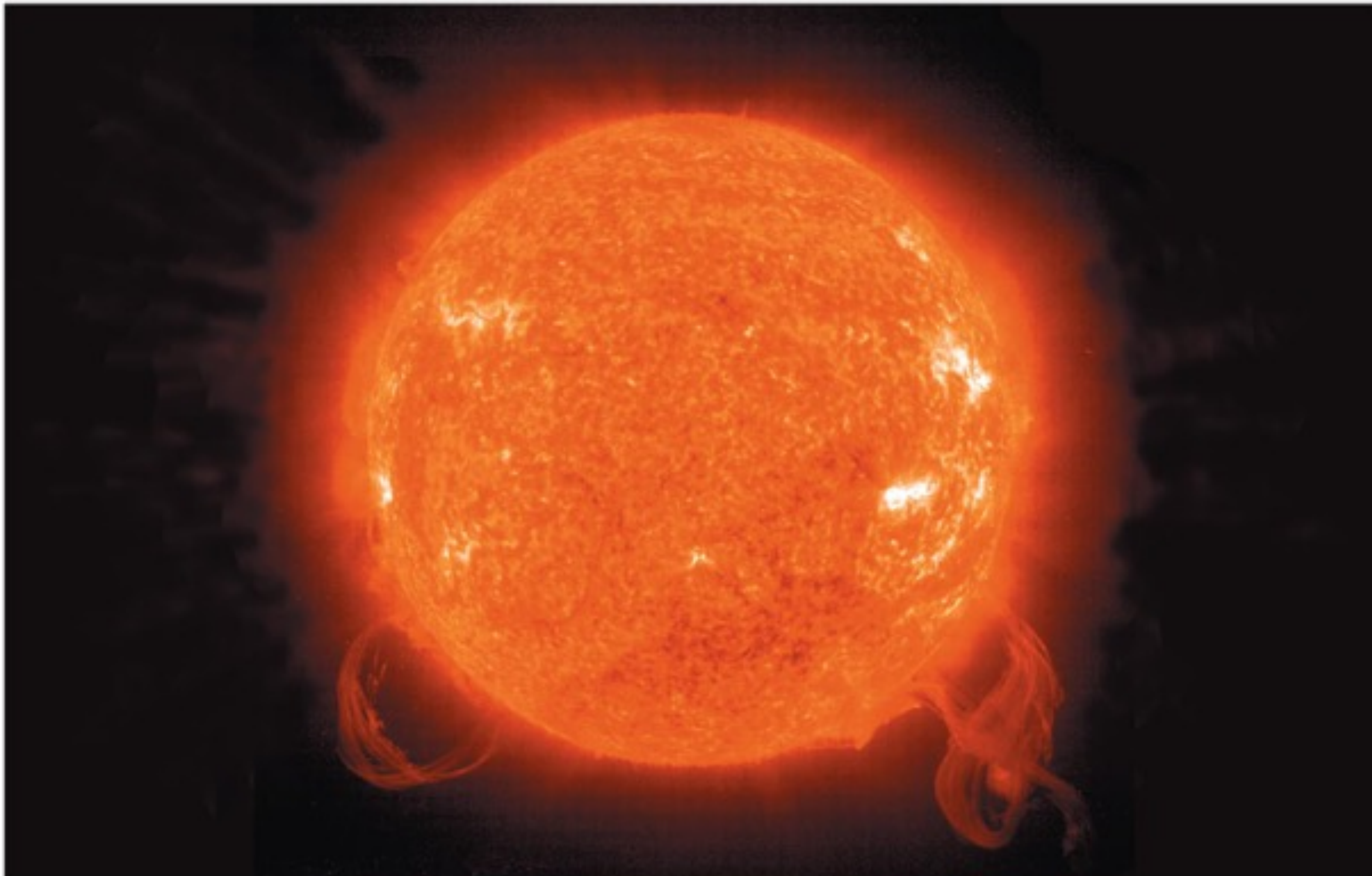
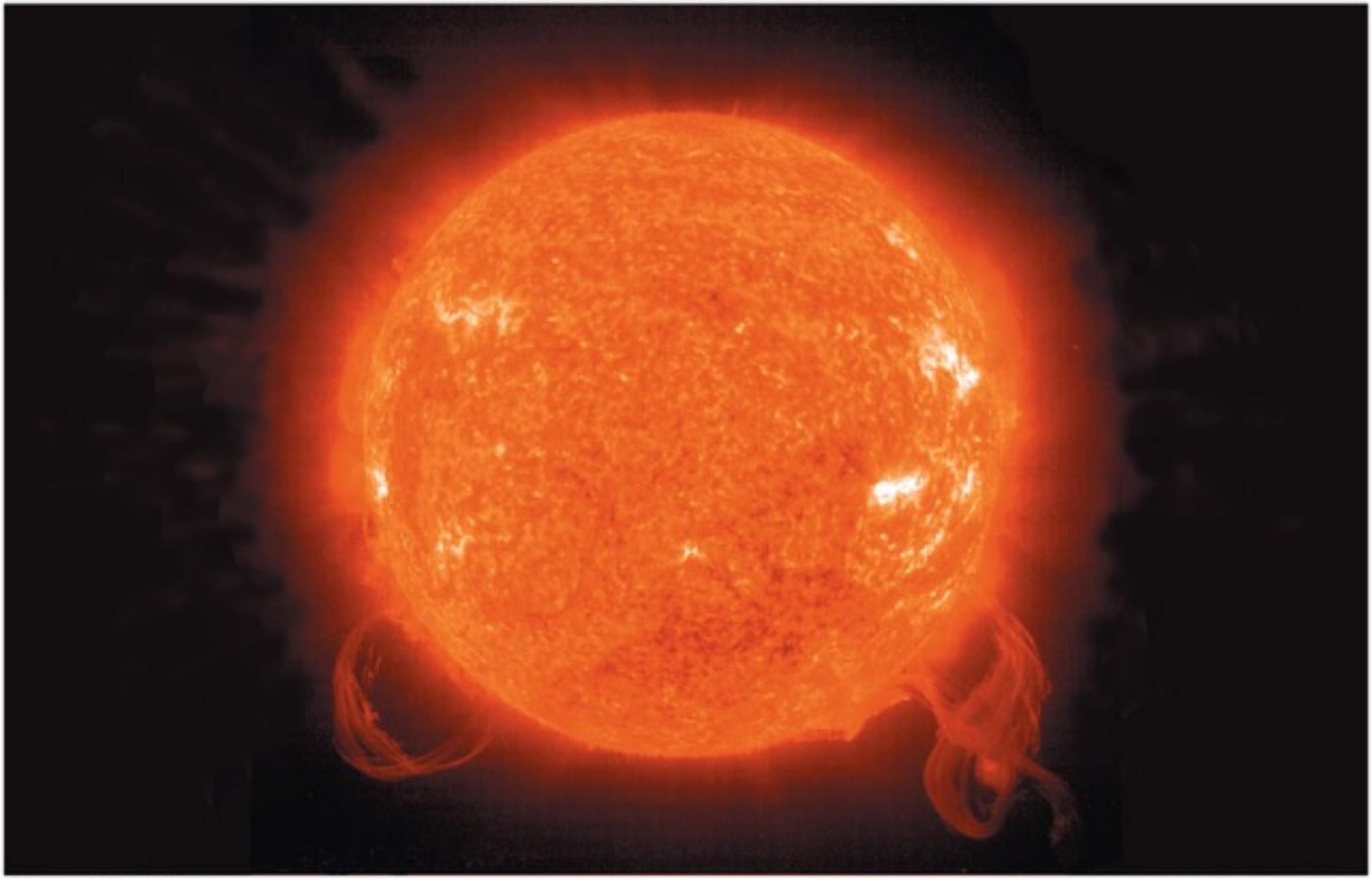
Our Star

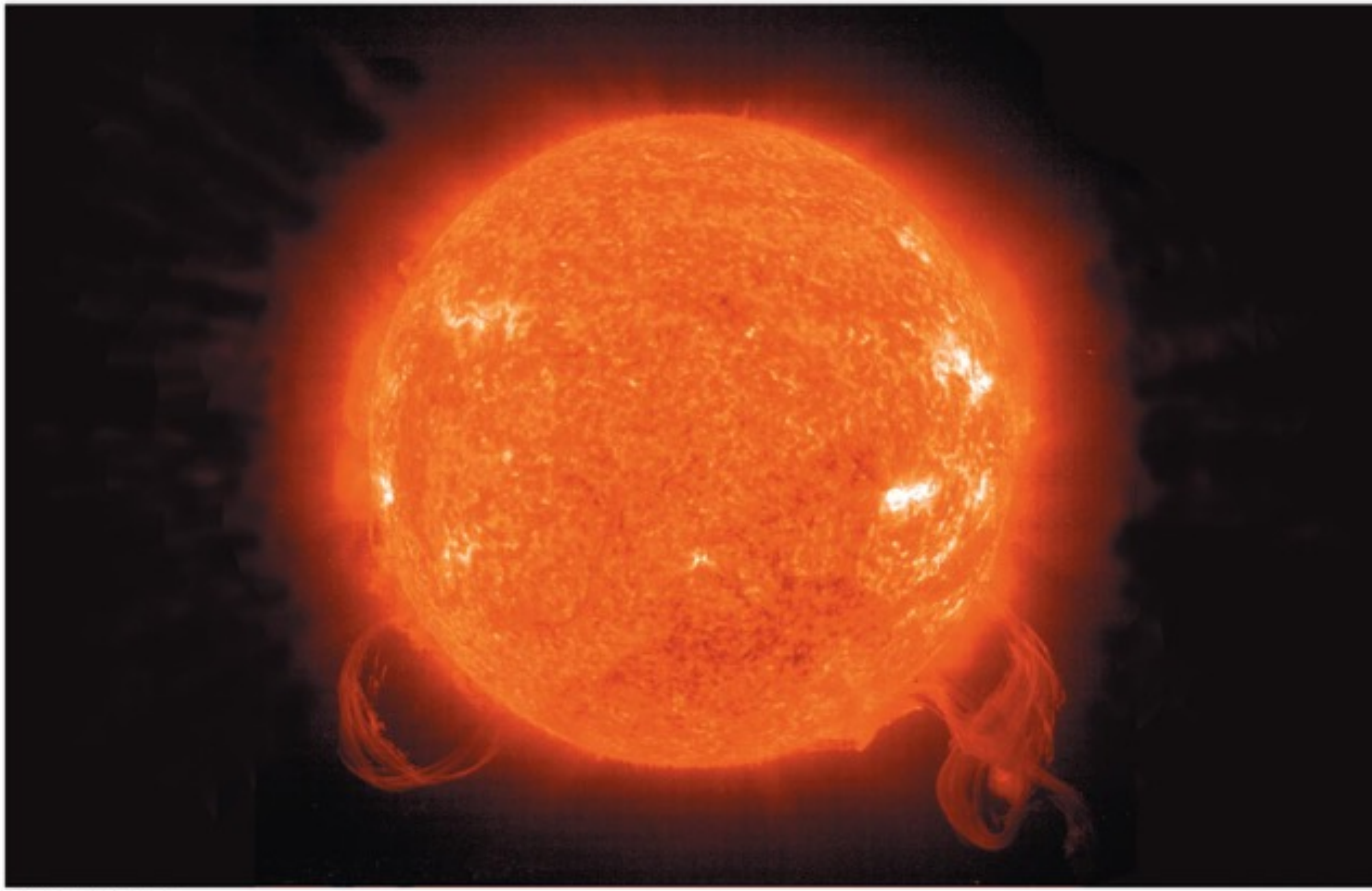


A Closer Look at the Sun

- Why was the Sun's energy source a major mystery?
- Why does the Sun shine?
- What is the Sun's structure?

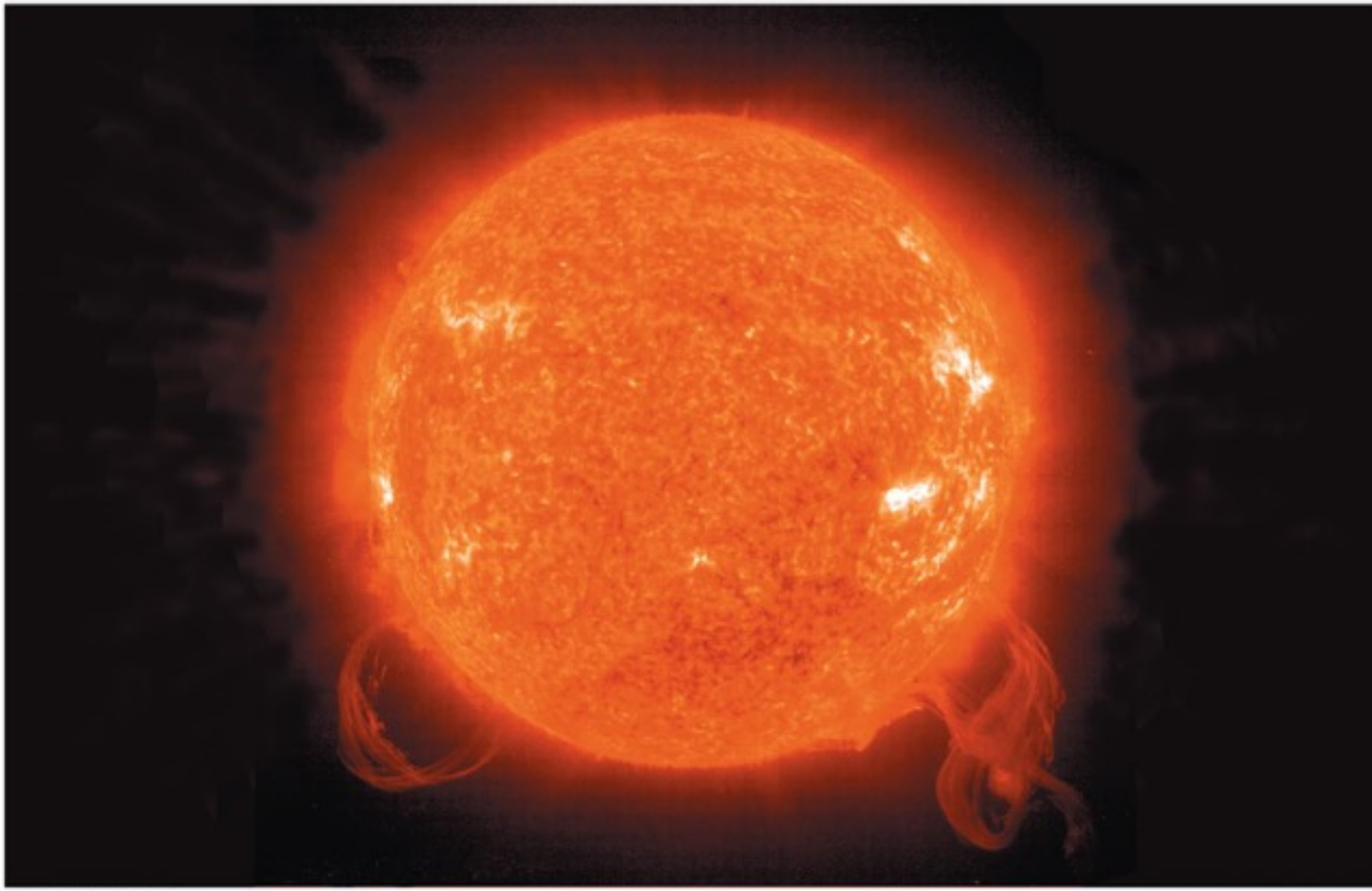
Why does the Sun shine?





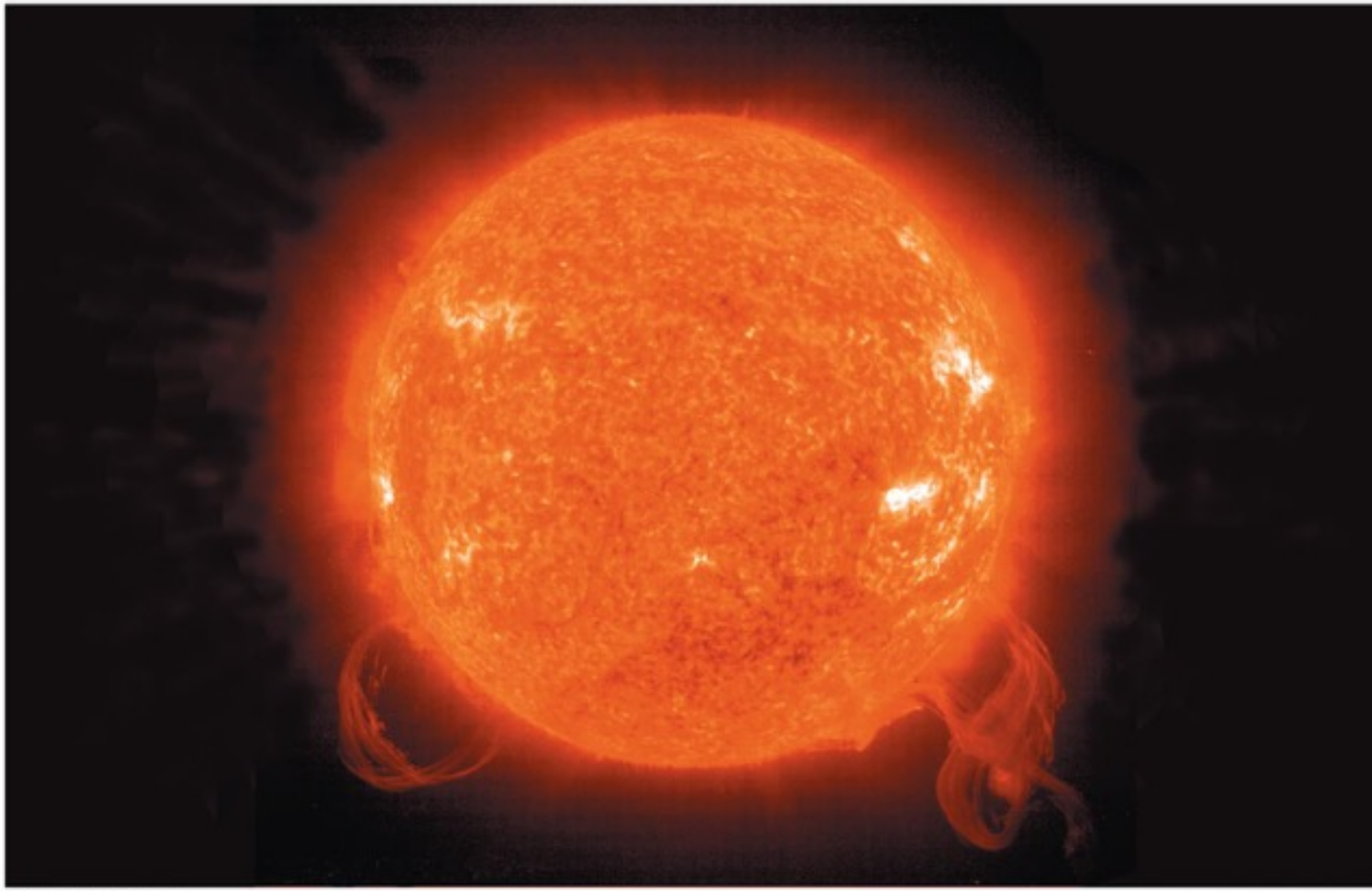
Is it on FIRE? ... NO!

$$\frac{\text{Chemical energy content}}{\text{Luminosity}} \sim 10{,}000 \text{ years}$$



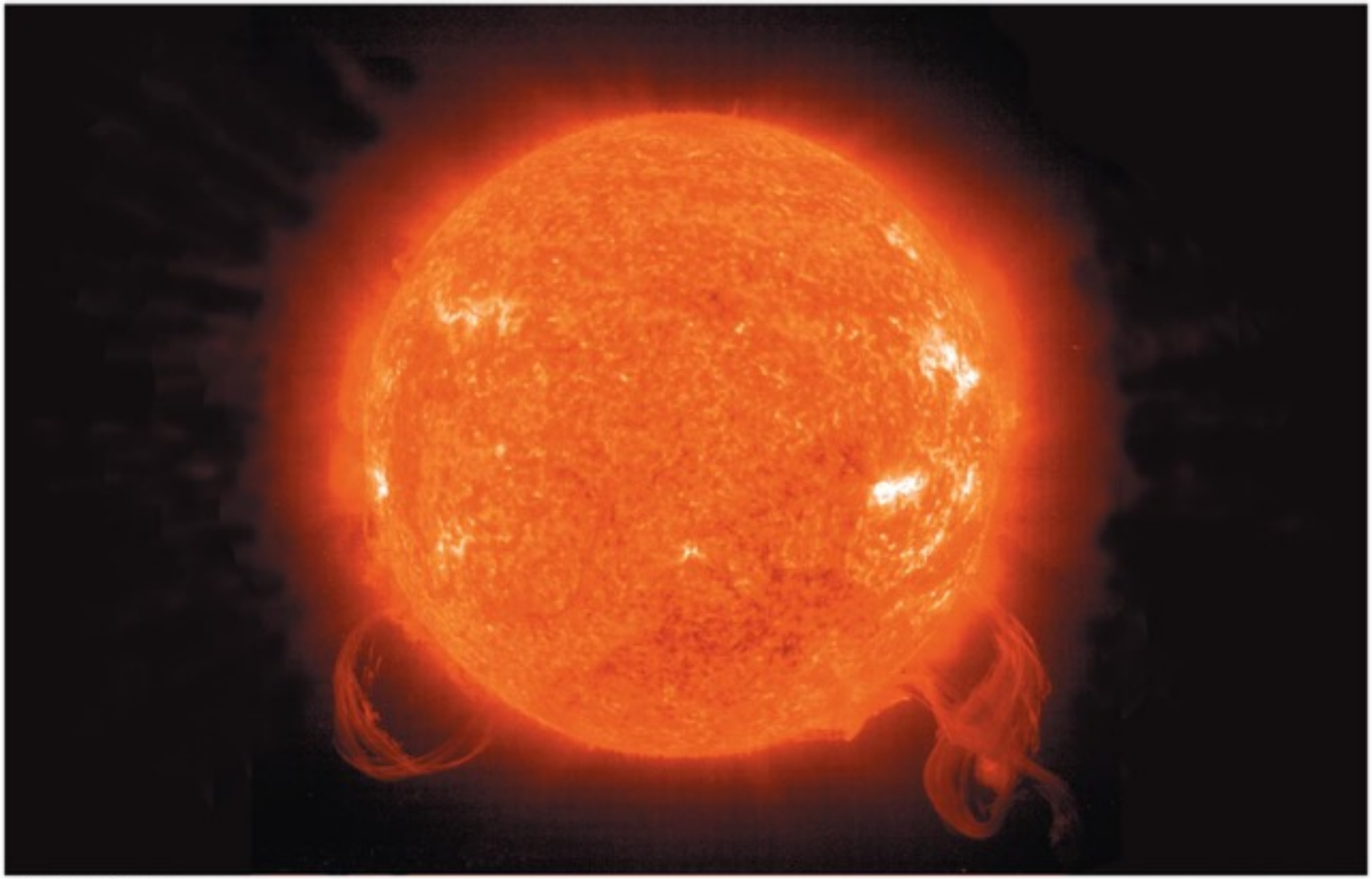
Is it CONTRACTING?

$$\frac{\text{Gravitational potential energy}}{\text{Luminosity}} \sim \text{25 million years}$$



Is it CONTRACTING? ... NO!

$$\frac{\text{Chemical energy content}}{\text{Luminosity}} \sim 10{,}000 \text{ years}$$



It can be powered by NUCLEAR ENERGY! ($E = mc^2$)

$$\frac{\text{Nuclear potential energy (core)}}{\text{Luminosity}} \sim 10 \text{ billion years}$$

How long will the Sun shine powered by nuclear fusion?

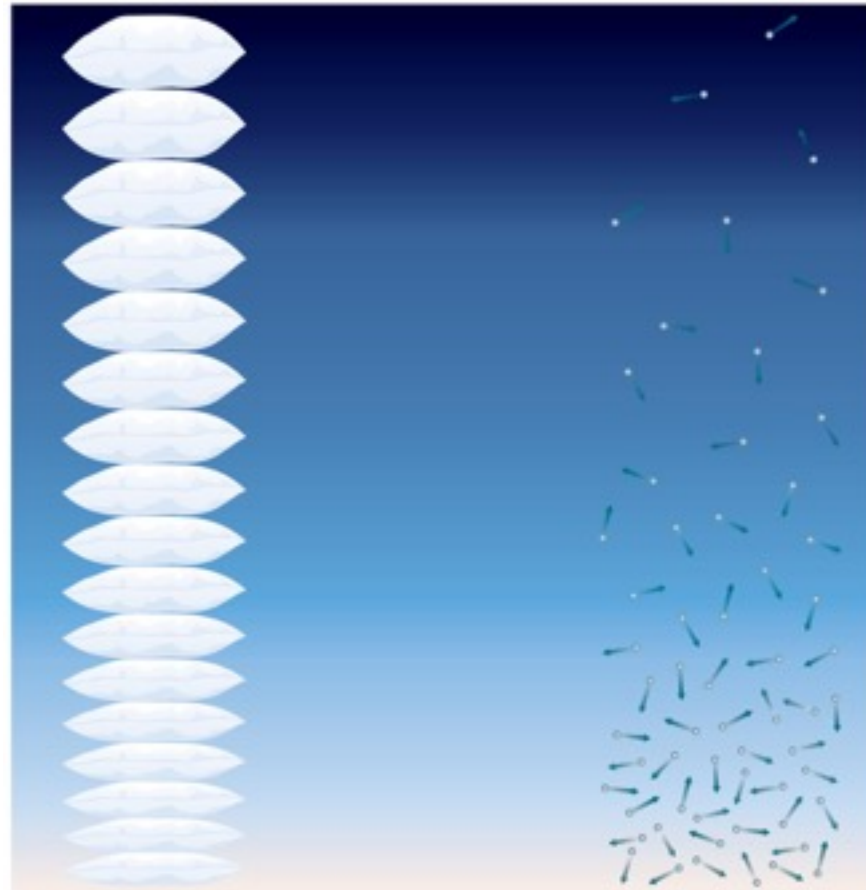
a) 5 billion years
b) 10 billion years
c) 15 billion years
d) 50 billion years
e) 100 billion years

Chapter 14

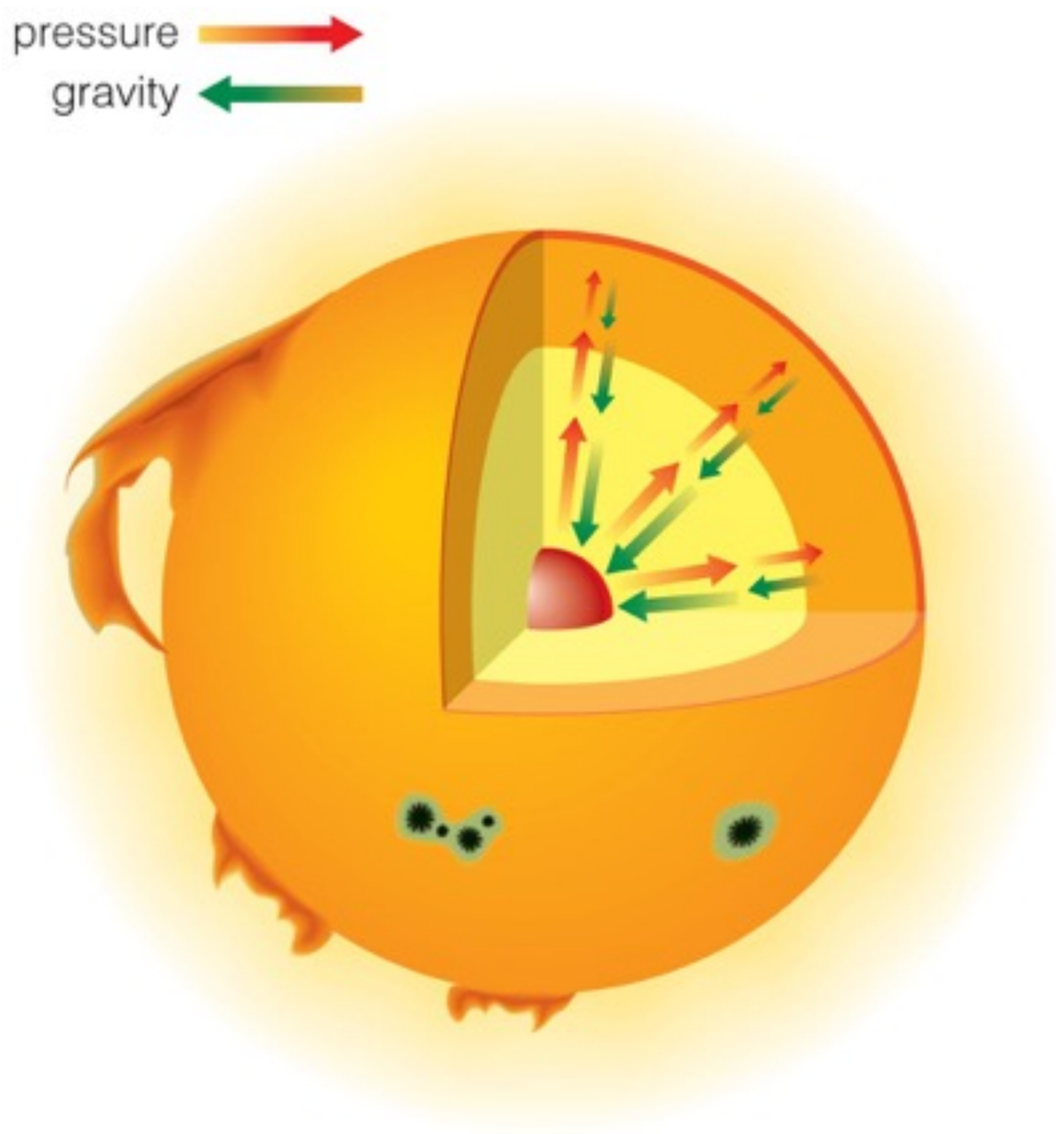
What balances the inward push of gravity inside the Sun?

a) the rigidity of the solid central core
b) electron degeneracy pressure
c) thermal pressure of the gas
d) neutron degeneracy pressure

Equilibrium

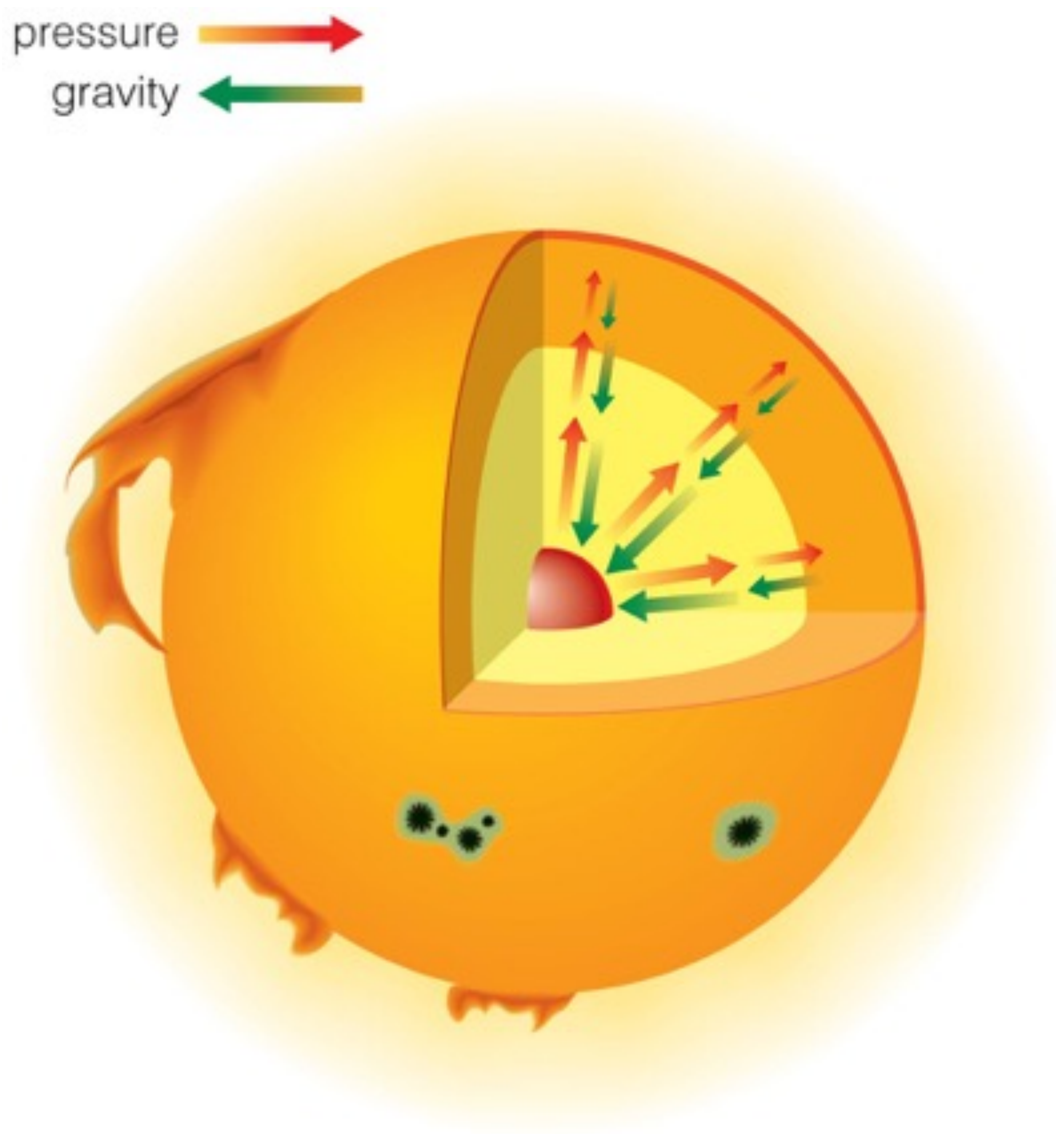


Weight of upper layers
compresses lower layers.



Gravitational equilibrium:

Energy supplied by fusion maintains the pressure that balances the inward crush of gravity.

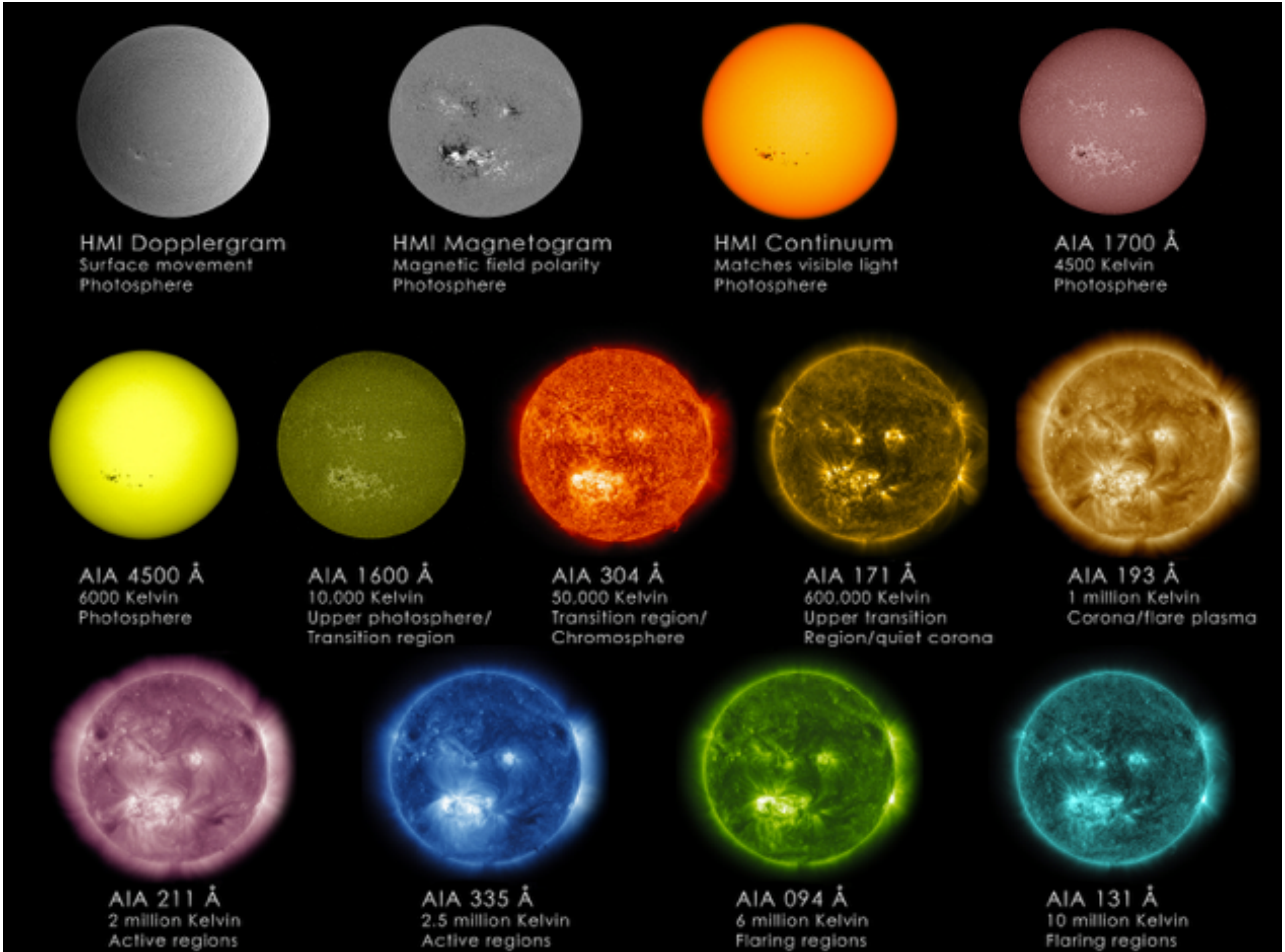


Gravitational contraction:

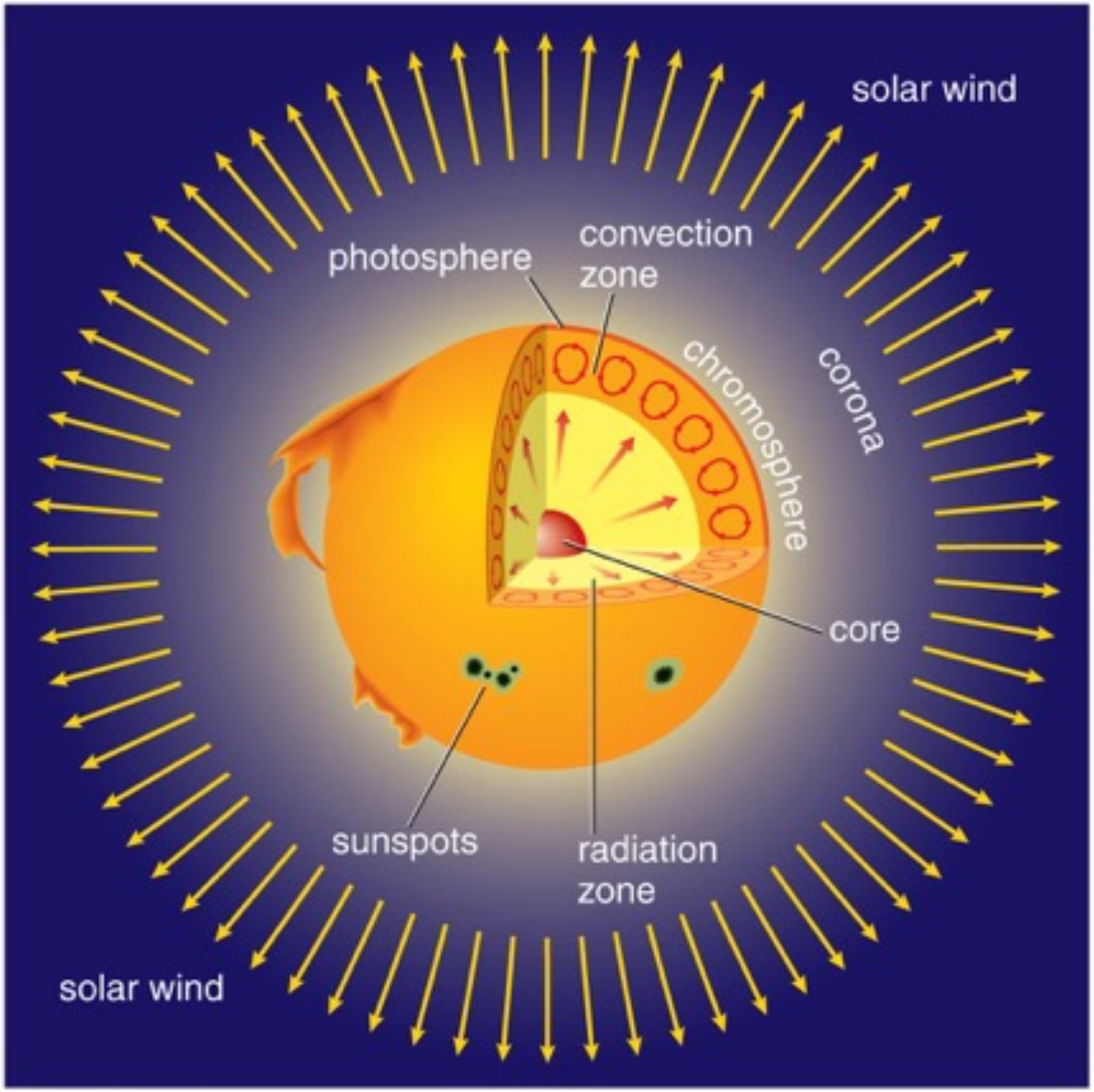
Provided the energy that heated the core as Sun was forming

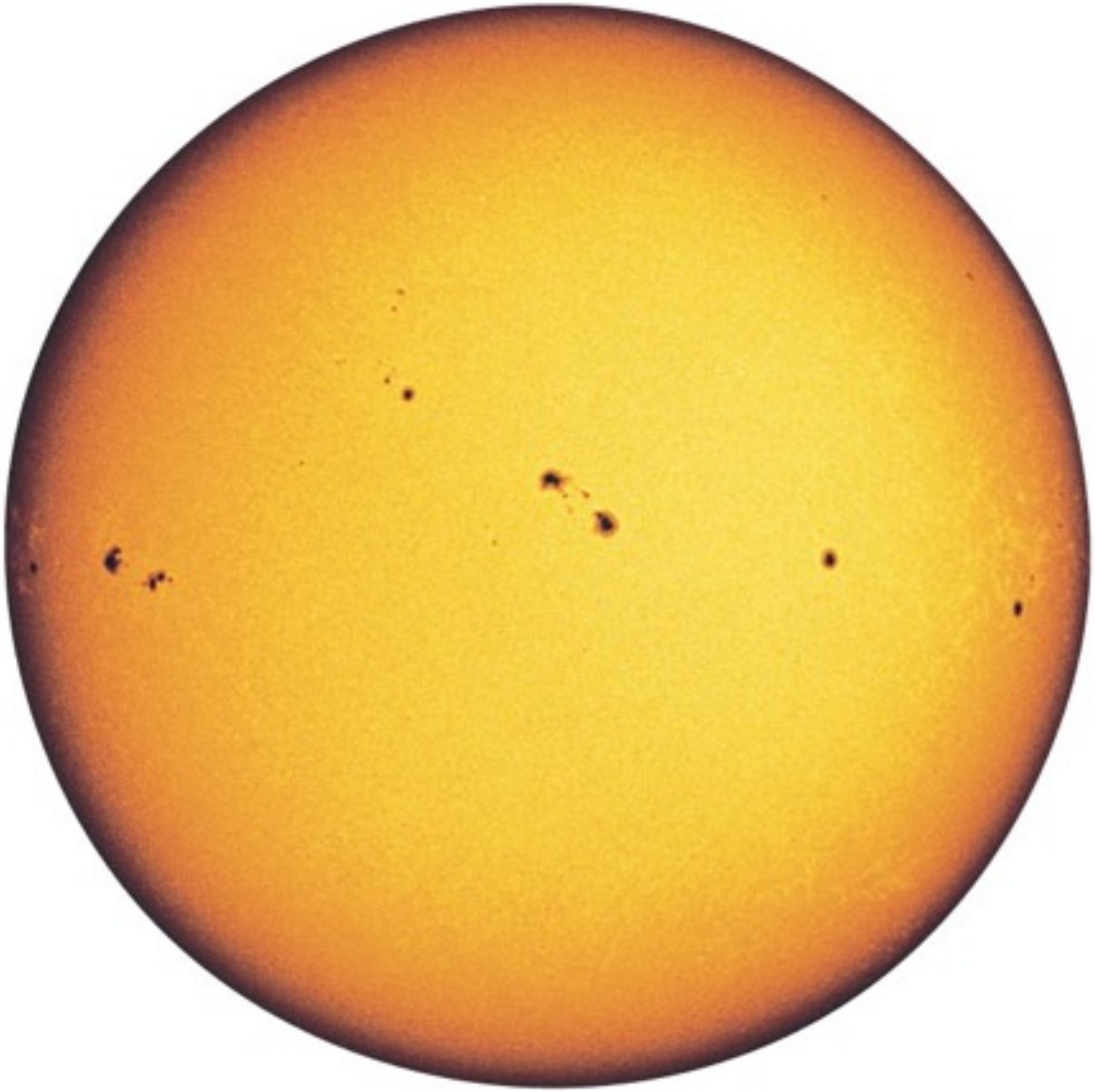
Contraction stopped when fusion began.

The Sun's Atmospheric Layers



What is the Sun's structure?





