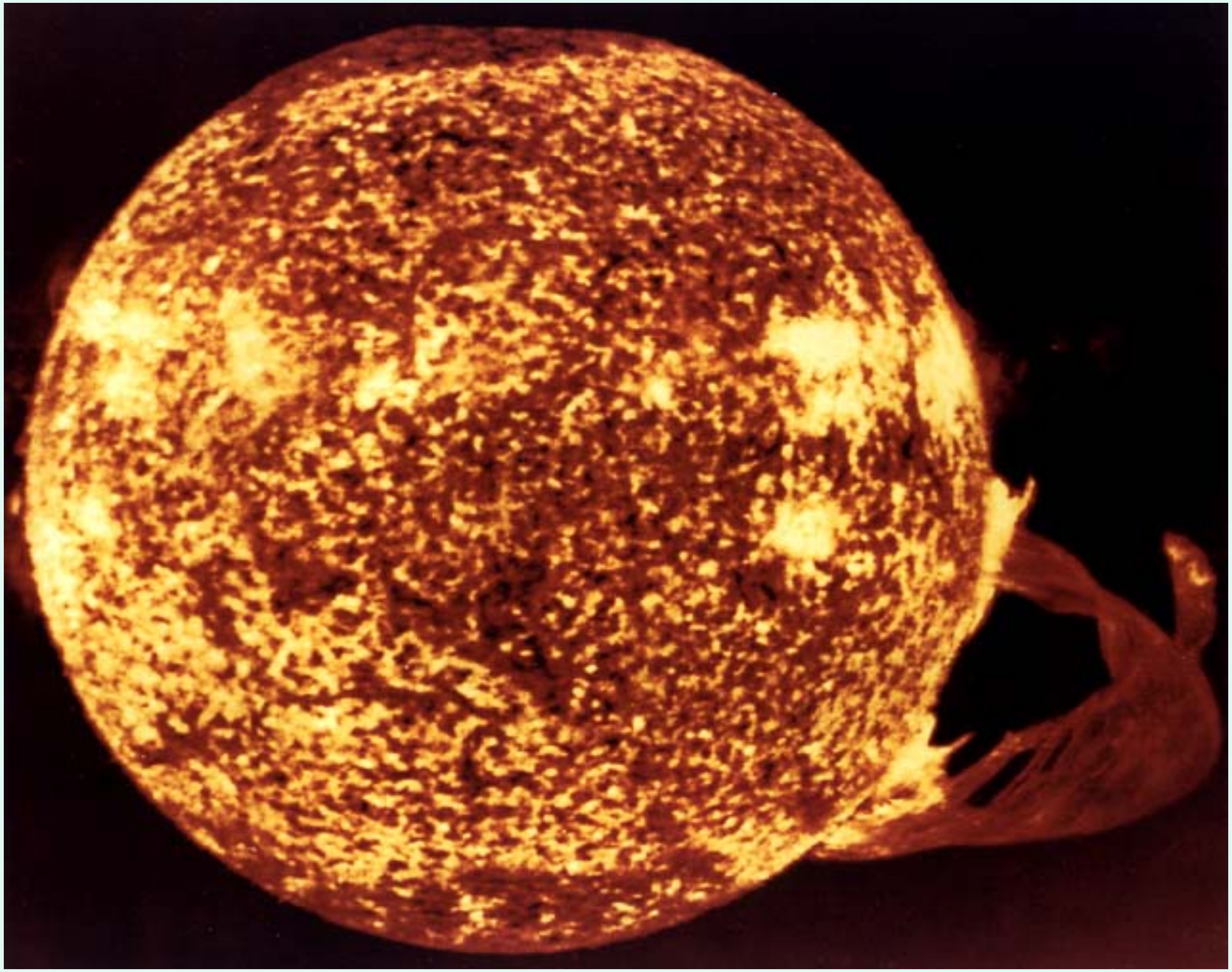
Astronomy 120



Prof. Jeff Kenney Class 7 June 5, 2018

Today in Astro 120!!!!!

What is a star?

What are different types of stars?

What is a main sequence star?

What is the energy source of stars?

How long do stars live?

What will happen to our Sun?

Why is the sun a star and the earth not a star? … MASS

More mass →

Stronger gravity ->

Stronger pressure ->

Higher temperatures ->

Nuclear fusion !!

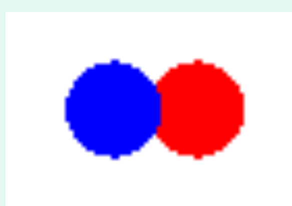
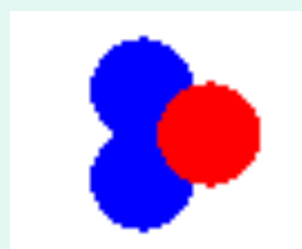
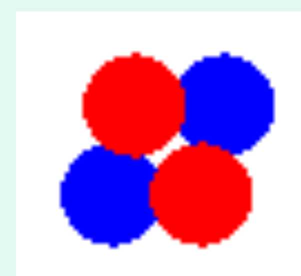
Need mass > 1/10 M_{sun} = 10^{-1} M_{sun} to have star

