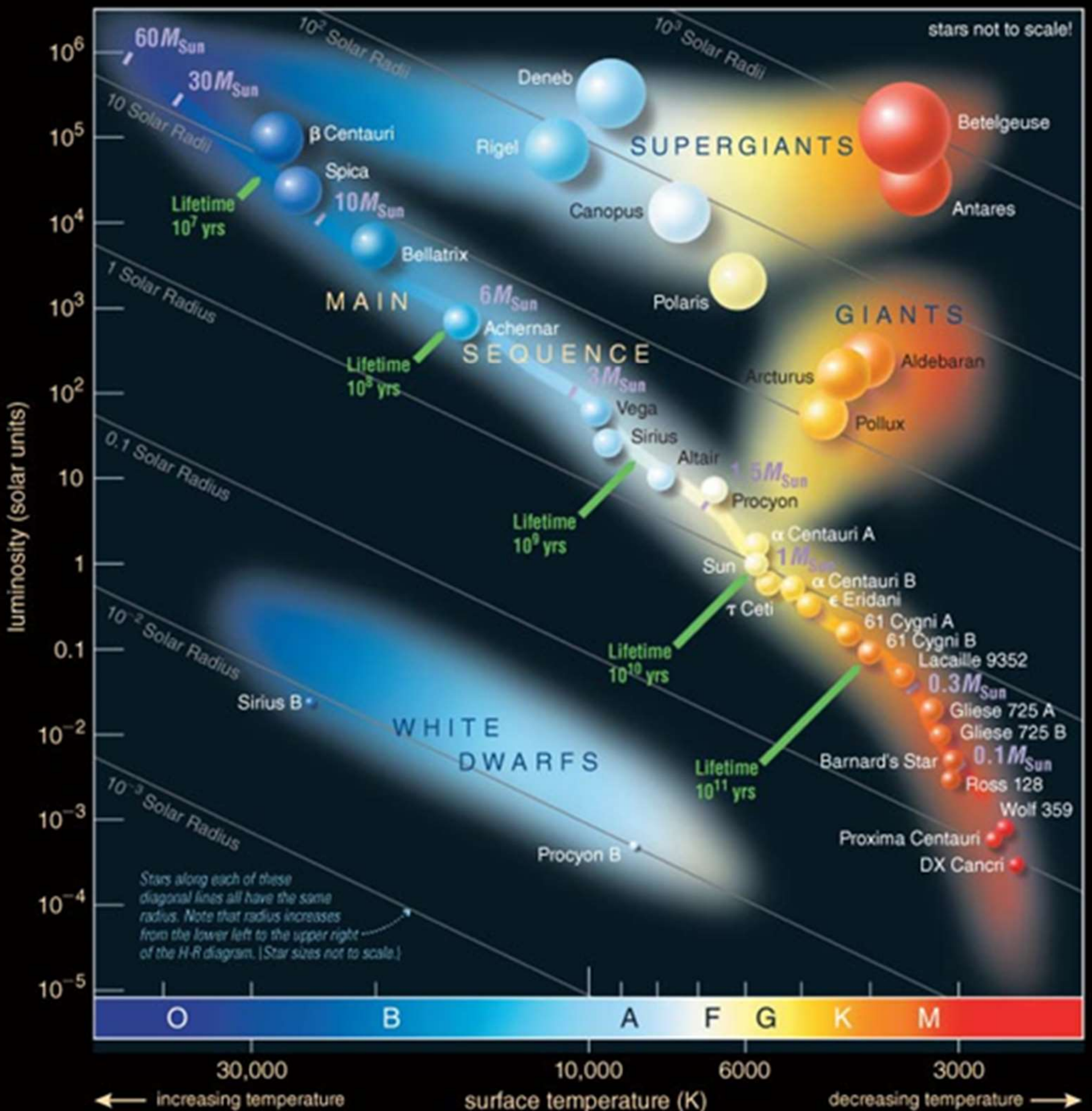
Solution: $r = \sqrt{\frac{L}{4\pi\sigma T^4}} = \sqrt{\frac{4.6\times10^{31}}{4\pi\times5.7\times10^{8}\times3650^4}} = 5.9 \times 10^{11} m$

→ **590 million meters, which is approximately 4 AU distance…**

What have we learned?

- How do we measure stellar luminosities?
  - If we measure a star's apparent brightness and distance, we can compute its luminosity with the inverse square law for light.
  - Parallax tells us distances to the nearest stars.
- How do we measure stellar temperatures?
  - A star's color and spectral type both reflect its temperature.
- How do we measure stellar masses?
  - Newton's version of Kepler's third law tells us the total mass of a binary system, if we can measure the orbital period (p) and average orbital separation of the system (a).

Next time…


stars not to scale!
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^{-2} Solar Radius
10^{-3} Solar Radius
$60 M_{Sun}$
$30 M_{Sun}$
$10 M_{Sun}$
$6 M_{Sun}$
$3 M_{Sun}$
$1.5 M_{Sun}$
$1 M_{Sun}$
$0.3 M_{Sun}$
$0.1 M_{Sun}$
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^{10} yrs
Lifetime 10^{11} yrs
SUPERGIANTS
GIANTS
MAIN SEQUENCE
WHITE DWARFS
Deneb
Rigel
Canopus
Polaris
Betelgeuse
Antares
β Centauri
Spica
Bellatrix
Achernar
Vega
Sirius
Altair
Procyon
Arcturus
Aldebaran
Pollux
α Centauri A
Sun
α Centauri B
ε Eridani
τ Ceti
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
Stars along each of these diagonal lines all have the same radius. Note that radius increases from the lower left to the upper right of the H-R diagram. (Star sizes not to scale.)
luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
O B A F G K M
30,000
10,000
6000
3000
increasing temperature
surface temperature (K)
decreasing temperature

End of Todays Lecture