Radius:

6.9×10^8 m

(109 times Earth)

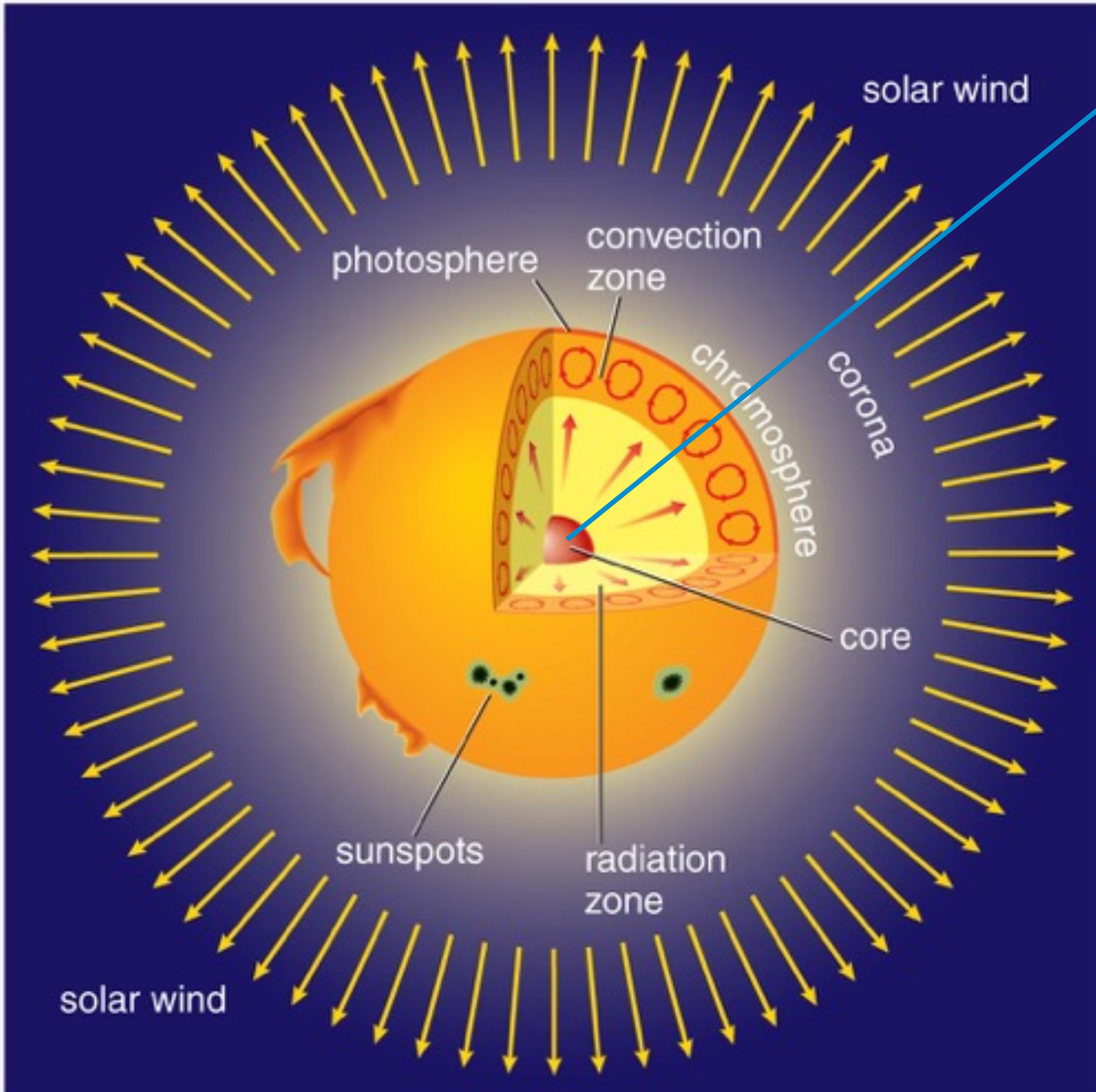
Mass:

2×10^{30} kg

(300,000 Earths)

Luminosity:

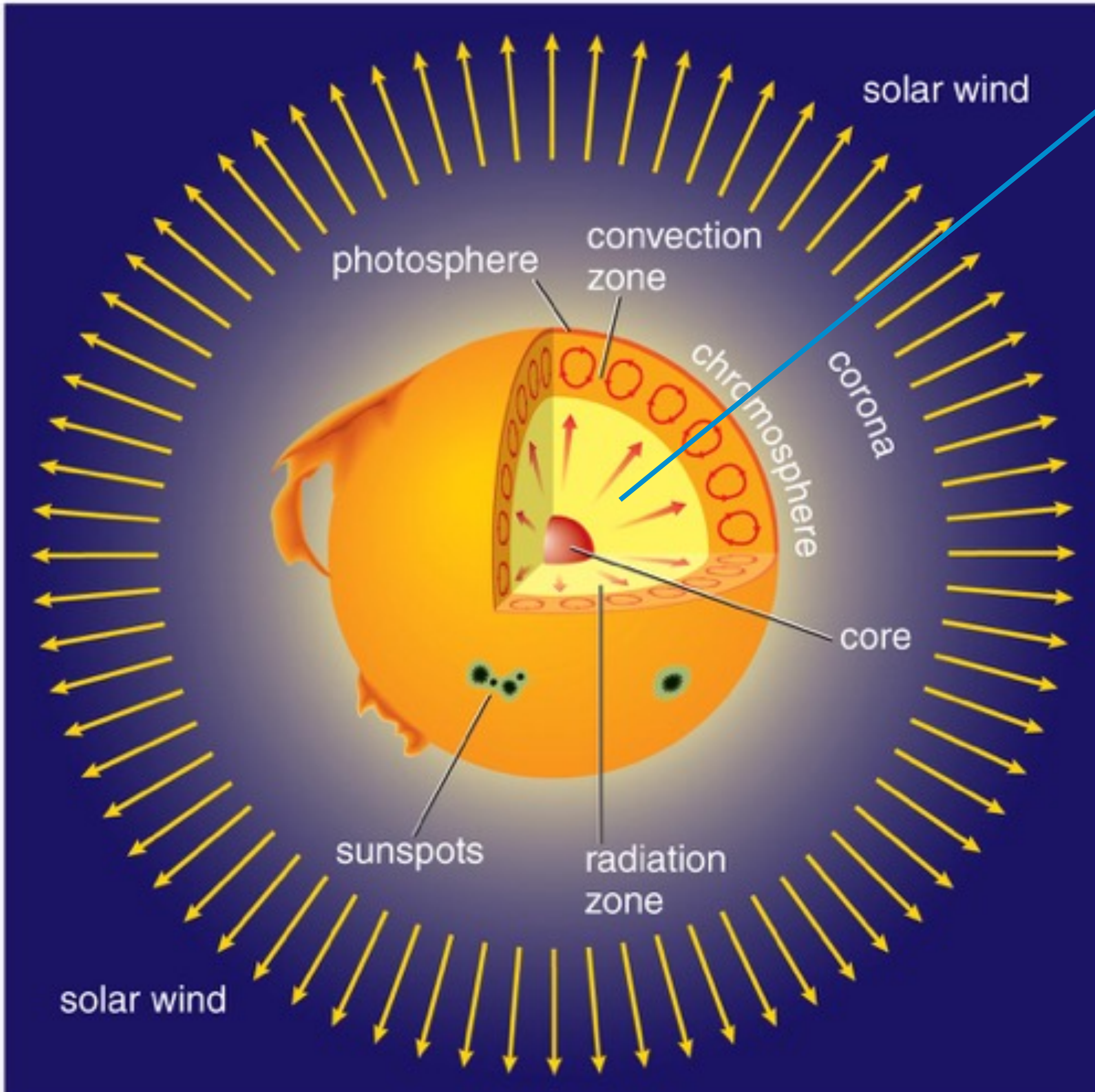
3.8×10^{26} watts



Core:

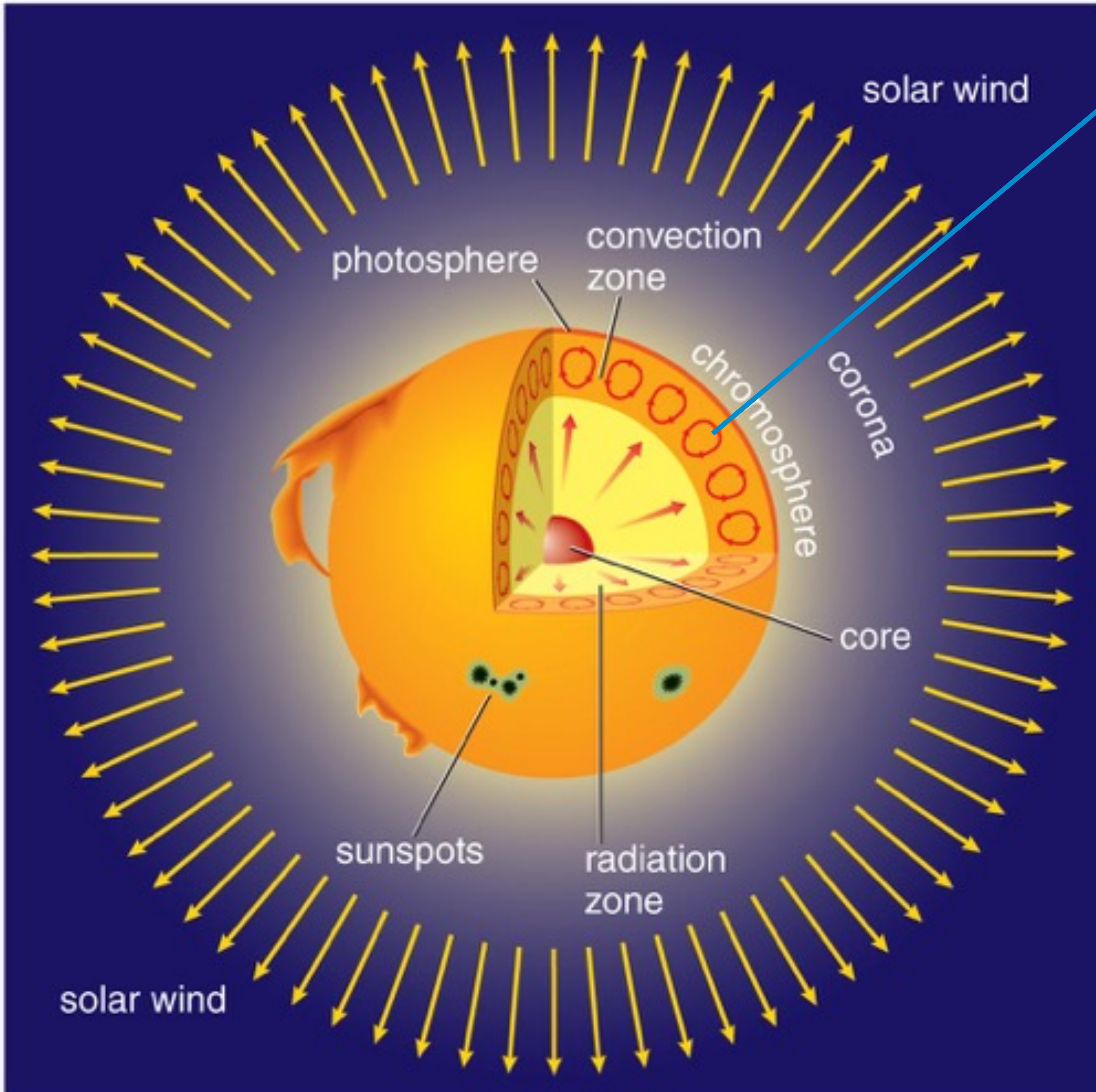
Energy generated by nuclear fusion

~ 15 million K



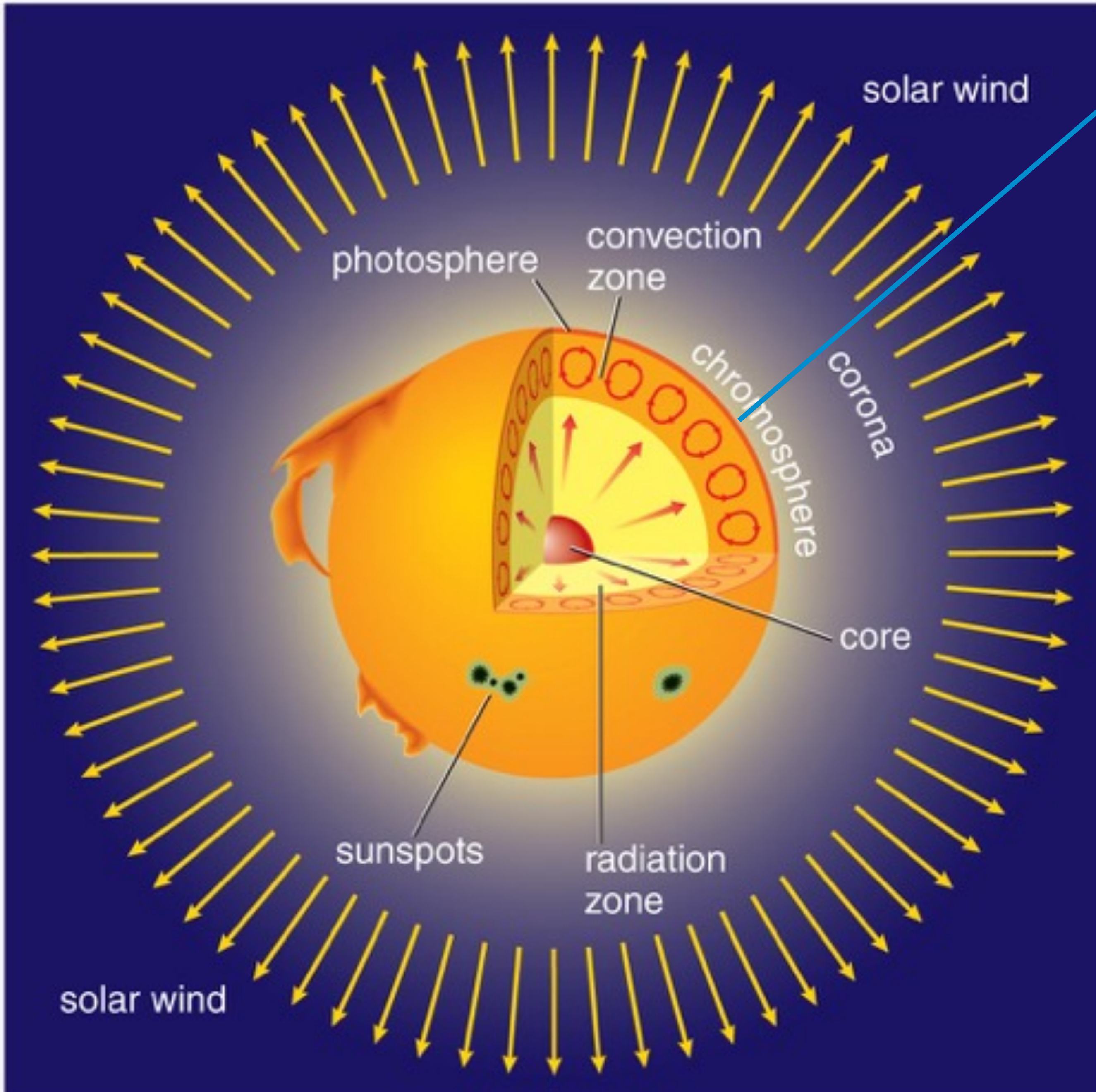
Radiation Zone:

Energy transported upward by photons



Convection Zone:

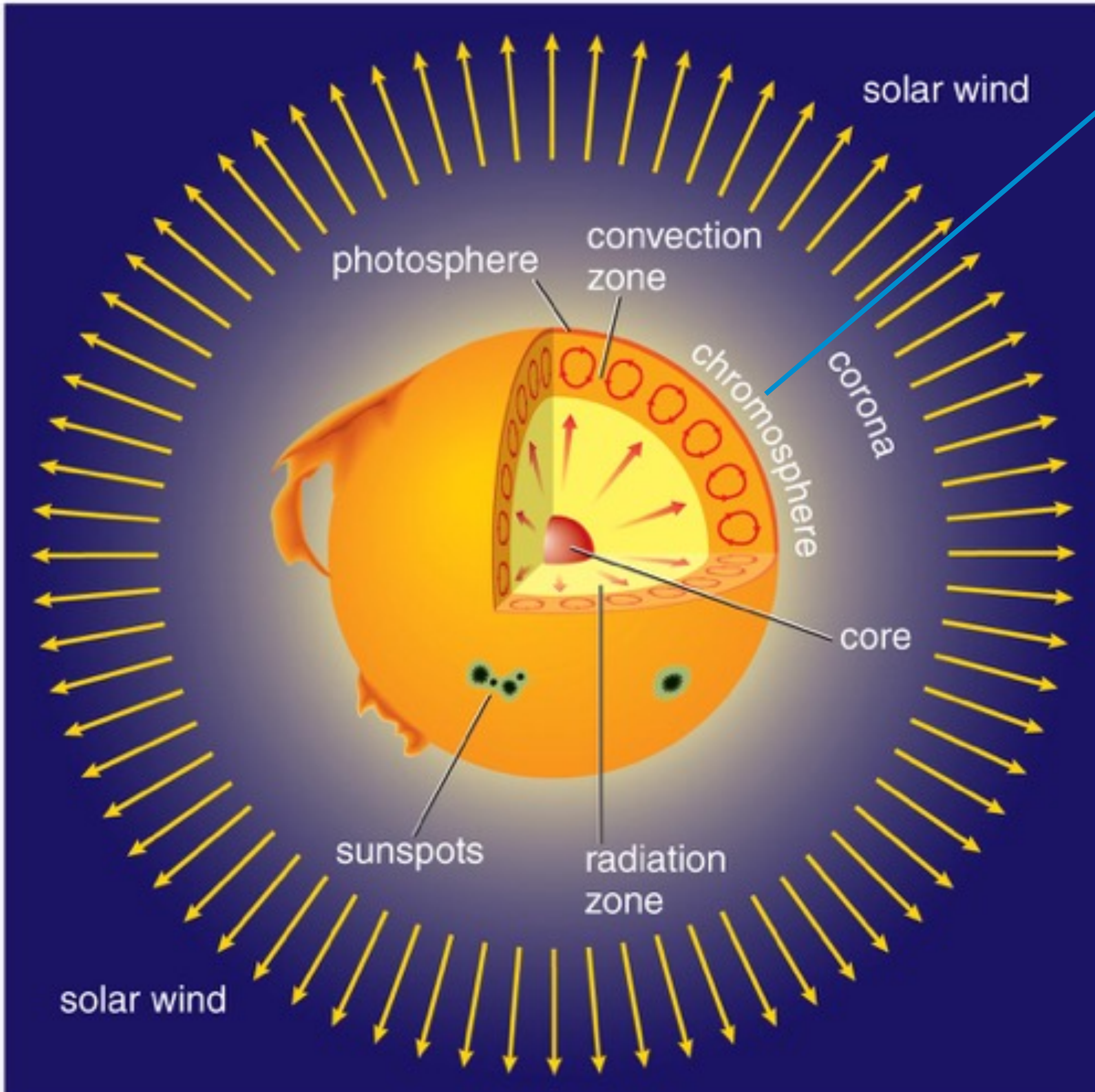
Energy transported upward by rising hot gas



Photosphere:

Visible surface of Sun

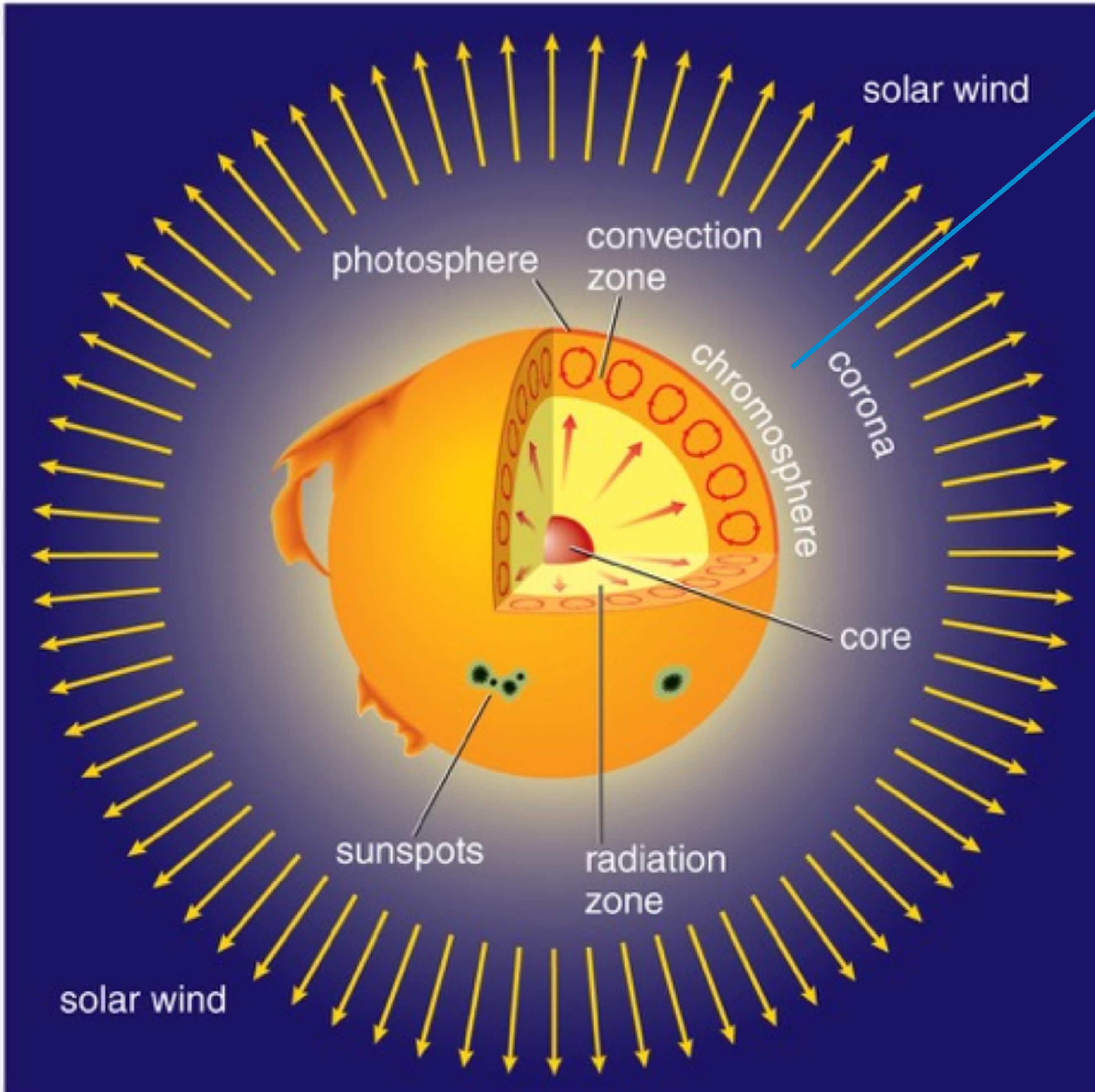
~ 6000 K



Chromosphere:

Middle layer of solar atmosphere

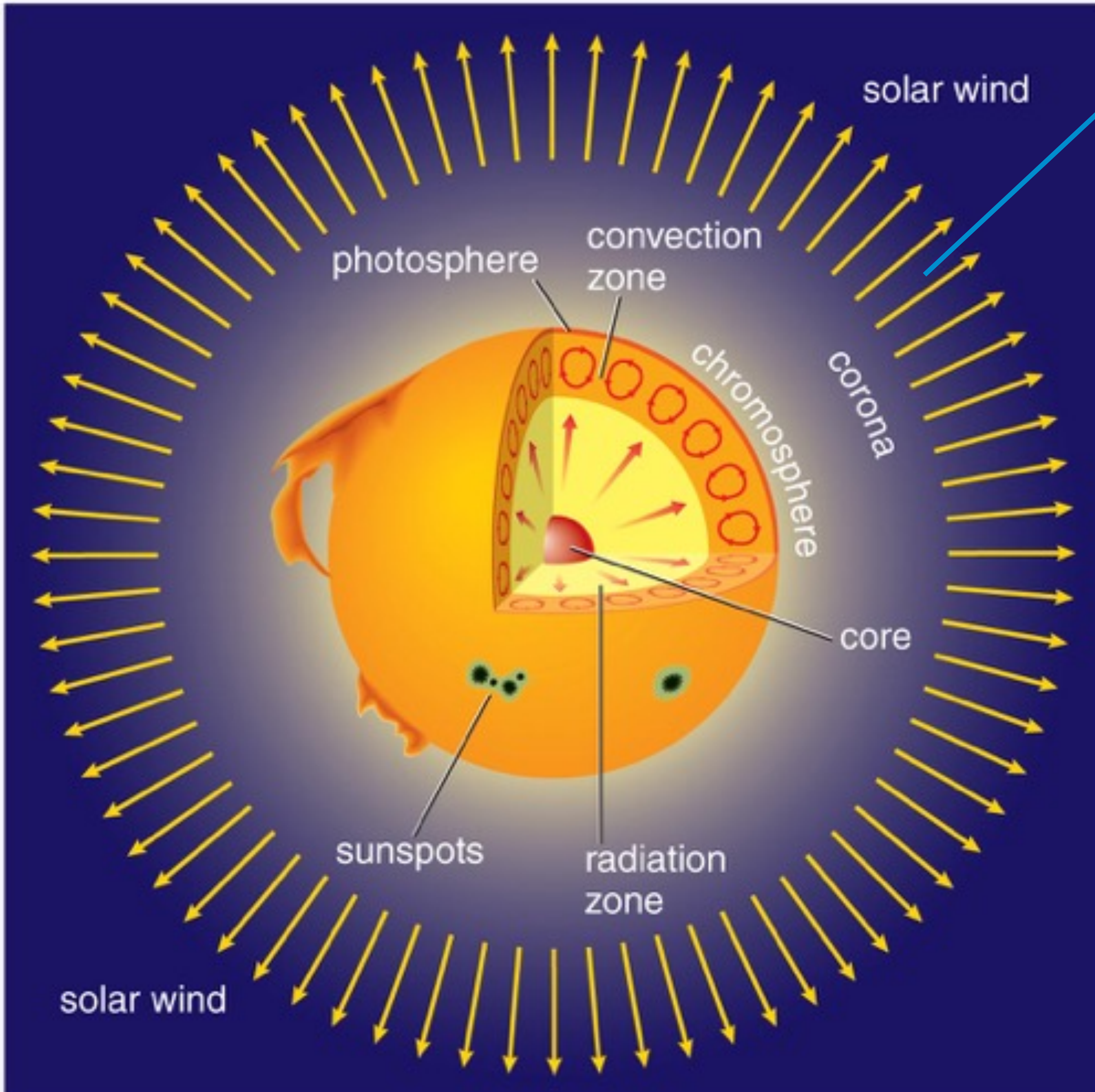
~ 10^4–10^5 K



Corona:

Outermost layer of solar atmosphere

~1 million K



Solar wind:

A flow of charged particles from the surface of the Sun

Chapter 14

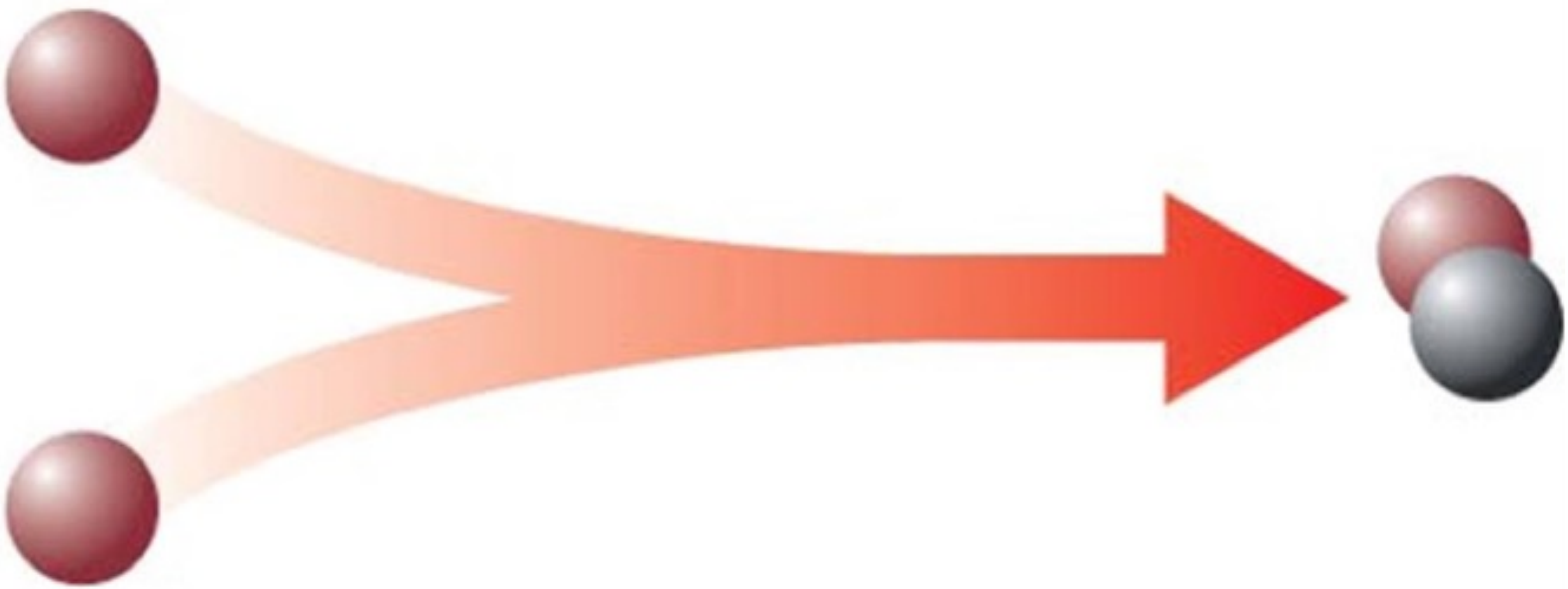
Which of the following parts of the Sun has the lowest temperature?

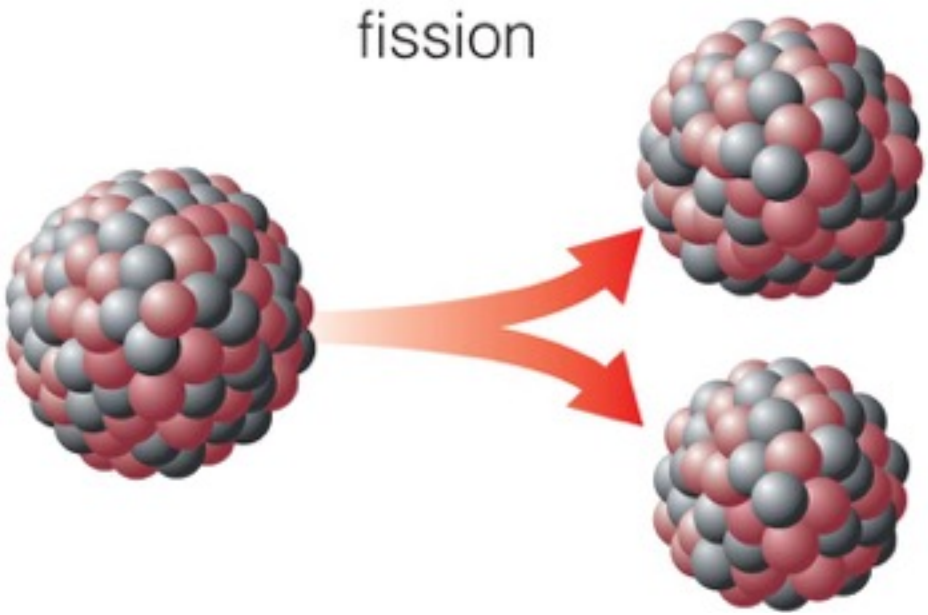
a) core
b) photosphere
c) chromosphere
d) corona

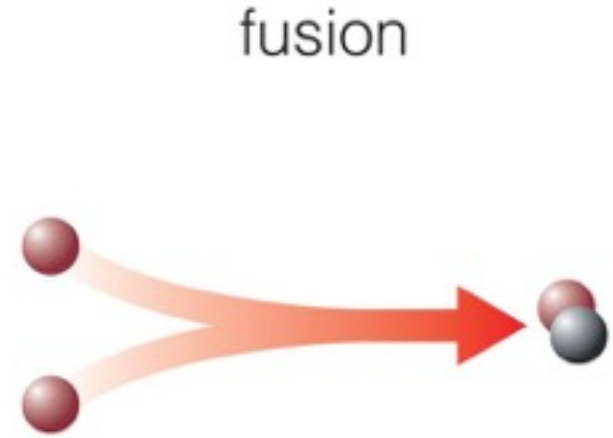
The Cosmic Crucible

- 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?

How does nuclear fusion occur in the Sun?







Fission

Big nucleus splits into smaller pieces.

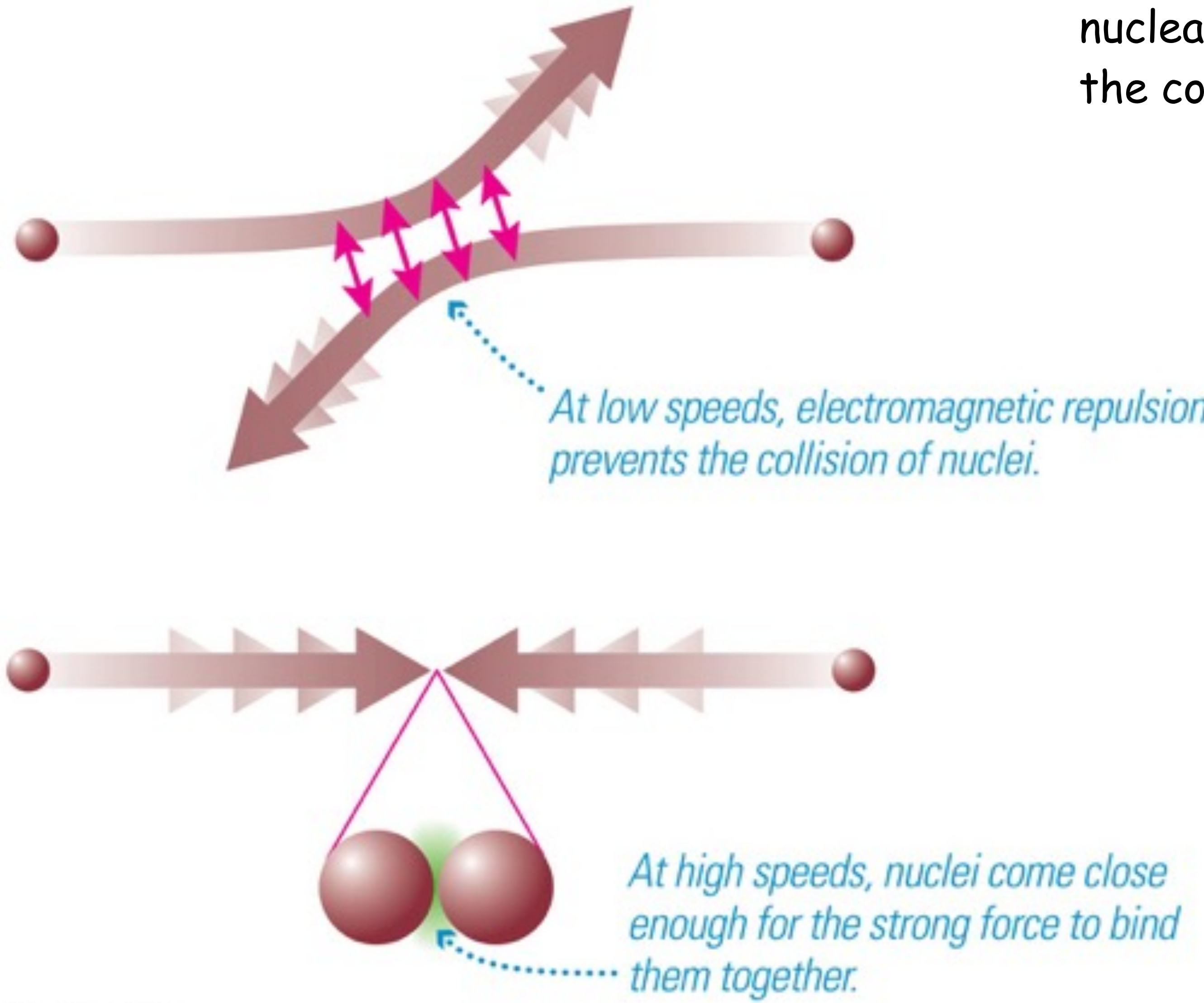
(Example: nuclear power plants)

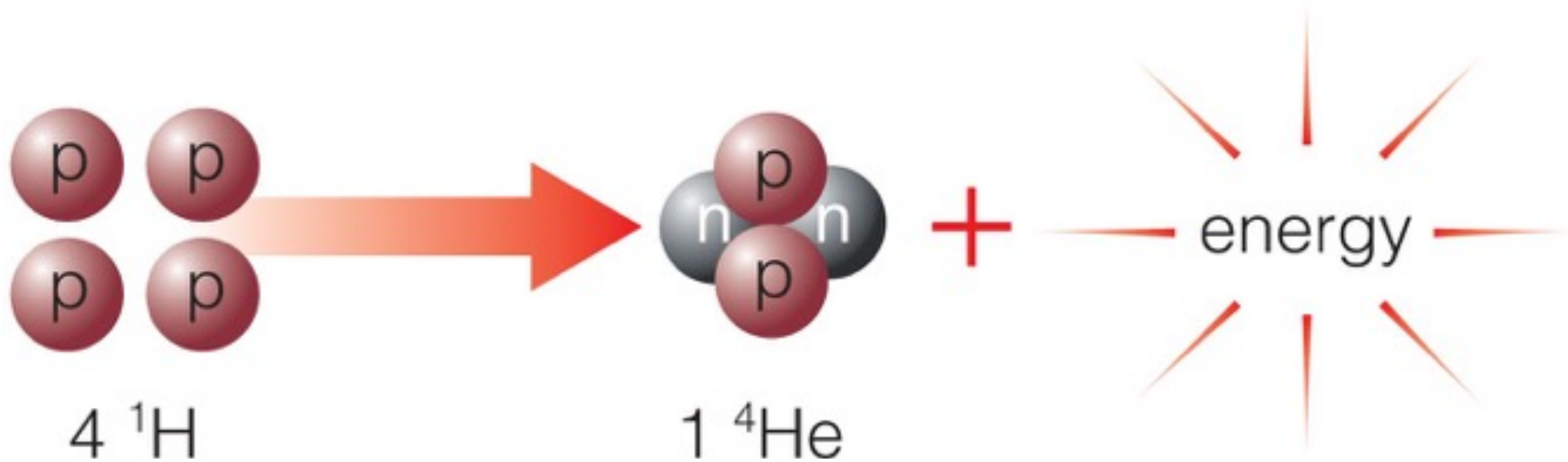
Fusion

Small nuclei stick together to make a bigger one.

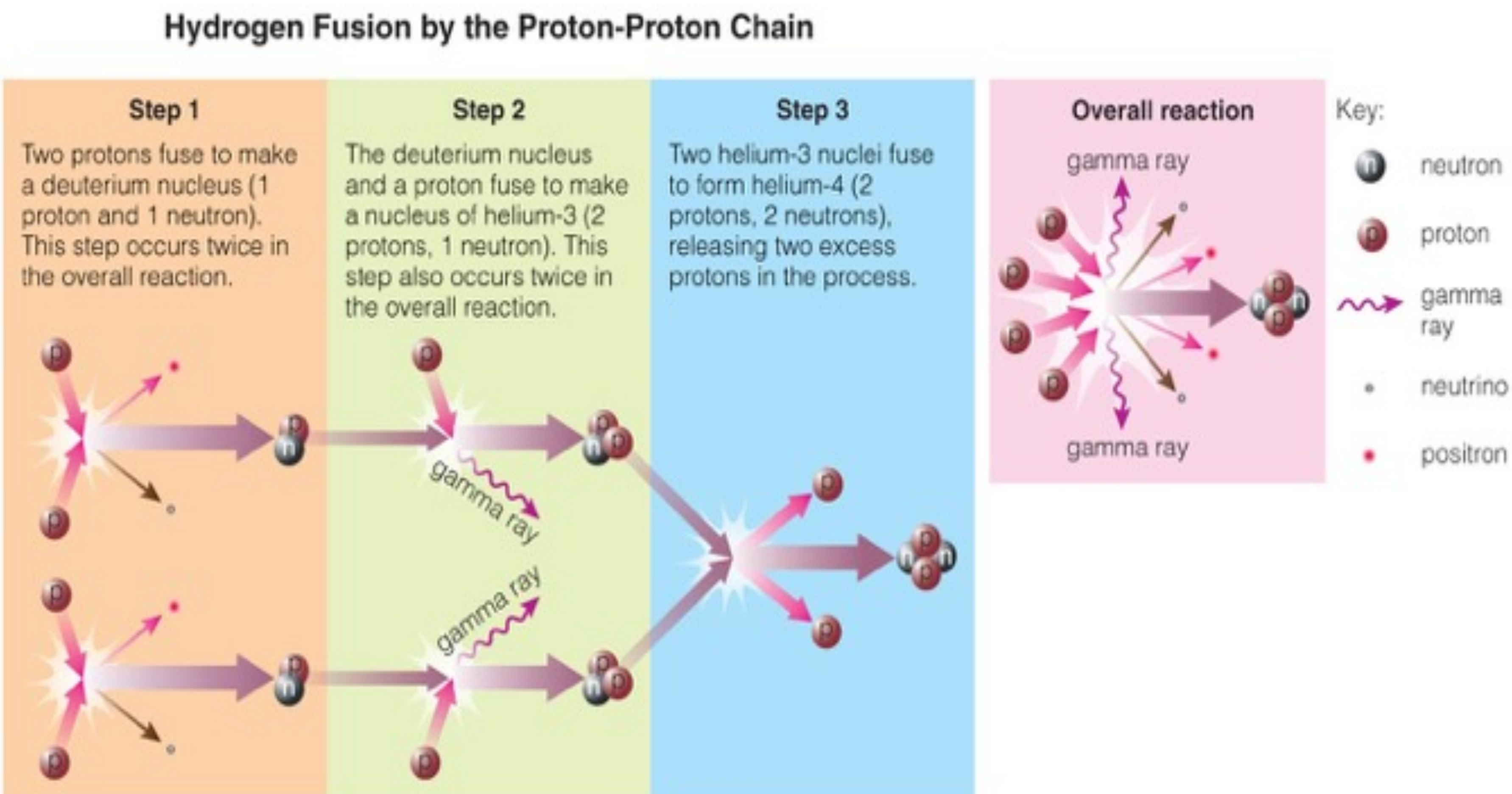
(Example: the Sun, stars)

High temperatures enable nuclear fusion to happen in the core.

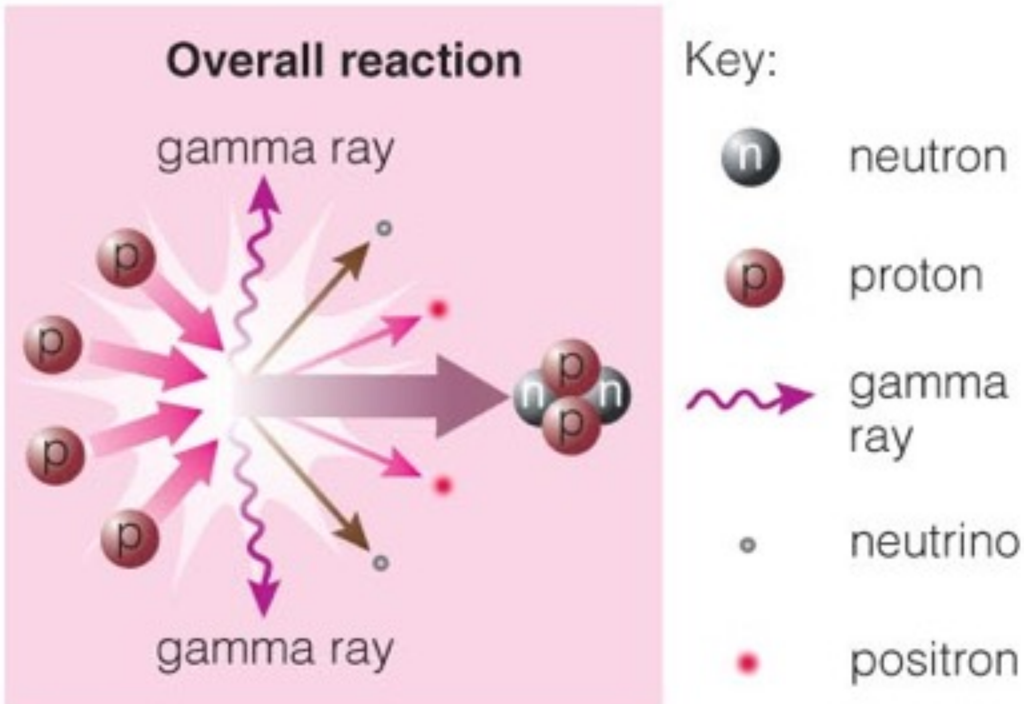




The Sun releases energy by fusing four hydrogen nuclei into one helium nucleus.



The proton–proton chain is how hydrogen fuses into helium in Sun.



<u>IN</u>

4 protons

<u>OUT</u>

^{4}He nucleus

2 gamma rays

2 positrons

2 neutrinos

Total mass is 0.7% lower.

Chapter 14

How do the nuclear reactions in the Sun's core produce energy?

a) The mass of the product of the reaction is greater than the mass of the hydrogen atoms that enter the reaction.
b) The mass of the product of the reaction is less than the mass of the hydrogen atoms that enter the reaction.
c) The chemical potential energy of the product of the reaction is greater than the chemical potential energy of the hydrogen atoms that enter the reaction.
d) The chemical potential energy of the product of the reaction is less than the chemical potential energy of the hydrogen atoms that enter the reaction.

What is the net fusion reaction that produces energy in the core of the Sun?