Mass of Jupiter ~ 10^{-3} M_{sun}

Mass of earth ~ 3×10^{-6} M_{sun}

The main nuclear reaction in sun’s core:
proton-proton chain

Cast of characters: **Nuclei** :

hydrogen	deuterium	helium-3	helium-4
H	^{2}H	^{3}He	^{4}He
			
p	p,n	2p,n	2p,2n

proton-proton chain

3 steps:

$^{1}H + {}^{1}H \text{ ---> } {}^{2}H + e^{+} + \nu$

$^{1}H + {}^{2}H \text{ ---> } {}^{3}He + \gamma$

these steps happen twice

$^{3}He + {}^{3}He \text{ ---> } {}^{4}He + {}^{1}H + {}^{1}H$

e^{+} = positron (same mass as electron, but opposite charge – a form of anti-matter)

ν = neutrino (ghostlike subatomic particle)

γ = gamma ray photon

proton-proton chain

3 steps:

$$^1H + {}^1H \longrightarrow {}^2H + e^+ + \nu$$

$$^1H + {}^2H \longrightarrow {}^3He + \gamma$$

these steps happen twice

$$^3He + {}^3He \longrightarrow {}^4He + {}^1H + {}^1H$$

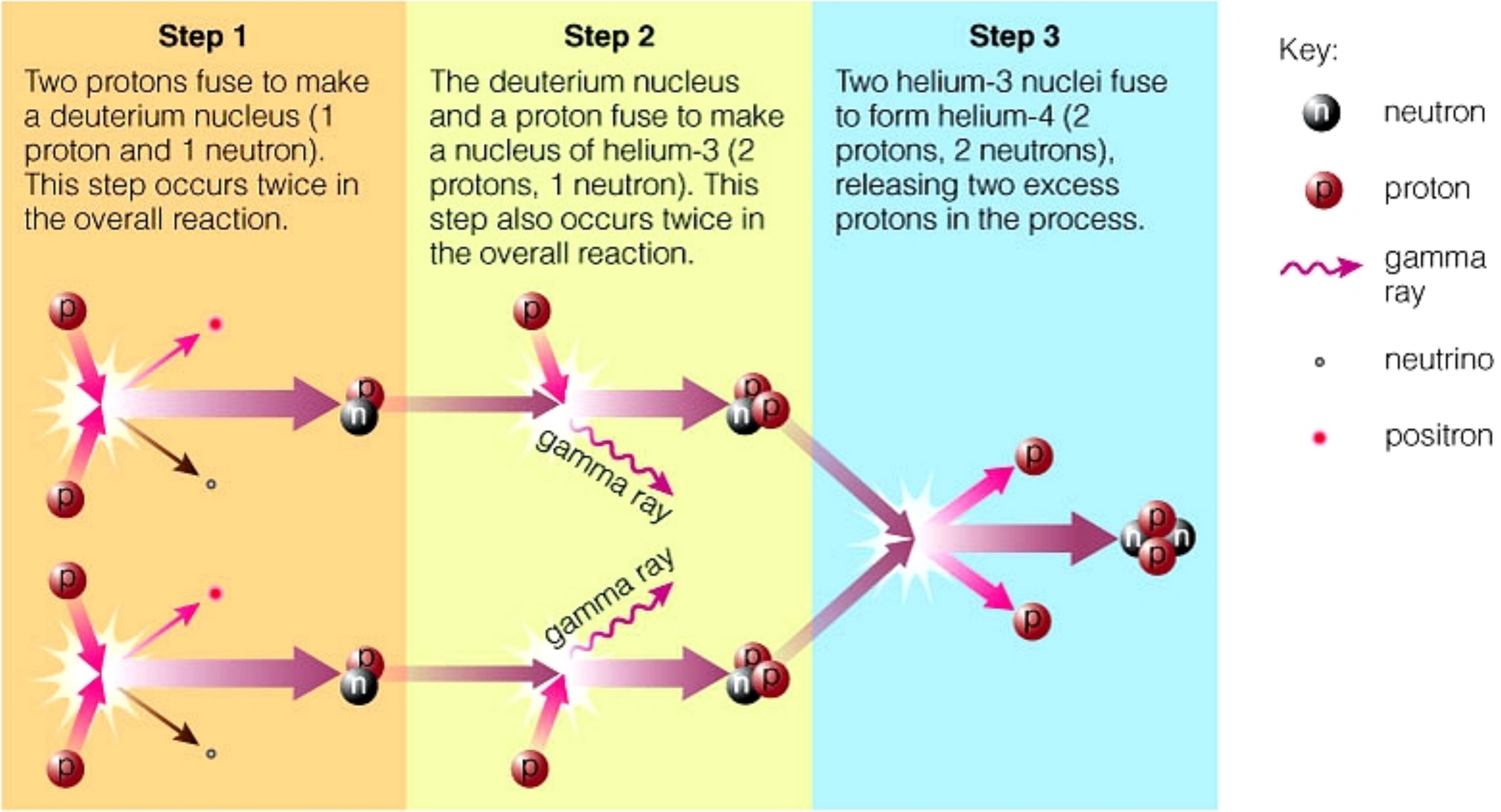
e^+ = positron (same mass as electron, but opposite charge – a form of anti-matter)

ν = neutrino (ghostlike subatomic particle)

γ = gamma ray photon

need high temperatures for fusion $T > 10^7$ K

Hydrogen Fusion by the Proton-Proton Chain



When Hydrogen (mass=m) and Deuterium (mass=2m) nuclei fuse to form a Helium-3 nucleus ...