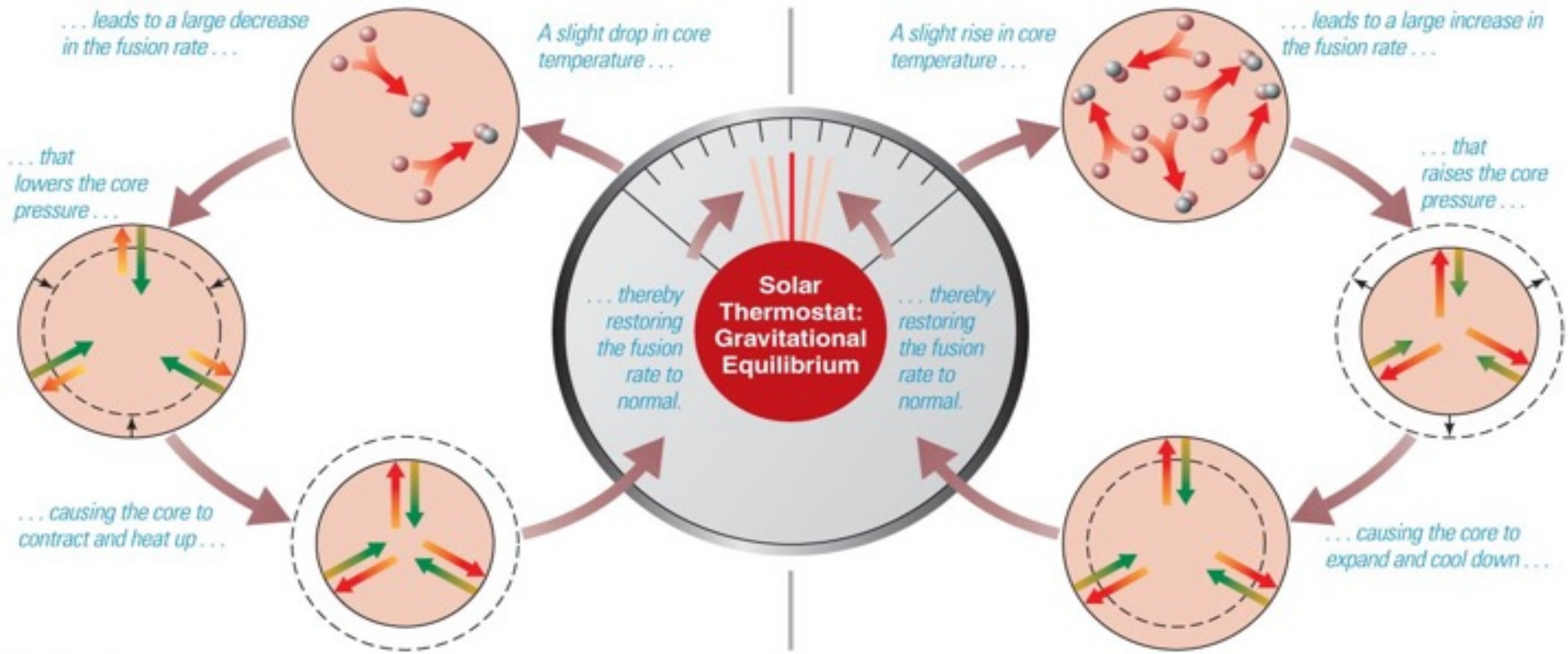
a) 4 hydrogen nuclei form 1 helium nucleus plus energy.
b) 2 hydrogen nuclei form 1 helium nucleus plus energy.
c) 6 hydrogen nuclei form 1 helium nucleus, 1 carbon nucleus plus energy.
d) 3 hydrogen nuclei form 1 helium nucleus plus energy.
e) 4 hydrogen nuclei form 1 helium nucleus, 1 carbon nucleus, plus energy.

Thought Question

What would happen inside the Sun if a slight rise in core temperature led to a rapid rise in fusion energy?

A. The core would expand and heat up slightly.
B. The core would expand and cool.
C. The Sun would blow up like a hydrogen bomb.

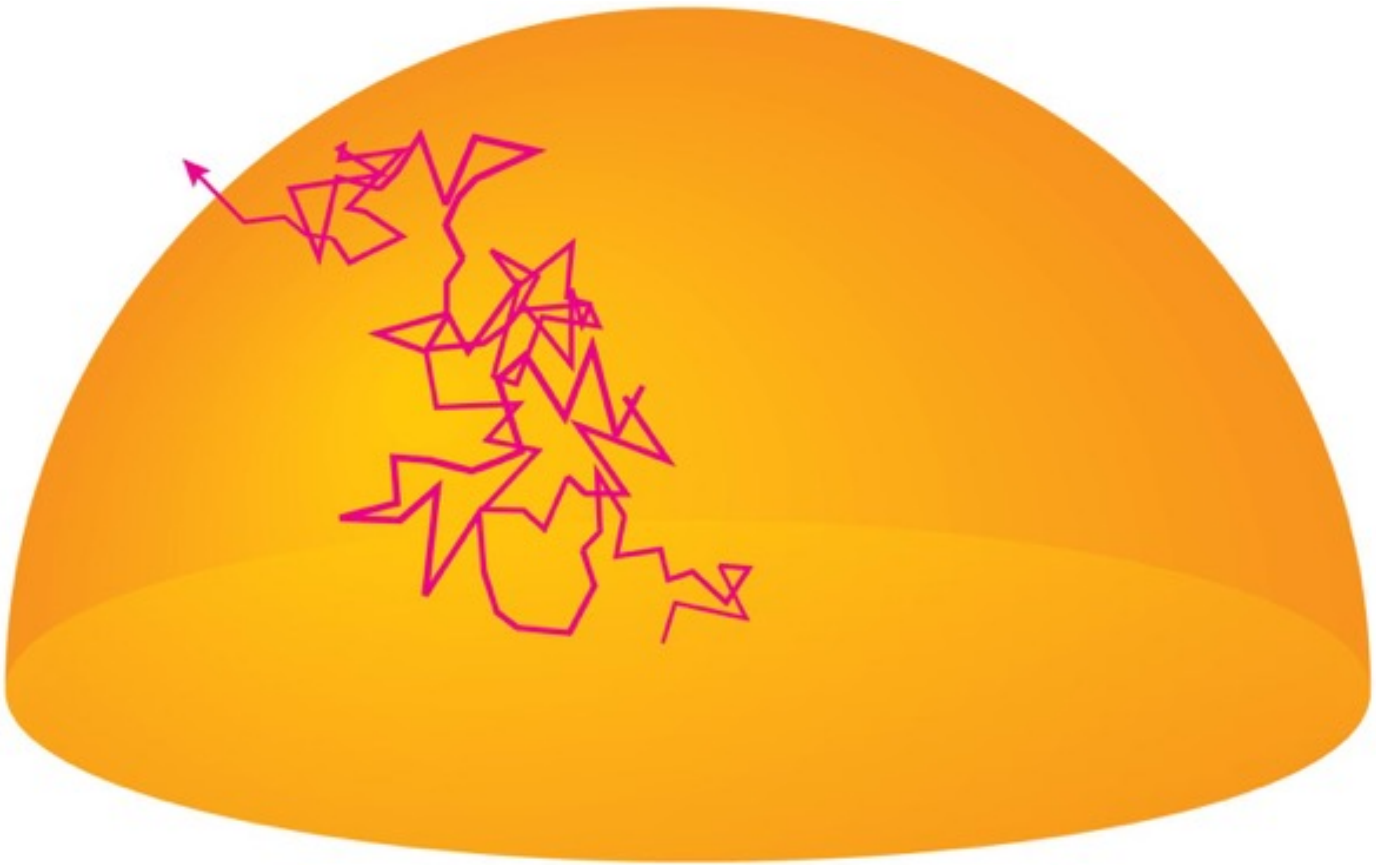
Solar Thermostat

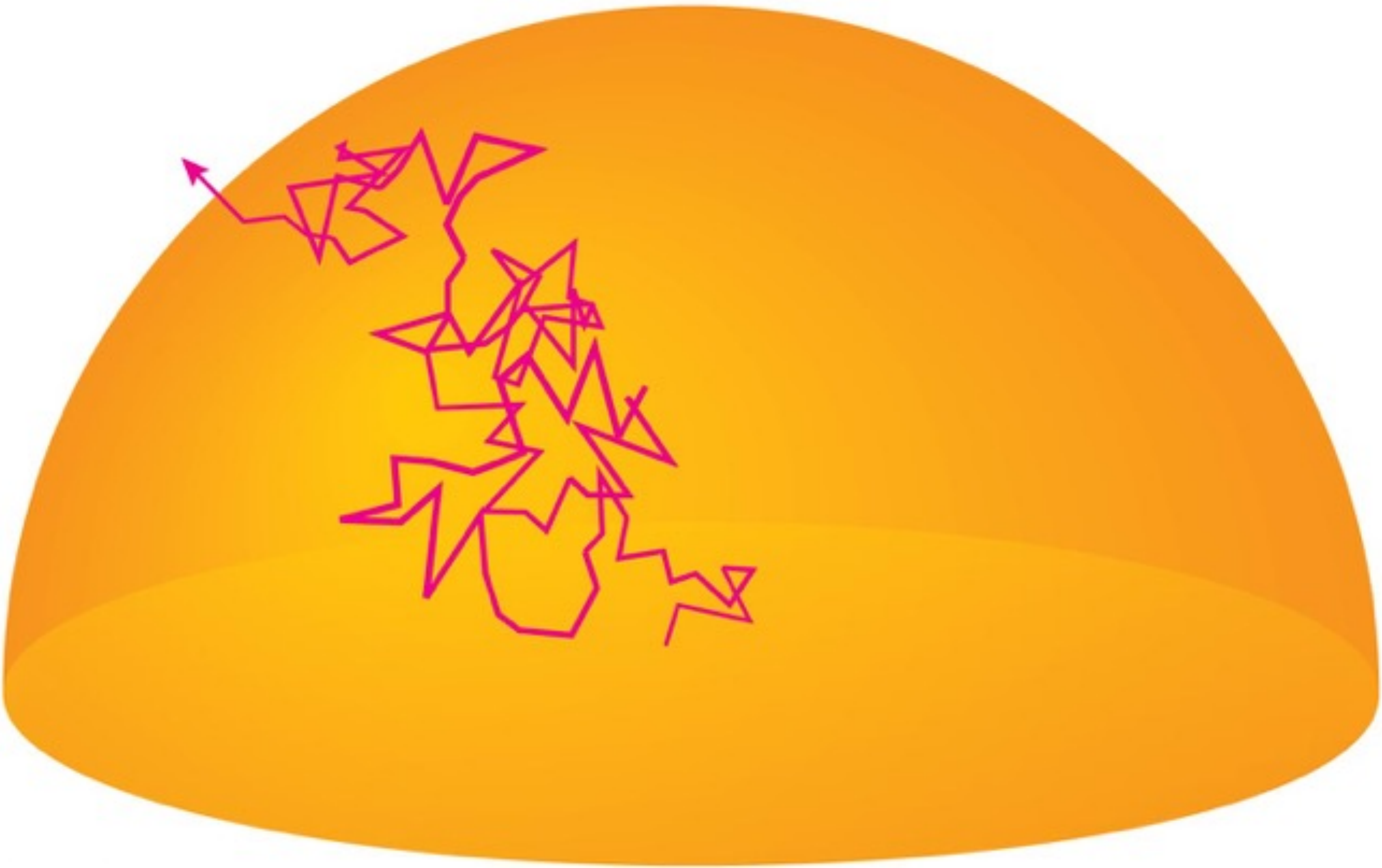


Decline in core temperature causes fusion rate to drop, so core contracts and heats up.

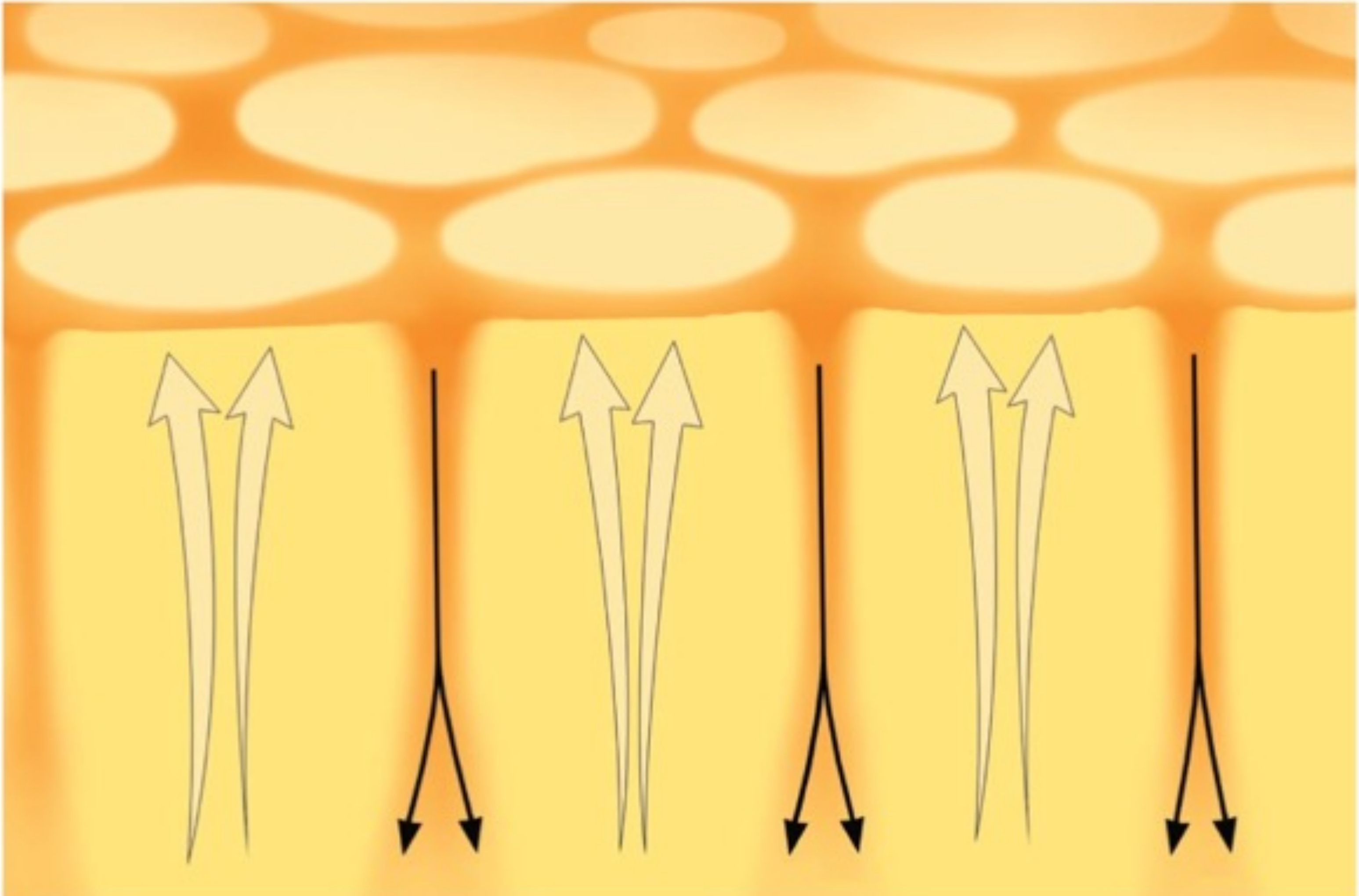
Rise in core temperature causes fusion rate to rise, so core expands and cools down.

How does the energy from fusion get out of the Sun?

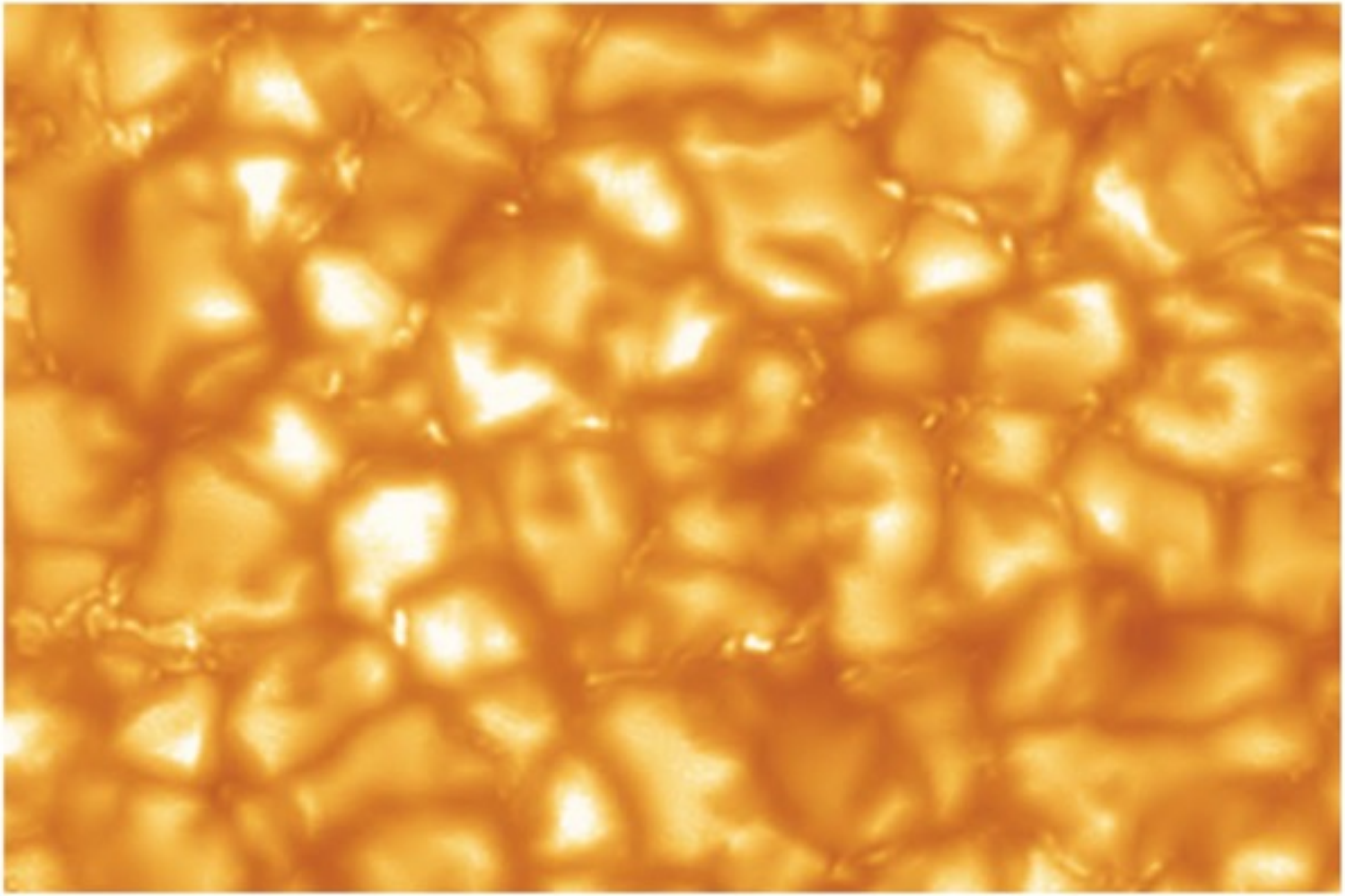




Energy gradually leaks out of radiation zone in form of randomly bouncing photons.



Convection (rising hot gas) takes energy to surface.



Bright blobs on photosphere show where hot gas is reaching the surface.

Chapter 14

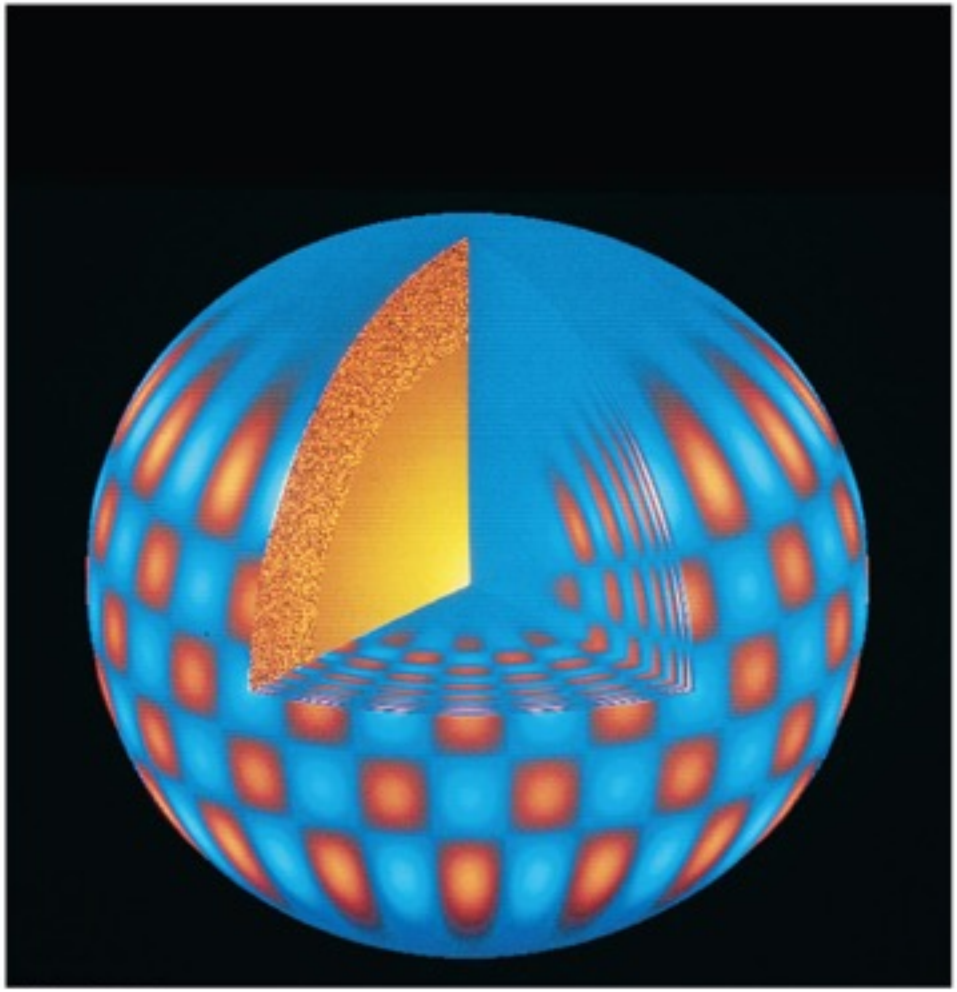
How long does it take for energy produced in the Sun's core to reach the photosphere?

a) a few seconds
b) a few hours
c) a few years
d) a few hundred years
e) a few hundred thousand years

What would happen if the temperature of the Sun's core increased suddenly?

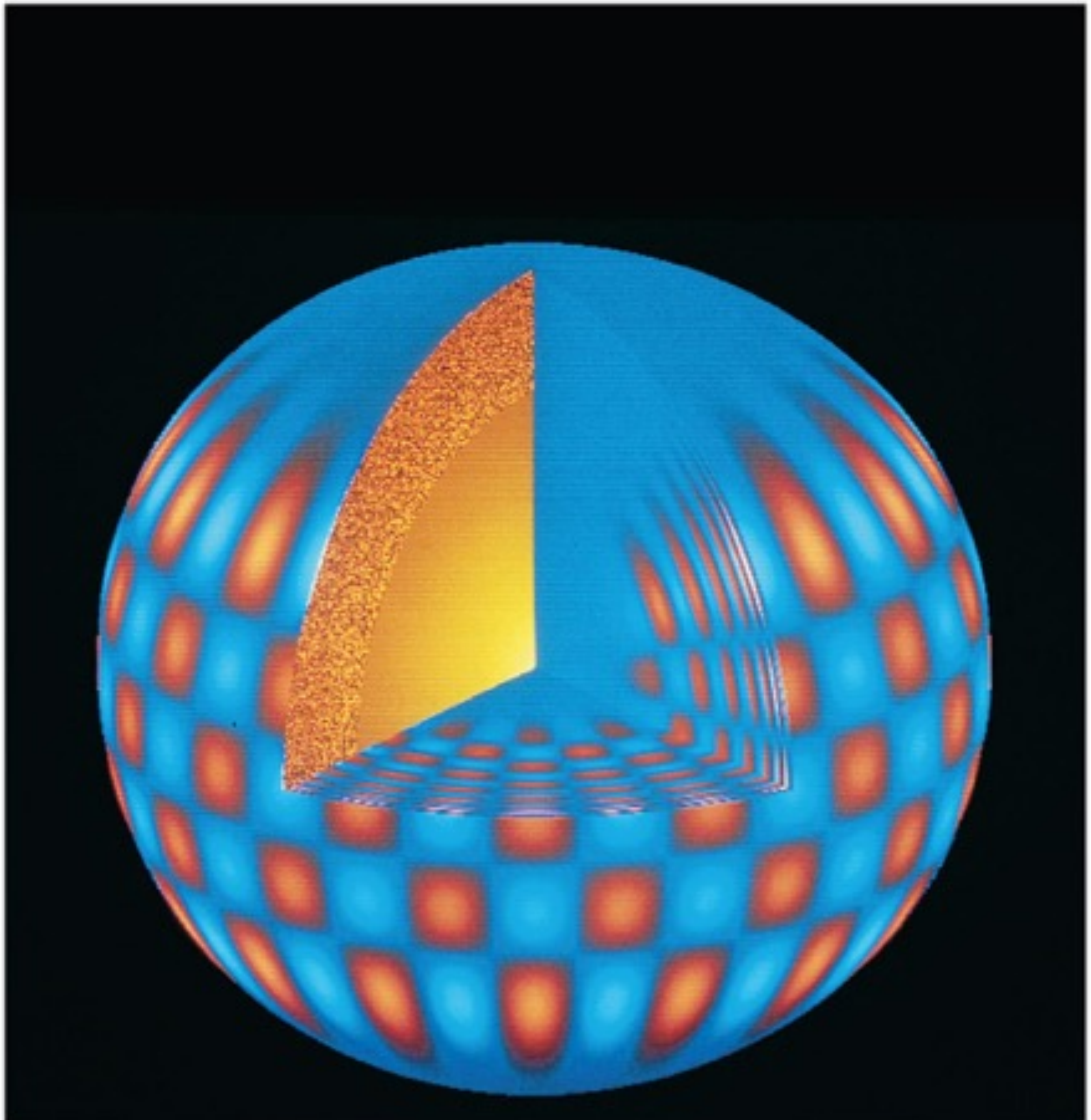
a) It would continue to increase in a runaway fusion reaction.
b) It would reach equilibrium at its new higher temperature with a higher rate of fusion.
c) The rate of fusion would increase causing the core to expand and cool back to its original temperature.
d) The Sun would undergo continuing oscillations in temperature and fusion reactions.

How we know what is happening inside the Sun?

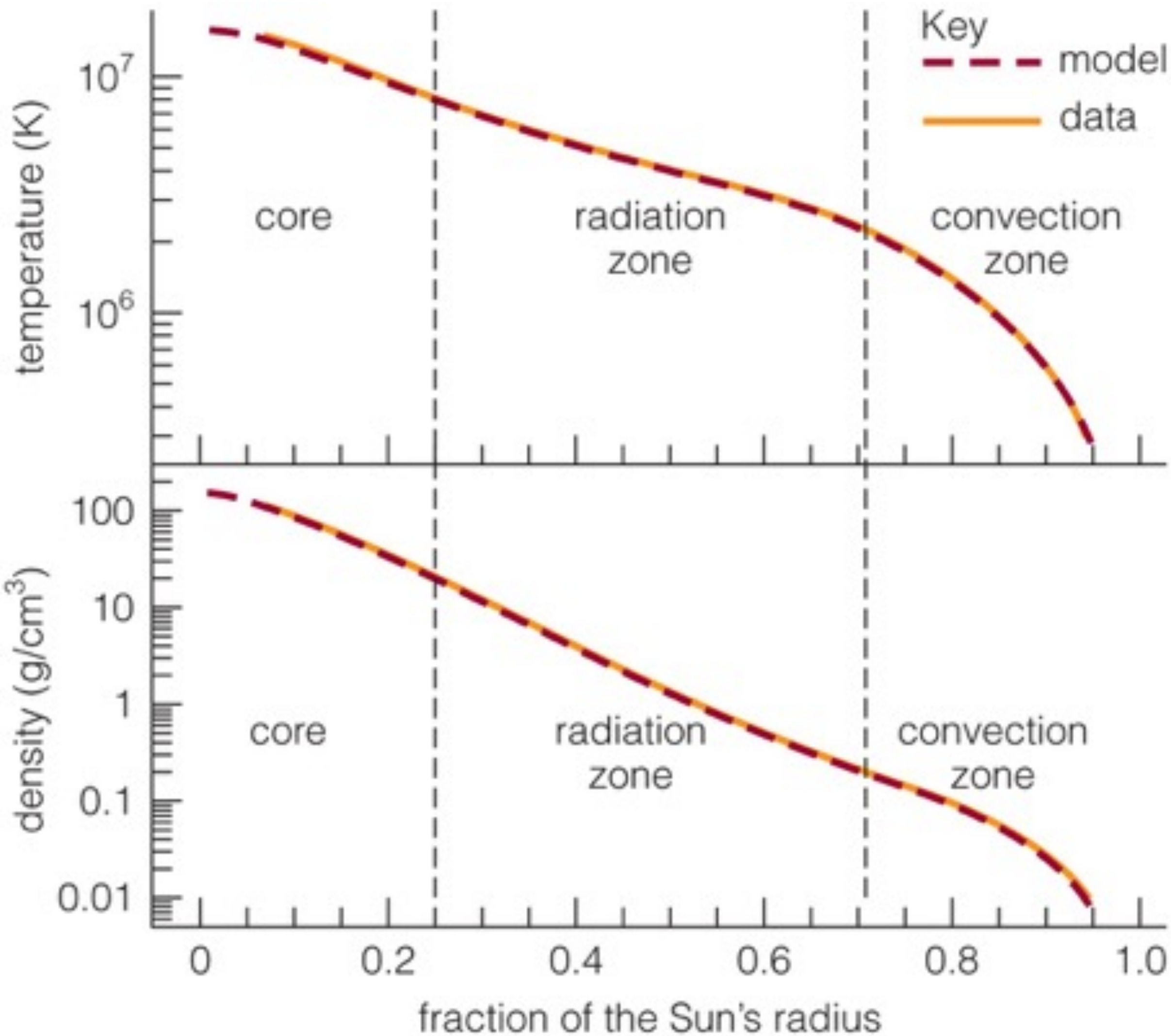


We learn about the inside of the Sun by …

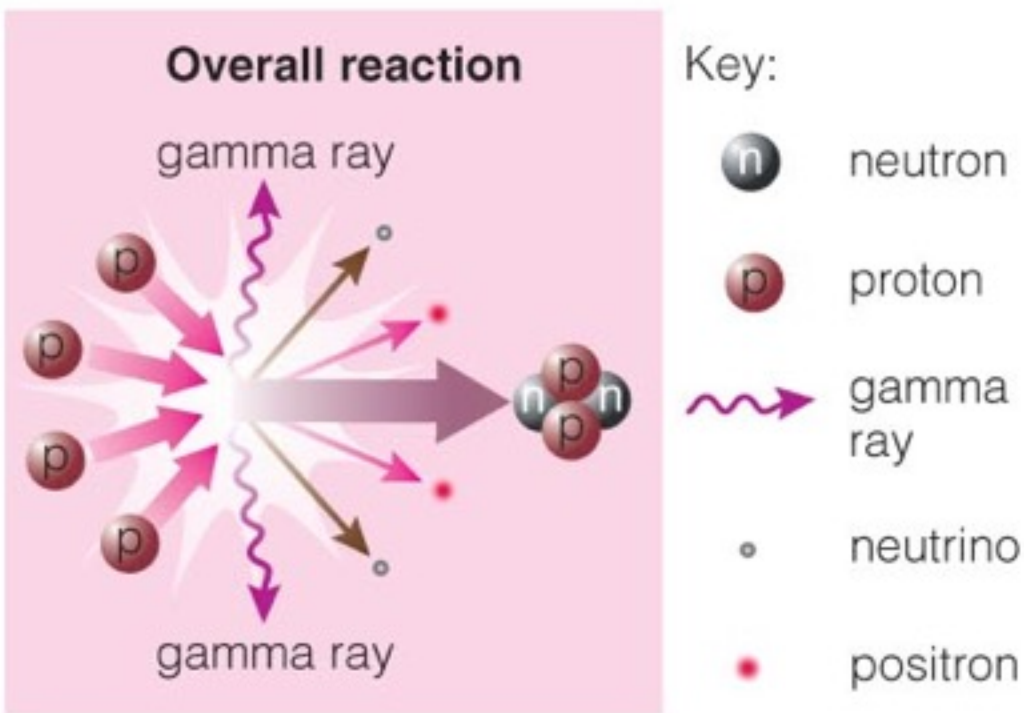
- making mathematical models
- observing solar vibrations
- observing solar neutrinos



Patterns of vibration on the surface tell us about what the Sun is like inside.

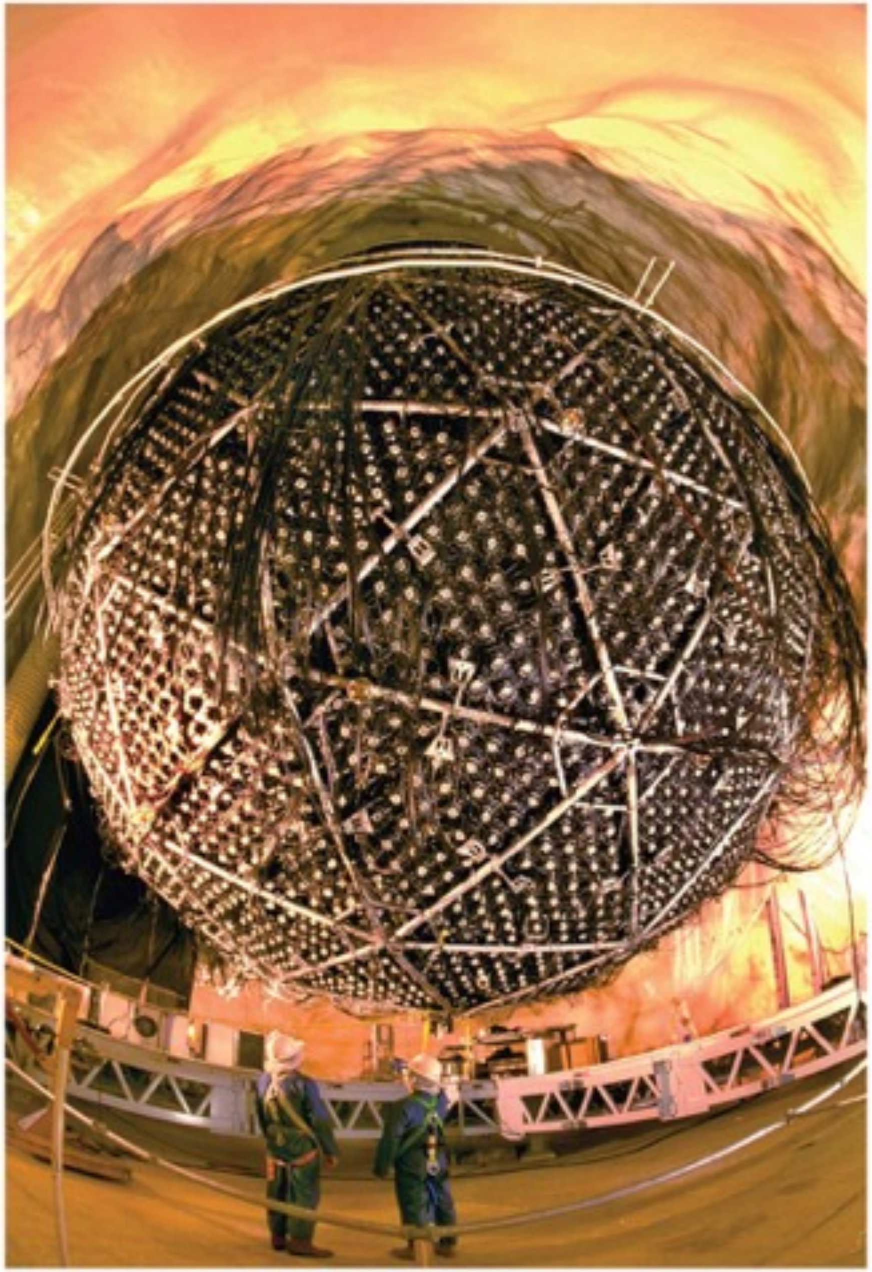


Data on solar vibrations agree very well with mathematical models of solar interior.



Neutrinos created during fusion fly directly through the Sun.

Observations of these solar neutrinos can tell us what's happening in core.



Solar neutrino problem:

Early searches for solar neutrinos failed to find the predicted number.

More recent observations find the right number of neutrinos, but some have changed form.

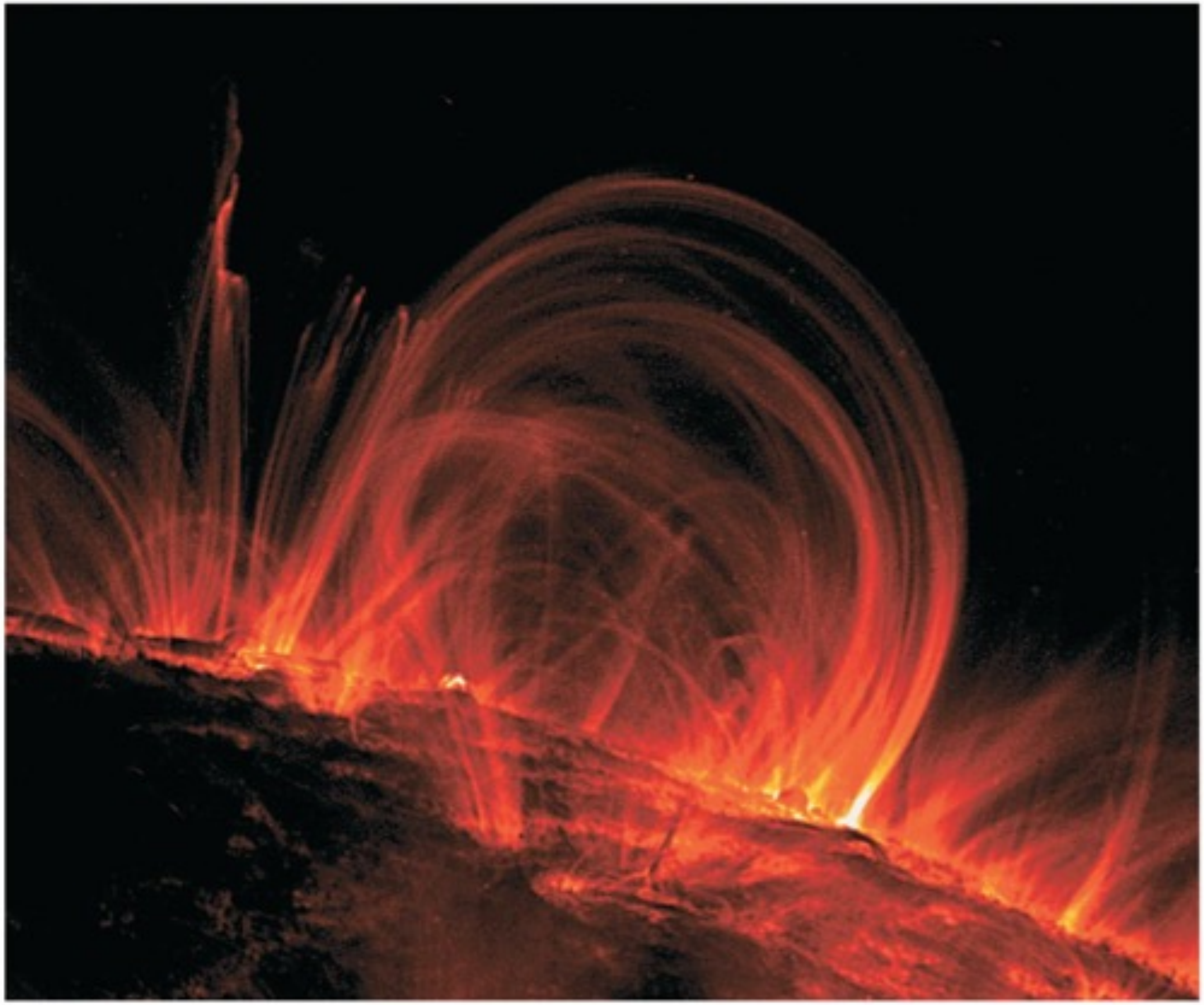
How can we observe nuclear fusion in the Sun's core?

a) We can't.
b) We can observe neutrinos produced in the core.
c) We can observe positrons produced in the core.
d) We can observe high energy gamma rays produced in the core.

The Sun-Earth Connection

- What causes solar activity?
- How does solar activity affect humans?
- How does solar activity vary with time?

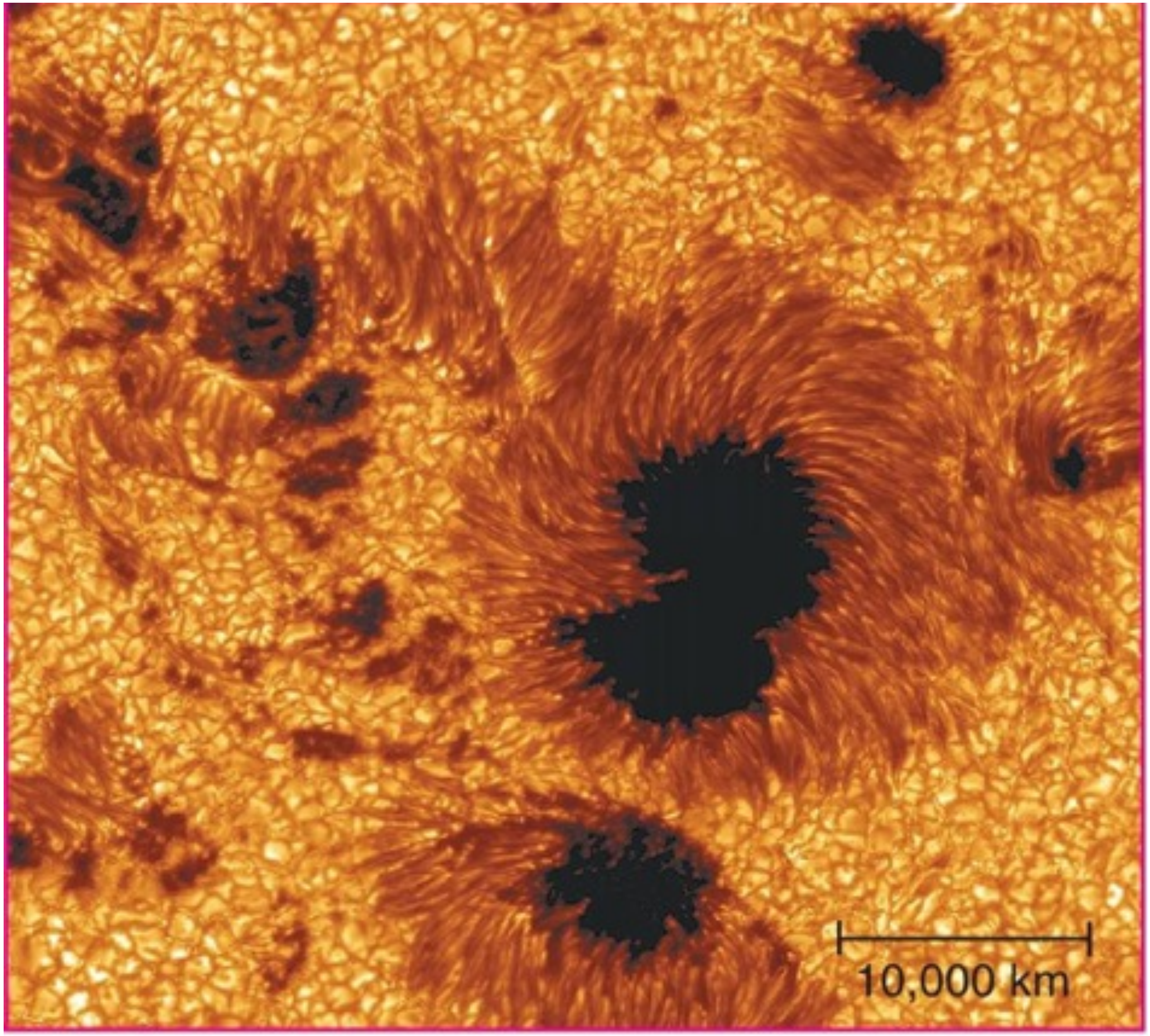
What causes solar activity?



Solar activity is like “weather”.

- Sunspots
- Solar flares
- Solar prominences

All these phenomena are related to magnetic fields.