A. The energy released is equal to mc^2

B. The energy released is equal to $3mc^2$

C. A small part of their mass is converted to energy

D. Most of their mass is converted to energy

E. It takes too much energy to go to Mass

Net result of p-p chain:

$6\,{}^{1}H \;\; \text{--->} \;\; {}^{4}He \; + \; 2\,{}^{1}H + 2\,e^{+} \; + 2\,\nu + 2\,\gamma$

$4\,{}^{1}H \;\; \text{--->} \;\; {}^{4}He \; + 2\,e^{+} \; + 2\,\nu + 2\,\gamma$

Net result of p-p chain:

$$6\,{}^{1}H \;\text{--->}\; {}^{4}He + 2\,{}^{1}H + 2\,e^{+} + 2\,\nu + 2\,\gamma$$

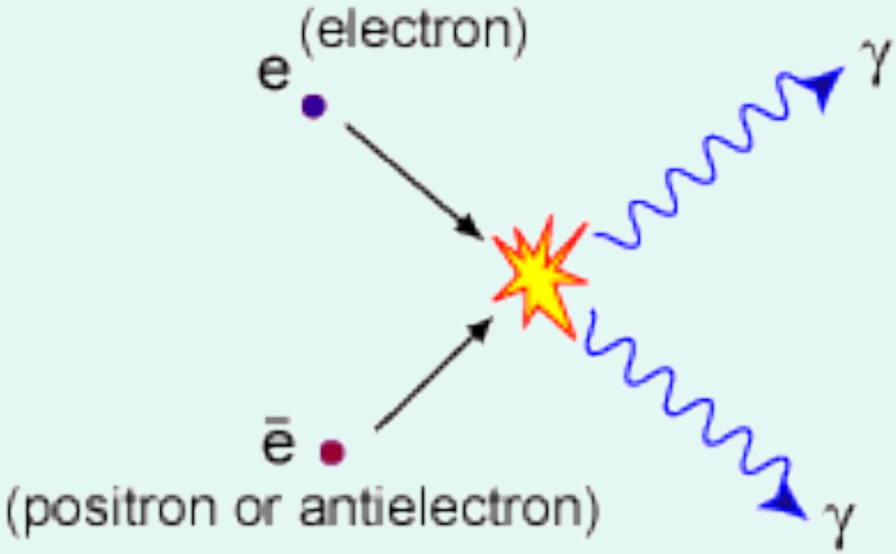
$$4\,{}^{1}H \;\text{--->}\; {}^{4}He + 2\,e^{+} + 2\,\nu + 2\,\gamma$$

very little mass, mostly energy

mass has been converted to energy according to $E = mc^2$

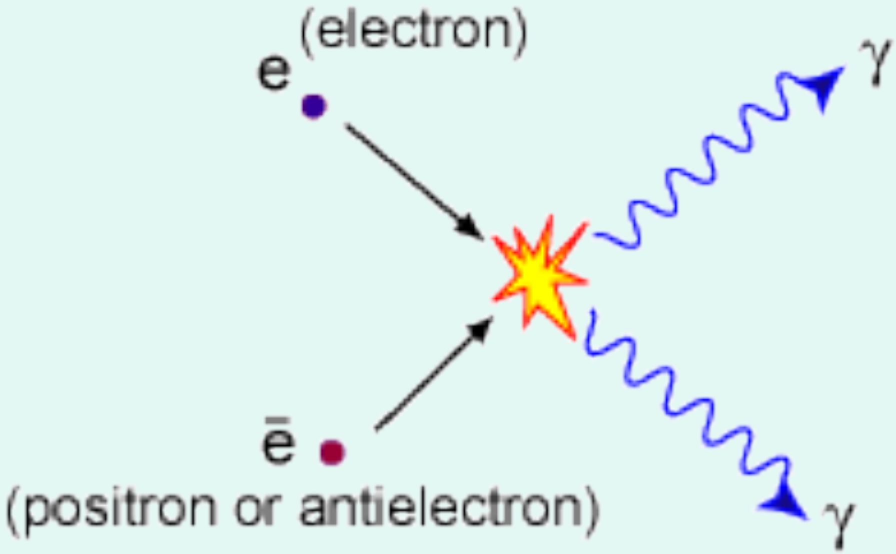
the sunlight we see comes *indirectly* from the positrons and γ-rays

most of energy comes from γ-ray in step 2. but a lot of energy also comes from the e+ colliding with an e- and annihilating each other, producing 2 more γ-rays



the sunlight we see comes *indirectly* from the positrons and γ-rays

most of energy comes from γ-ray in step 2. but a lot of energy also comes from the e+ colliding with an e- and annihilating each other, producing 2 more γ-rays



Q: where do the e^-s come from?

The γ-rays do not escape the sun (the sun is opaque to γ-rays), but interact with other particles in the core.

Eventually, the result is that each γ-ray is converted to many UV-optical-IR photons which do escape.