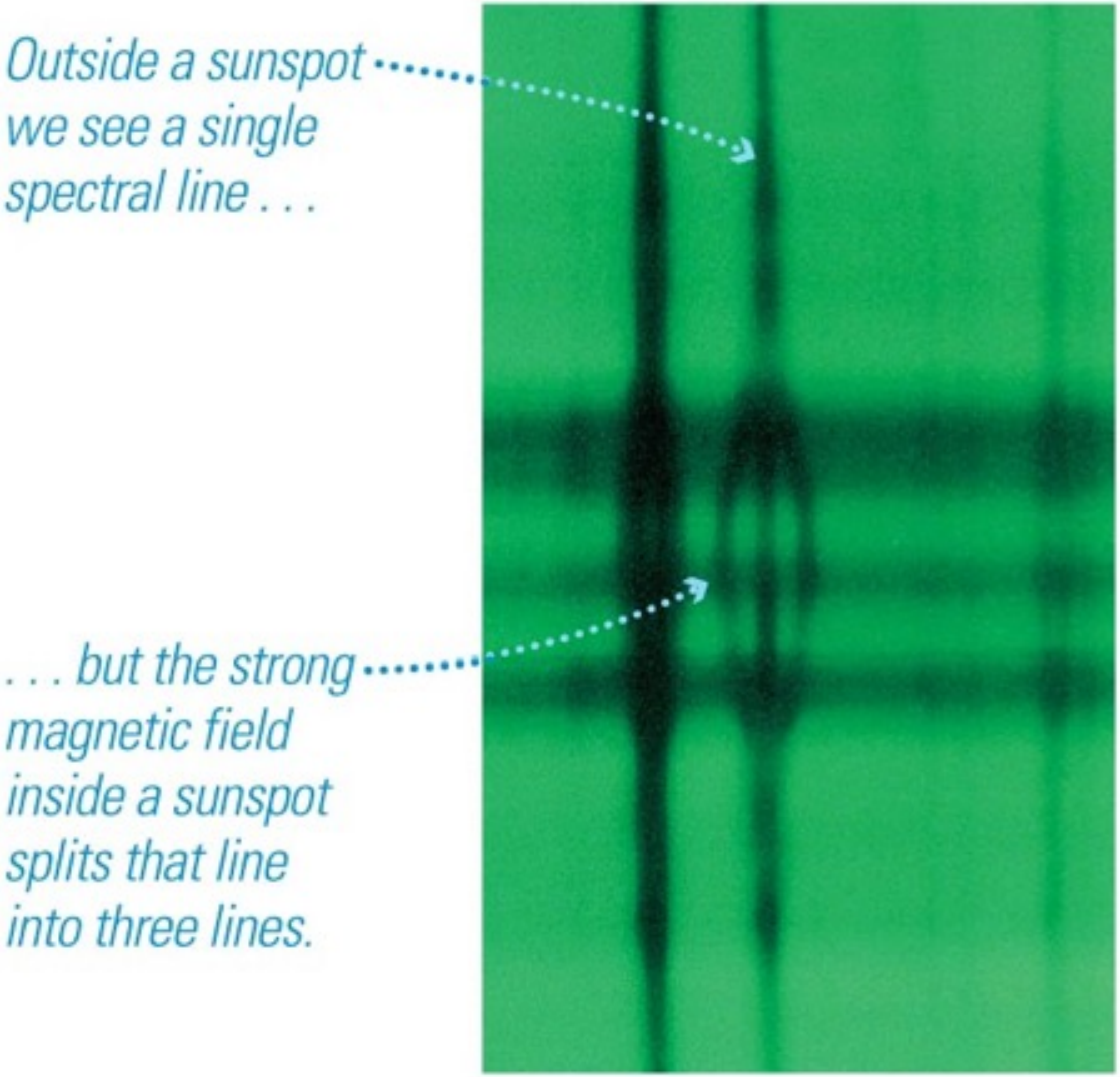
Sunspots

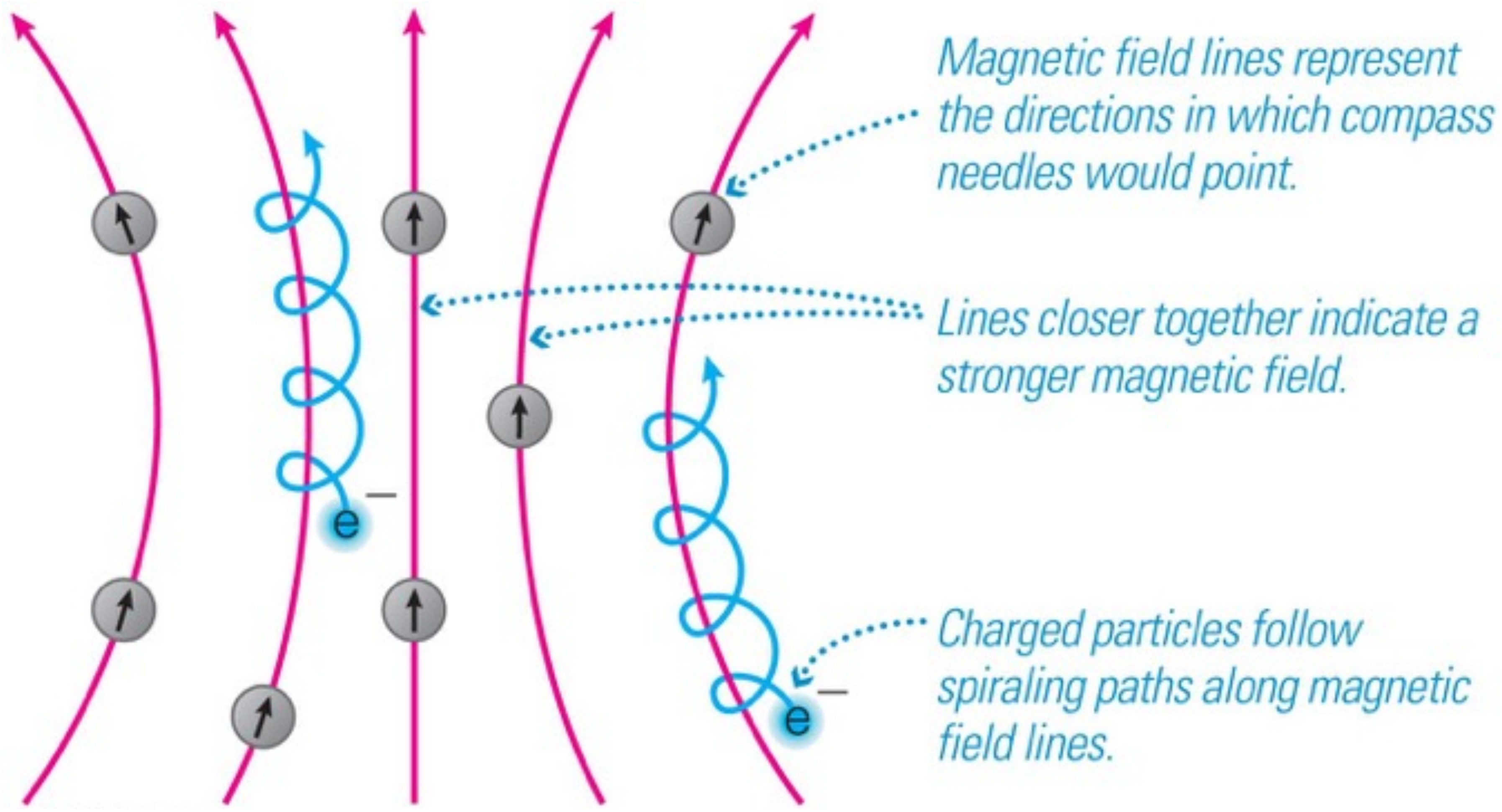
Are cooler than other parts of the Sun’s surface (4000 K)

Are regions with strong magnetic fields

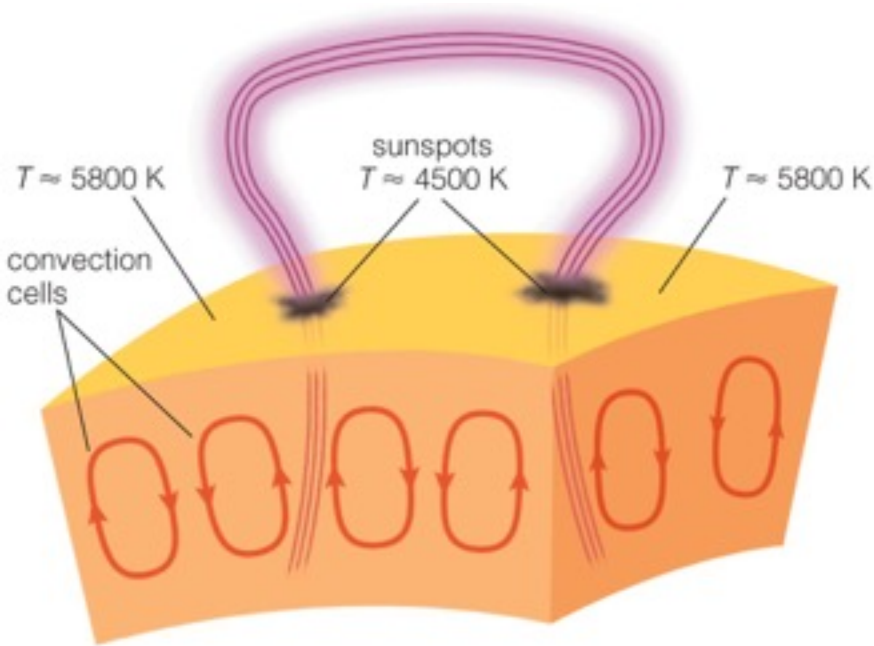
Zeeman Effect

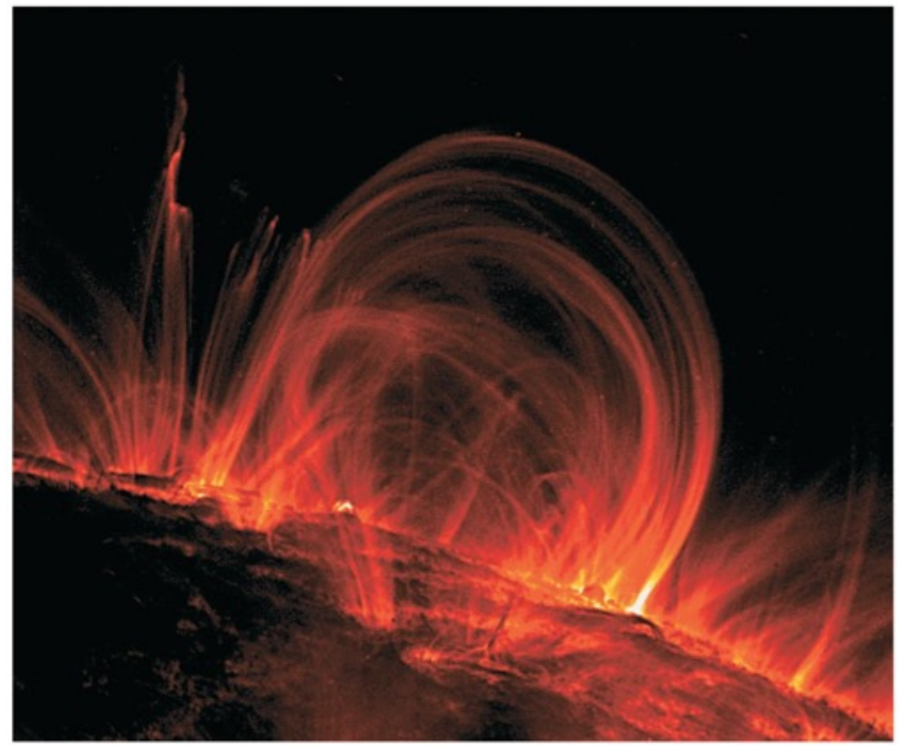
We can measure magnetic fields in sunspots by observing the splitting of spectral lines.



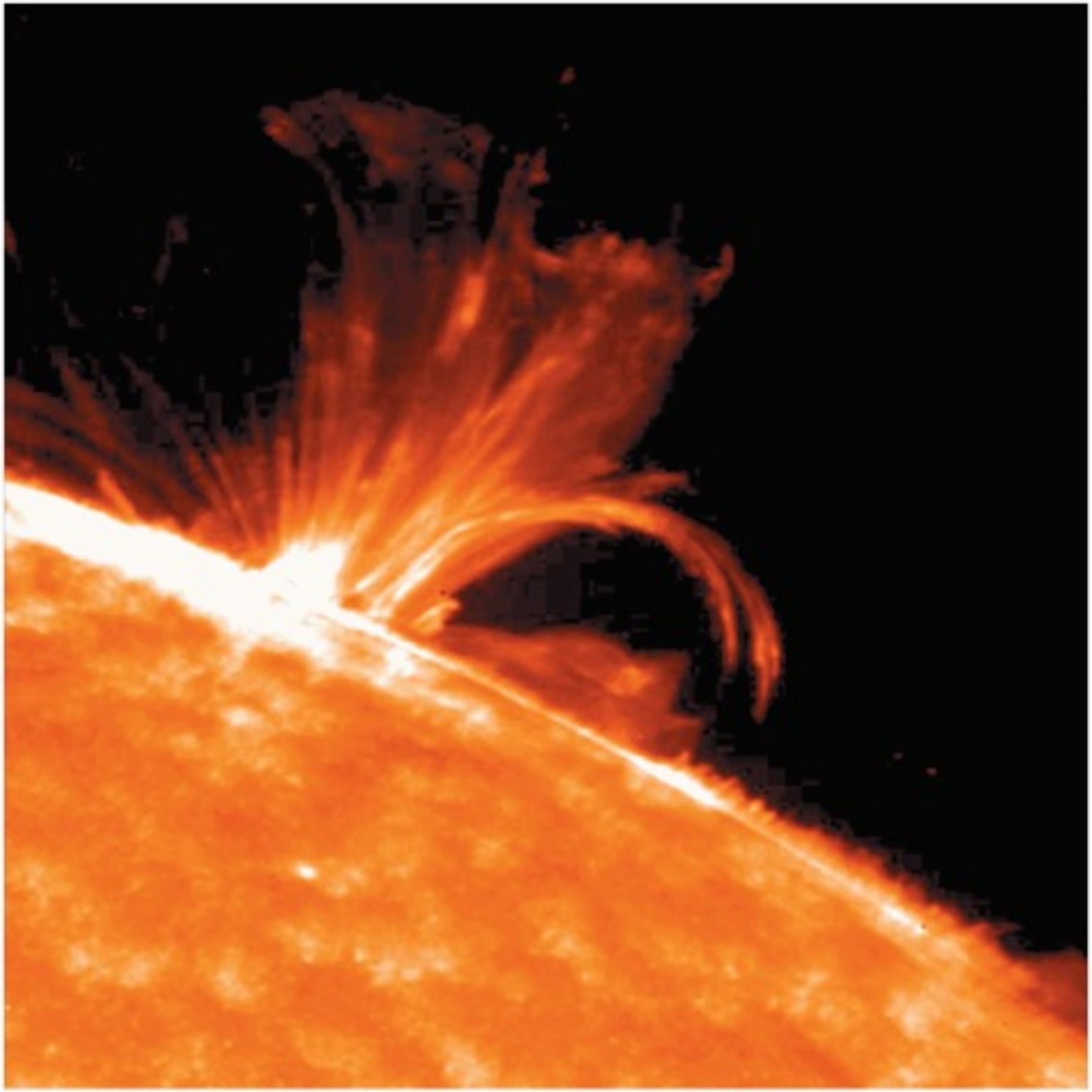


Charged particles spiral along magnetic field lines.

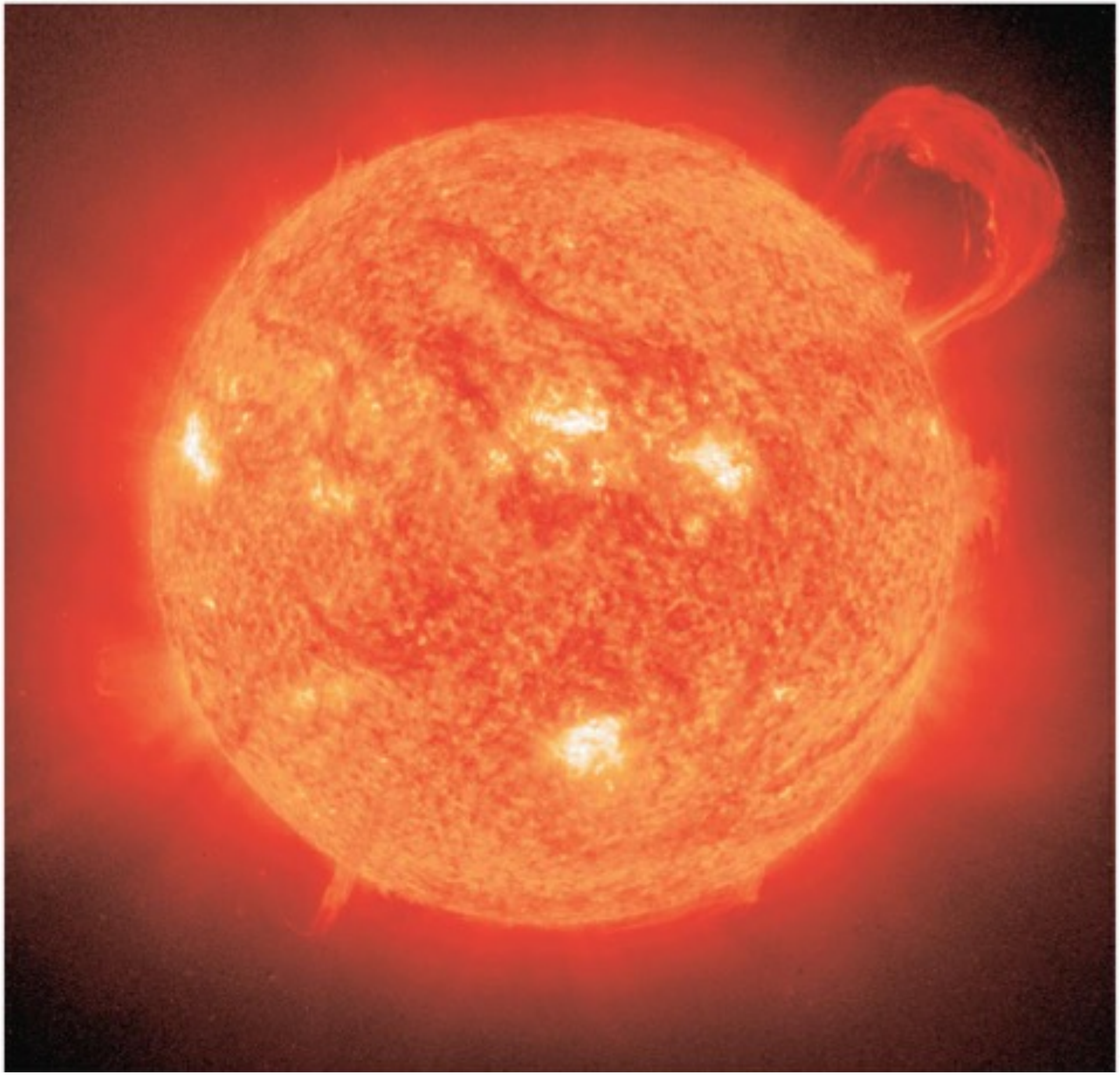




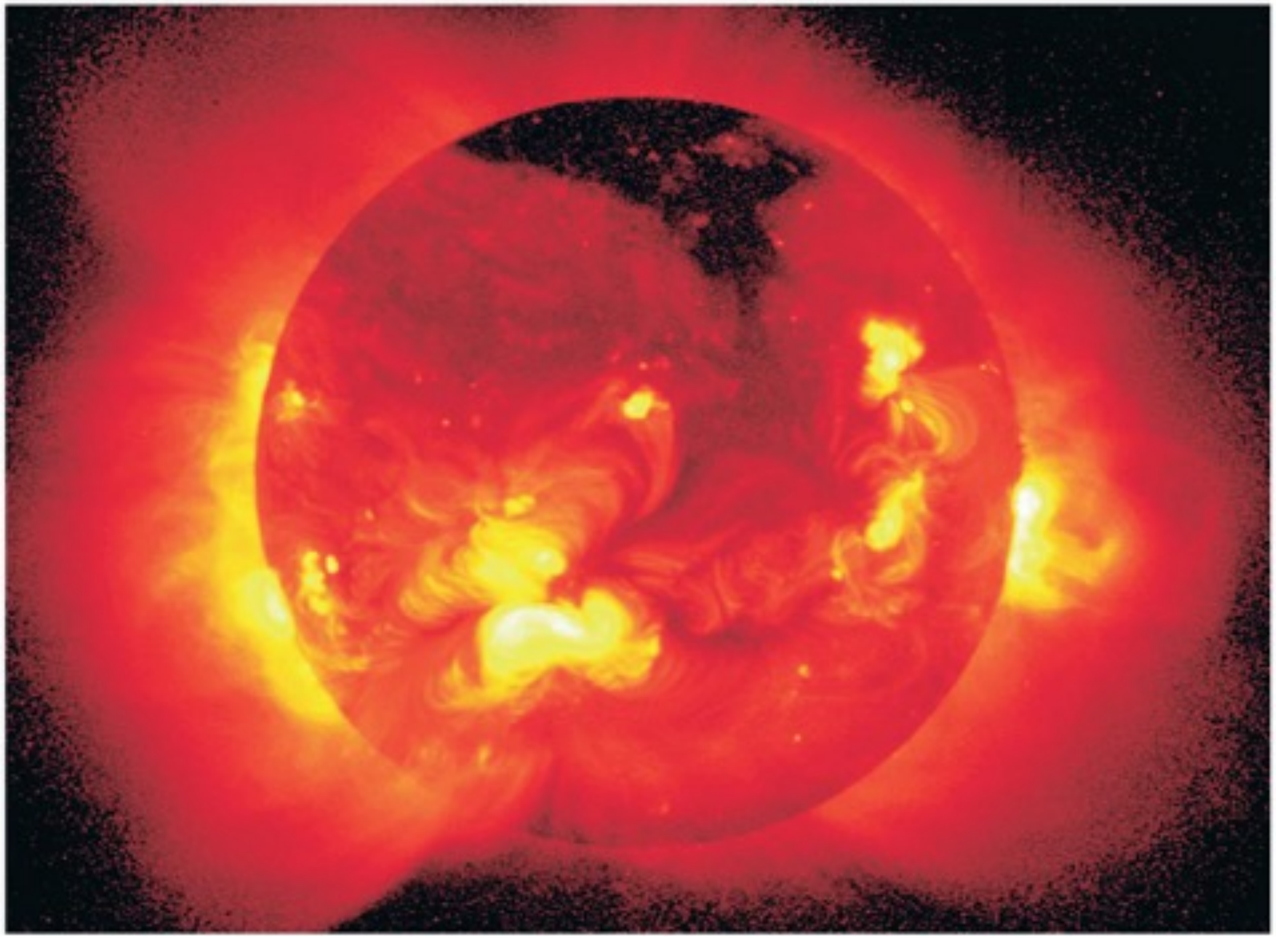
Loops of bright gas often connect sunspot pairs.



Magnetic activity causes solar flares that send bursts of X rays and charged particles into space.

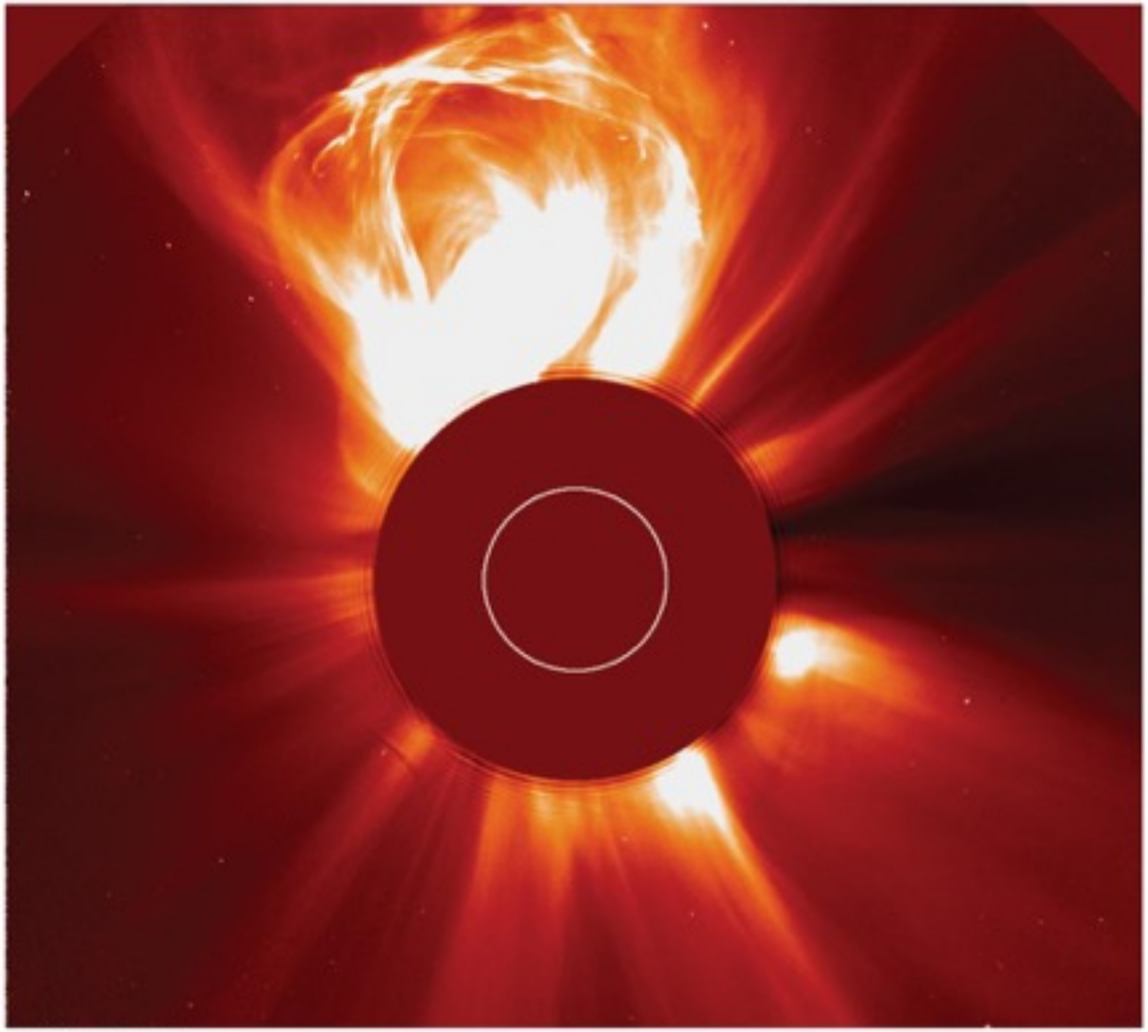


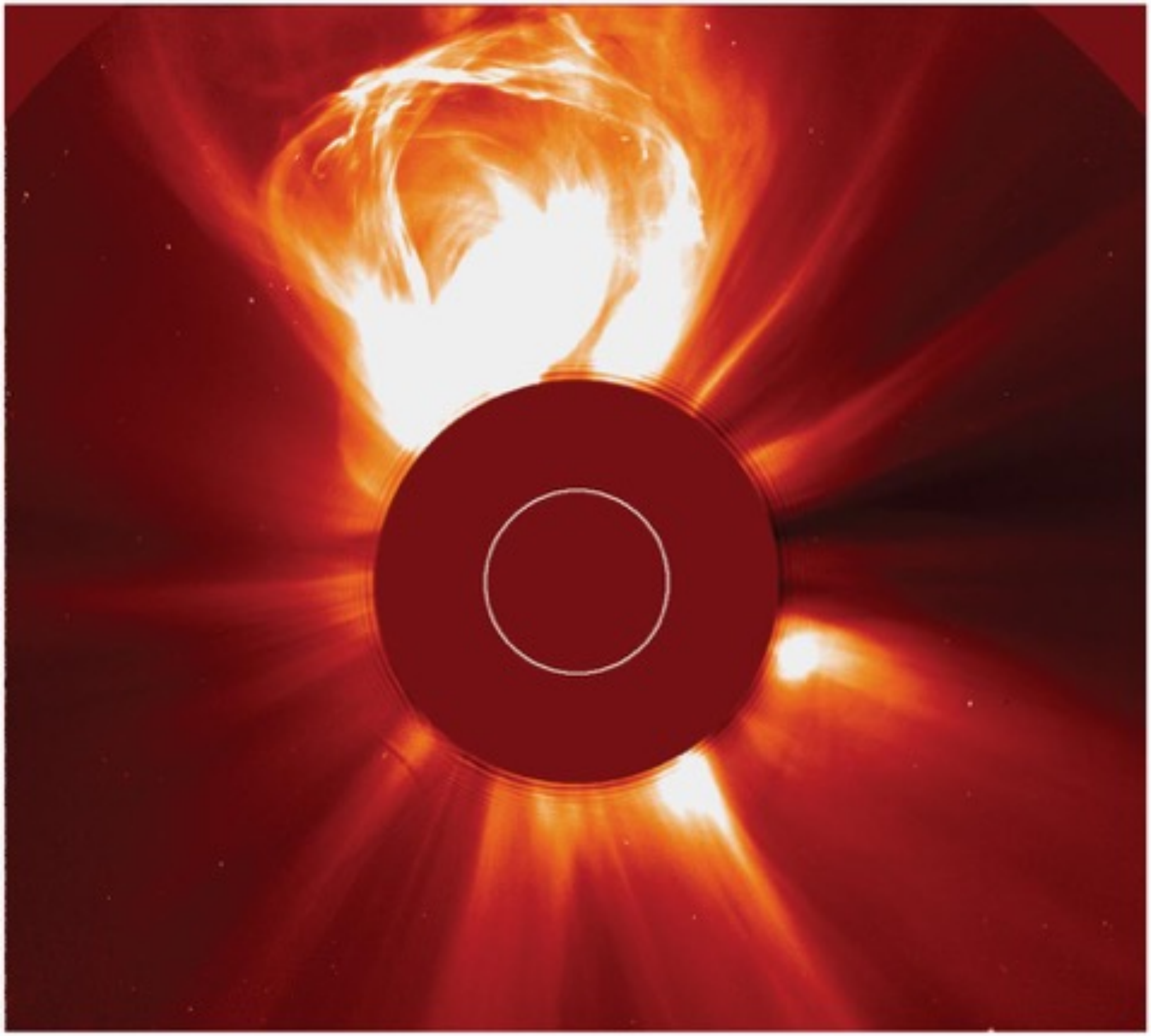
Magnetic activity also causes solar prominences that erupt high above the Sun’s surface.



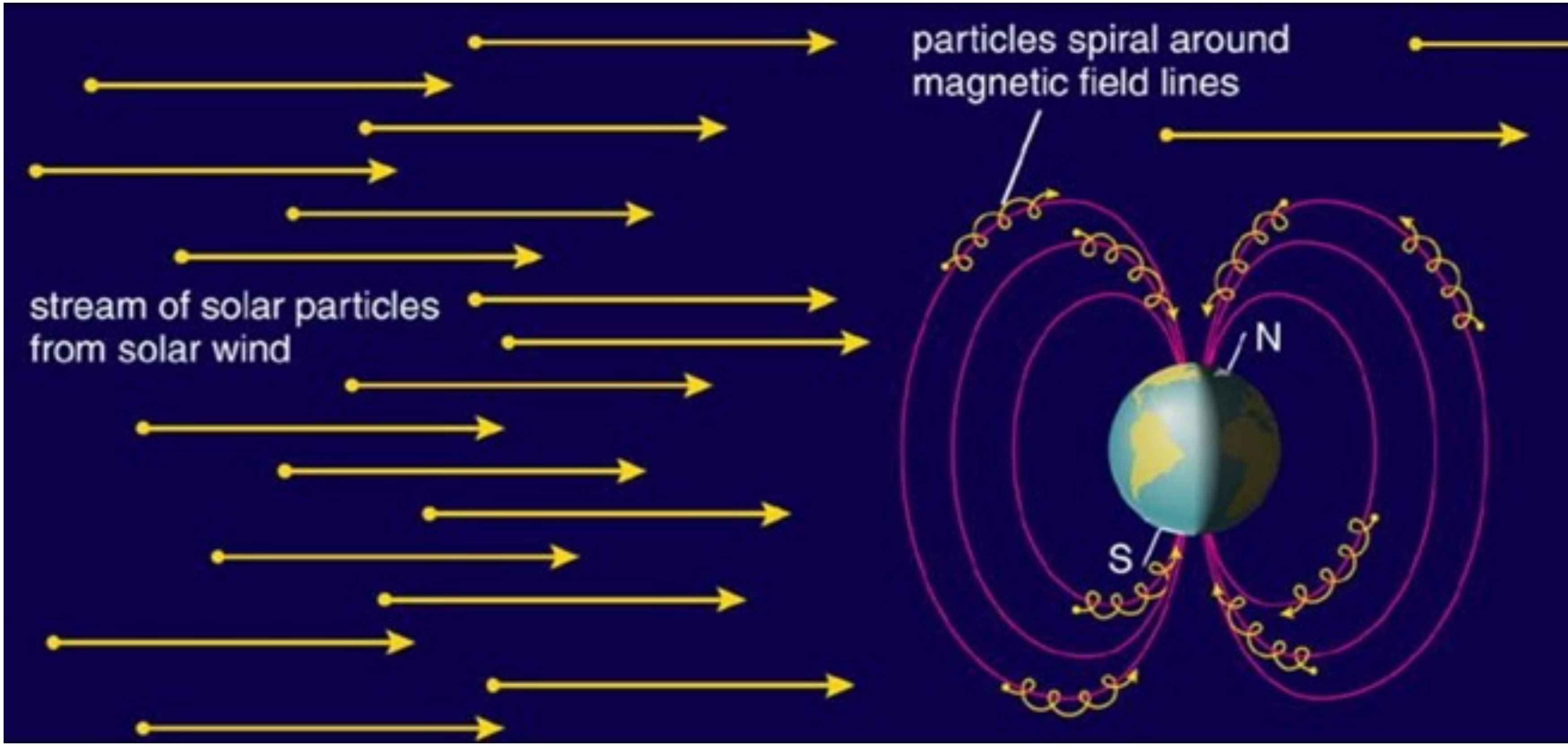
The corona appears bright in X-ray photos in places where magnetic fields trap hot gas.

How does solar activity affect humans?



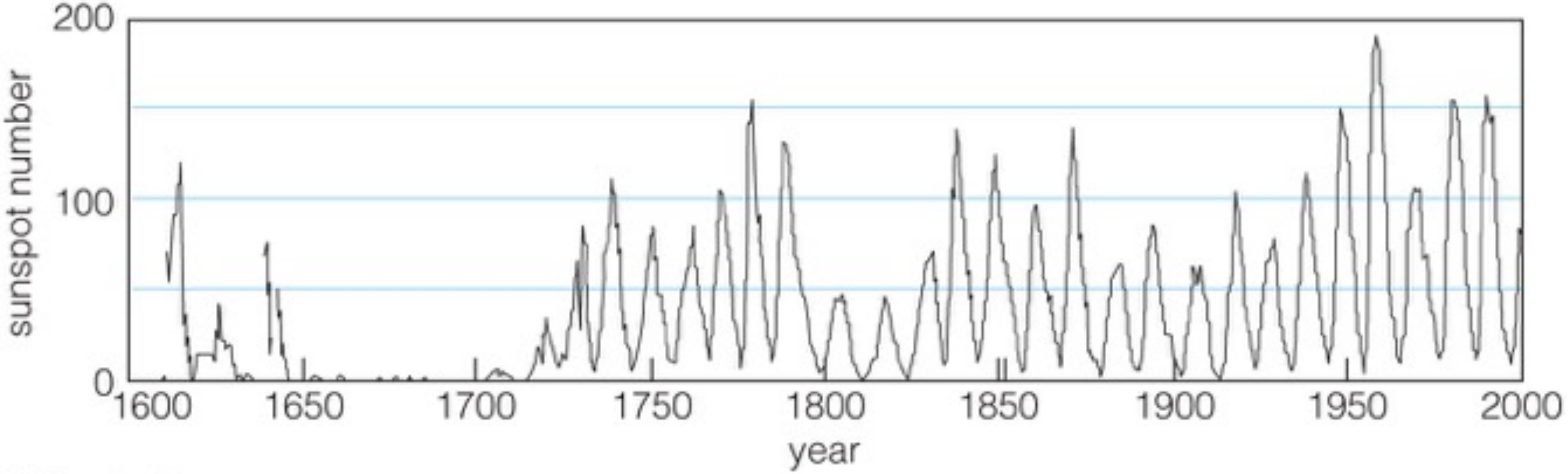


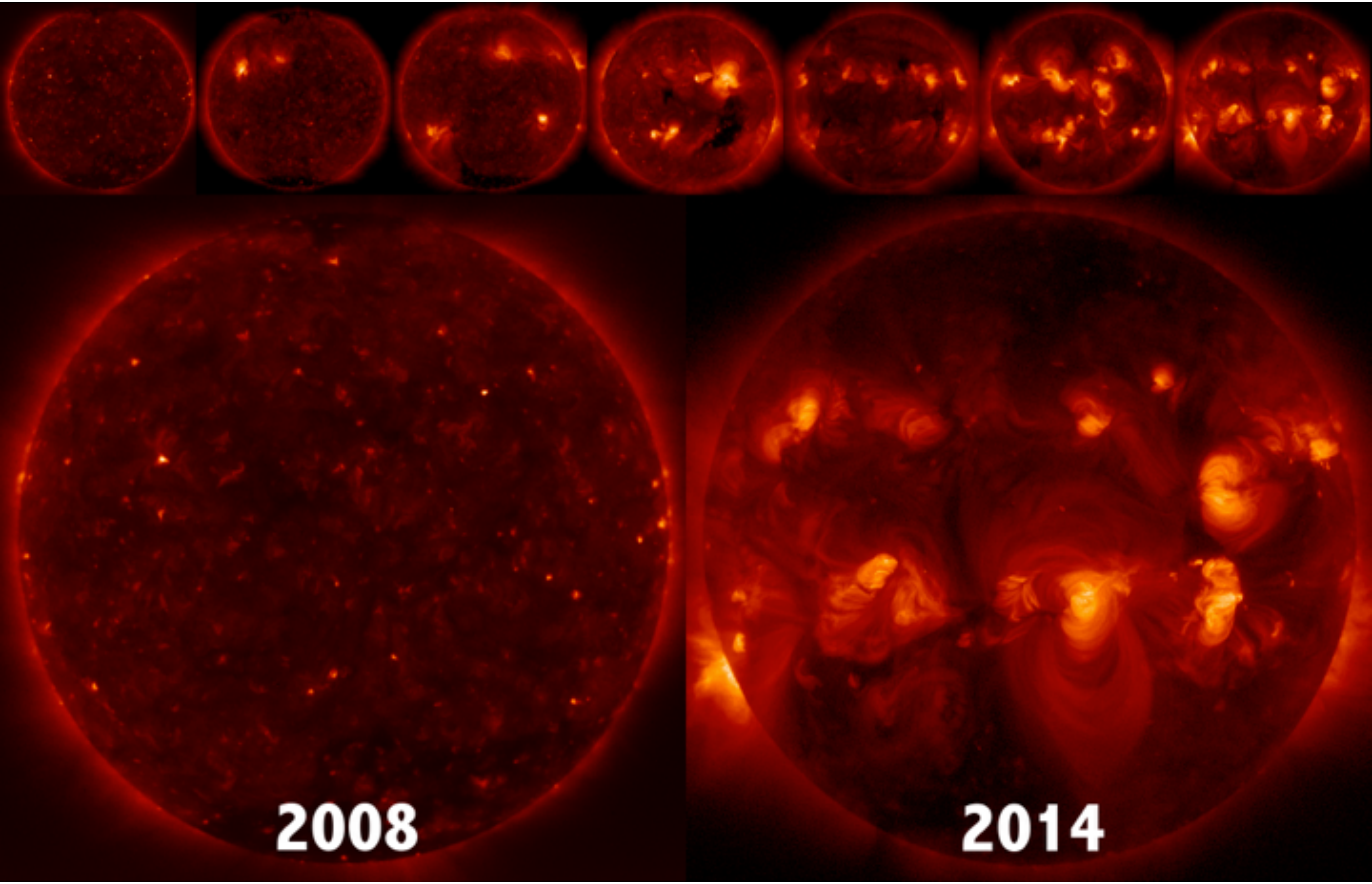
Coronal mass ejections send bursts of energetic charged particles out through the solar system.

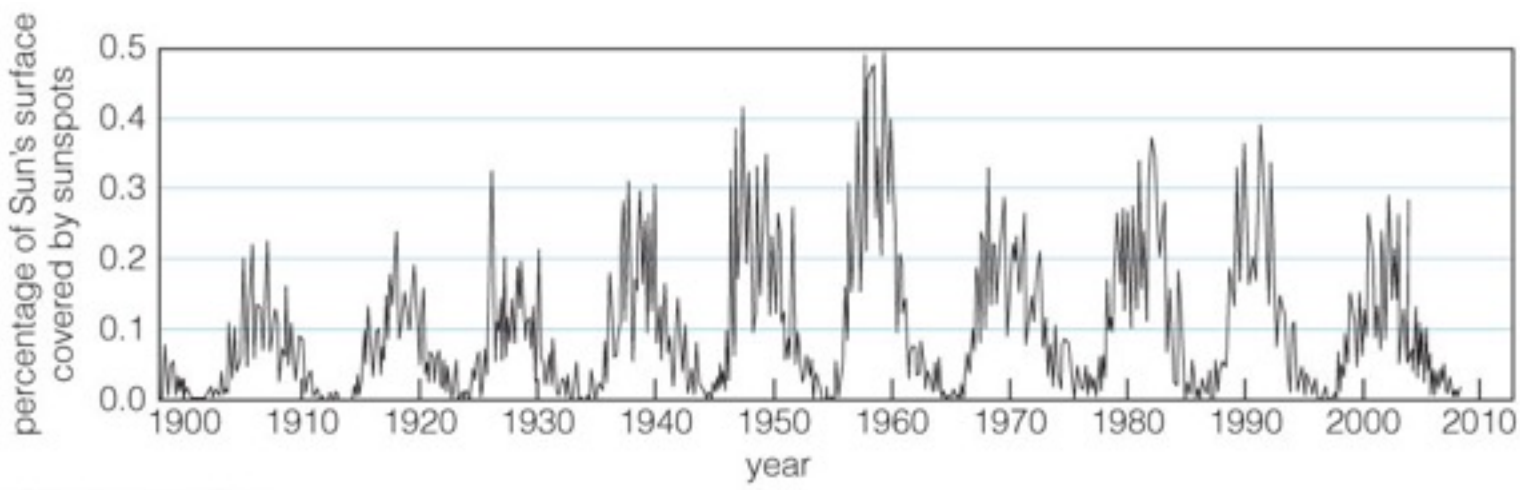


Charged particles streaming from the Sun can disrupt electrical power grids and can disable communications satellites.

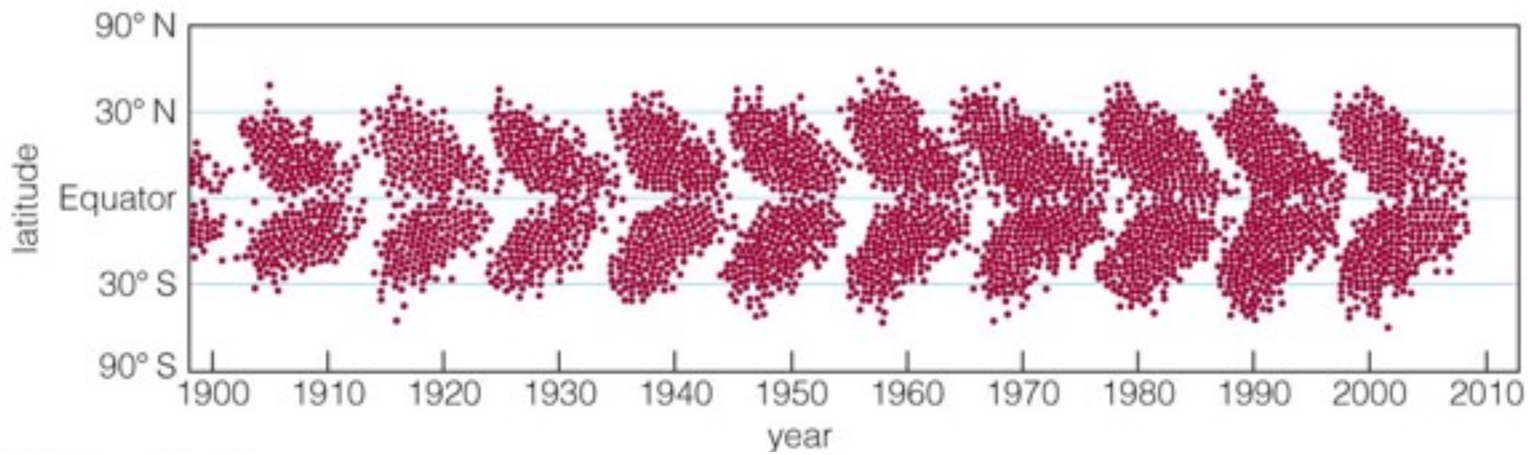
How does solar activity vary with time?

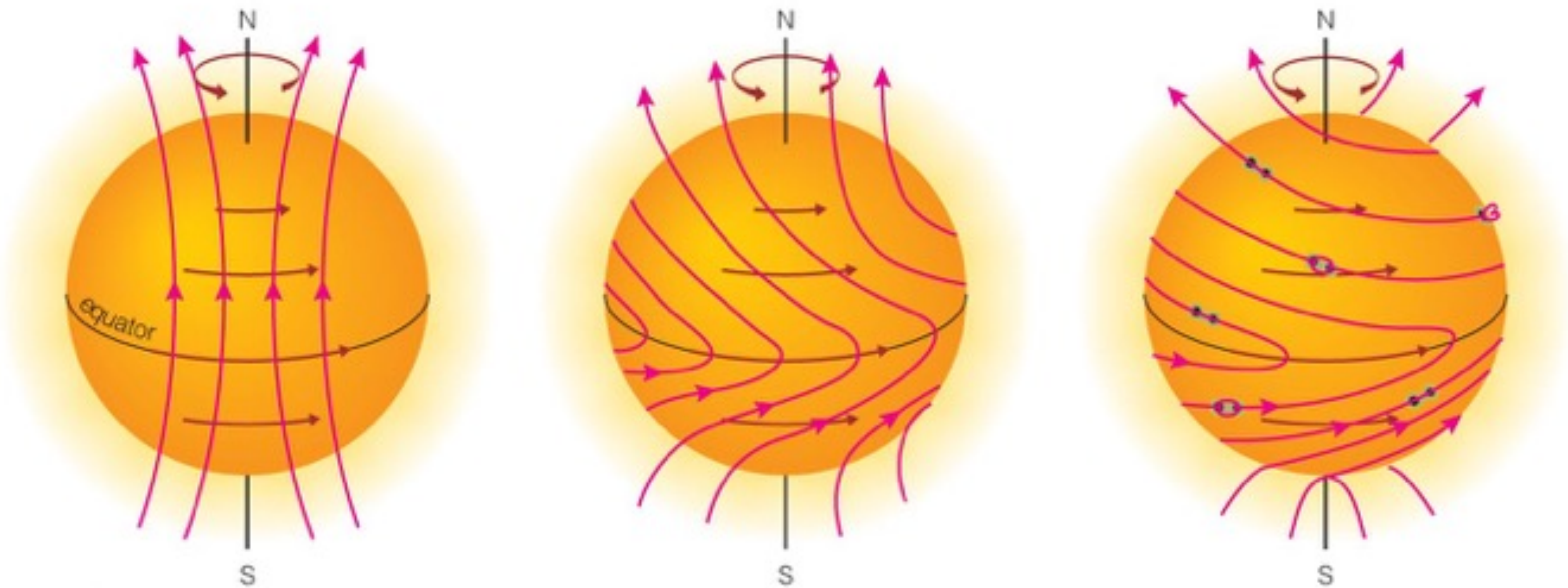



2008
2014



The number of sunspots rises and falls in an 11-year cycle.





The sunspot cycle has something to do with winding and twisting of the Sun's magnetic field.

Why are sunspots cooler than the rest of the photosphere?

a) They are where cooler gas sinks as part of the convection cells bringing heat to the photosphere.
b) They are areas of slightly different composition that absorbs radiative energy from below less efficiently than the rest of the photosphere.
c) They are areas of magnetic fields that inhibit convective transport of heat from below.
d) They are regions of denser gas.
e) They are at higher altitudes, where temperatures are slightly lower, than the surrounding photosphere.