The γ-rays do not escape the sun (the sun is opaque to γ-rays), but interact with other particles in the core.

Eventually, the result is that each γ-ray is converted to many UV-optical-IR photons which do escape.

Although it takes 170,000 yrs for the energy of each γ-ray to reach the surface from the core!

Q: why does it take so long?

Net result of p-p chain:

$$6\ ^1H \dashrightarrow\ ^4He + 2\ ^1H + 2\ e^+ + 2\ \nu + 2\ \gamma$$

$$4\ ^1H \dashrightarrow\ ^4He + 2\ e^+ + 2\ \nu + 2\ \gamma$$

very little mass, mostly energy

mass has been converted to energy according to $E = mc^2$

Add up mass (in p-p chain):

Mass of 4 H nuclei:	4.00 m_p
Mass of 1 ^{4}He nucleus + 2e^+ + 2ν + 2γ:	3.97 m_p
difference:	0.03 m_p

(m_p = proton mass)

Add up mass (in p-p chain):

Mass of 4 H nuclei:	4.00 m_p
Mass of 1 ^{4}He nucleus + 2e^+ + 2ν + 2γ:	3.97 m_p
difference:	0.03 m_p

Q: what happens to this mass of 0.03 m_p?

A: it gets converted into energy

if you measure how much energy is produced (in photons & neutrinos), you find it is equivalent to: 4.3×10^{-12} Joules

Add up mass (in p-p chain):

Mass of 4 H nuclei:	$4.00\ m_p$
Mass of 1 ^{4}He nucleus + $2e^+$ + 2ν + 2γ:	$3.97\ m_p$
difference:	$0.03\ m_p$

Q: what happens to this mass of $0.03\ m_p$?
A: it gets converted into energy

if you measure how much energy is produced (in photons & neutrinos), you find it is equivalent to:
4.3×10^{-12} Joules = $\mathbf{0.03\ m_p c^2}$

in other words, **mass gets converted into energy**
this is basis of einstein's equation $E = mc^2$

$E = mc^2$

- Mass & energy are in some fundamental way equivalent, in that they can be converted from one into the other

$E = mc^2$

- Mass & energy are in some fundamental way equivalent, in that they can be converted from one into the other

- The amount of energy you can get from a given mass depends on c^2 and the most you could ever get out is mc^2

$E = mc^2$

- Mass & energy are in some fundamental way equivalent, in that they can be converted from one into the other
- The amount of energy you can get from a given mass depends on c^2 and the most you could ever get out is mc^2
- it says something is special about the speed of light

$$\text{efficiency} = \frac{\text{energy output (in form of EM energy)}}{\text{total mass-energy of input ingredients}}$$

$$\text{efficiency} = \frac{\text{energy output (in form of EM energy)}}{\text{total mass-energy of input ingredients}}$$

$$\text{efficiency} = \frac{0.03\ m_p c^2}{4\ m_p c^2} = 0.007 = 0.7\% \sim 1\%$$

$$\text{efficiency} = \frac{\text{energy output (in form of EM energy)}}{\text{total mass-energy of input ingredients}}$$

$$\text{efficiency} = \frac{0.03\ m_p c^2}{4\ m_p c^2} = 0.007 = 0.7\% \sim 1\%$$

Q: is this efficient?

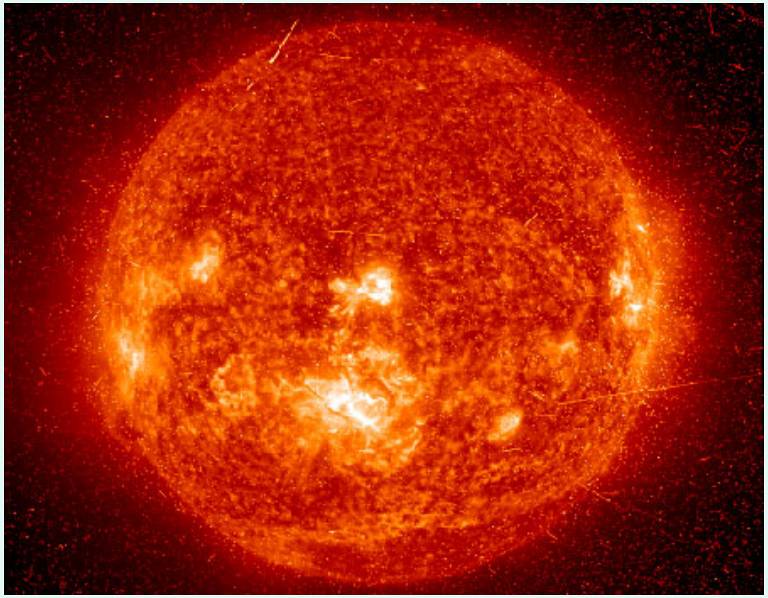
Energy Efficiency

Chemical (gas, oil, biofuel) ~10^{-7}%

Energy Efficiency

Chemical (gas, oil, biofuel) ~10^{-7}%

Nuclear (fusion, fission) ~1%



Energy Efficiency

Chemical (gas, oil, biofuel) ~10^{-7}%

Nuclear (fusion, fission) ~1%

Gravity – small fall (hydroelectric) ~10^{-7}%

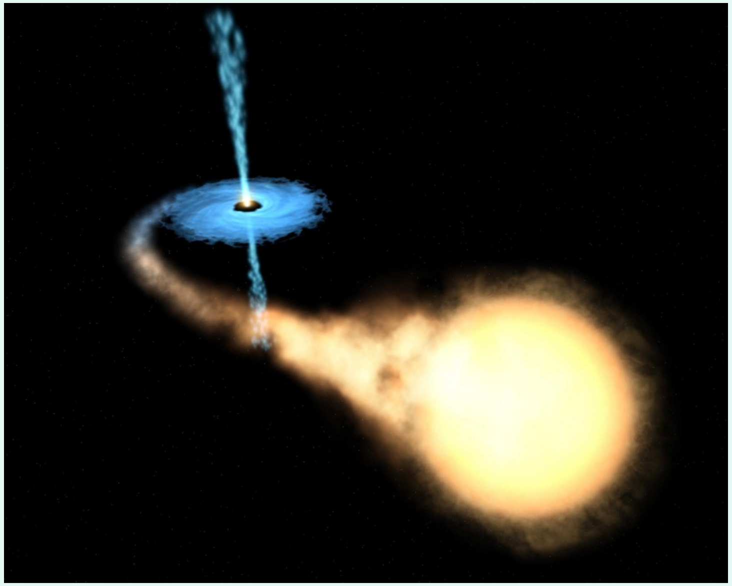
Energy Efficiency

Chemical (gas, oil, biofuel) ~10^{-7}%

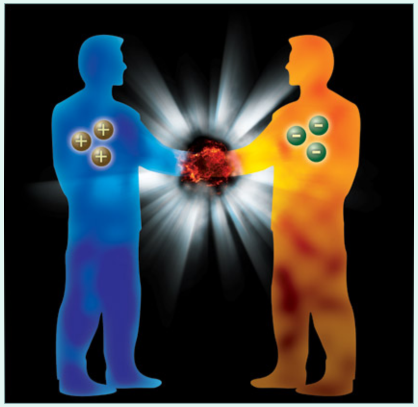
Nuclear (fusion, fission) ~1%

Gravity – small fall (hydroelectric) ~10^{-7}%

Gravity – big fall (black hole/quasar) ~30%



Energy Efficiency



Chemical (gas, oil, biofuel) ~10^{-7}%

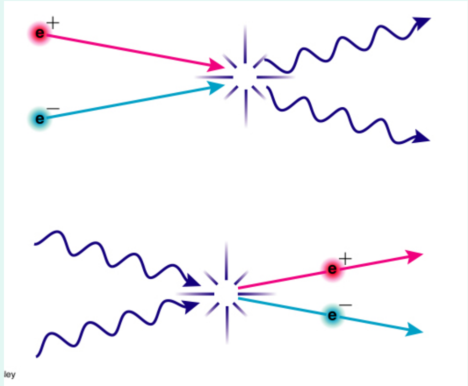
Nuclear (fusion, fission) ~1%

Gravity – small fall (hydroelectric) ~10^{-7}%

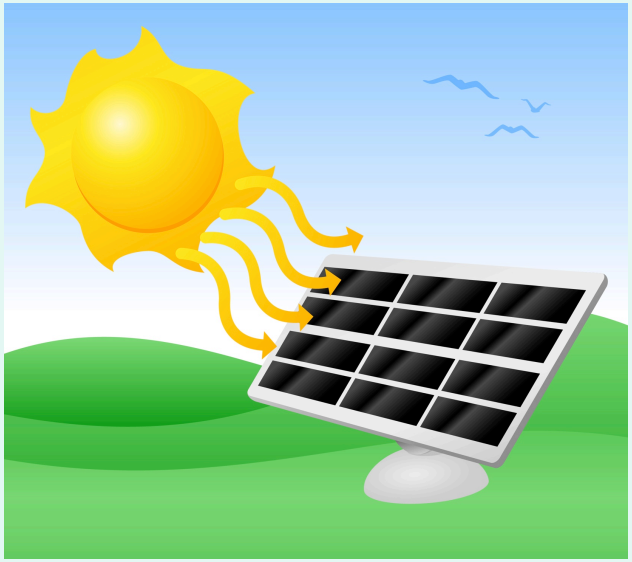
Gravity – big fall (black hole/quasar) ~30%

Matter-antimatter annihilation 100%

(but hard to get the stuff!)



solar energy



solar photons are *already* EM energy

(although not quite in the most useful form for us, electricity)

energy source for solar photons is ….

……nuclear fusion!

conversion of optical photons to electricity is moderately efficient (5-20%). A big limitation: not that many photons per square meter!

Lifetimes of Stars

- Initial mass is the most important fundamental property of a star, since it determines ***the entire life history of a star***

- Initial mass determines:

  L, T, color, size, lifetime

Lifetimes of Stars

- Initial mass is the most important fundamental property of a star, since it determines ***the entire life history of a star***

- Initial mass determines:

  L, T, color, size, lifetime

- elemental composition is 2nd-most important property

Q: how can we estimate the lifetime of a star?