Chapter 14

Which of the following is *not* an effect of solar storms on Earth?

a) increased auroral activity
b) increased atmospheric drag on Earth-orbiting satellites
c) increased sea-level temperatures near the equator
d) disrupted radio communications with satellites
e) disruption to electrical power grids

Surveying the Stars

Properties of Stars

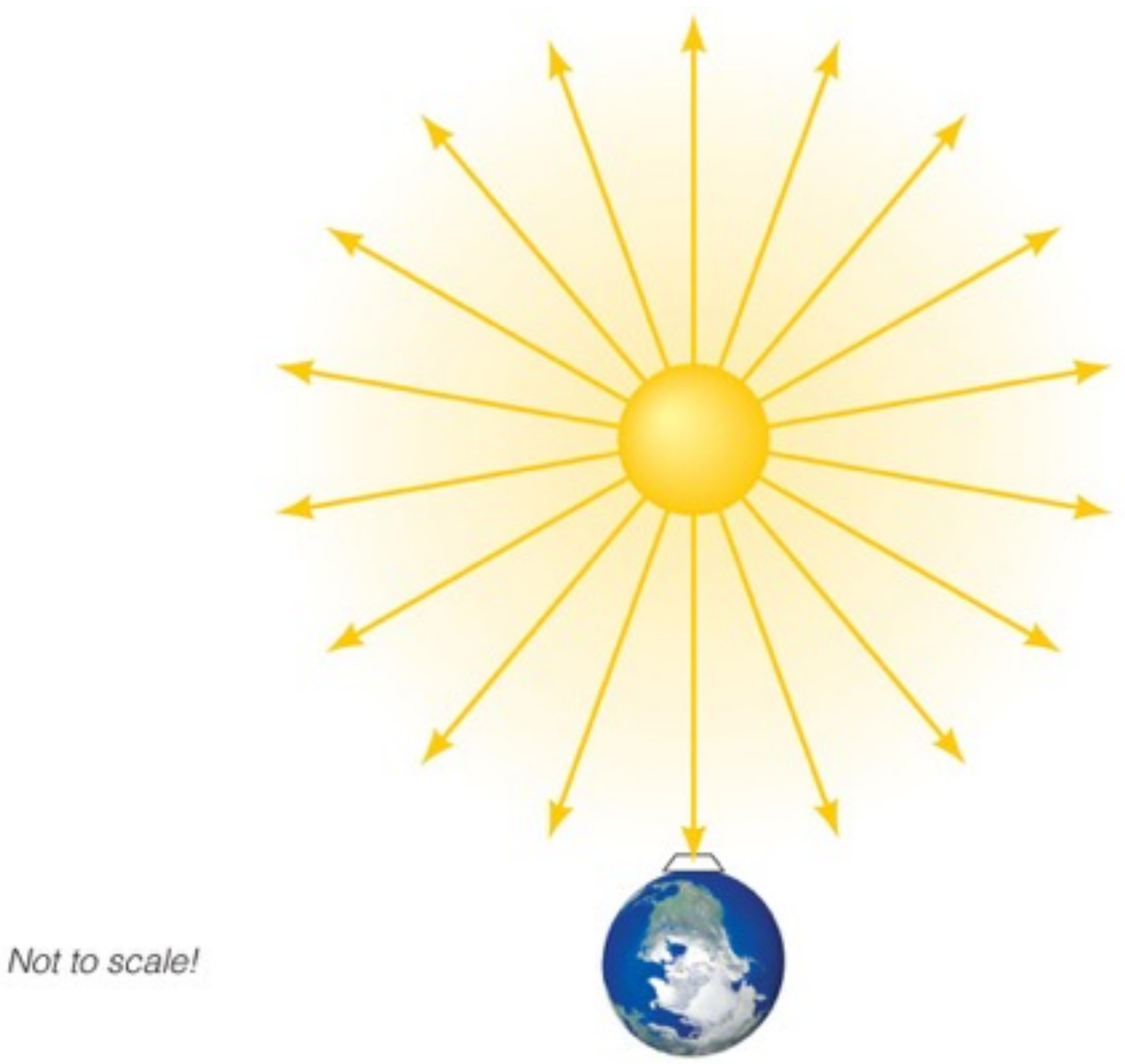
- How do we measure stellar luminosities?
- How do we measure stellar temperatures?
- How do we measure stellar masses?

Chapter 15

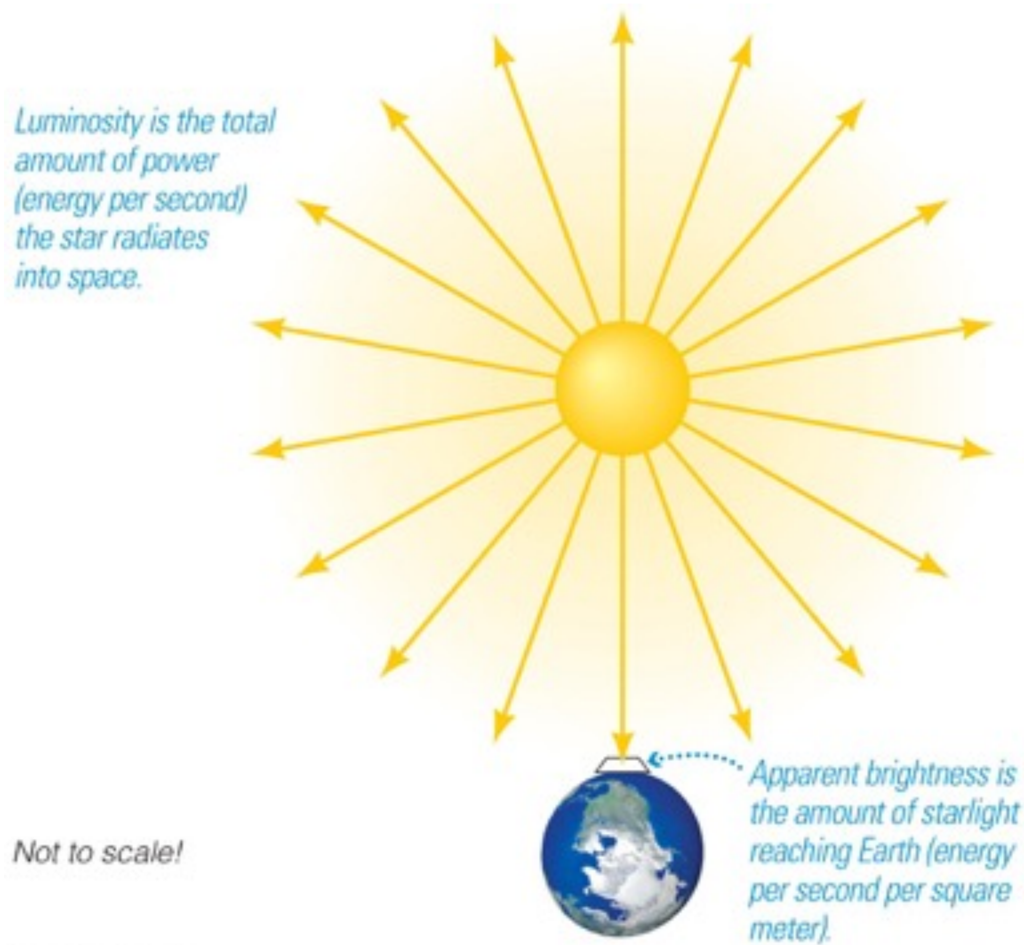
The total amount of power that a star radiates is called its

a) absolute brightness
b) apparent brightness
c) luminosity
d) absolute magnitude

How do we measure stellar luminosities?



The brightness of a star depends on both distance and luminosity.



Luminosity:

Amount of power a star radiates

(energy per second = watts)

Apparent brightness:

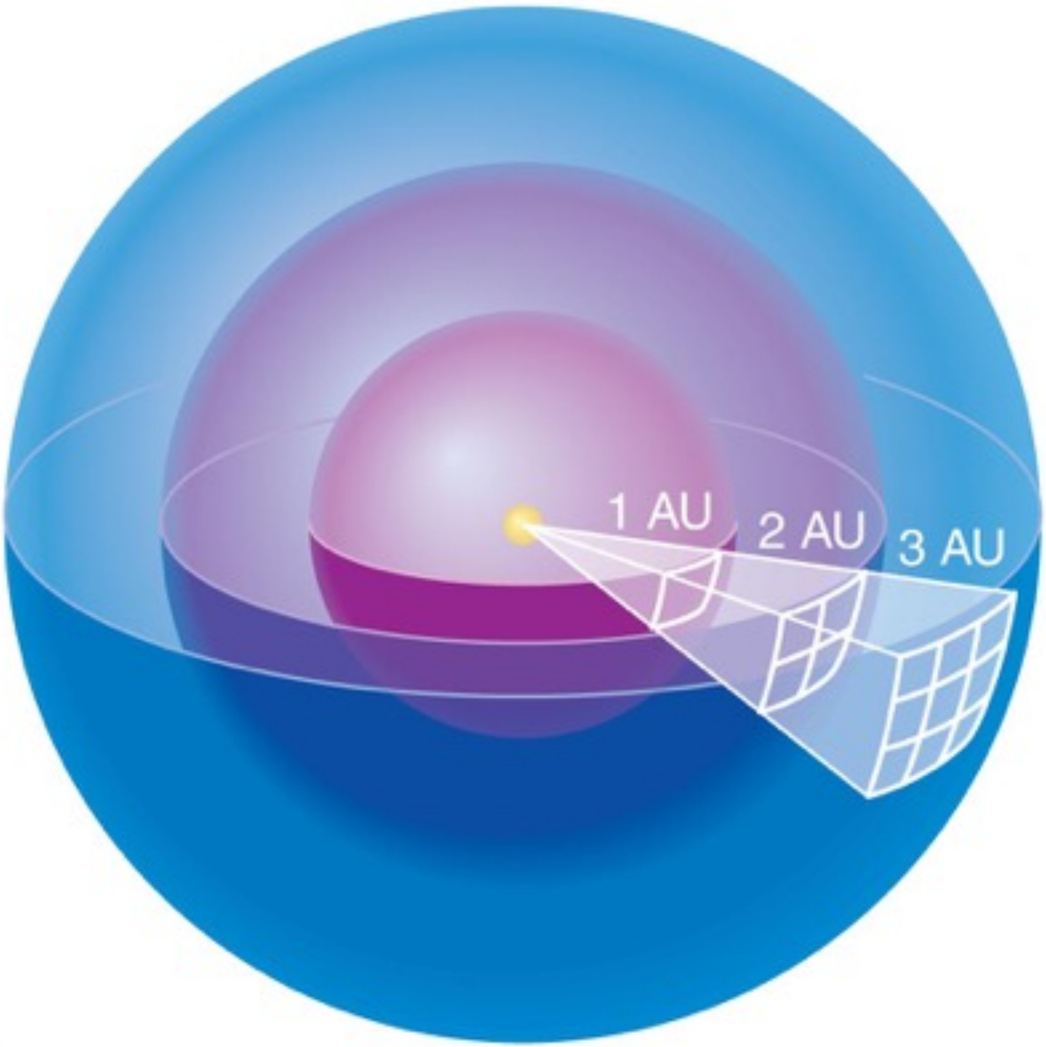
Amount of starlight that reaches Earth

(energy per second per square meter)

Thought Question

Alpha Centauri and the Sun have about the same luminosity. Which one appears brighter?

A. Alpha Centauri
B. The Sun



The amount of luminosity passing through each sphere is the same.

Area of sphere:

$$4\pi\,(\text{radius})^2$$

Divide luminosity by area to get brightness.

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:

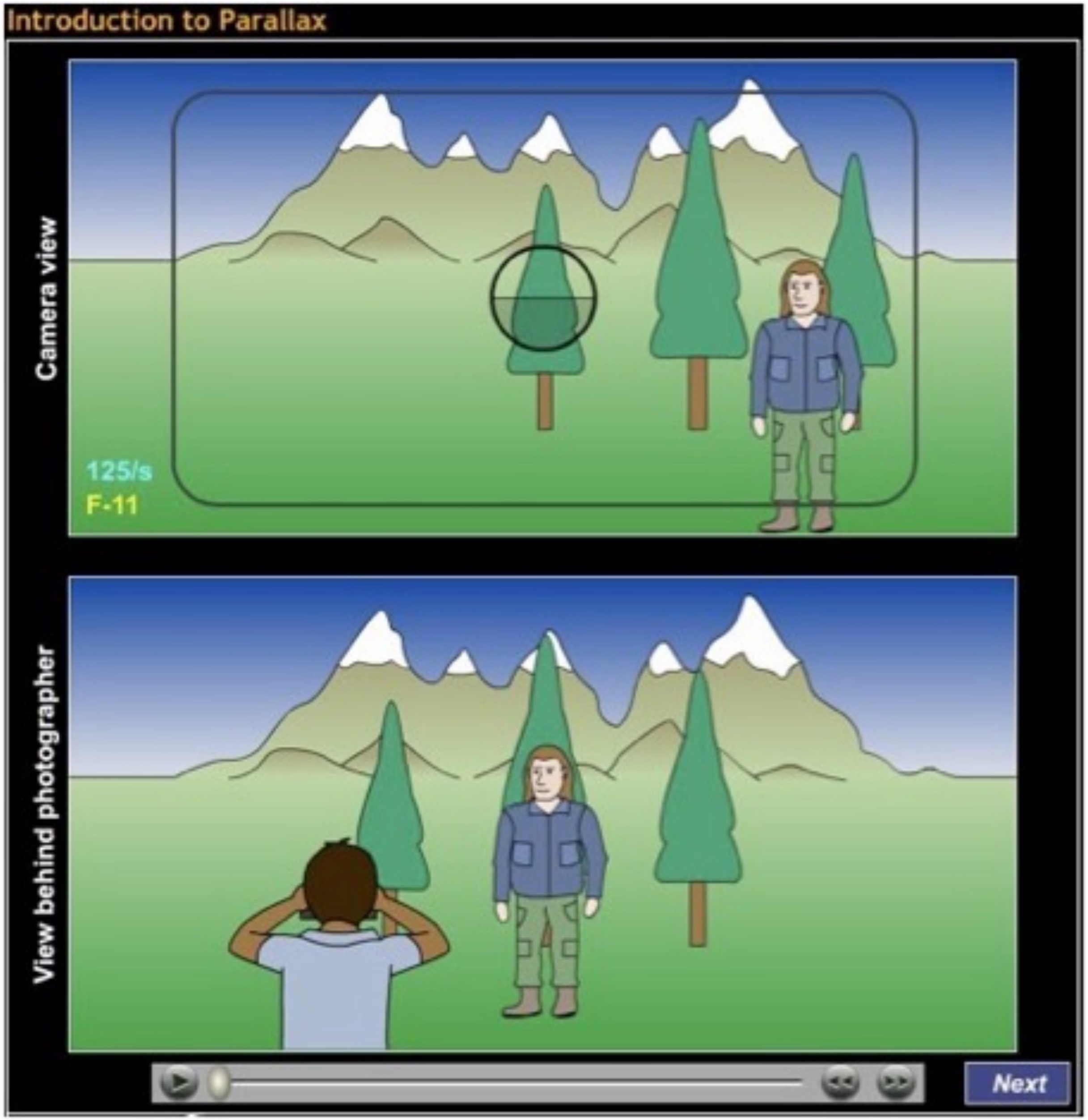
$$\text{Luminosity} = 4\pi\,(\text{distance})^2 \times (\text{brightness})$$

Thought Question

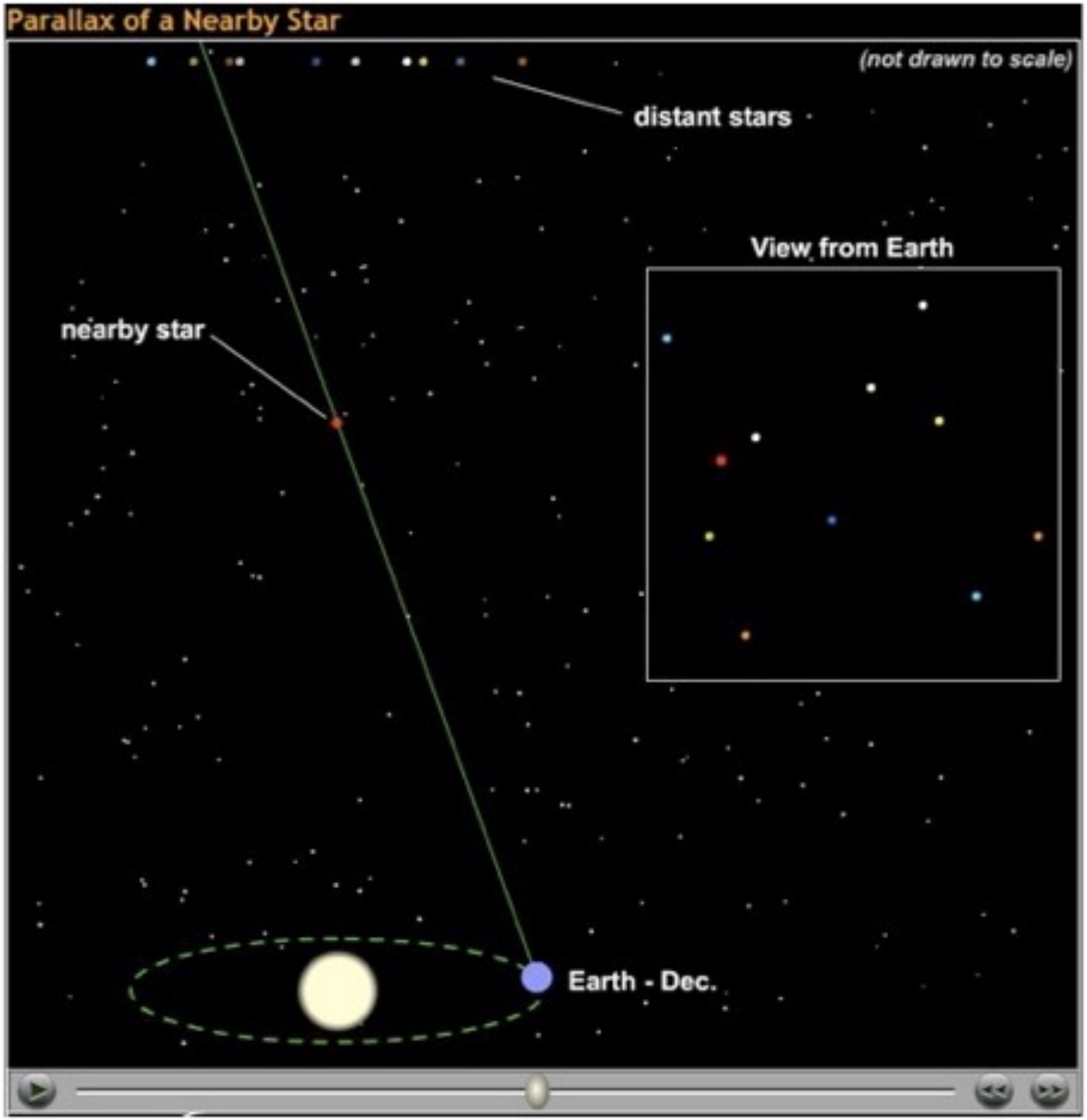
How would the apparent brightness of Alpha Centauri change if it were three times farther away?

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 brighter.

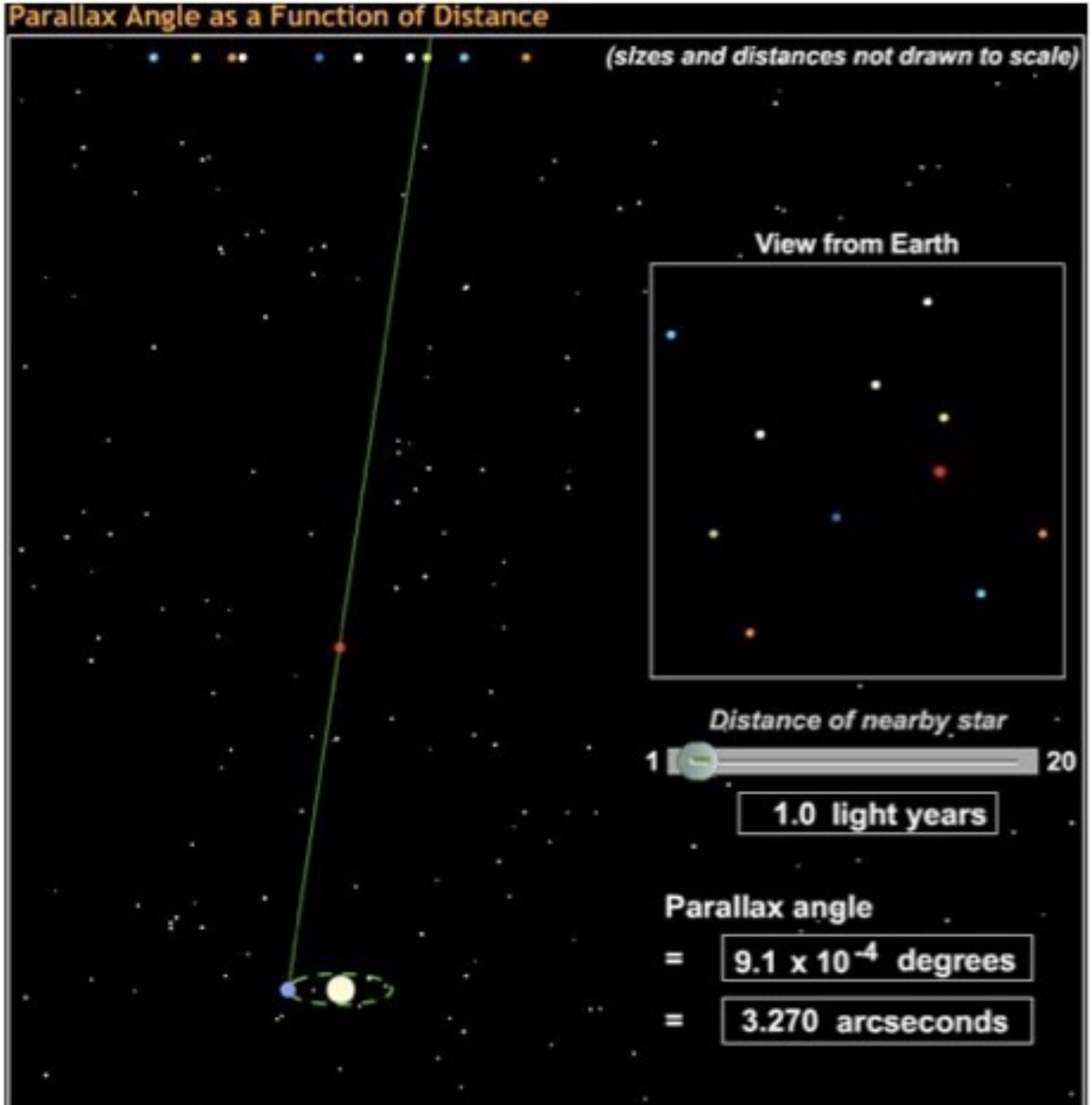
So how far away are these stars?



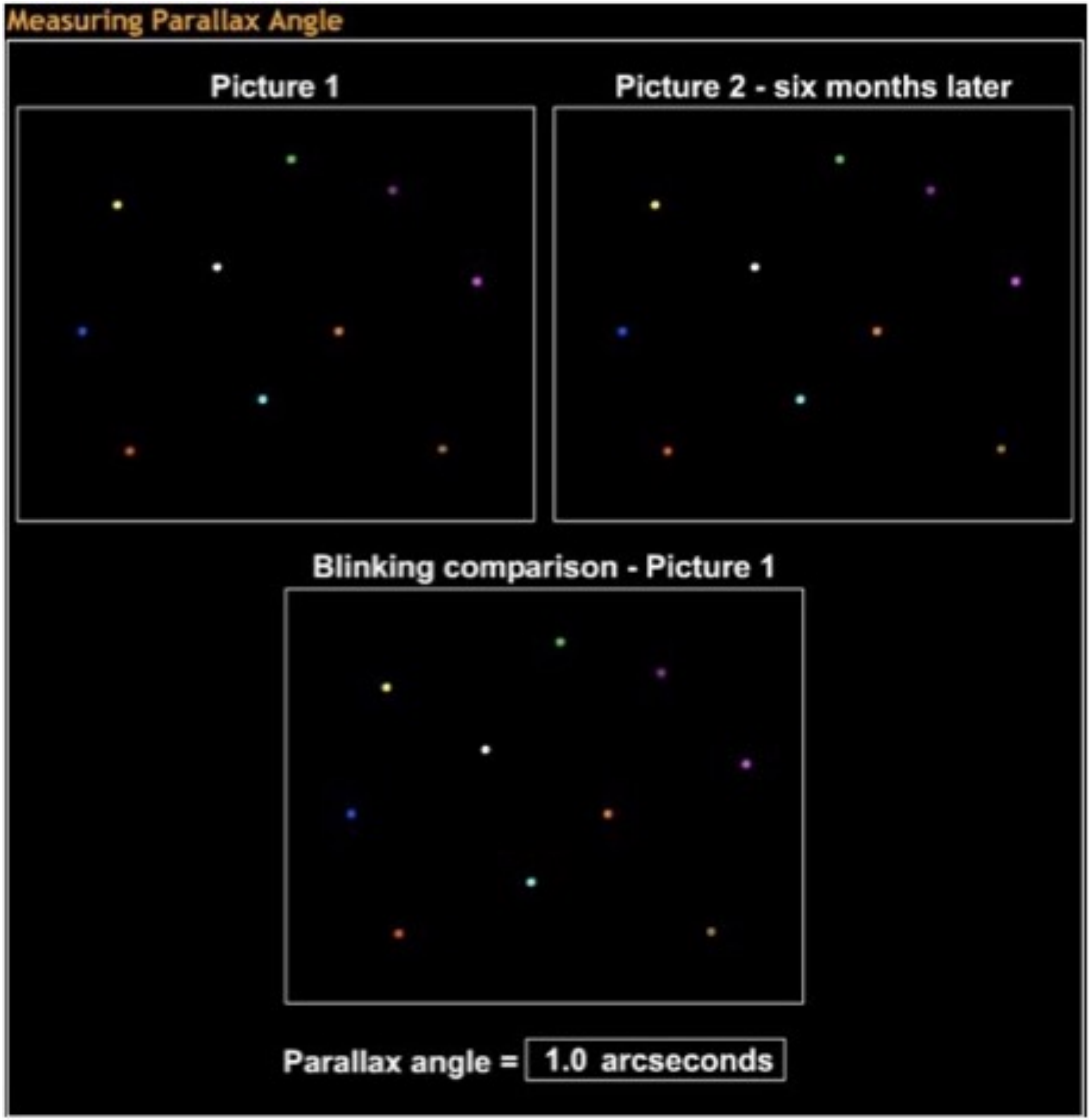
Parallax is the apparent shift in position of a nearby object against a background of more distant objects.



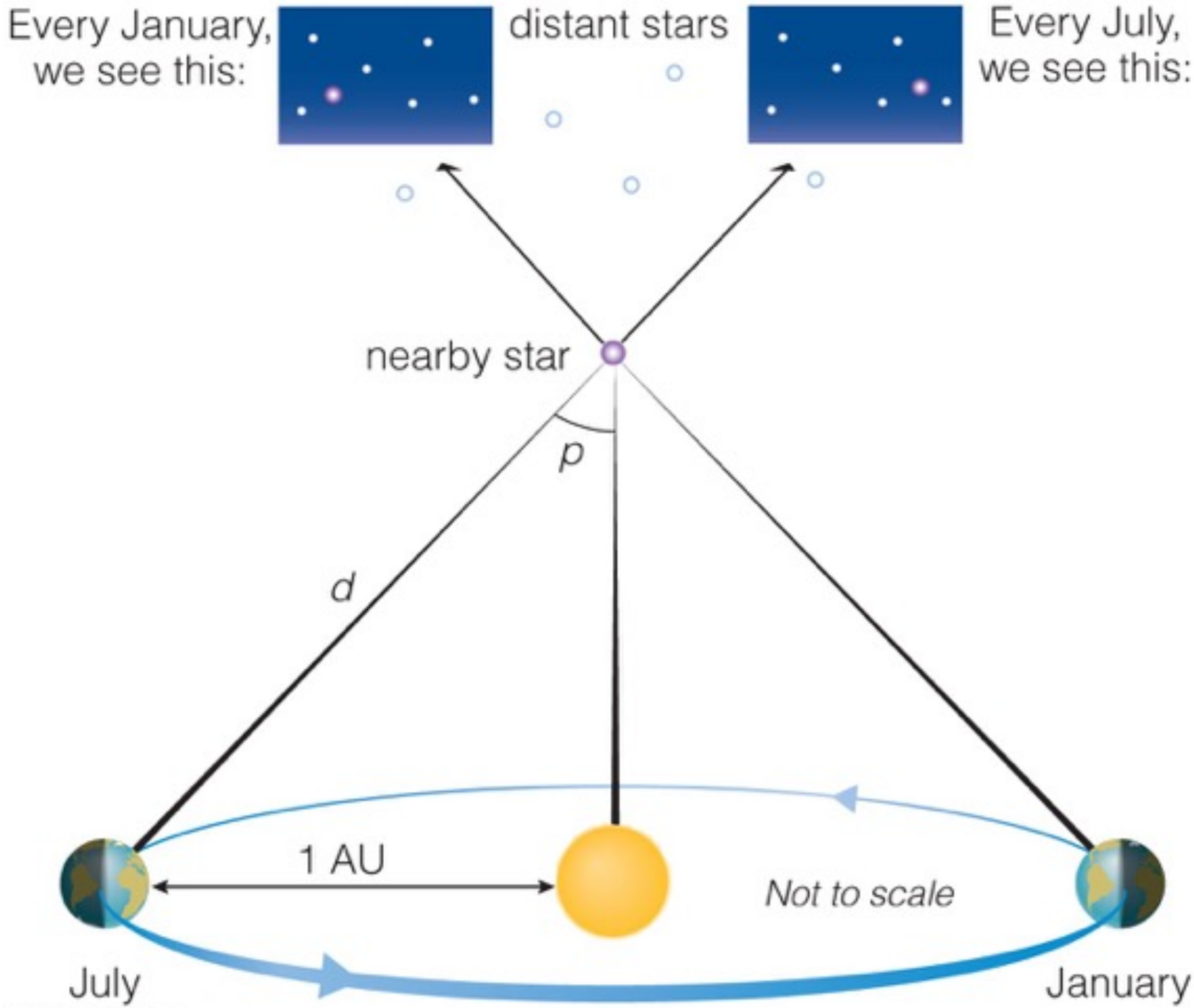
Apparent positions of nearest stars shift by about an arcsecond as Earth orbits Sun.



Parallax angle depends on distance.



Parallax is measured by comparing snapshots taken at different times and measuring the shift in angle to


Every January, we see this:
distant stars
Every July, we see this:
nearby star
p
d
1 AU
Not to scale
July
January

Parallax and Distance

p = parallax angle

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

$$d \text{ (in light-years)} = 3.26 \times \frac{1}{p \text{ (in arcseconds)}}$$

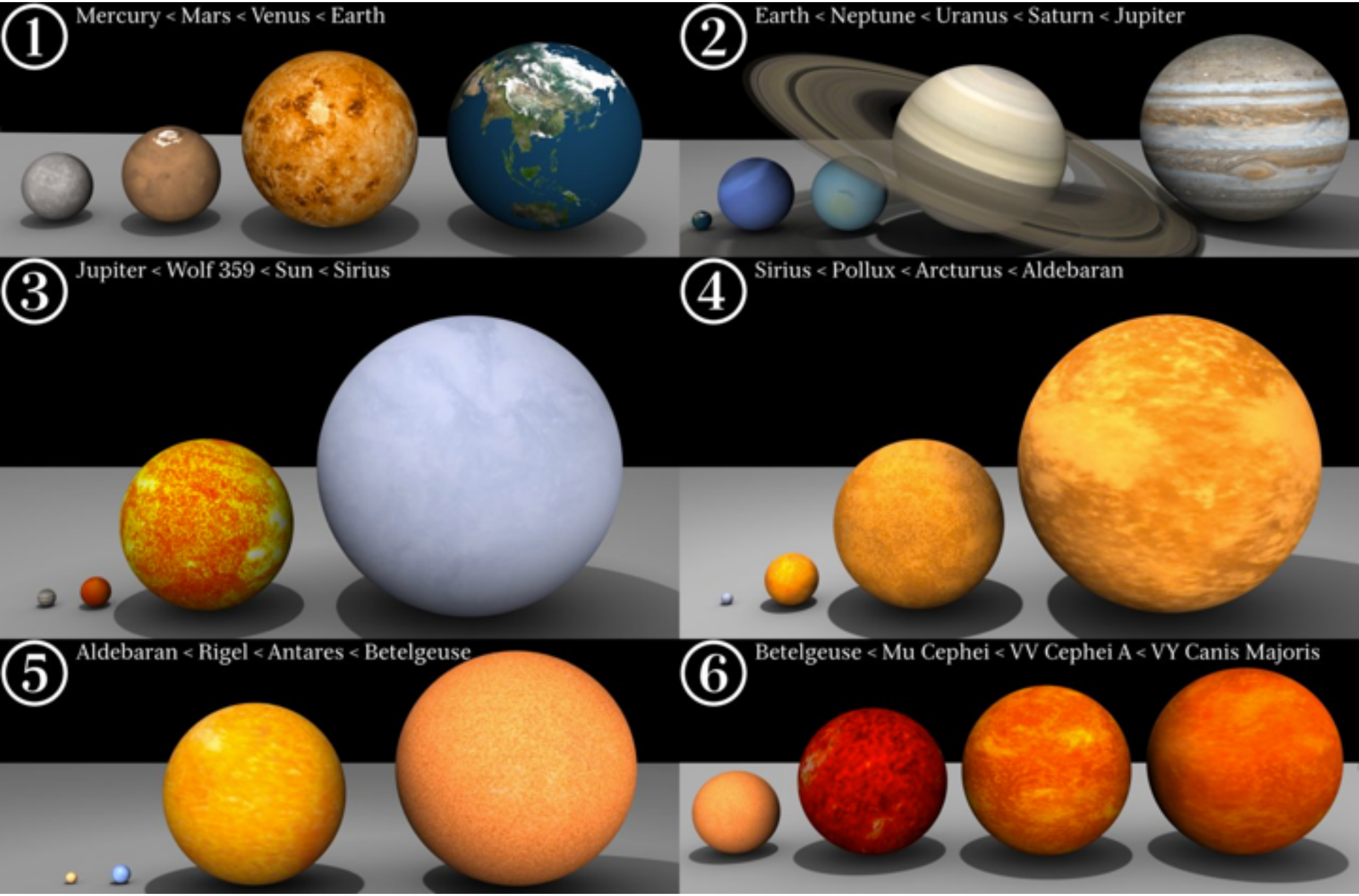
Most luminous stars:

10^6 L_{Sun}

Least luminous stars:

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

(L_{Sun} is luminosity of Sun)



1
Mercury < Mars < Venus < Earth
2
Earth < Neptune < Uranus < Saturn < Jupiter
3
Jupiter < Wolf 359 < Sun < Sirius
4
Sirius < Pollux < Arcturus < Aldebaran
5
Aldebaran < Rigel < Antares < Betelgeuse
6
Betelgeuse < Mu Cephei < VV Cephei A < VY Canis Majoris

Chapter 15

How does the apparent brightness of a star depend on its distance from Earth?

a) The apparent brightness is independent of distance from Earth.
b) The apparent brightness is inversely proportional to distance.
c) The apparent brightness is proportional to distance.
d) The apparent brightness is inversely proportional to the square of the distance.
e) The apparent brightness is proportional to the distance squared.

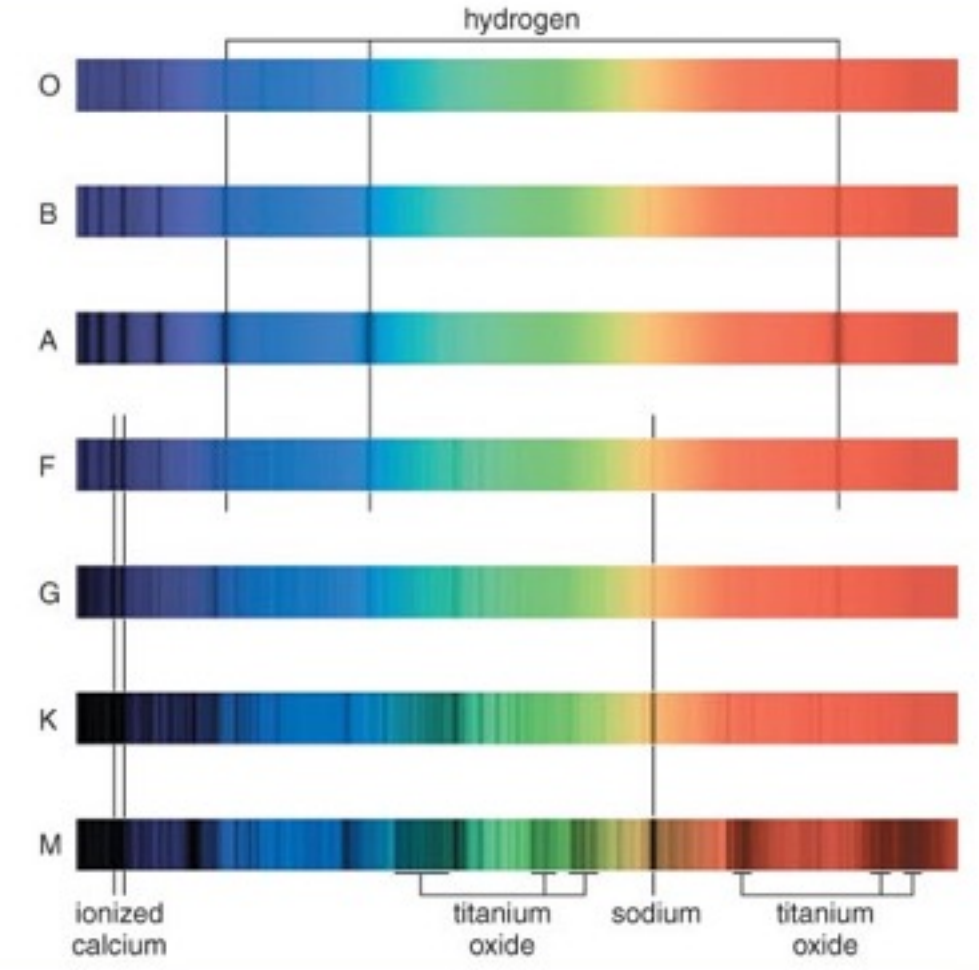
The Magnitude Scale

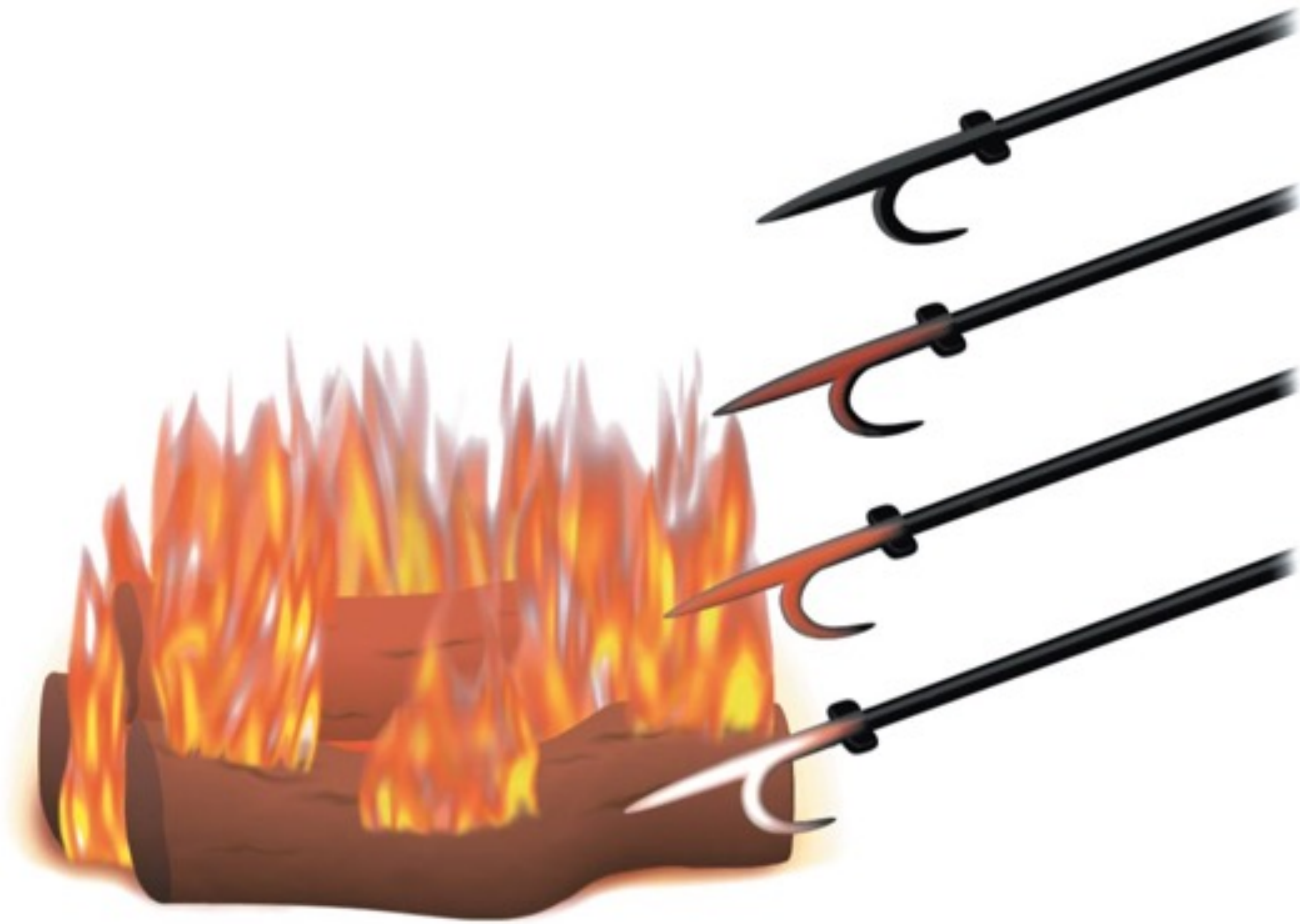
$m =$ apparent magnitude, $M =$ absolute magnitude

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

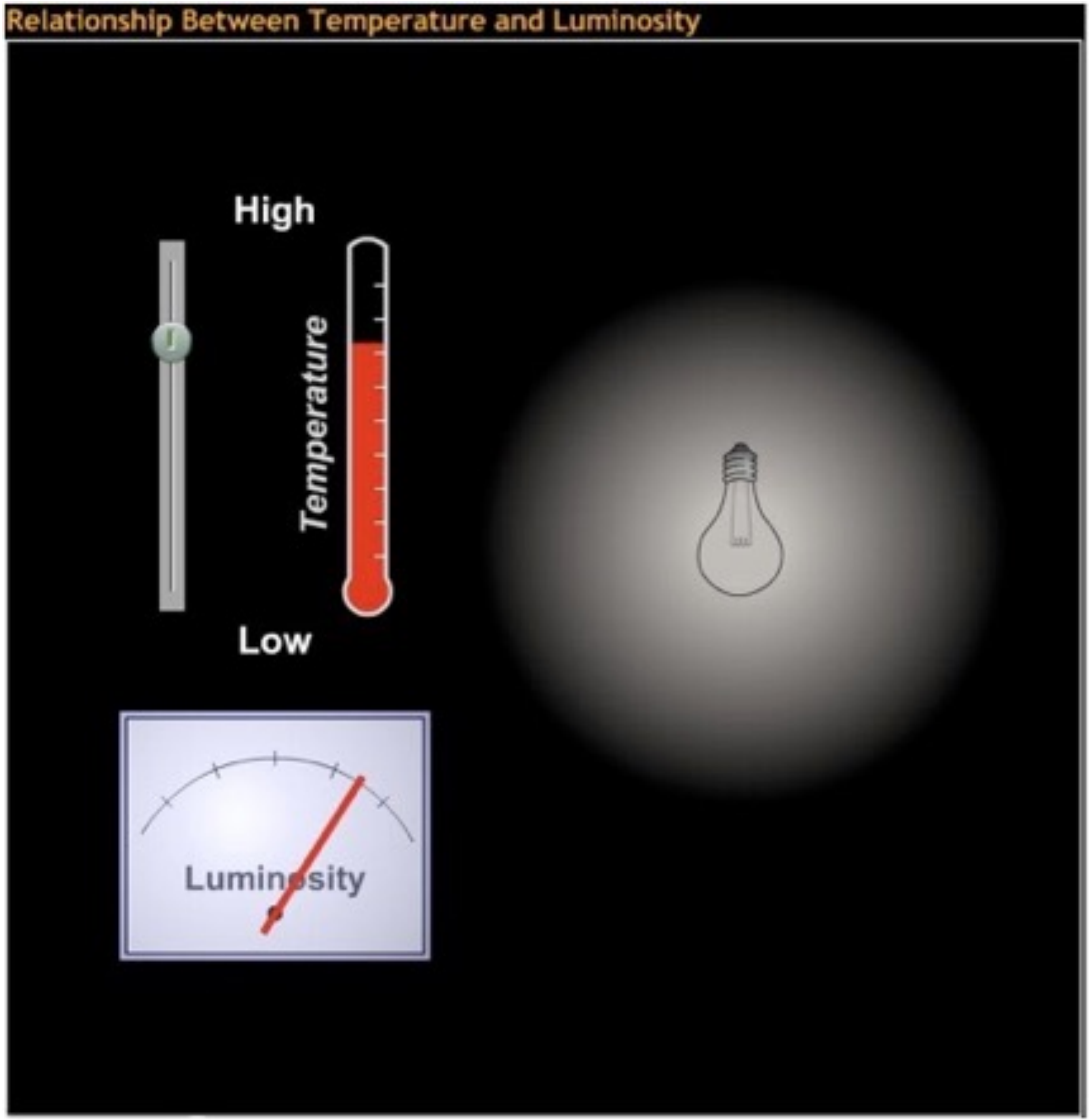
$$\frac{\text{Luminosity of star 1}}{\text{Luminosity of star 2}} = (100^{1/5})^{M_1 - M_2}$$

How do we measure stellar temperatures?





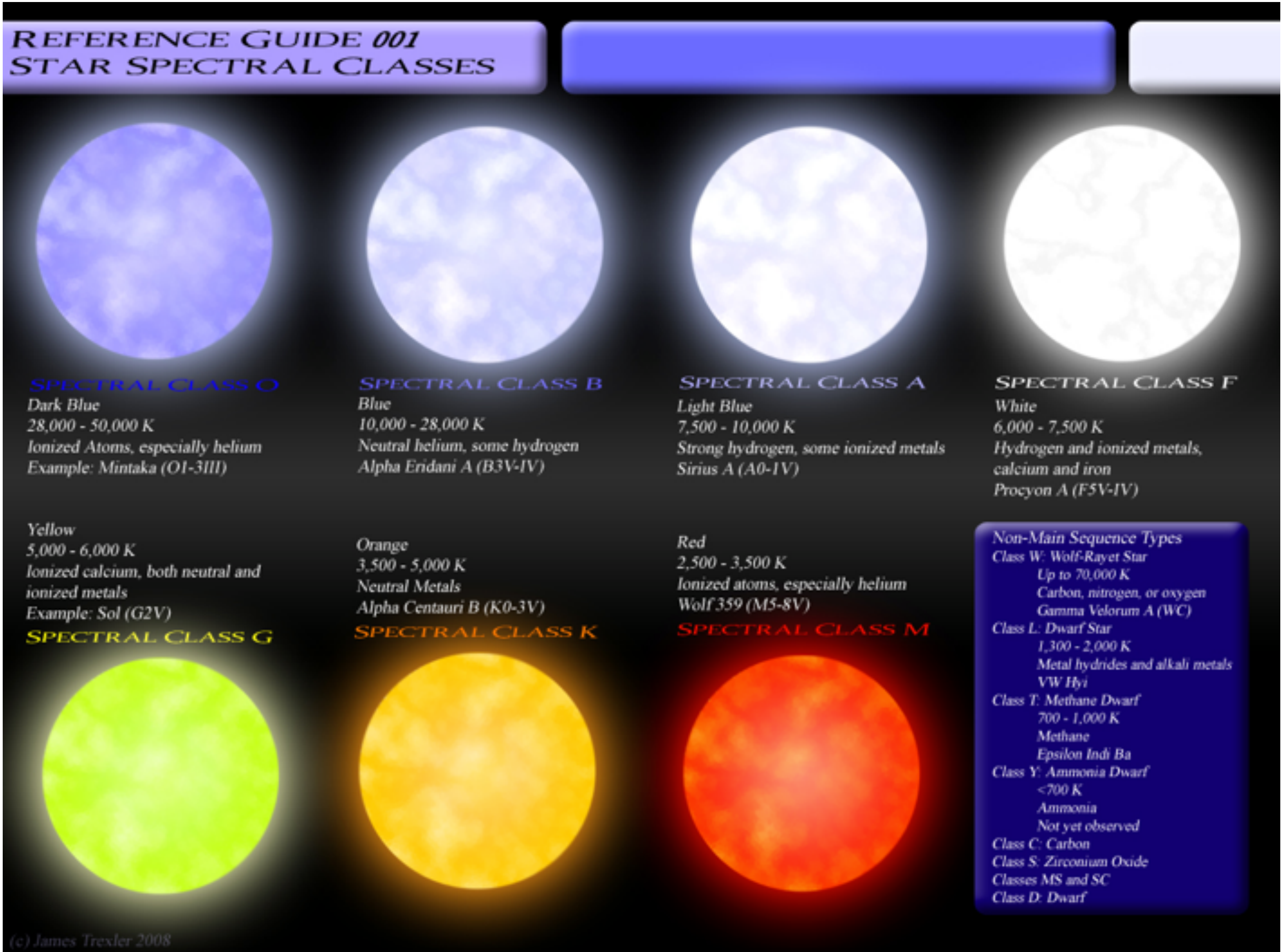
Every object emits thermal radiation with a spectrum that depends on its temperature.



An object of fixed size grows more luminous as its temperature rises.

Properties of Thermal Radiation

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



Reference Guide 001
Star Spectral Classes
Spectral Class O
Dark Blue
28,000 - 50,000 K
Ionized Atoms, especially helium
Example: Mintaka (O1-3III)
Spectral Class B
Blue
10,000 - 28,000 K
Neutral helium, some hydrogen
Alpha Eridani A (B3V-IV)
Spectral Class A
Light Blue
7,500 - 10,000 K
Strong hydrogen, some ionized metals
Sirius A (A0-1V)
Spectral Class F
White
6,000 - 7,500 K
Hydrogen and ionized metals, calcium and iron
Procyon A (F5V-IV)
Yellow
5,000 - 6,000 K
Ionized calcium, both neutral and ionized metals
Example: Sol (G2V)
Spectral Class G
Orange
3,500 - 5,000 K
Neutral Metals
Alpha Centauri B (K0-3V)
Spectral Class K
Red
2,500 - 3,500 K
Ionized atoms, especially helium
Wolf 359 (M5-8V)
Spectral Class M
Non-Main Sequence Types
Class W: Wolf-Rayet Star
Up to 70,000 K
Carbon, nitrogen, or oxygen
Gamma Velorum A (WC)
Class L: Dwarf Star
1,300 - 2,000 K
Metal hydrides and alkali metals
VW Hyi
Class T: Methane Dwarf
700 - 1,000 K
Methane
Epsilon Indi Ba
Class Y: Ammonia Dwarf
<700 K
Ammonia
Not yet observed
Class C: Carbon
Class S: Zirconium Oxide
Classes MS and SC
Class D: Dwarf
(c) James Trexler 2008

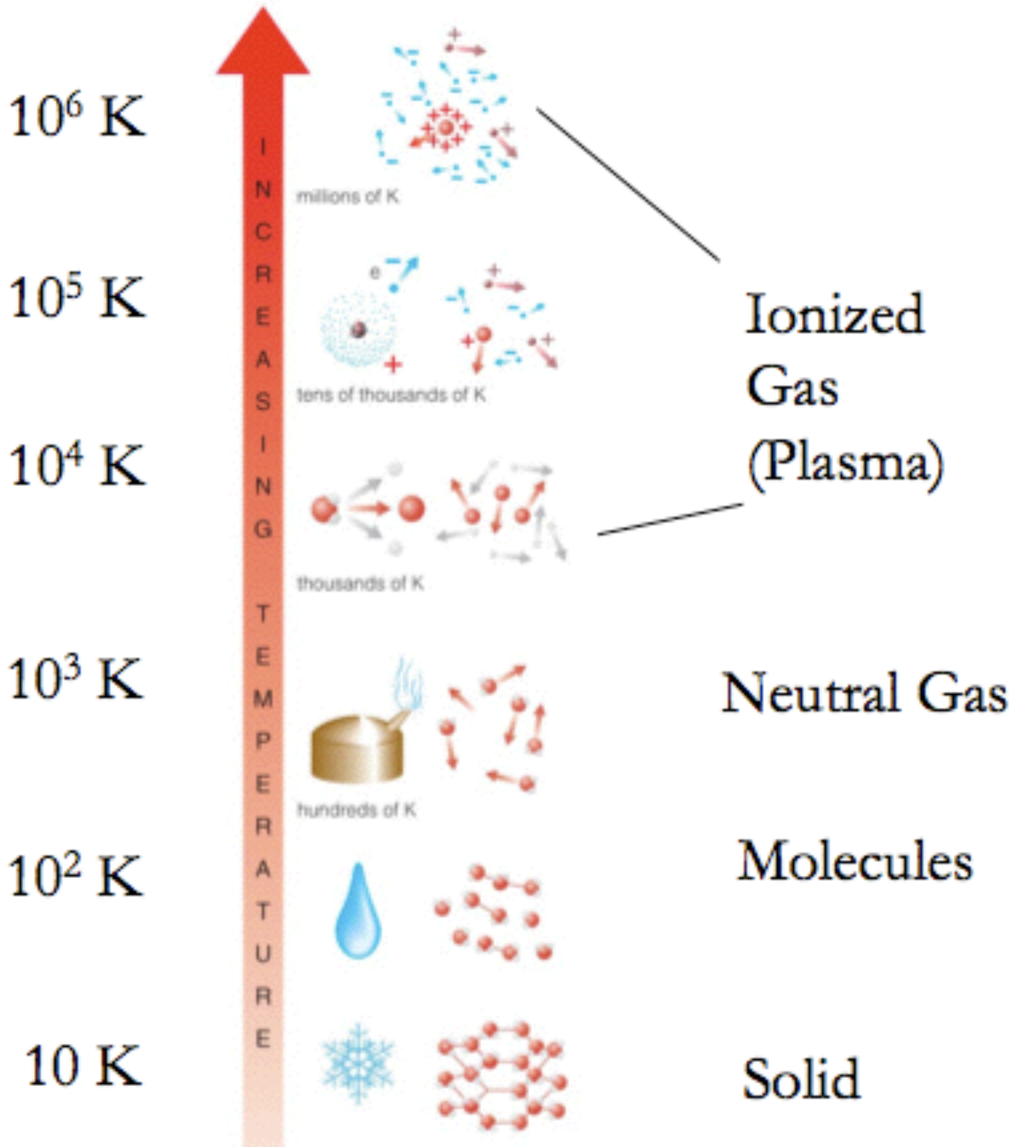
Hottest stars:

50,000 K

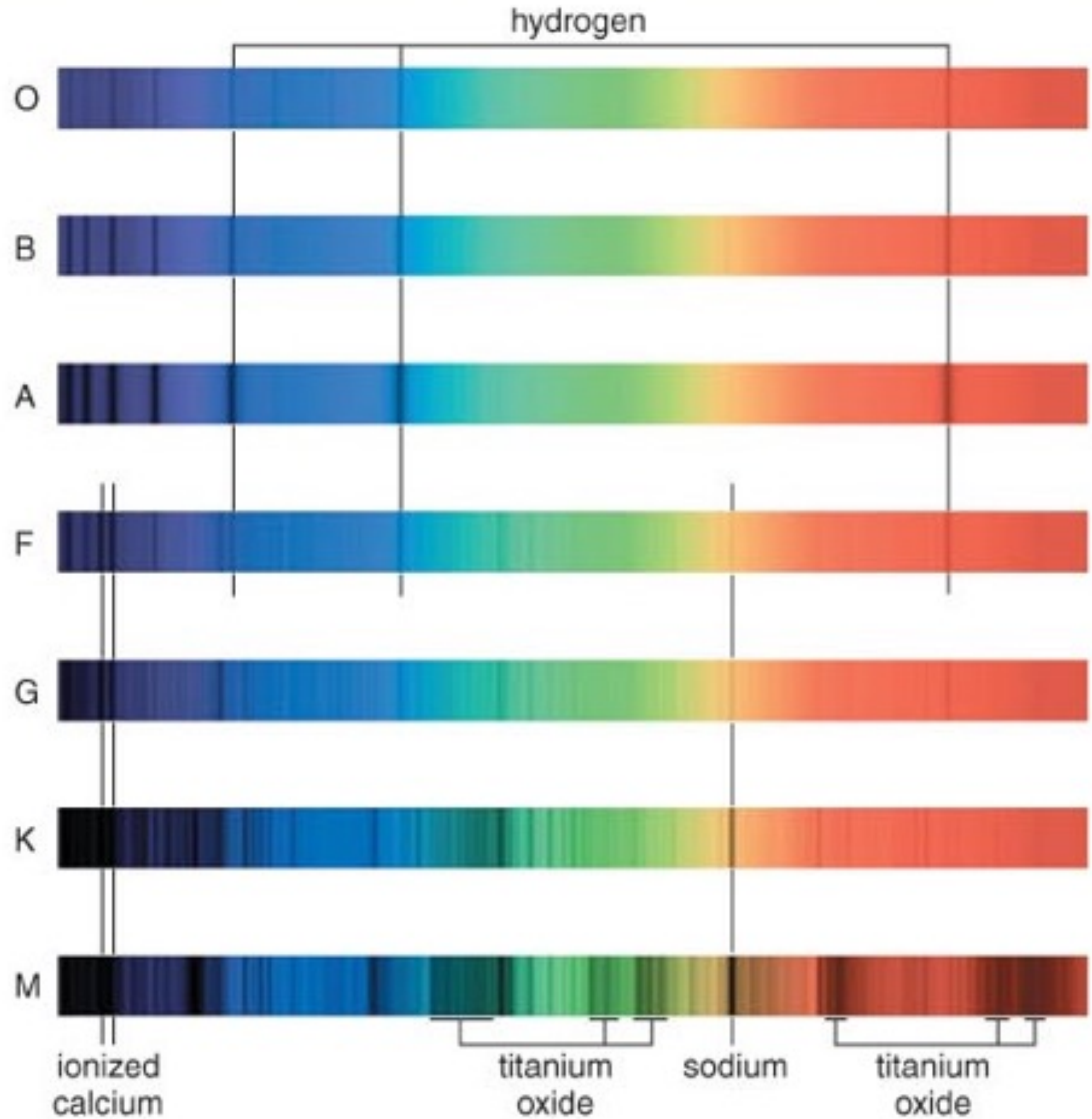
Coolest stars:

3000 K

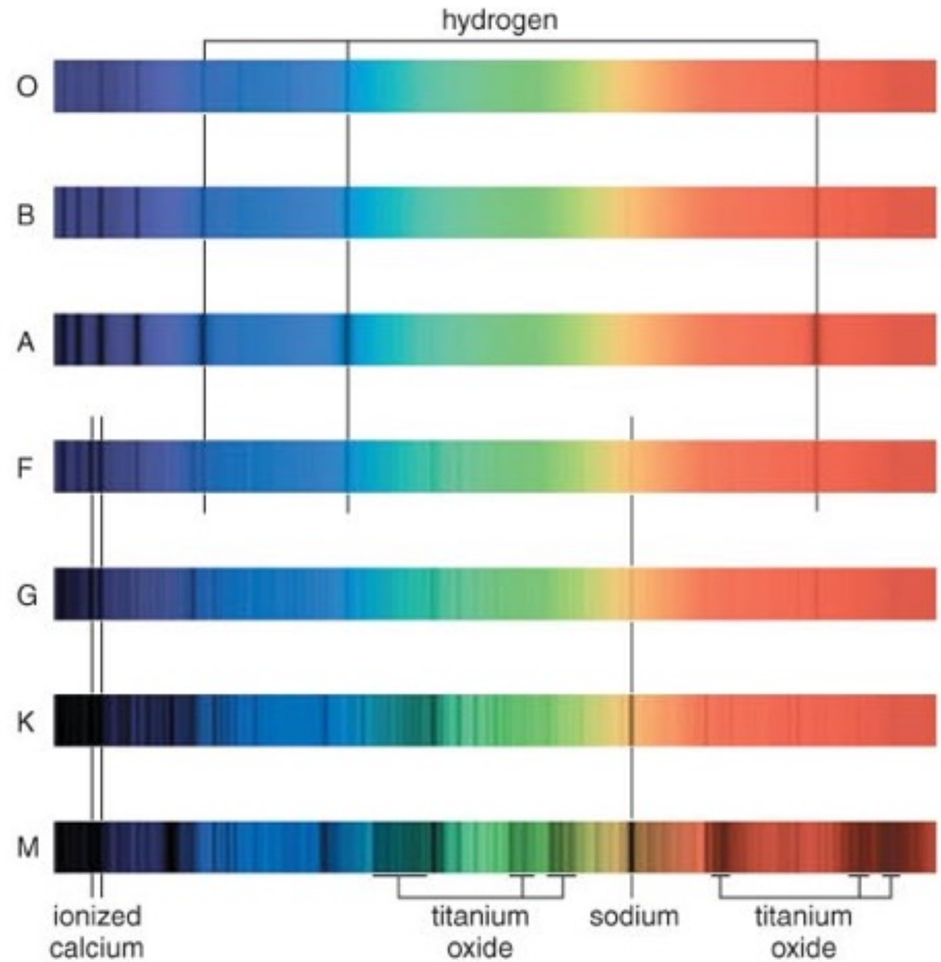
(Sun's surface is 5800 K.)



Level of ionization also reveals a star's temperature.



Absorption lines in star's spectrum tell us its ionization level.



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

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

Remembering Spectral Types

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

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

Thought Question

Which kind of star is hottest?

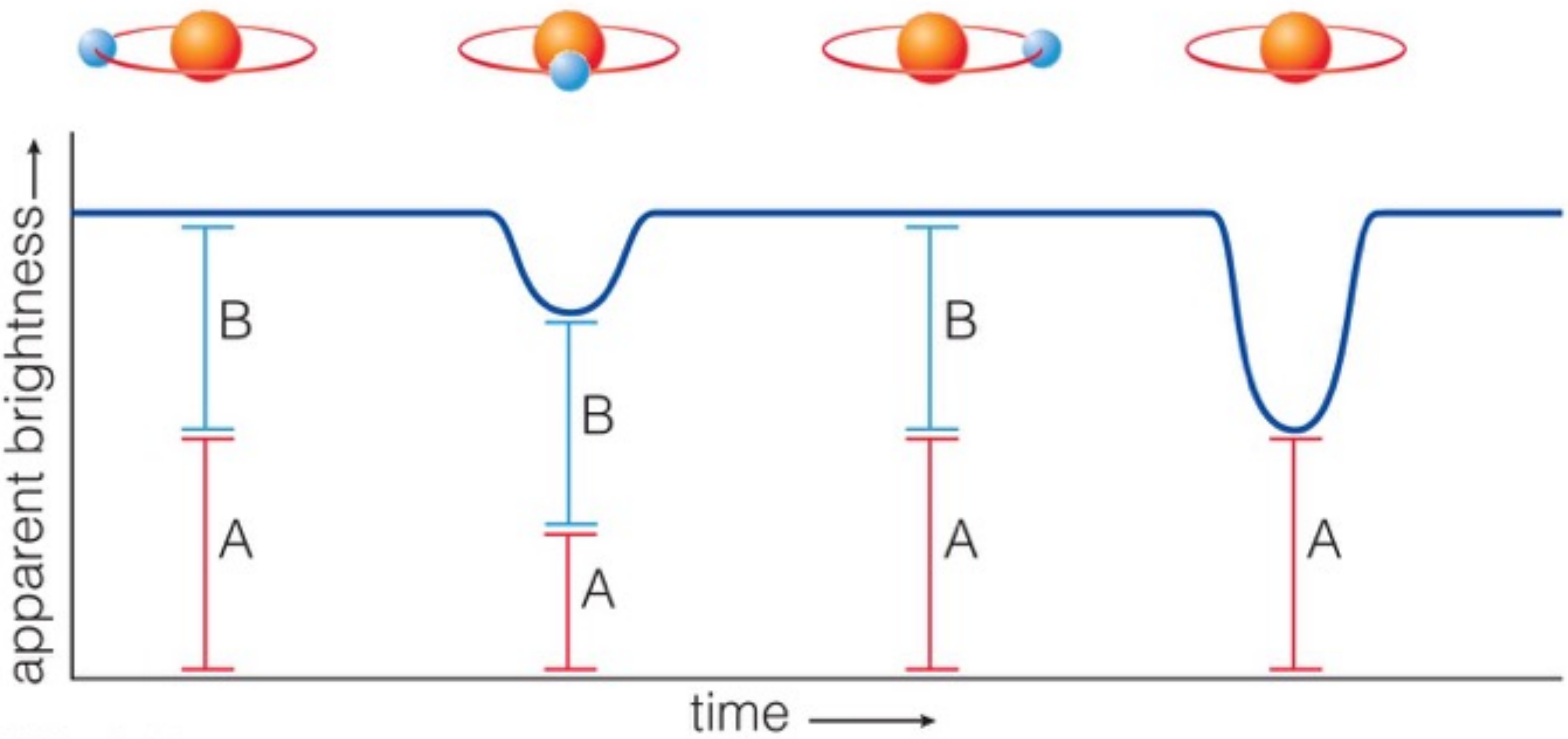
A. M star
B. F star
C. A star
D. K star

Pioneers of Stellar Classification

- Annie Jump Cannon and the “calculators” at Harvard laid the foundation of modern stellar classification.

Binaries

How do we measure stellar masses?



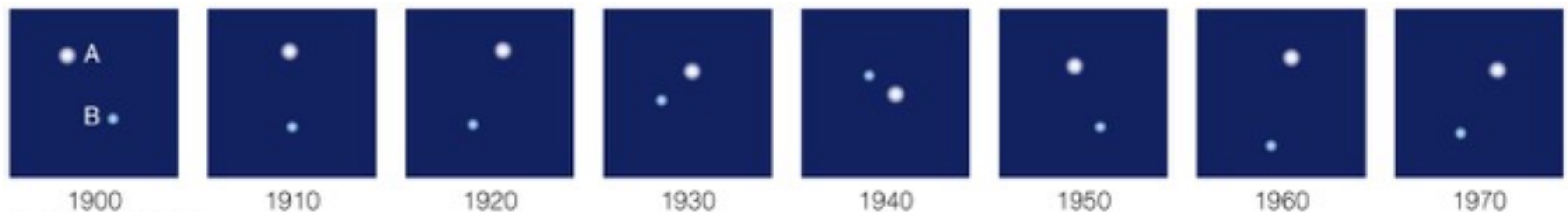
The orbit of a binary star system depends on strength of gravity.

Types of Binary Star Systems

- Visual binary
- Eclipsing binary
- Spectroscopic binary

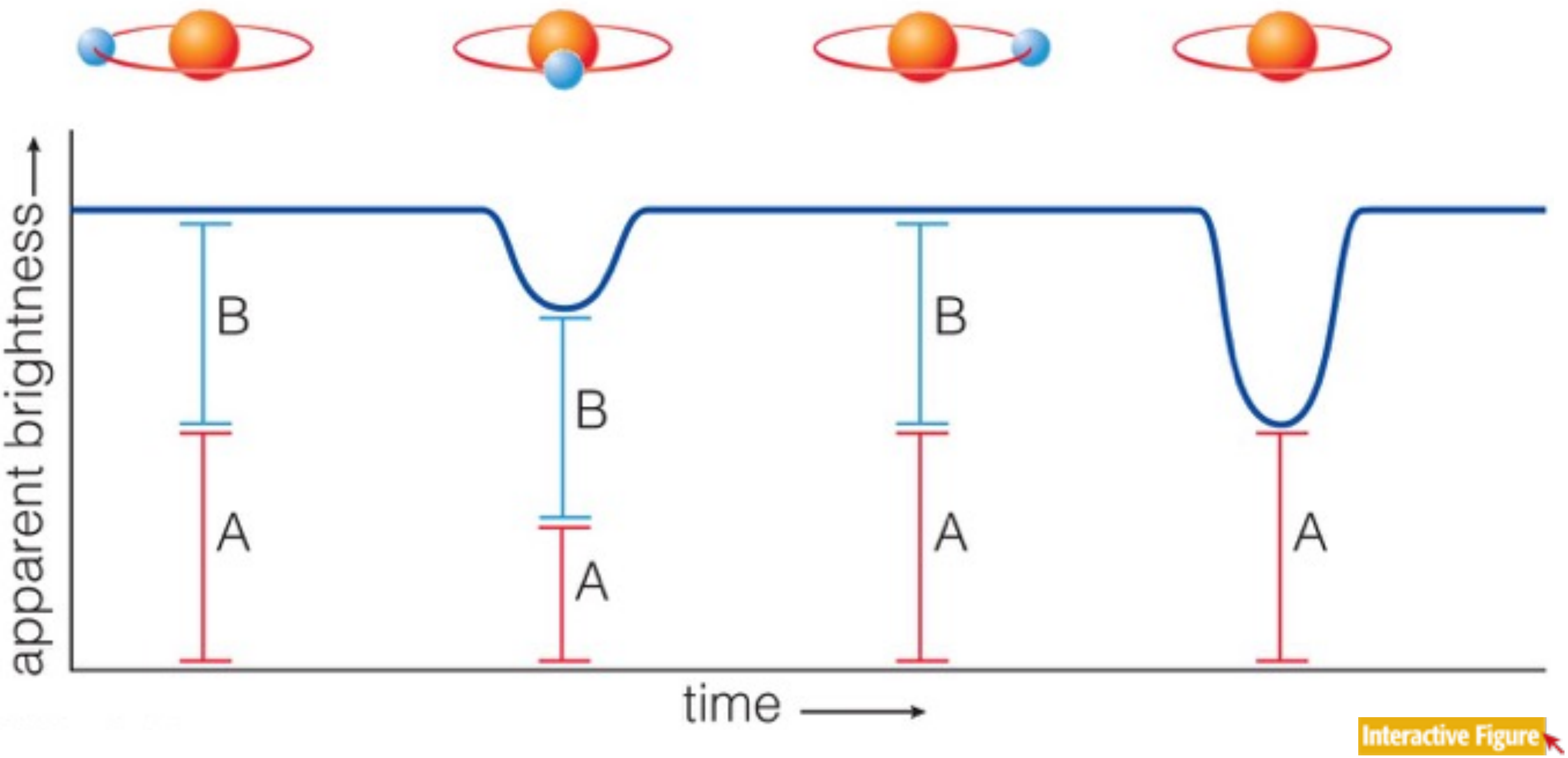
About half of all stars are in binary systems.

Visual Binary



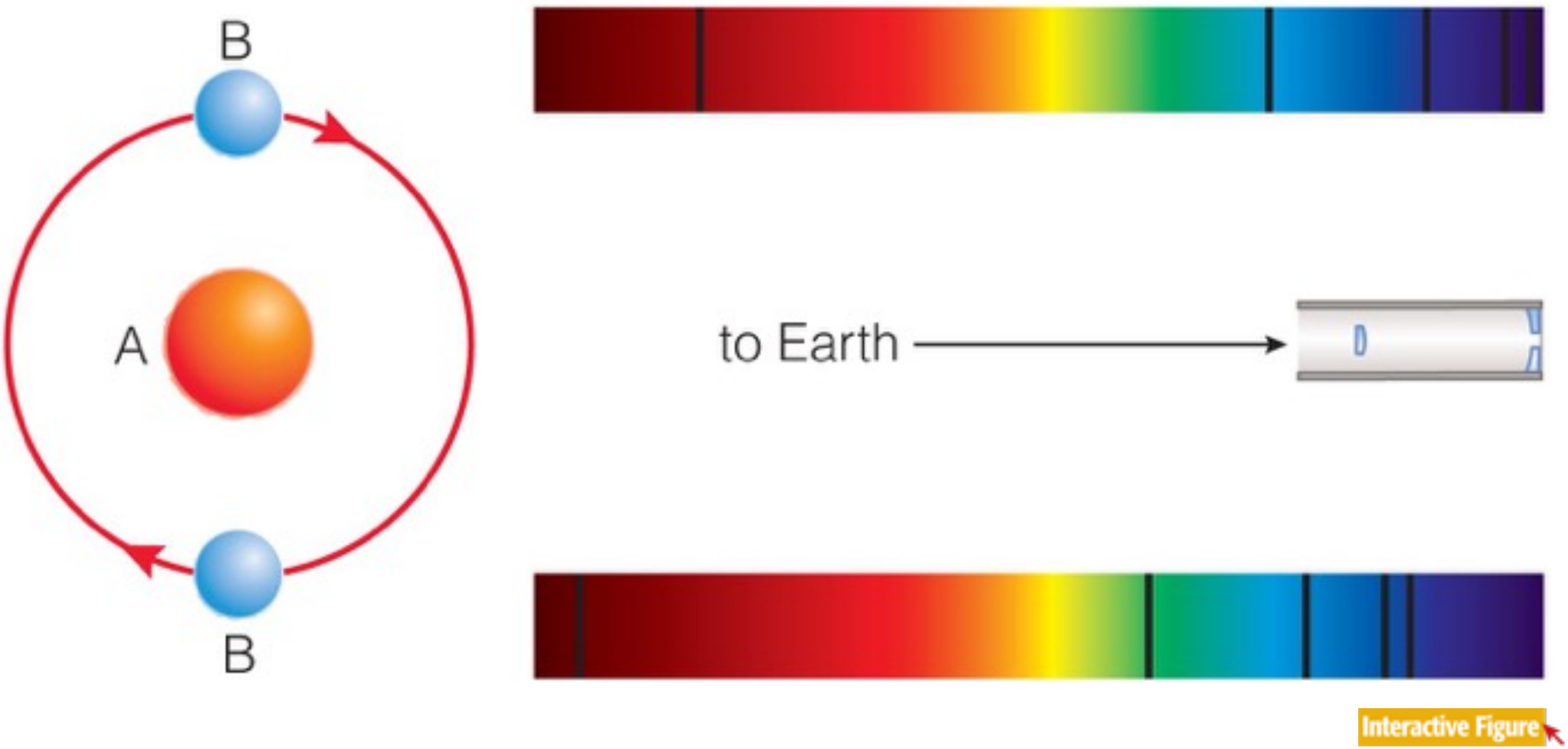
We can directly observe the orbital motions of these stars.

Eclipsing Binary



We can measure periodic eclipses.

Spectroscopic Binary



We determine the orbit by measuring Doppler shif

We measure mass using gravity.

Direct mass measurements are possible only for stars in binary star systems.

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

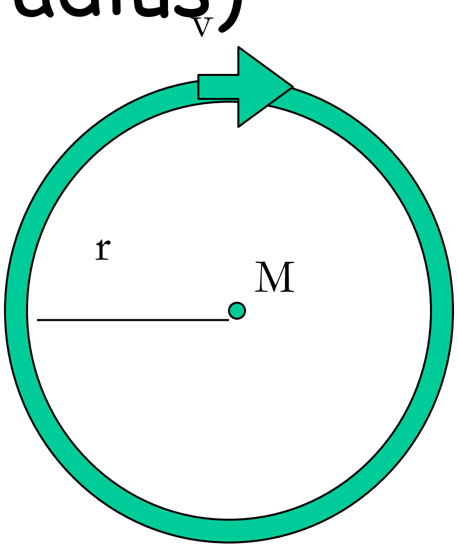
p = period

a = average separation

Need two out of three observables to measure mass:

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

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



Most massive stars:

$100 M_{Sun}$

Least massive stars:

$0.08 M_{Sun}$

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

Chapter 15

Which type of binary star system provides the most accurate determination of the stars' masses?

a) spectroscopic binary
b) visual binary
c) eclipsing binary
d) All of the above are equally accurate.
e) A and C

Chapter 15

Which type of binary star system provides both the masses and radii of its constituent stars?

a) spectroscopic binary
b) visual binary
c) eclipsing binary
d) All of the above.
e) None of the above.

What properties of a binary star system are needed to determine the masses of the stars?

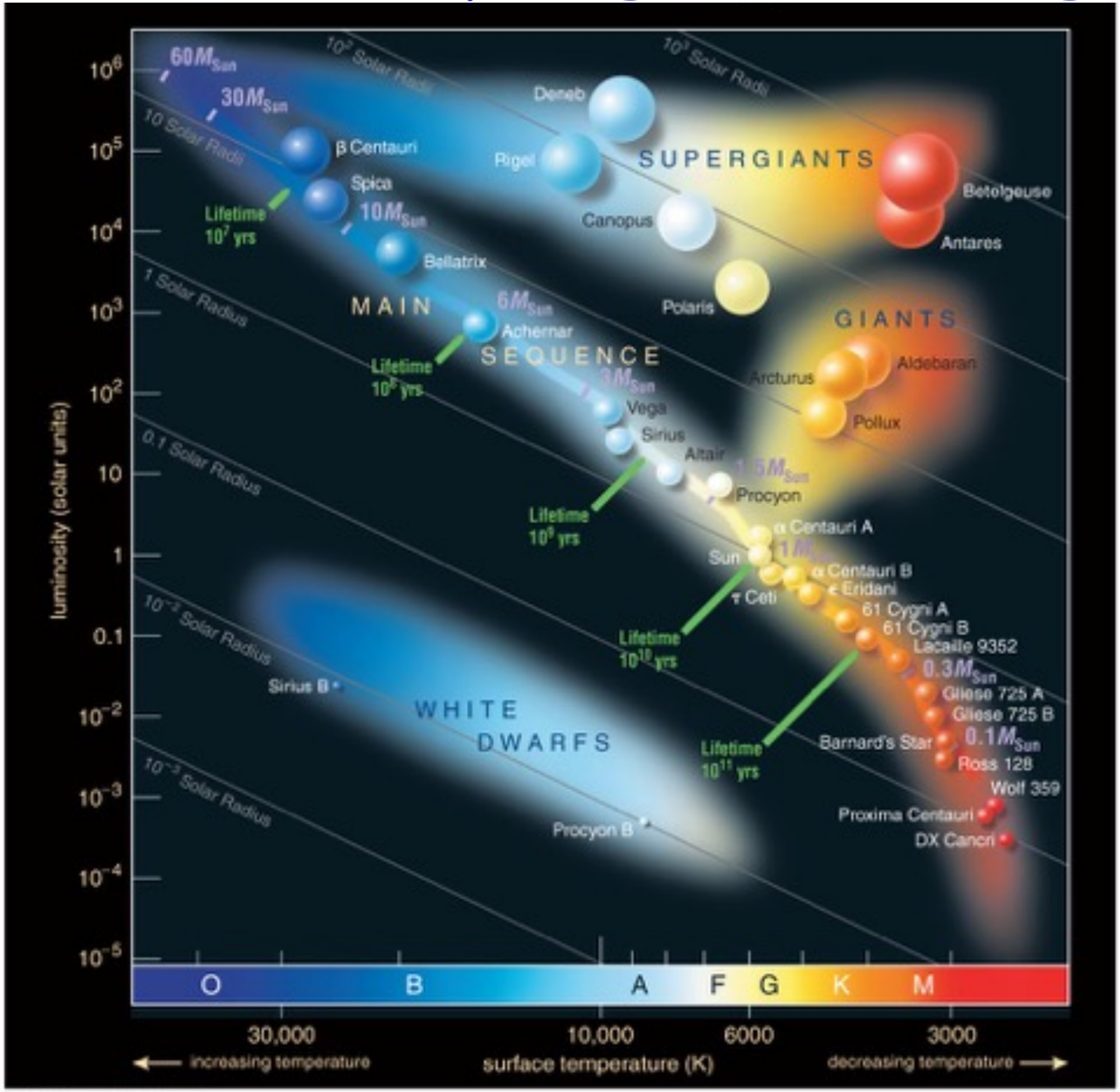
a) stellar size and orbit size
b) orbit size and spectral type
c) stellar size and spectral type
d) orbit size and orbit period
e) orbit period and stellar size

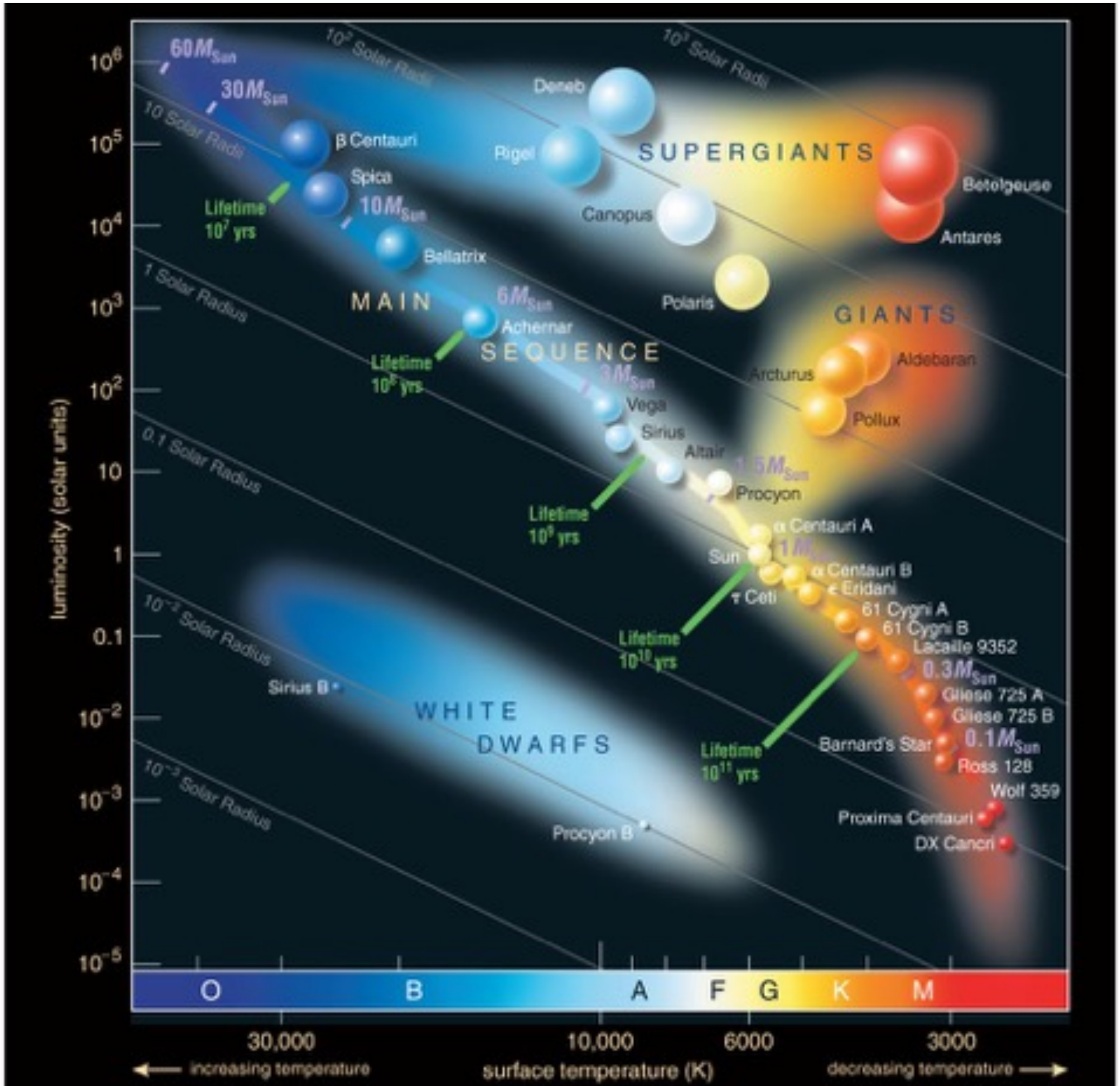
Patterns Among Stars

Our goals for learning:

- What is a Hertzsprung-Russell diagram?
- What is the significance of the main sequence?
- What are giants, supergiants, and white dwarfs?
- Why do the properties of some stars vary?

What is a Hertzsprung-Russell diagram?

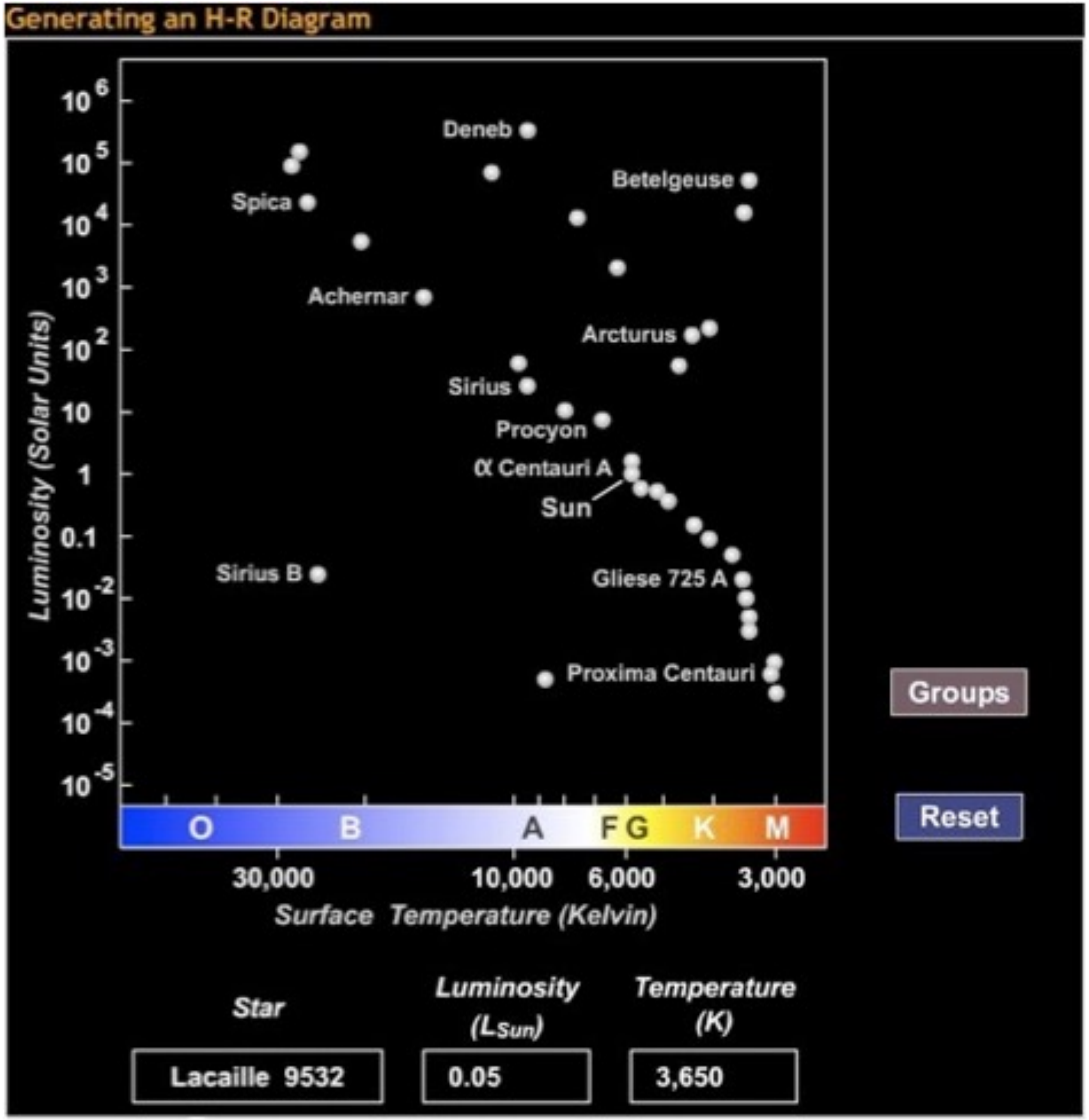


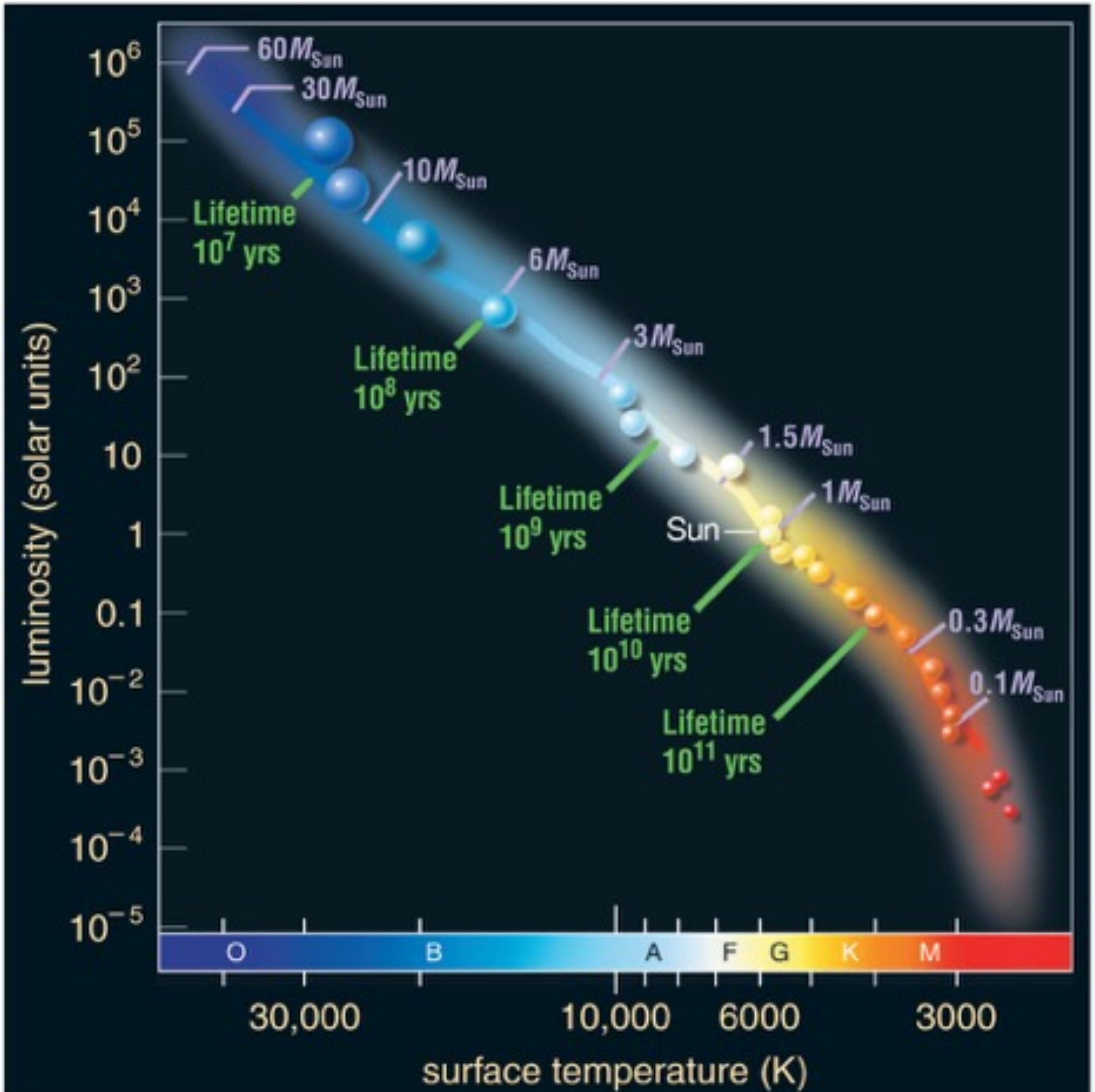


Luminosity

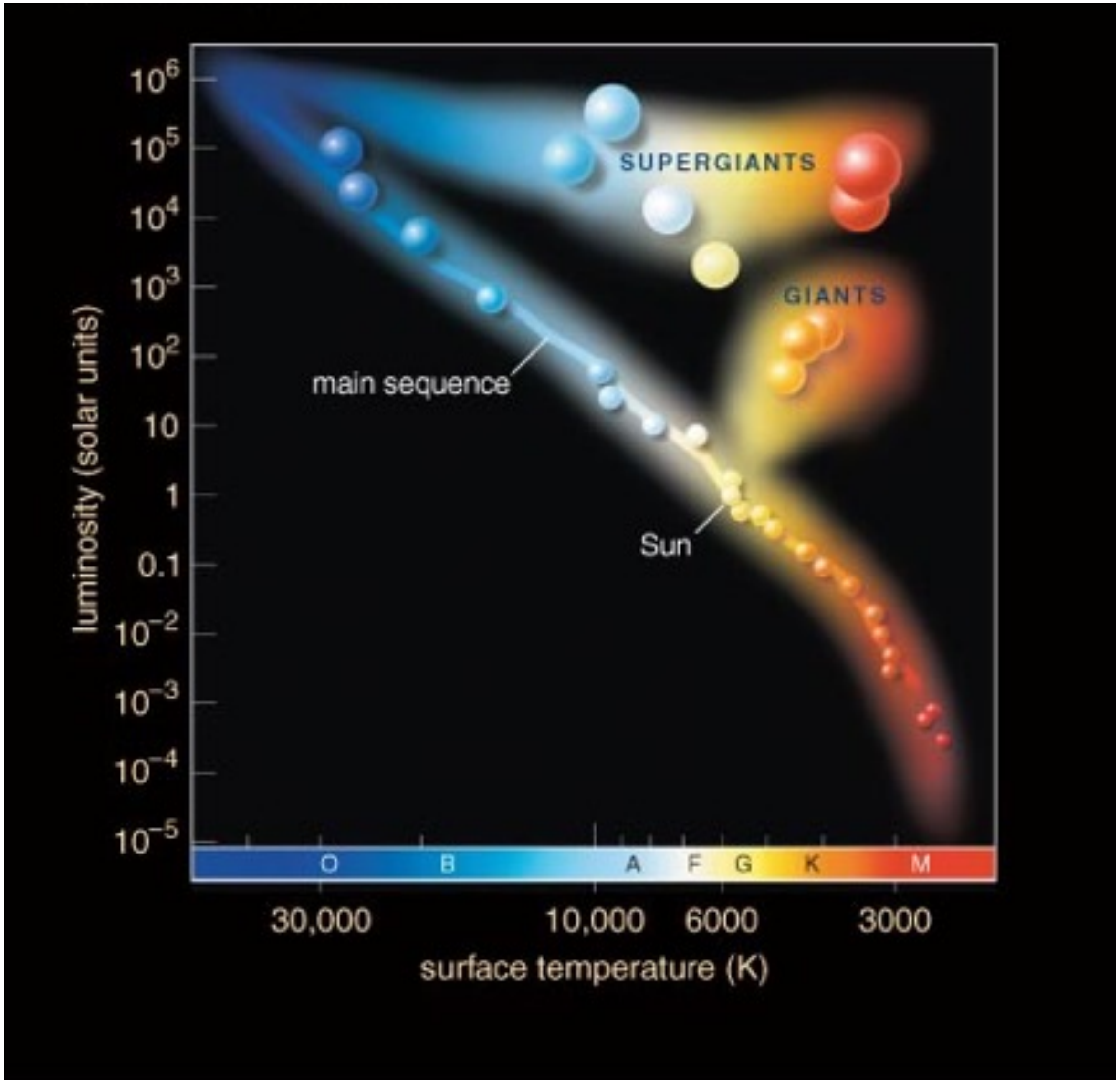
Temperature

An H-R diagram plots the luminosity and temperature of stars.