Total energy supply available in star = E

$E \propto$ mass of hydrogen fuel

$\propto$ total mass of star

or: $E \propto M$

which means the same as E = (some constant) x M

a star with 10X the mass of the sun has an energy supply 10X larger

Q: what else do we need, other than the energy supply, to estimate the lifetime of a star?

Q: what else do we need, other than the energy supply, to estimate the lifetime of a star?

The rate at which that energy supply is being used, which is…

Q: what else do we need, other than the energy supply, to estimate the lifetime of a star?

The rate at which that energy supply is being used, which is…

…the luminosity!

mass-luminosity relationship for stars

it turns out that:

$L \propto M^{3.5}$

So a star with 10x the mass of the sun has $10^{3.5}$ x = 3000 times more luminosity!!

some of you don't like this power of 3.5.

this means the same thing as:

$M^{3.5} \quad = M^3 M^{0.5} \quad = M^3 \sqrt{M}$

Why does the luminosity of a star have a strong dependence on mass?

stars with more mass have their insides squeezed to higher pressures & temperatures, so…

a small increase in **mass** leads to …

a small increase in **pressure**, which leads to..

a small increase in **temperature**, which leads to …

a LARGE increase in **luminosity**, since luminosity has a strong T dependence: $L = 4\pi\sigma R^2 T^4$

mass-lifetime relation for stars

Since $L \propto M^{3.5}$

massive stars burn their fuel much more rapidly, so have shorter lifetimes t_{life}

$$t_{life} = \frac{\text{total energy supply}}{\text{rate at which energy consumed}} = \frac{E}{L} \propto \frac{M}{M^{3.5}} \propto M^{-2.5}$$

$t_{life} \propto M^{-2.5}$ $\quad (= 1 / M^2 \sqrt{M})$

Our Sun has a main sequence lifetime of 10^{10} years. According to the mass-lifetime relation, a star with a mass of 10 M_{sun} has a lifetime of:

Our Sun has a main sequence lifetime of 10^{10} years. According to the mass-lifetime relation, a star with a mass of 10 M_{sun} has a lifetime of:

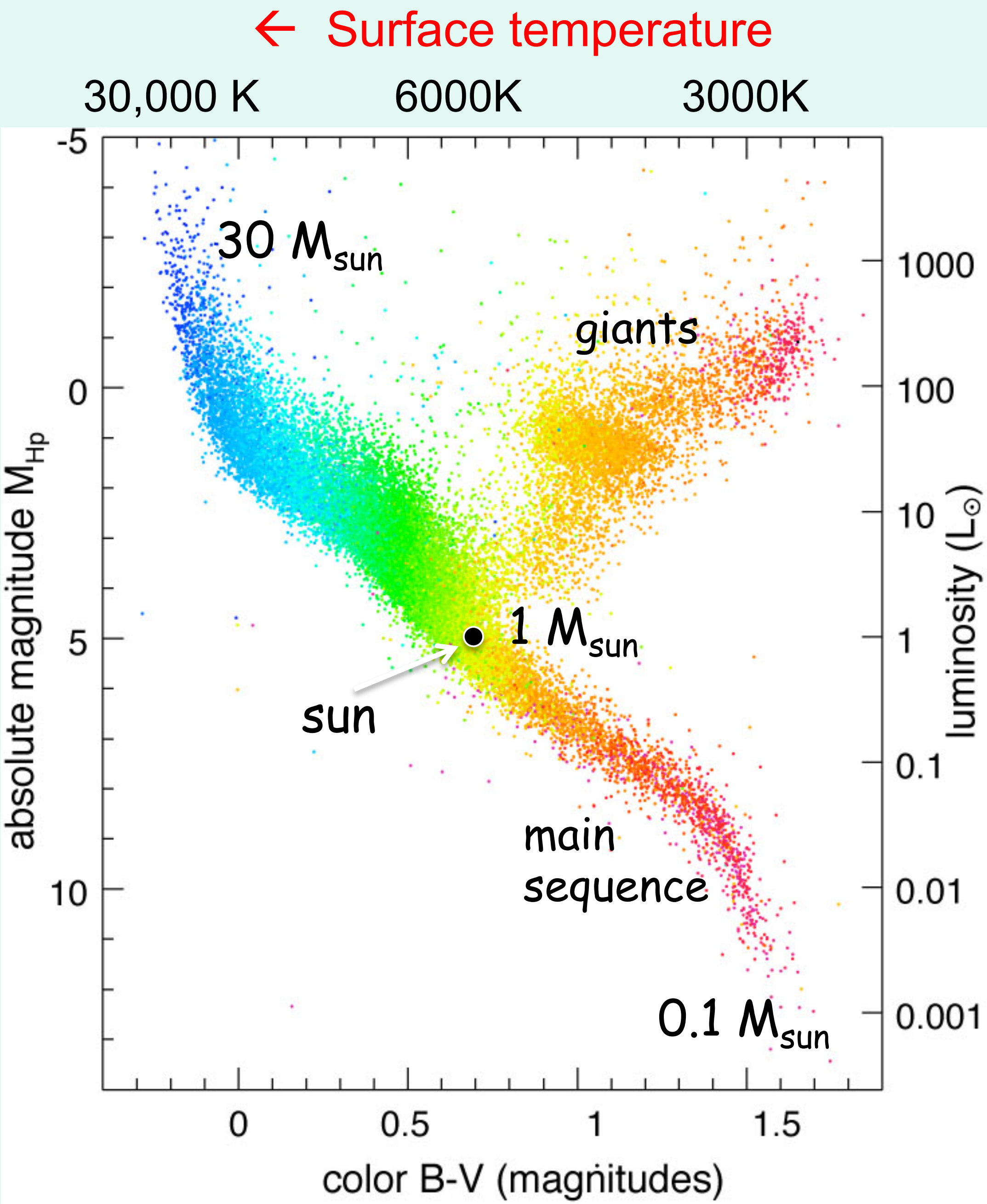
A. 10^{7} years
B. $3x10^{7}$ years
C. 10^{8} years
D. $3x10^{8}$ years
E. 10^{9} years