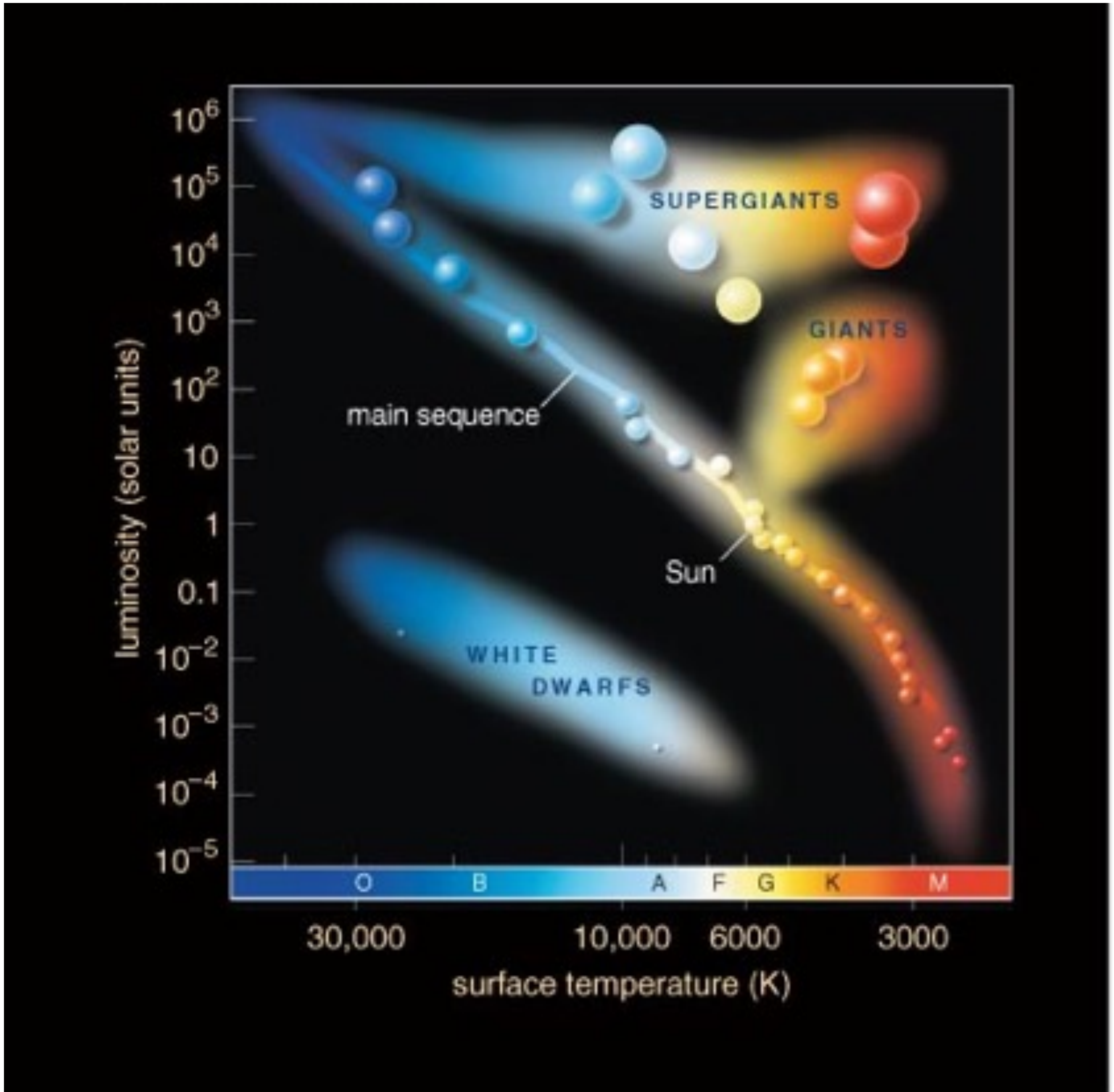

Generating an H-R Diagram
Luminosity (Solar Units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^-2
10^-3
10^-4
10^-5
Deneb
Betelgeuse
Spica
Achernar
Arcturus
Sirius
Procyon
α Centauri A
Sun
Sirius B
Gliese 725 A
Proxima Centauri
O
B
A
F G
K
M
30,000
10,000
6,000
3,000
Surface Temperature (Kelvin)
Groups
Reset
Star
Luminosity (LSun)
Temperature (K)
Lacaille 9532
0.05
3,650



Most stars fall somewhere on the main sequence of the H-R diagram.



Stars with lower T and higher L than main-sequence stars must have larger radii. These stars are called giants and supergiants.



Stars with higher T and lower L than main-sequence stars must have smaller radii. These stars are called white dwarfs.

A star's full classification includes spectral type (line identities) and luminosity class (line shapes, related to the size of the star):

- I - supergiant
- II - bright giant
- III - giant
- IV - subgiant
- V - main sequence

Examples: Sun - G2 V

Sirius - A1 V

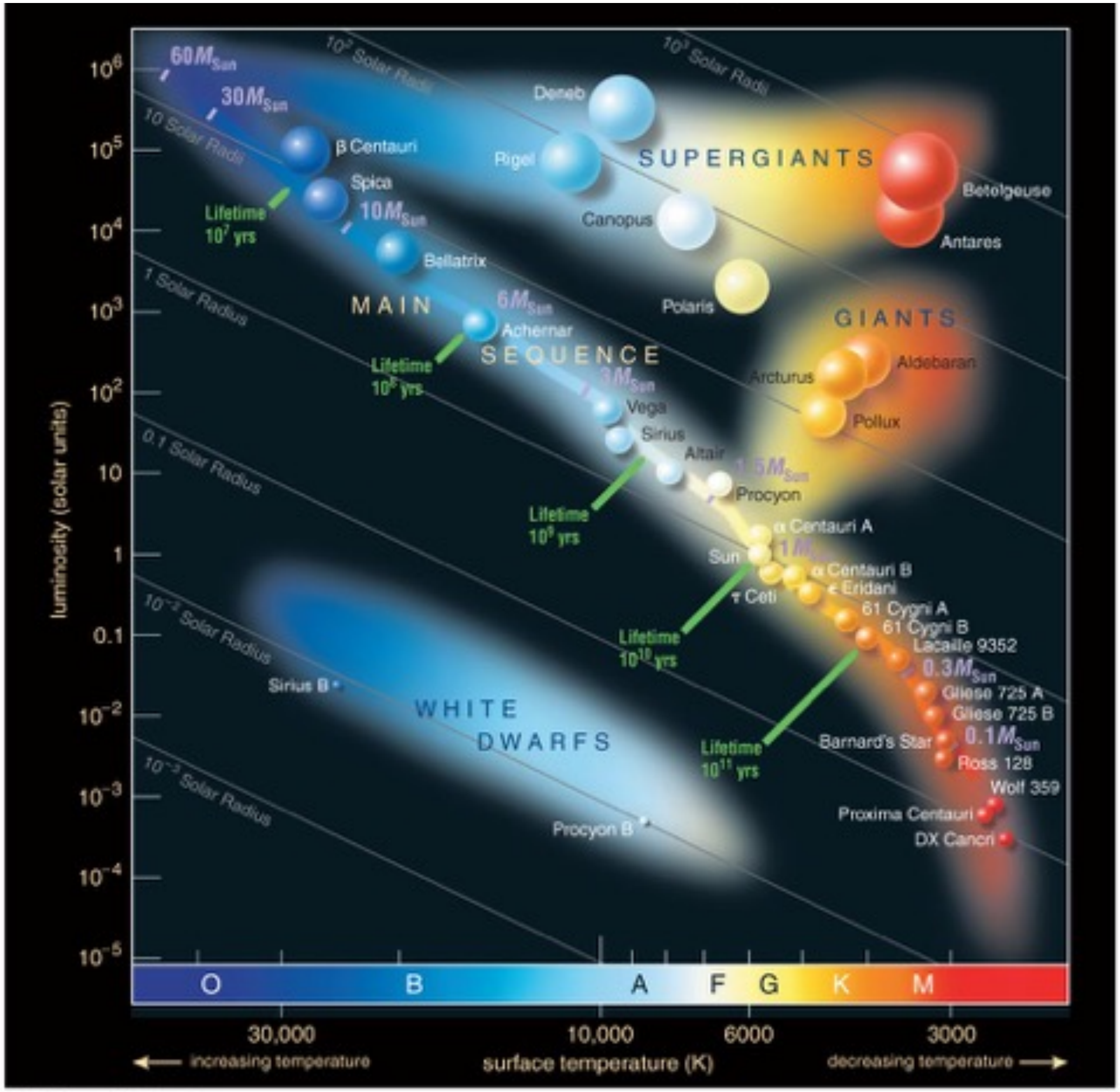
Proxima Centauri - M5.5 V

Betelgeuse - M2 I

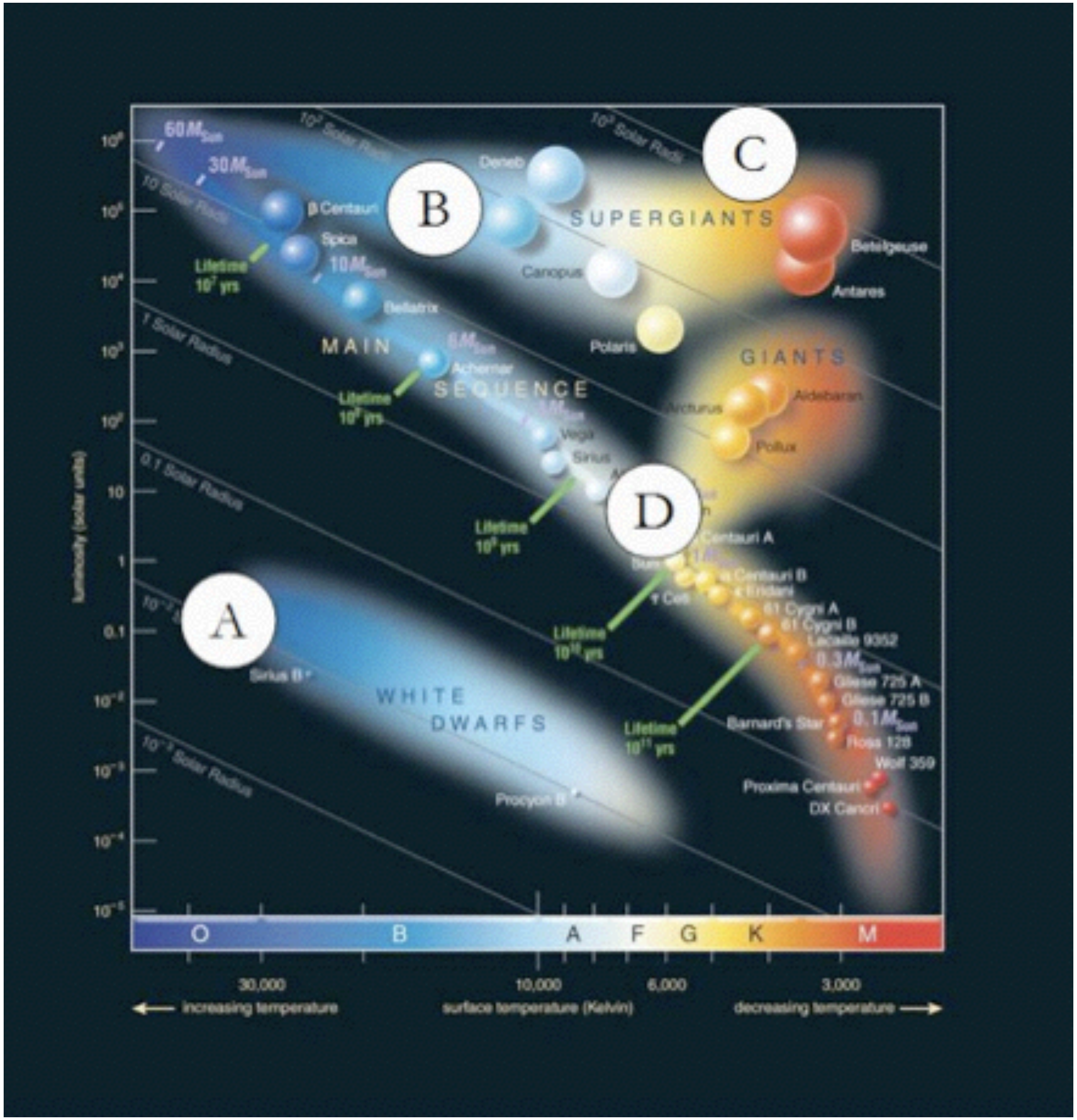
H-R diagram depicts:

- Temperature
- Color
- Spectral type
- Luminosity
- Radius

Luminosity



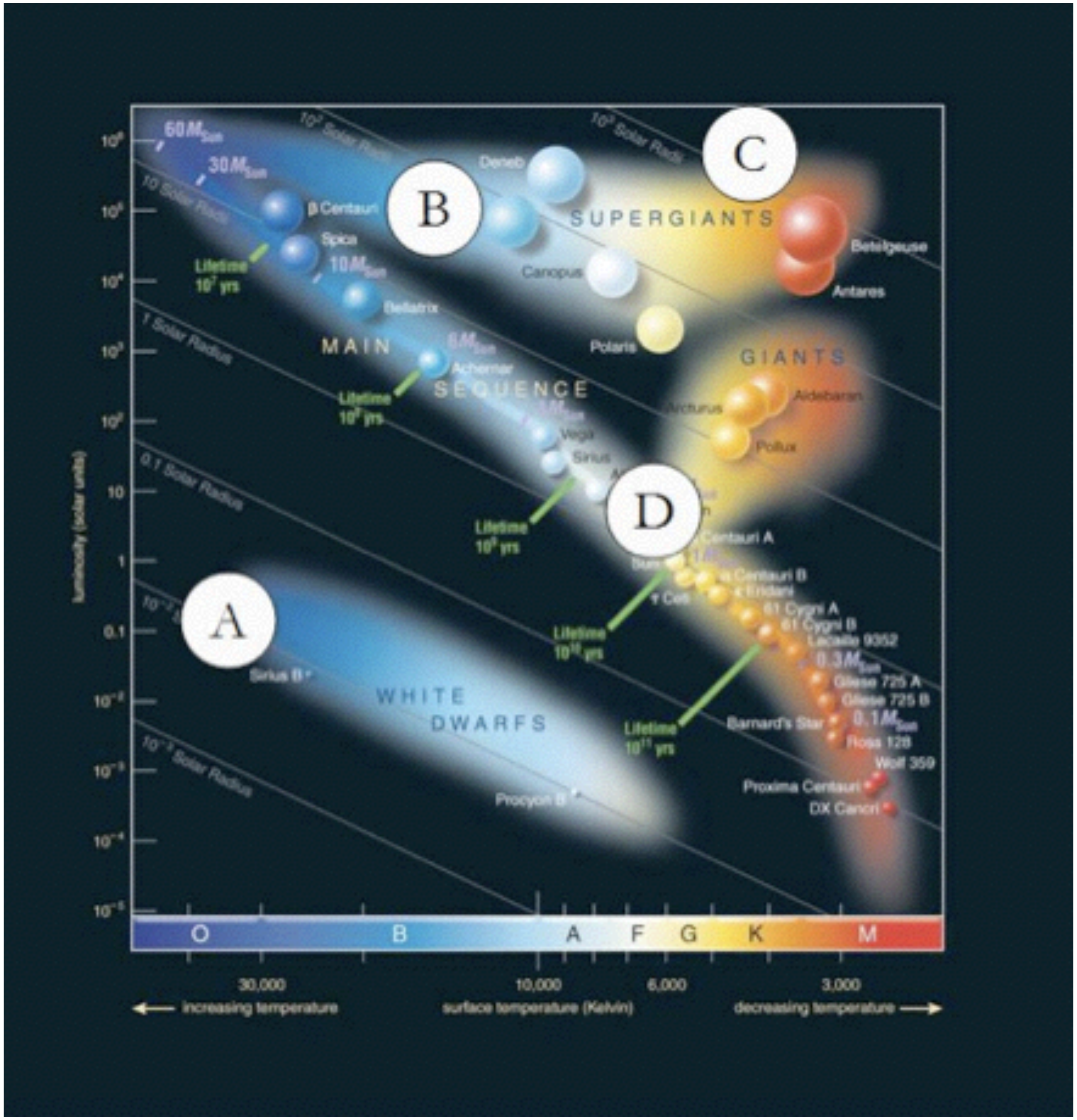
Temperature



Luminosity ↑

← Temperature

Which star is the hottest?

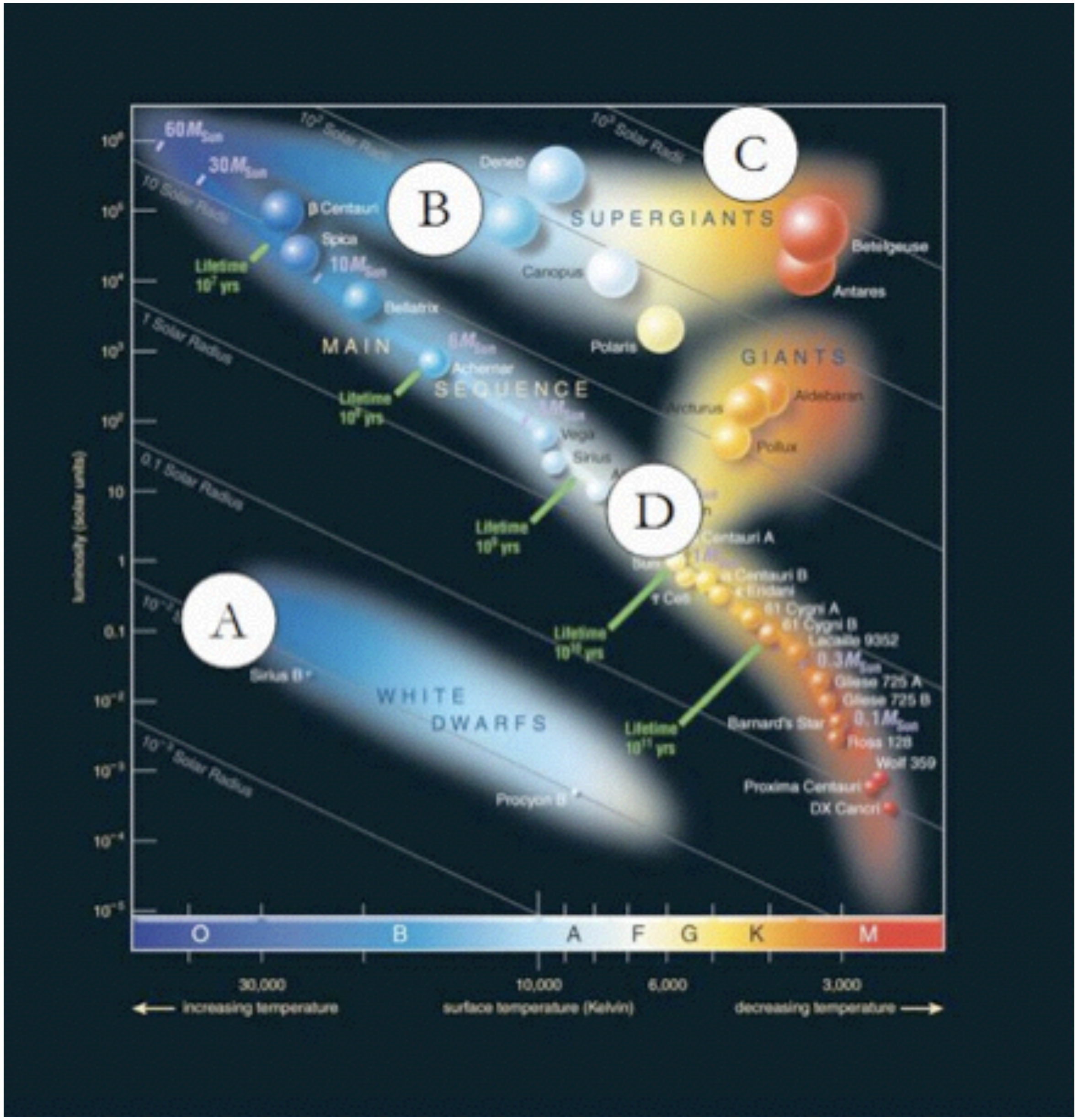


Luminosity

Temperature

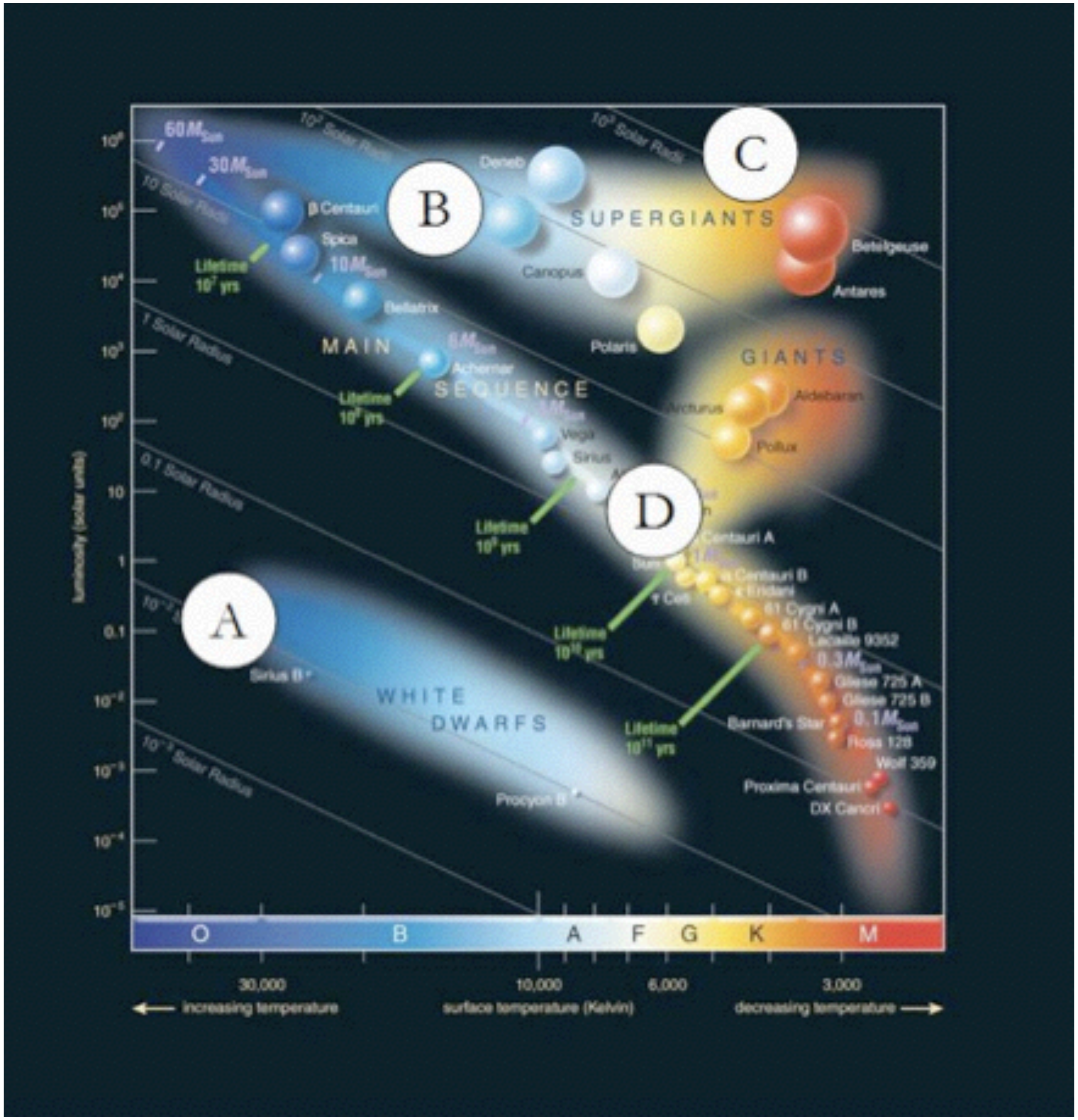
Which star is the most luminous?

Luminosity



Temperature

Which star is a main-sequence star?

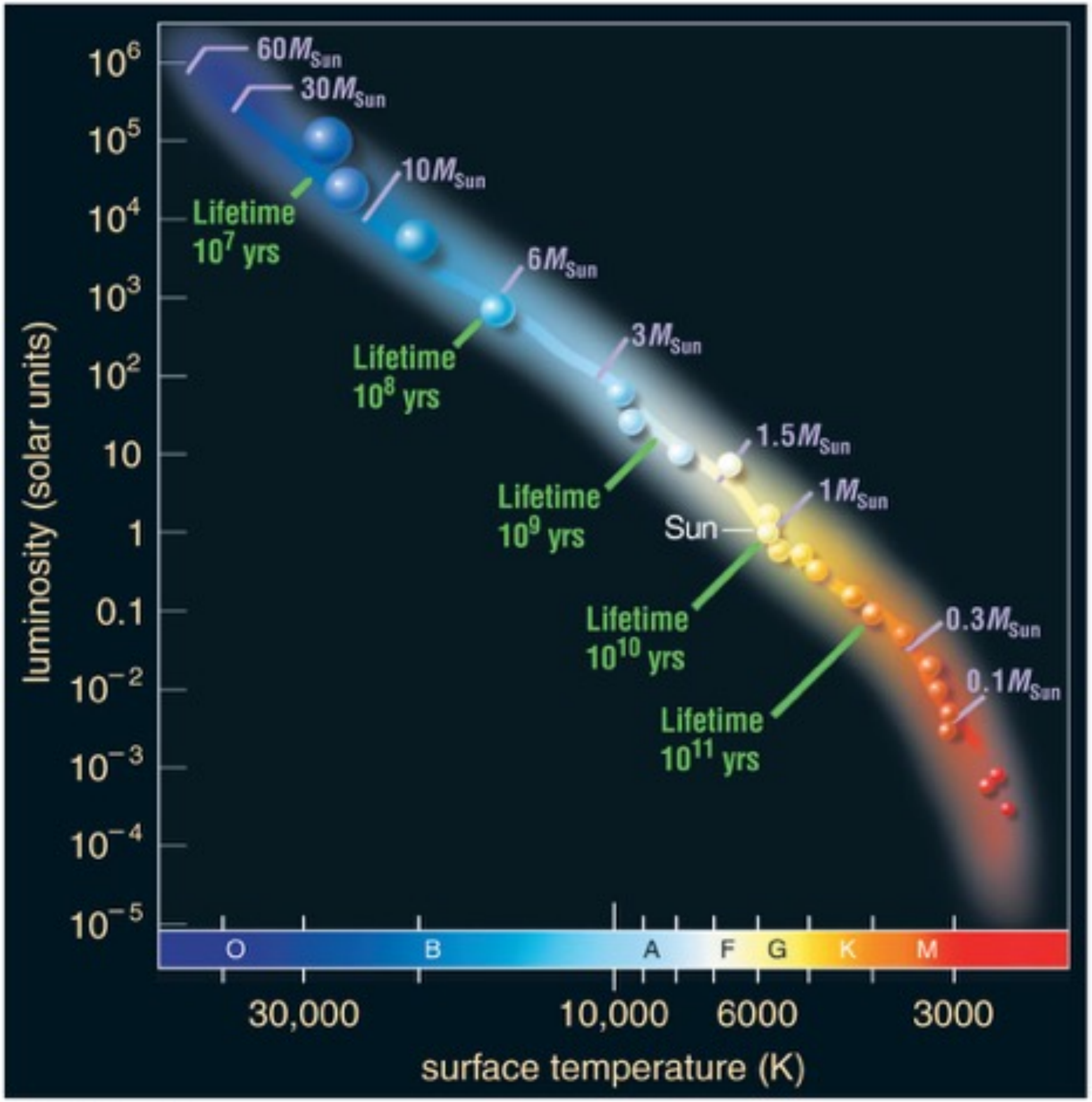


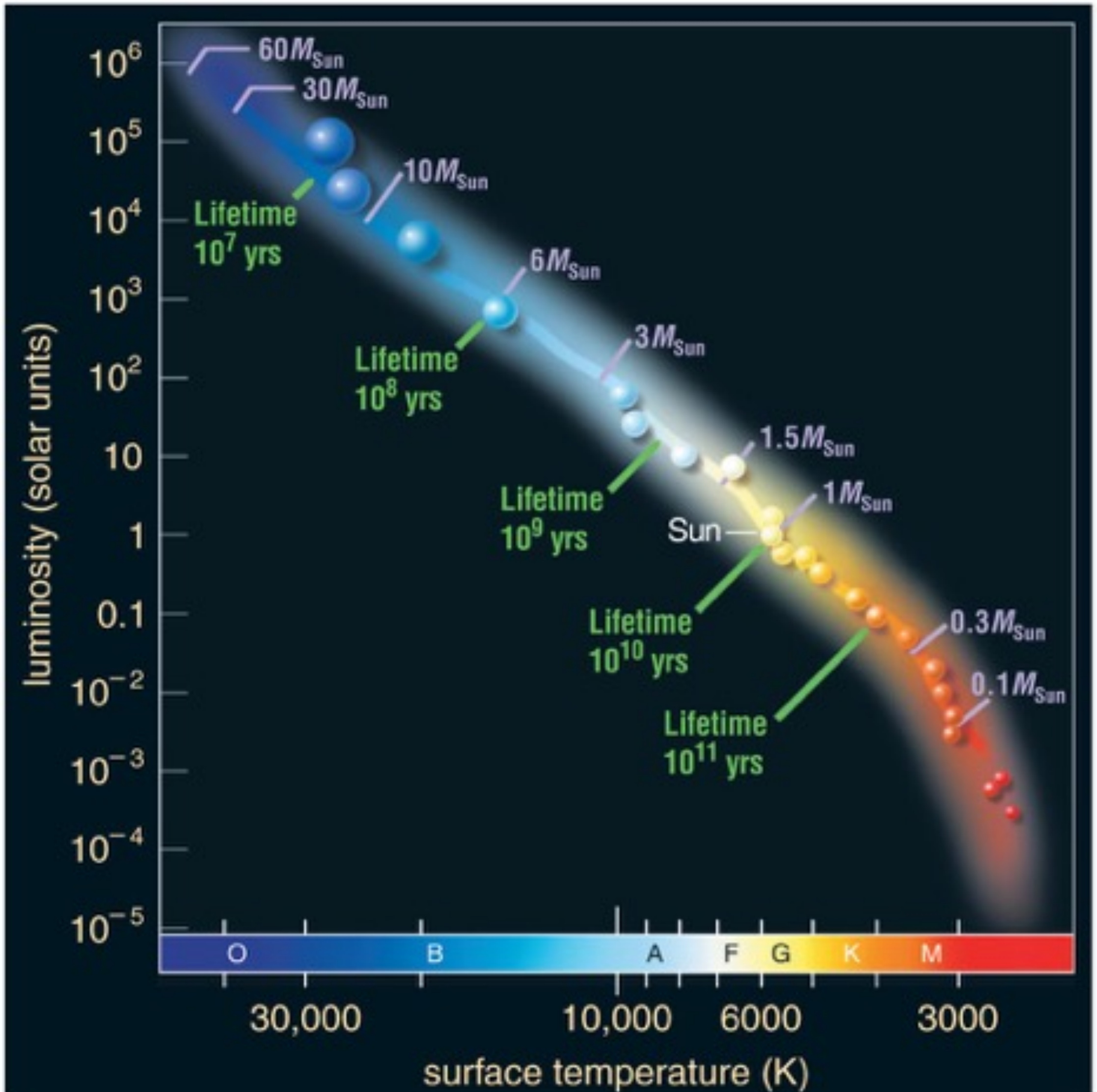
Luminosity

Temperature

Which star has the largest radius?

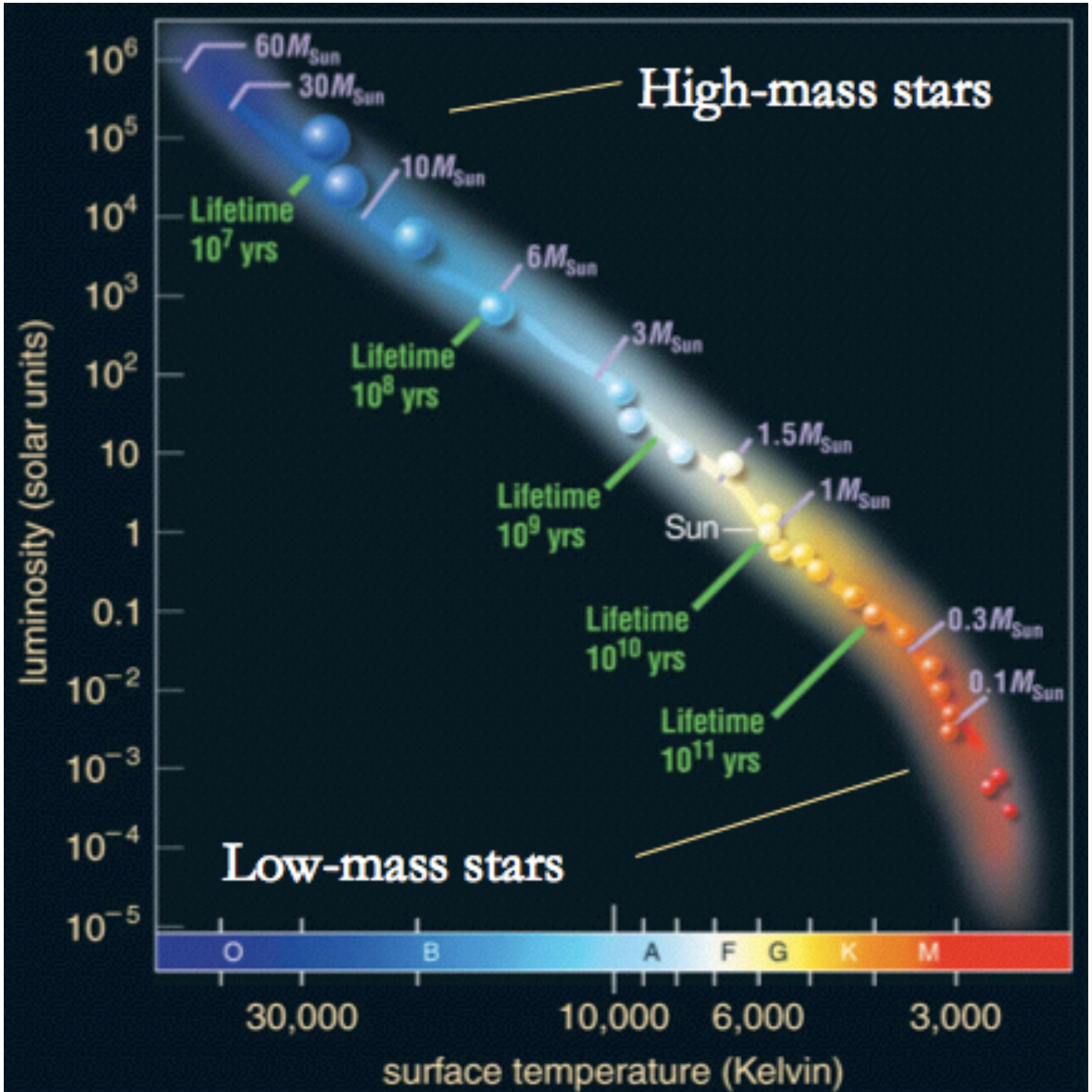
What is the significance of the main sequence?



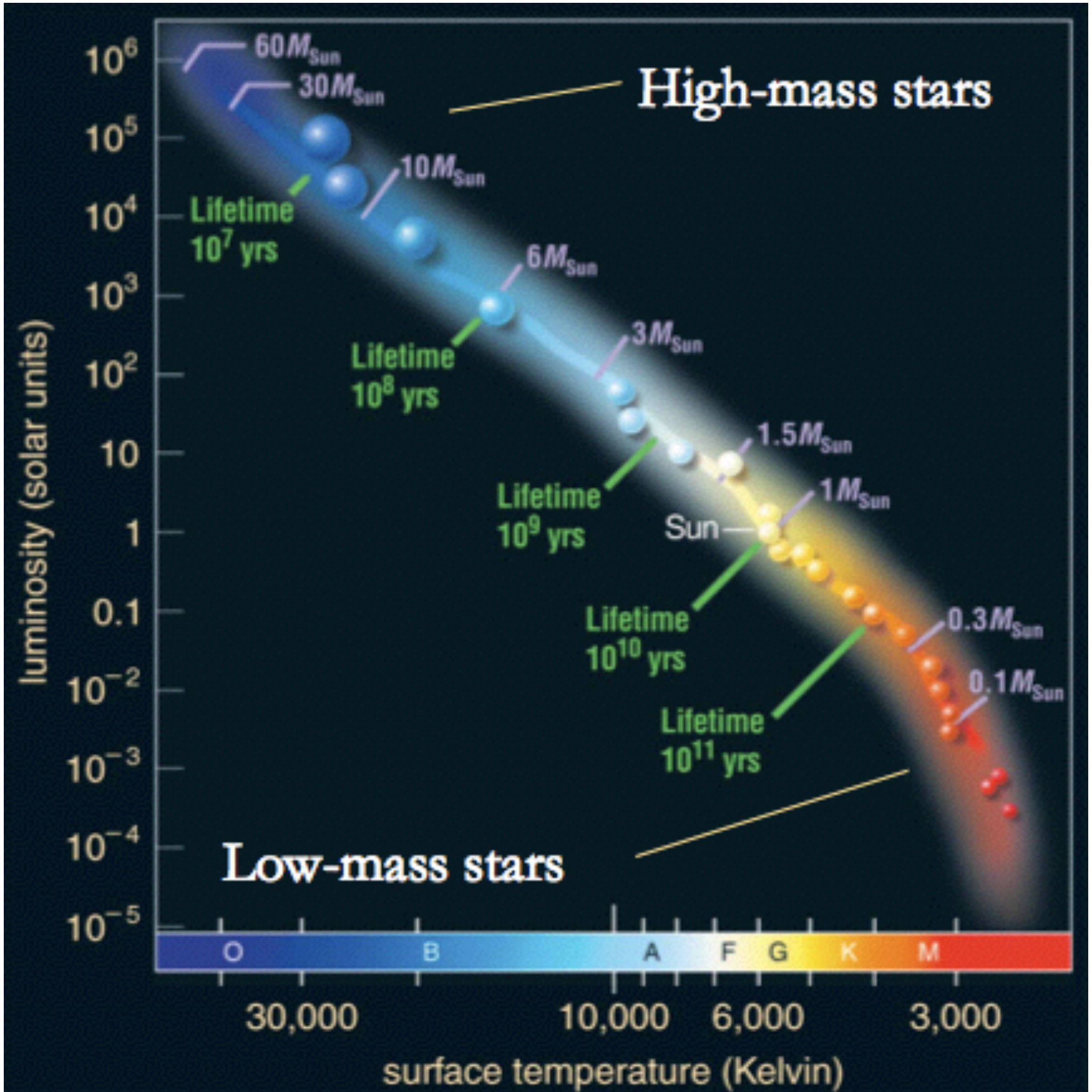


Main-sequence stars are fusing hydrogen into helium in their cores like the Sun.

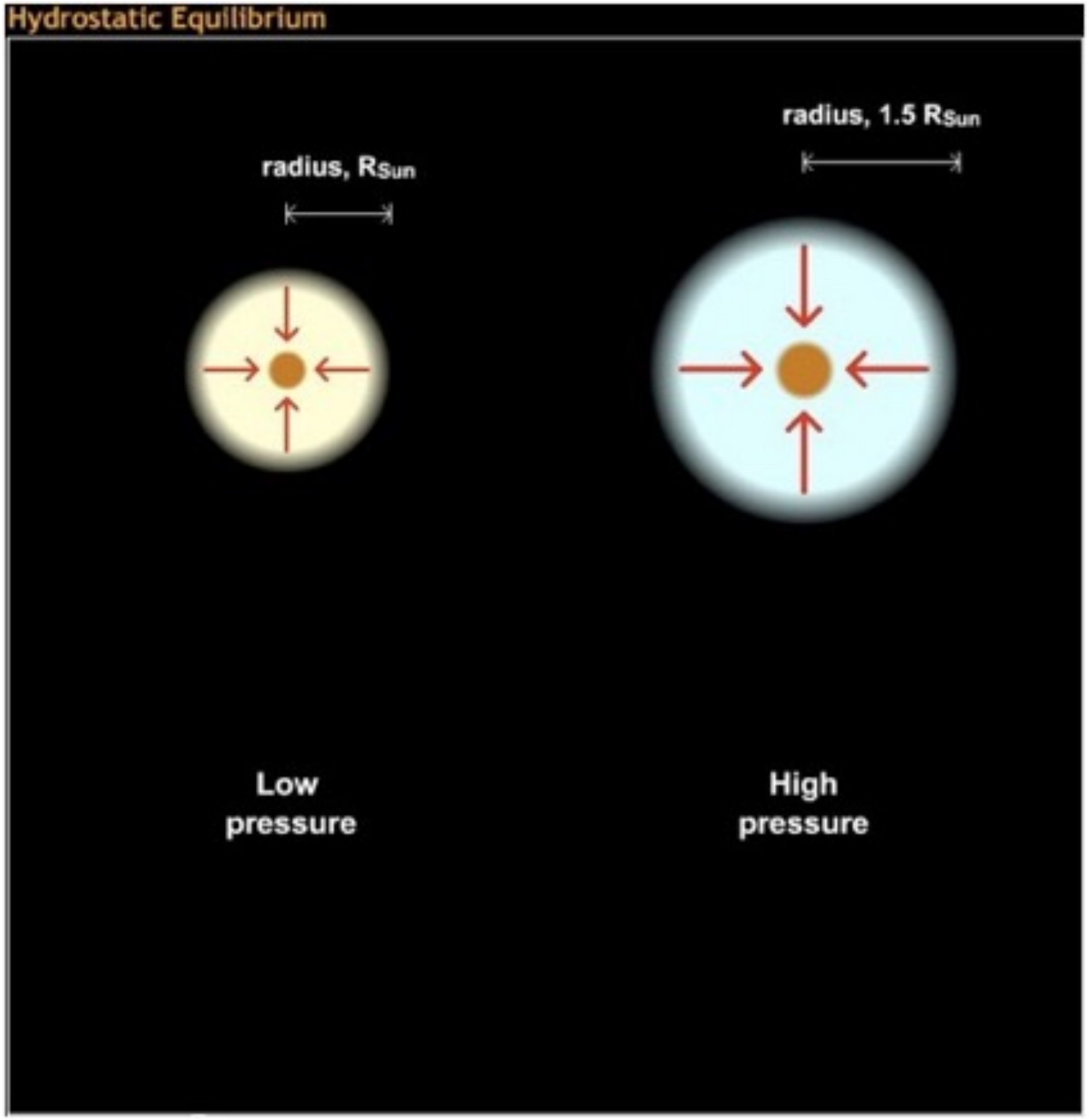
-Luminous main-sequence stars are hot (blue). Less luminous ones are cooler (yellow or red).



Mass measurements of main-sequence stars show that the hot, blue stars are much more massive than the cool, red ones.