what happens to the star at the end of this so-called 'lifetime'?

this lifetime refers strictly to the time that star is ***burning H in its core***. This is its ***main sequence lifetime.***

the star doesn't cease to exist, but it changes in fundamental and sometime dramatic ways.

Luminosity-Temperature or HR (Hertzsprung-Russell) diagram of stars near the Sun (in Solar Neighborhood)



when a star is ***burning H in its core***, its lies on the ***main sequence***

main sequence is a mass sequence

L and T are related since stars are well approximated by spherical blackbodies

Luminosity = Area x Flux

L = A F

Area = $4\pi R^2$ for sphere

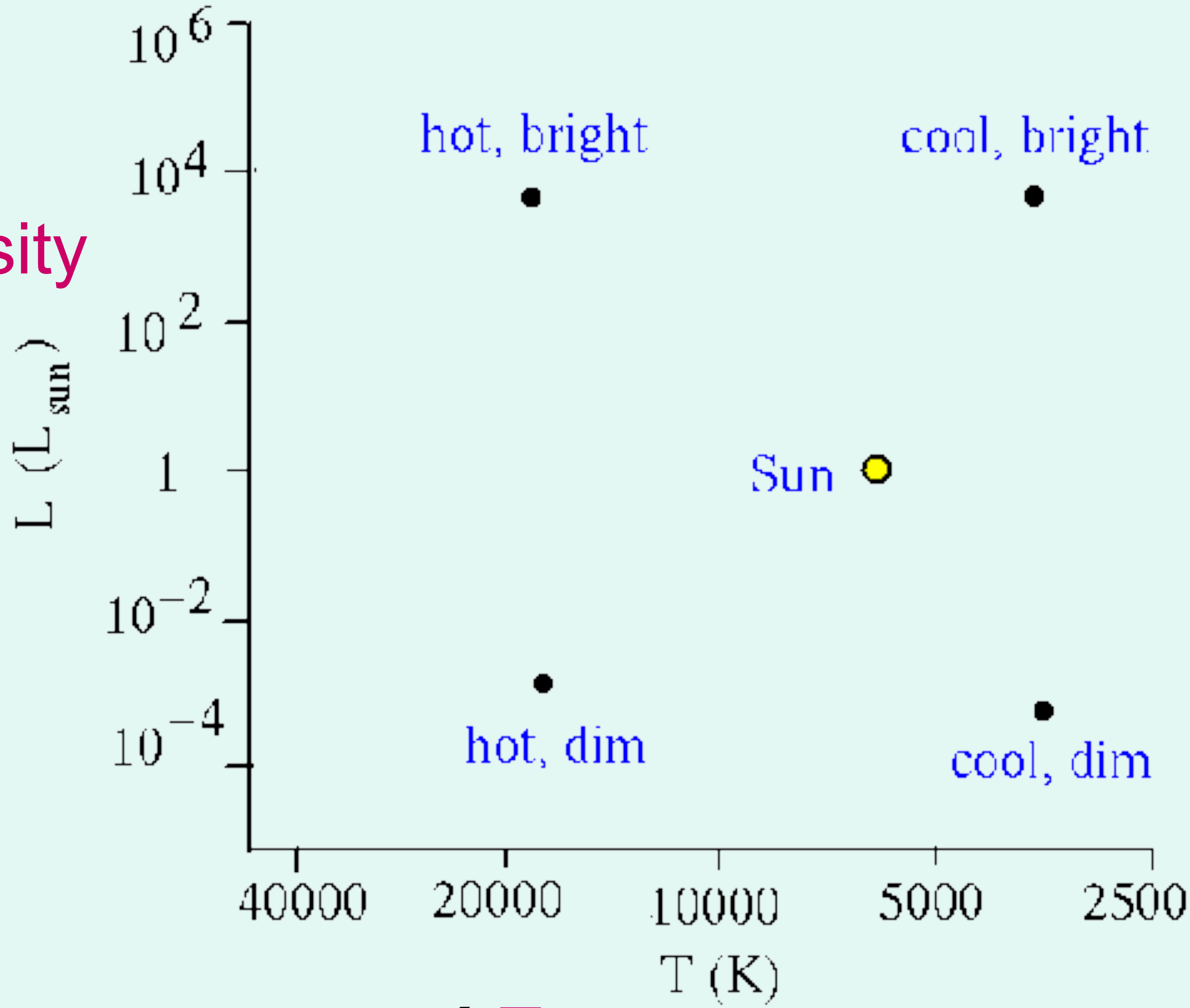
Flux = $\sigma_{SB} T^4$ for "blackbody" source