The mass of a normal, hydrogen-burning star determines its luminosity and spectral type.



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.

Stellar Properties Review

Luminosity: from brightness and distance

$10^{-4} L_{Sun}$–$10^{6} L_{Sun}$

Temperature: from color and spectral type

3000 K–50,000 K

Mass: from period (p) and average separation (a) of binary star orbit

$0.08 M_{Sun}$–$100 M_{Sun}$

Mass and Lifetime

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

Sun's life expectancy: 10 billion years

Life expectancy of $10M_{Sun}$ star:

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

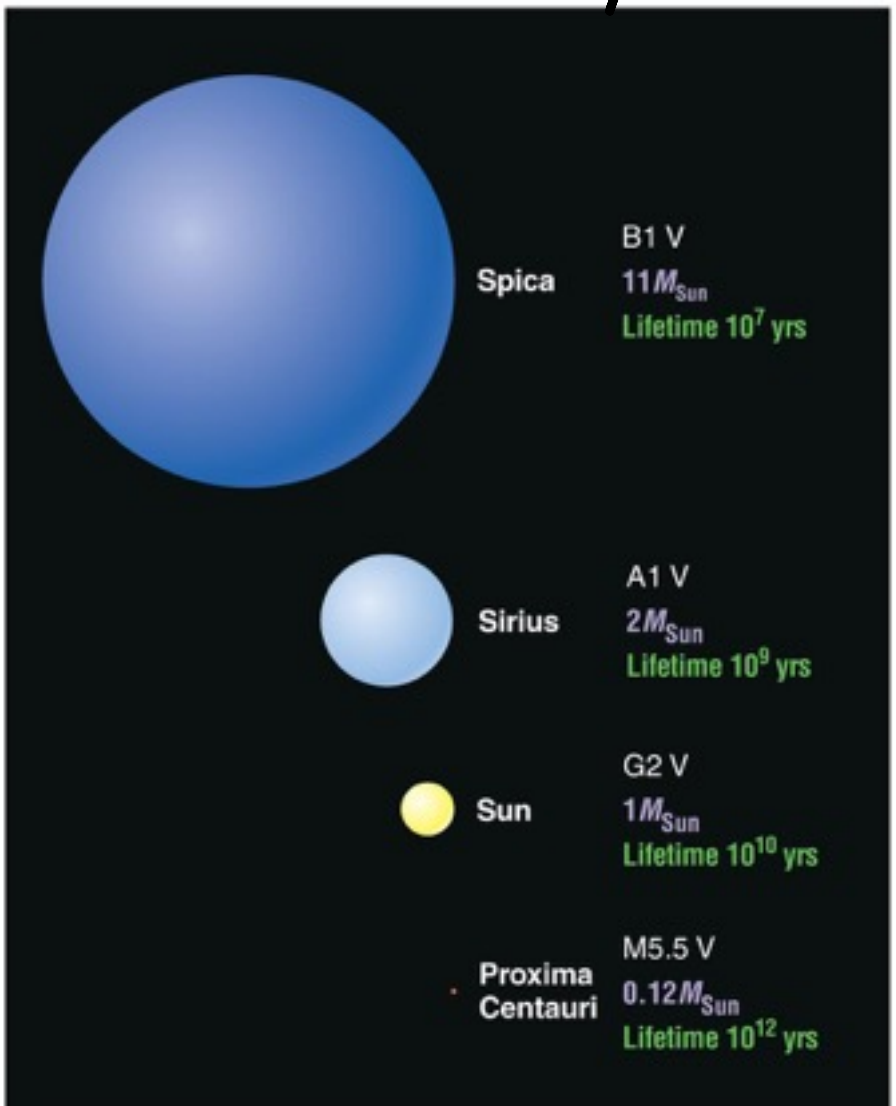
10 million years ~ 10 billion years × $10/10^4$

Life expectancy of $0.1M_{Sun}$ star:

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

100 billion years ~ 10 billion years × 0.1/0.01

Main-Sequence Star Summary



High-Mass Star:

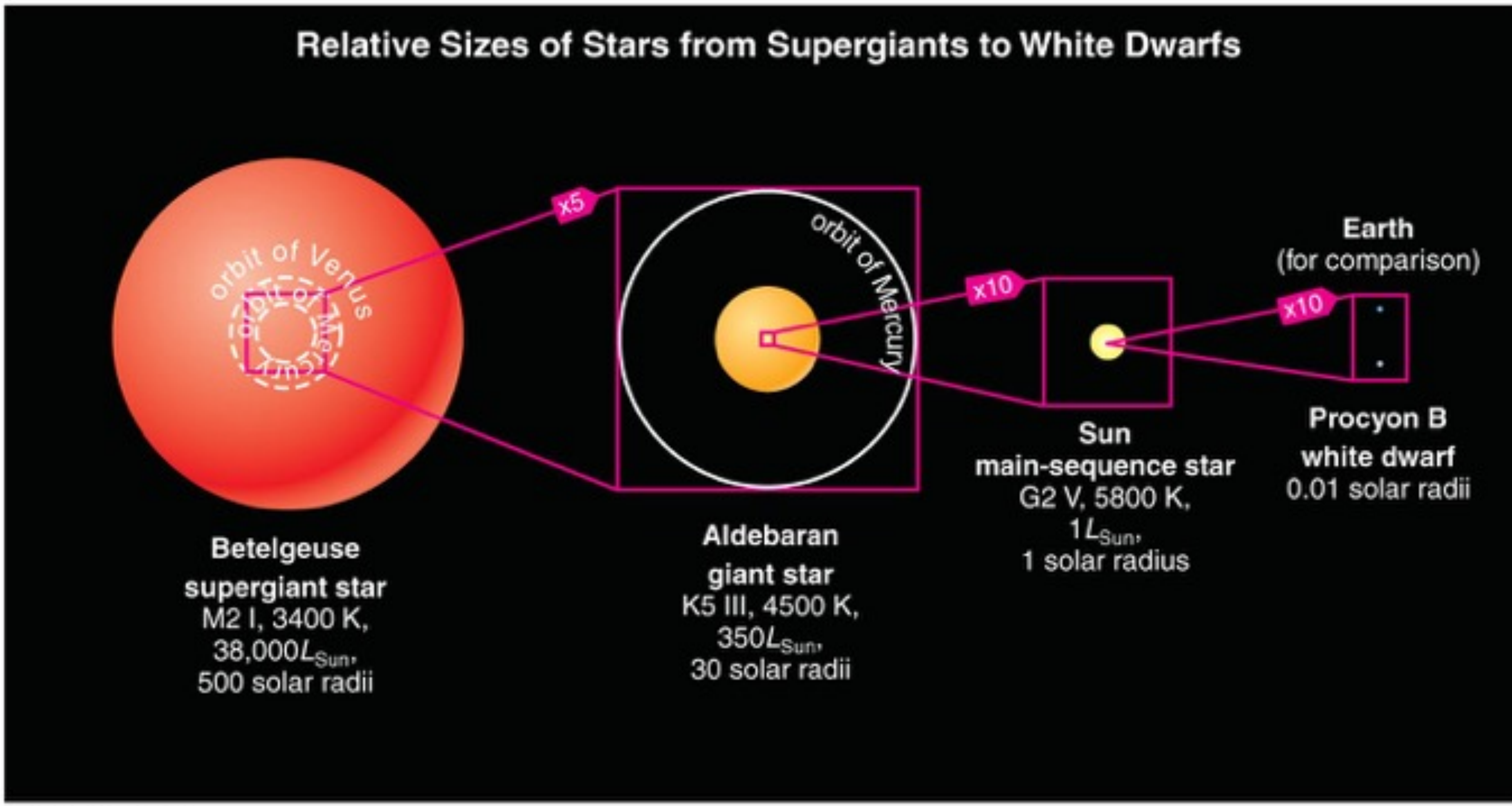
- High luminosity
- Short-lived
- Larger radius
- Blue

Low-Mass Star:

- Low luminosity
- Long-lived
- Small radius
- Red

What are giants, supergiants, and white dwarfs?

Sizes of Giants and Supergiants

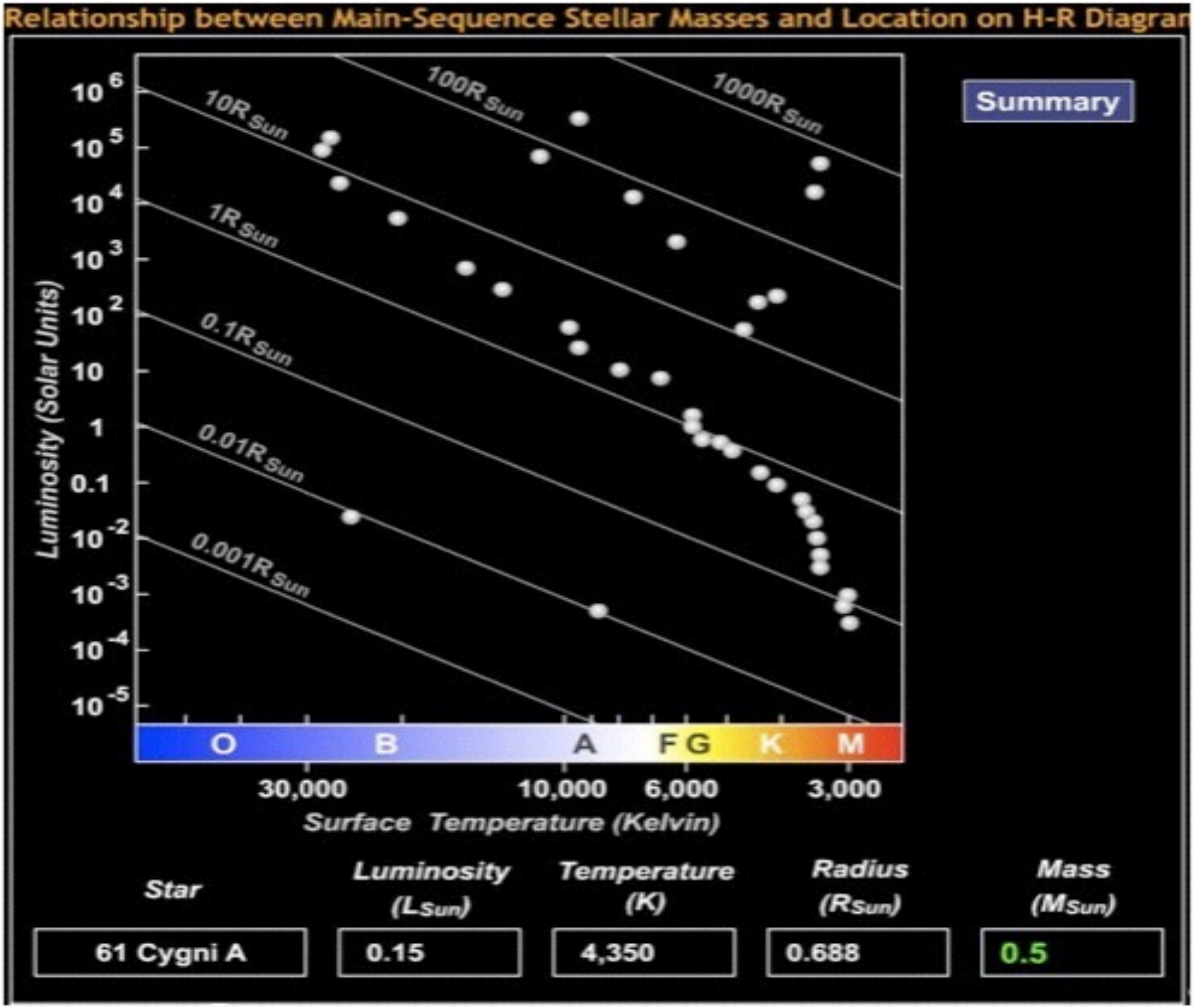


Off the Main Sequence

- 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.

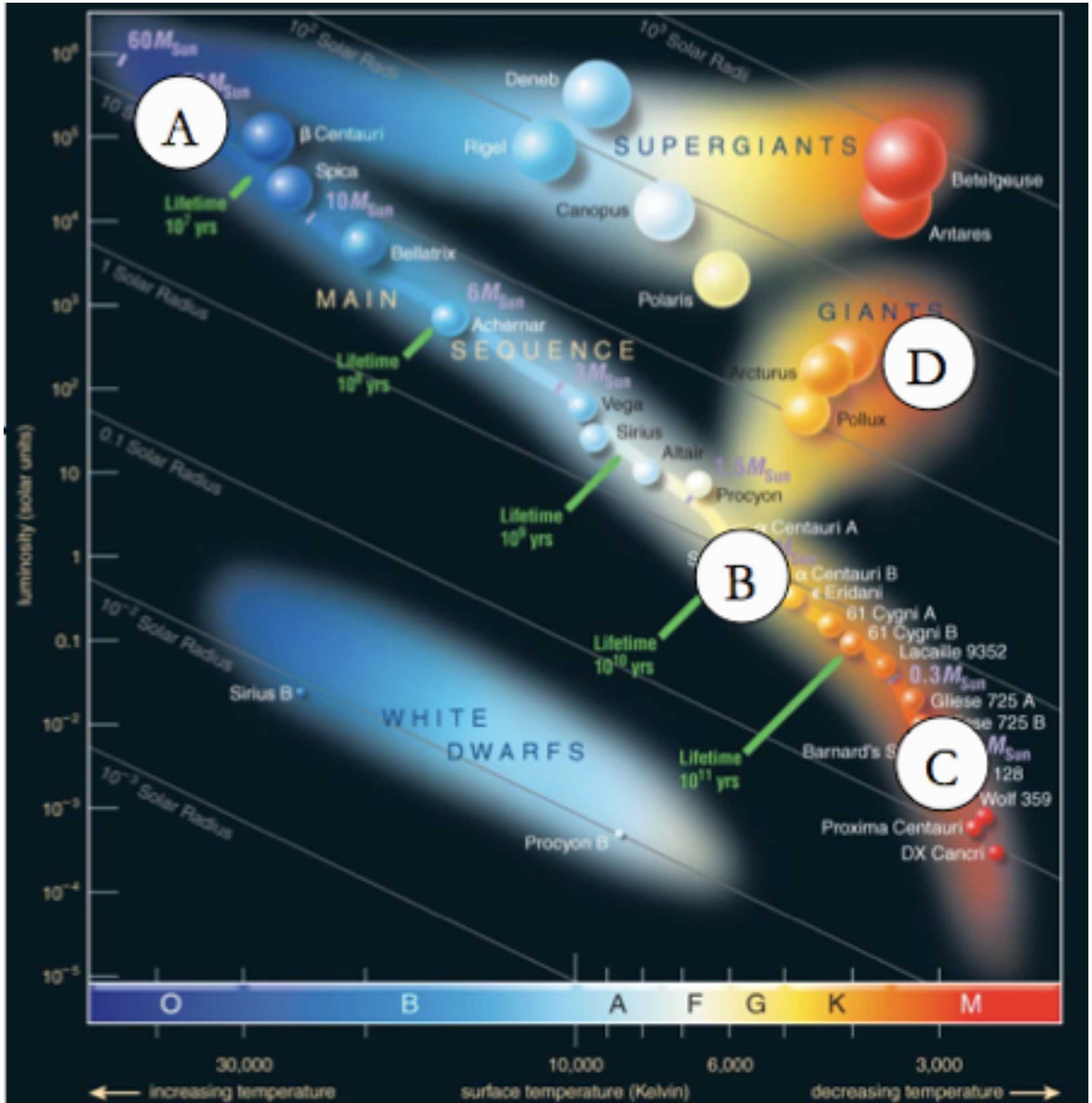
- All stars become larger and redder after exhausting their core hydrogen: **giants** and **supergiants**.

- Most stars end up small and white after fusion has ceased: **white dwarfs**.



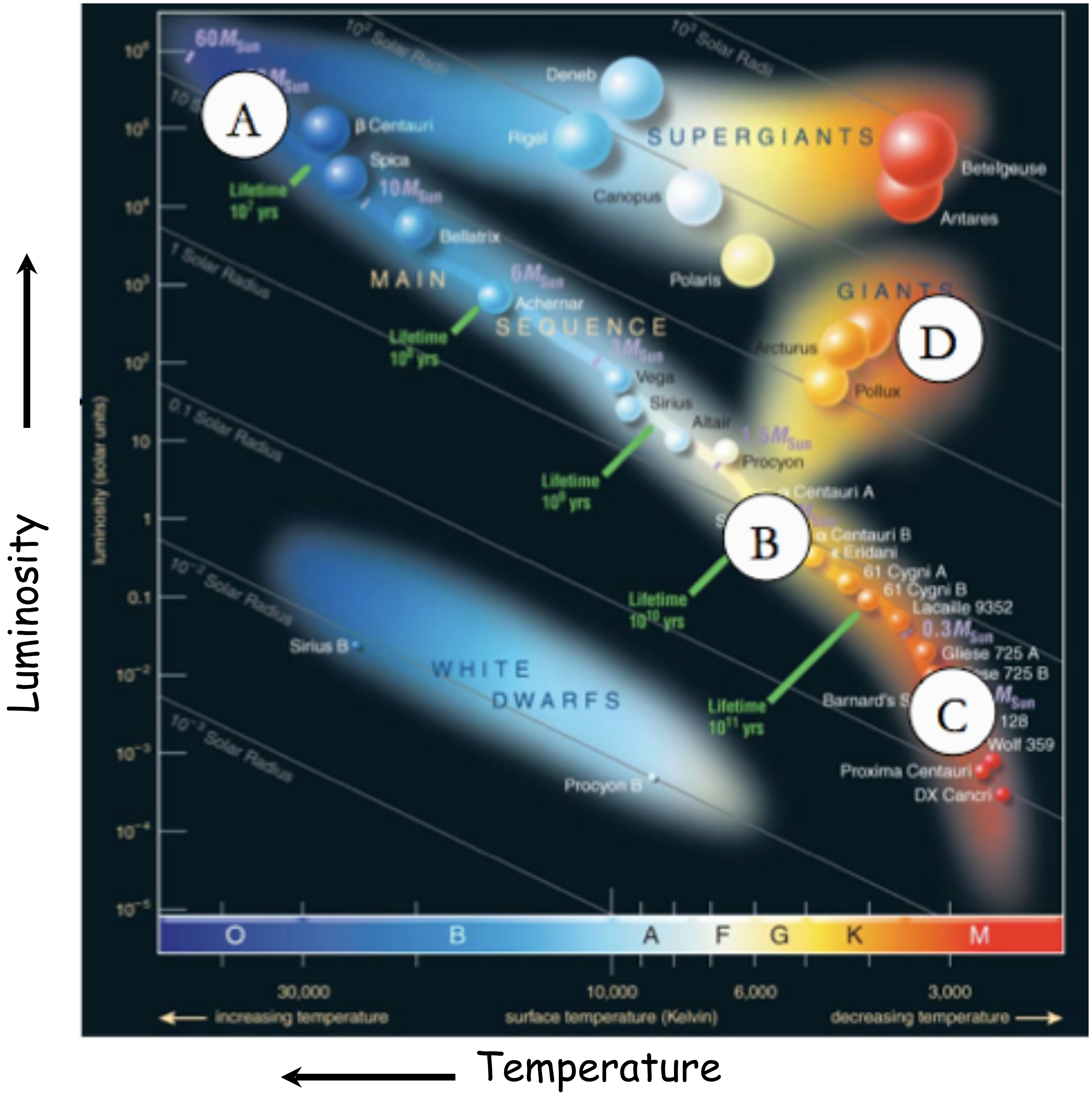
Relationship between Main-Sequence Stellar Masses and Location on H-R Diagram
Summary
Luminosity (Solar Units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^-2
10^-3
10^-4
10^-5
10R Sun
100R Sun
1000R Sun
1R Sun
0.1R Sun
0.01R Sun
0.001R Sun
O
B
A
F G
K
M
30,000
10,000
6,000
3,000
Surface Temperature (Kelvin)
Star
Luminosity (LSun)
Temperature (K)
Radius (RSun)
Mass (MSun)
61 Cygni A
0.15
4,350
0.688
0.5

Luminosity



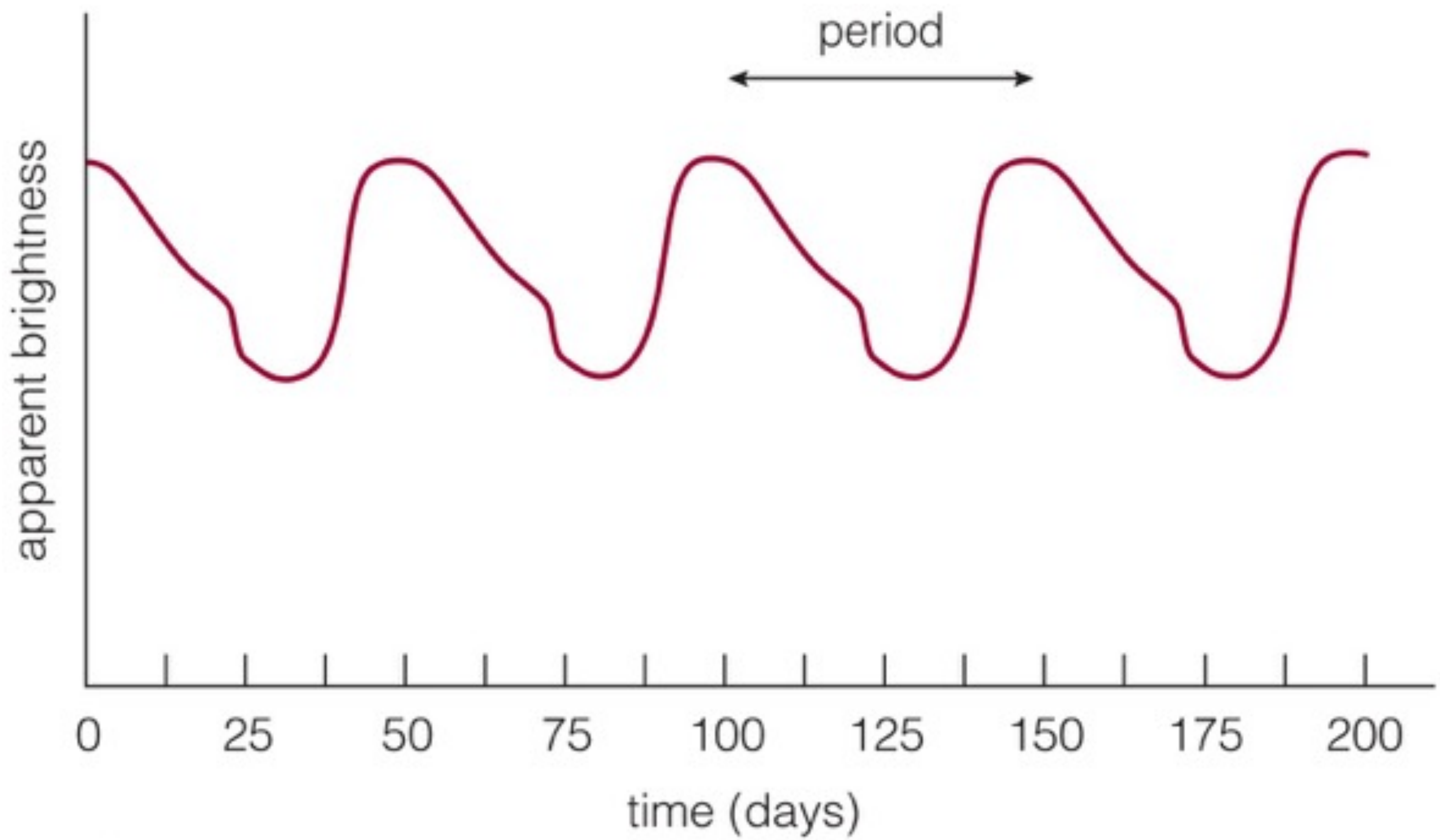
Temperature

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



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

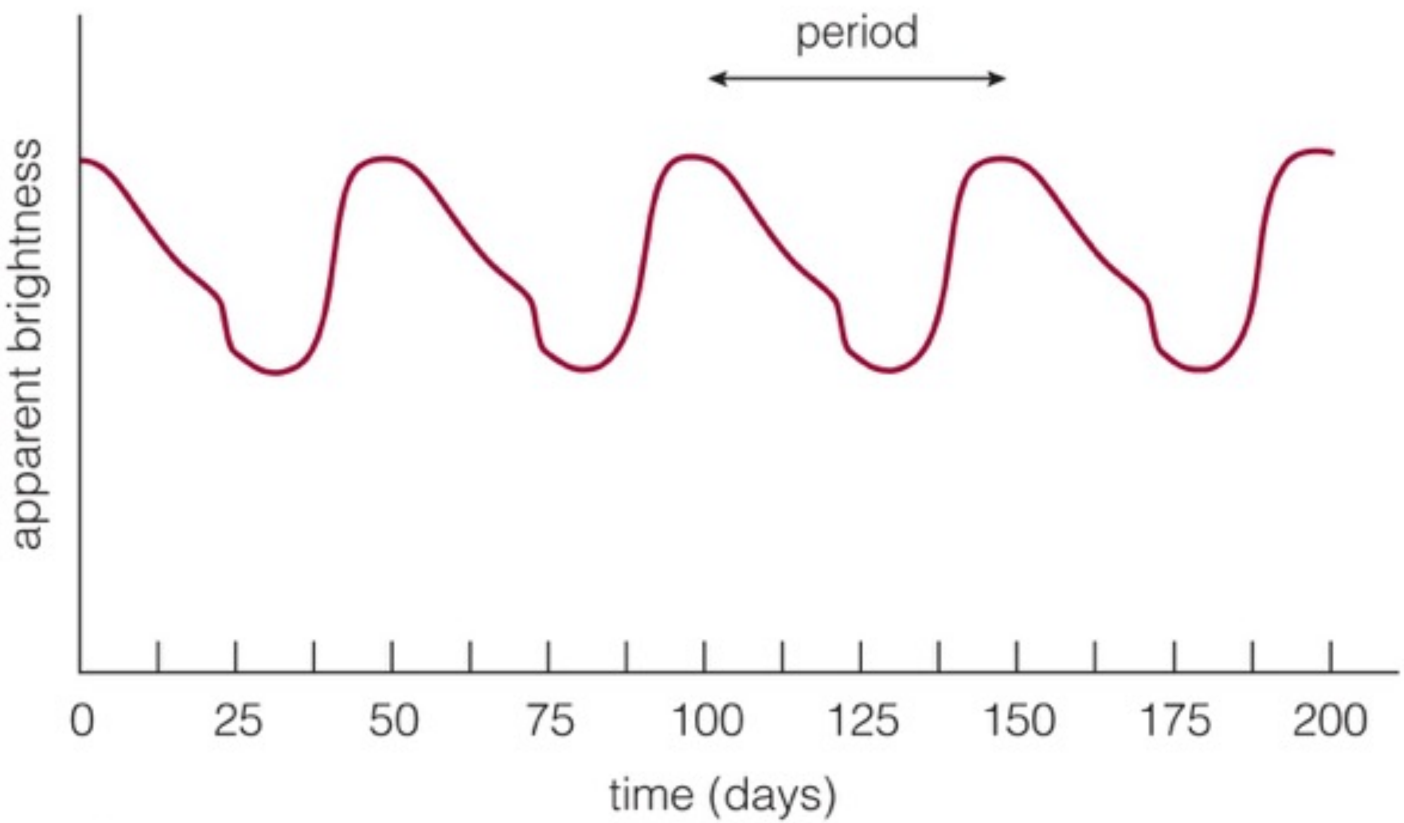
Why do the properties of some stars vary?



Variable Stars

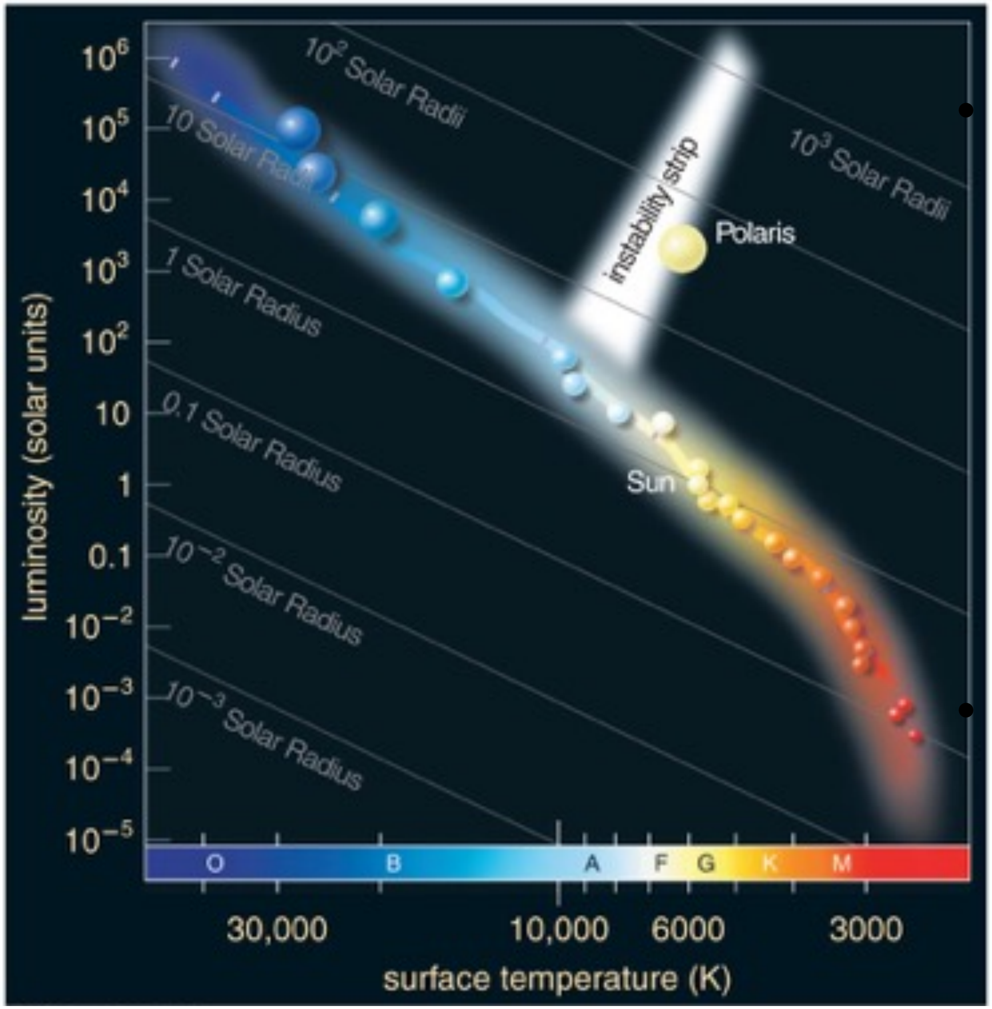
- Any star that varies significantly in brightness with time is called a variable star.
- Some stars vary in brightness because they cannot achieve proper balance between power welling up from the core and power radiated from the surface.
- Such a star alternately expands and contracts, varying in brightness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

Chapter 15

What is special about Cepheid variable stars?

a) They are useful in measuring the distances of other galaxies.
b) Their variability enables us to determine their masses.
c) Their variability enables us to determine their rotation rates.
d) They are useful in studying sunspots on other stars.
e) They are useful in understanding stellar flares.

Star Clusters

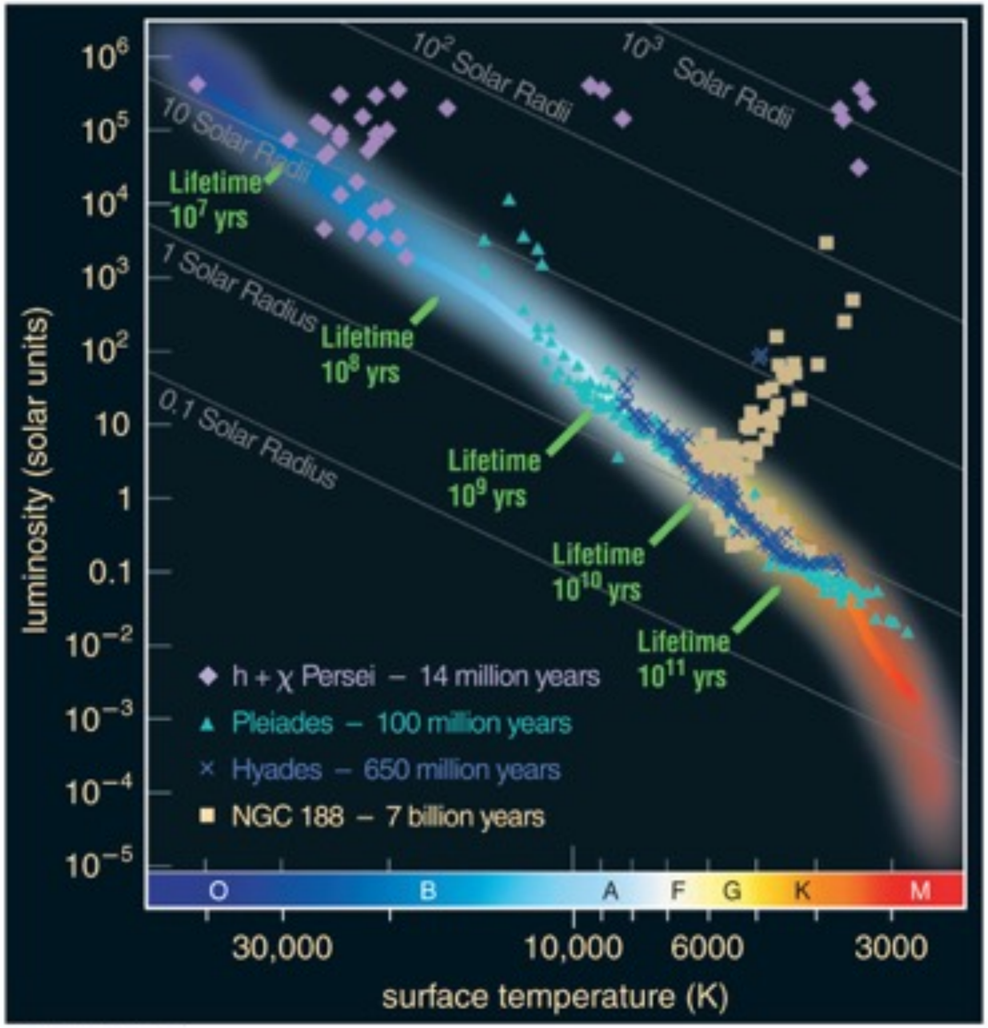
- What are the two types of star clusters?
- How do we measure the age of a star cluster?

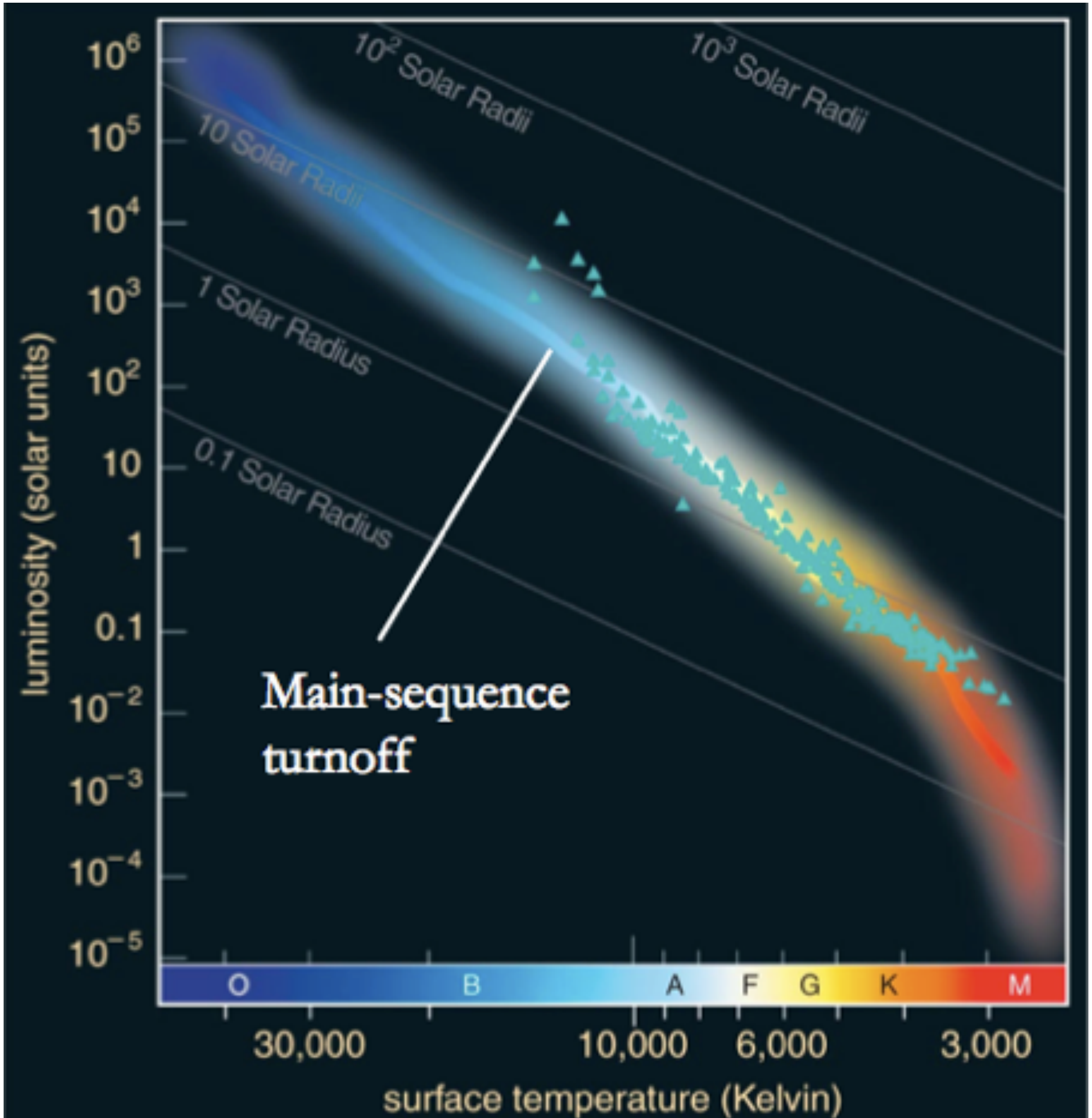
What are the two types of star clusters?

Open cluster: A few thousand loosely packed stars

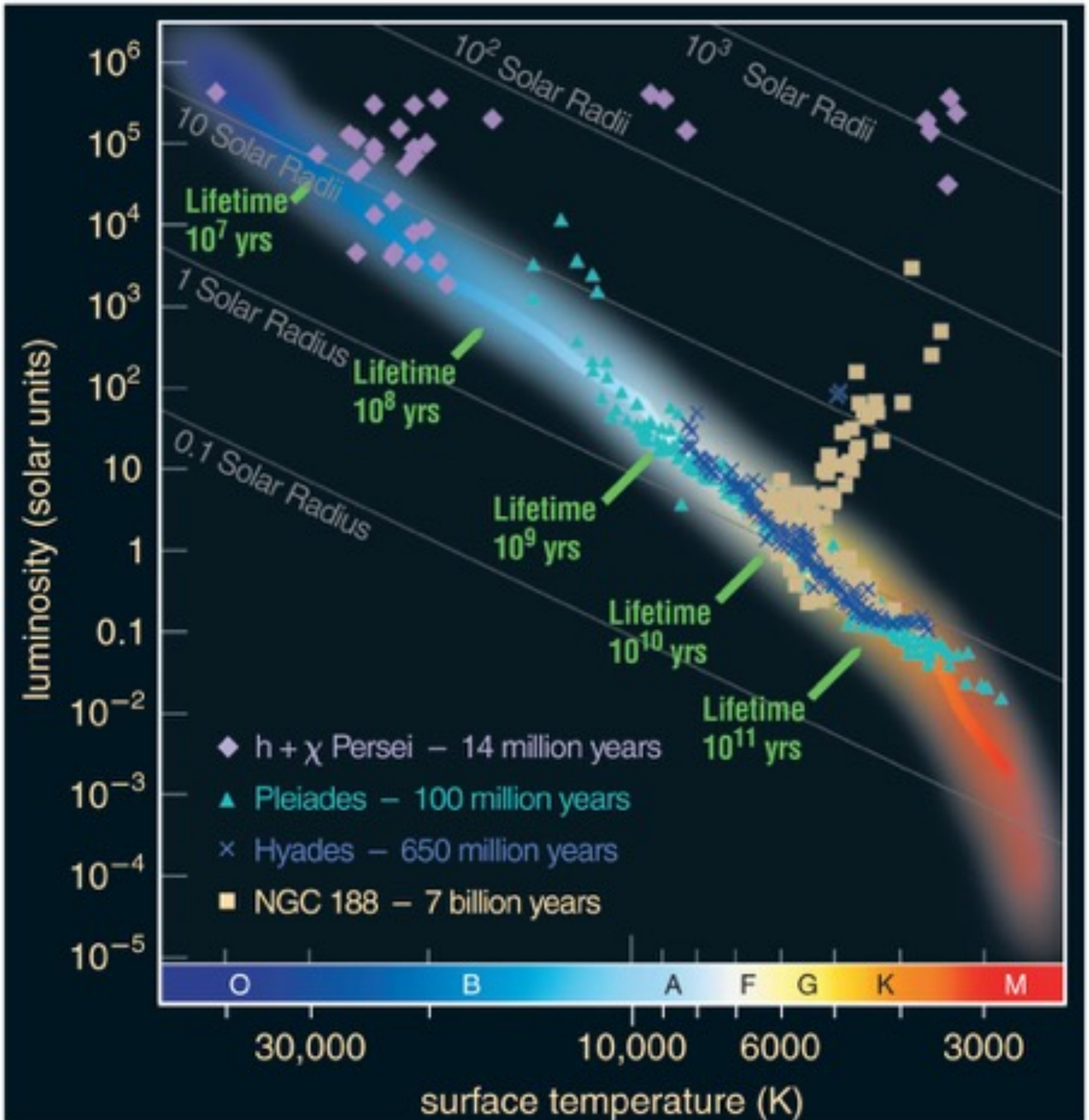
Globular cluster: Up to a million or more stars in a dense ball bound together by gravity

How do we measure the age of a star cluster?

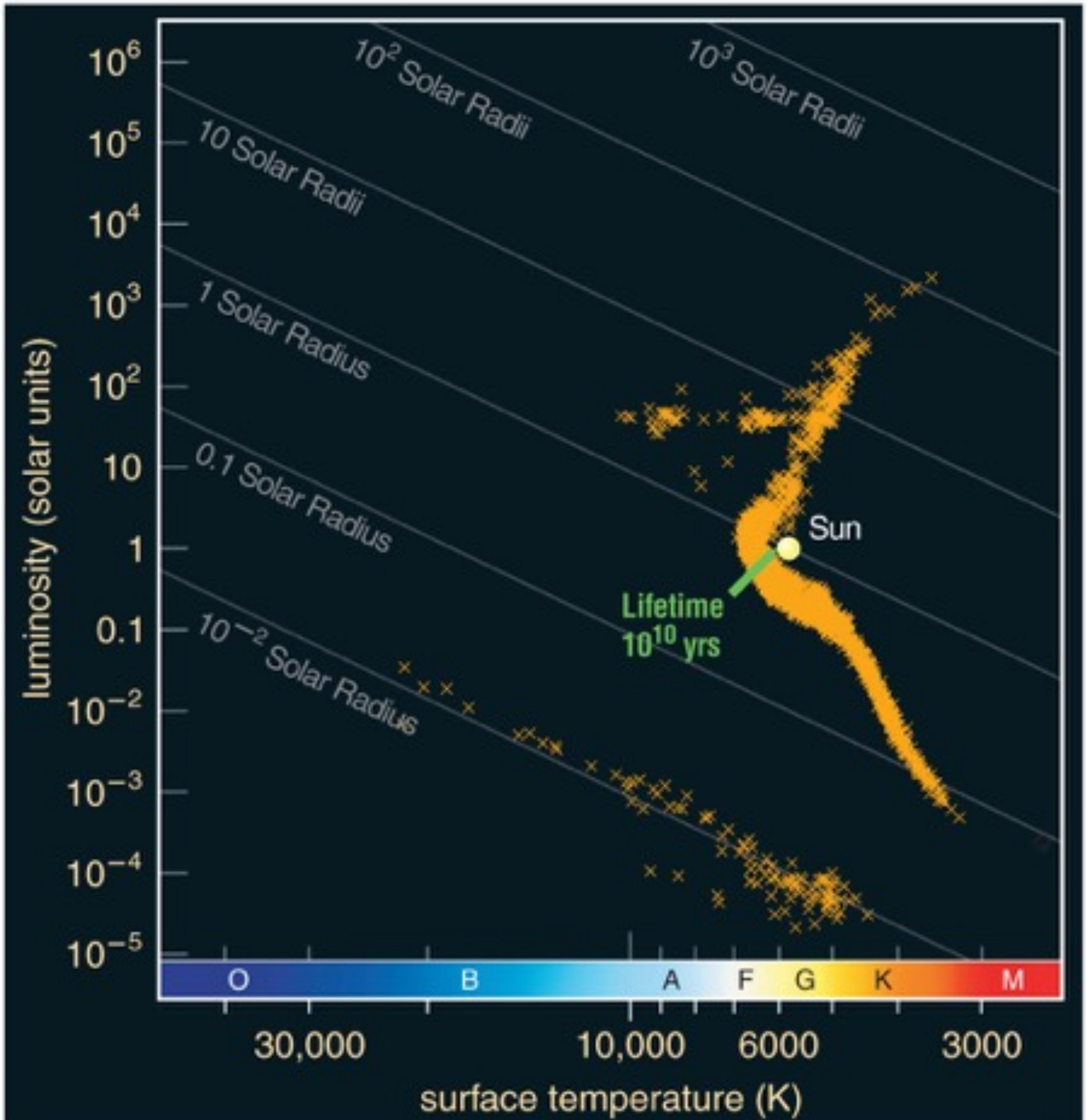




The Pleiades cluster now has no stars with life expectancy less than around 100 million years.



The 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.

Chapter 15

The main-sequence turnoff of a star cluster tells us the cluster's

a) age.
b) mass.
c) distance.
d) composition.

Chapter 15

Which of the following main-sequence turnoffs indicates the oldest globular cluster?

a) O5
b) O9
c) B7
d) B2
e) G2