L luminosity : rate of energy output (in form of EM radiation) in all directions, integrated over all wavelengths (erg s^{-1})

$L = 4\pi R^2 \sigma_{SB} T^4$ for stars

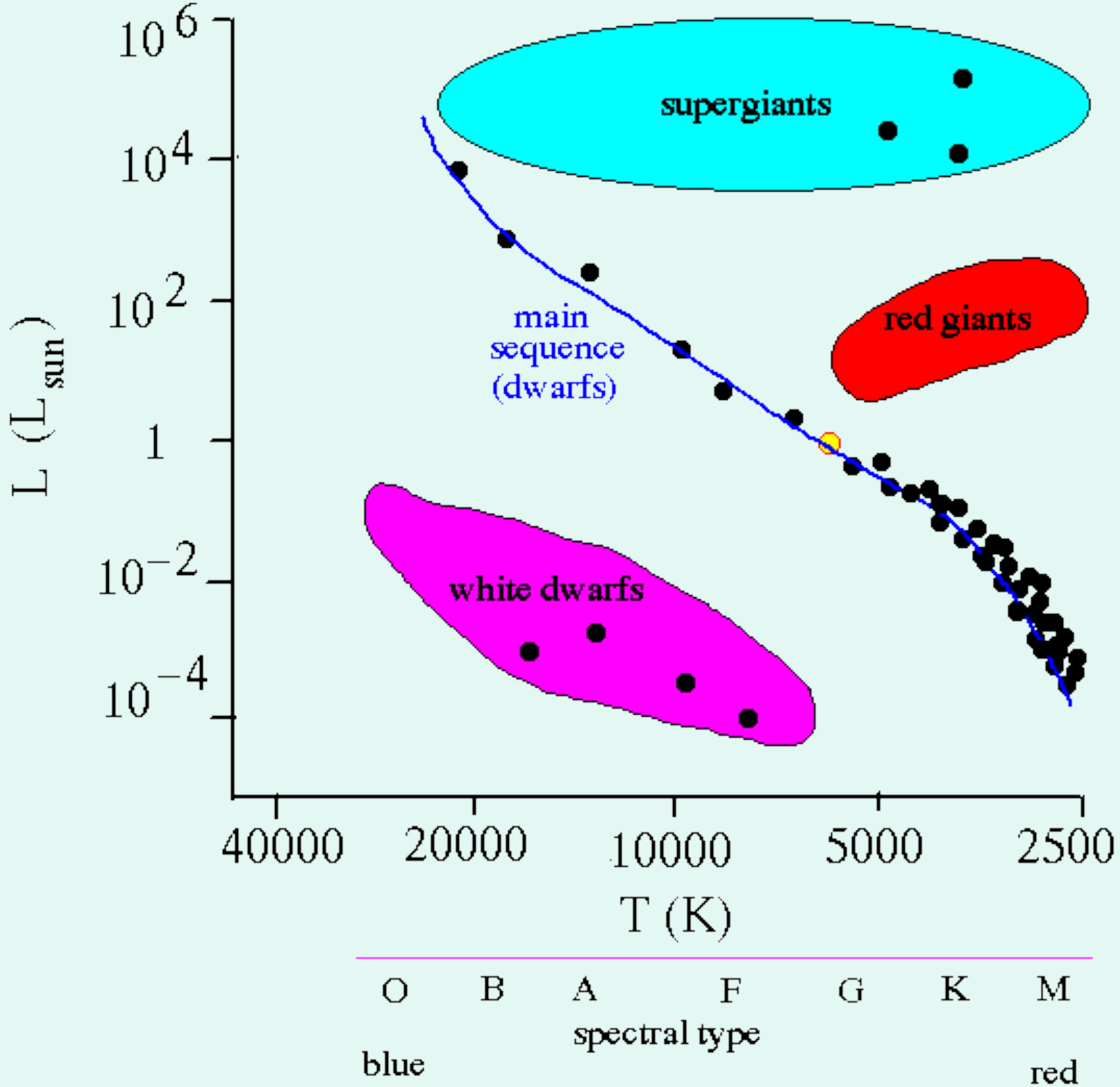
HR Diagram -- schematic

Luminosity



←Temperature

HR diagram – schematic with types of stars



Stars in the "red giant region" of the HR diagram must be larger than the sun because they:

A. have large diameters measured by interferometry

B. are much older than the sun

C. have large diameters measured by parallax

D. are much more luminous than the sun yet have about the same temperature

E. have large diameters measured by the small angle formula

how do we know these giant stars are giant?

It is NOT because we have measured their diameters!

We know it because of their location in the L-T diagram TOGETHER with $L = 4\pi\sigma R^2T^4$

how do we know these giant stars are giant?

It is NOT because we have measured their diameters!

We know it because of their location in the L-T diagram TOGETHER with $L = 4\pi\sigma R^2 T^4$

suppose you have 2 stars at the same temperature T

one has a luminosity L larger by a factor of 10^4

how can that be?

how do we know these giant stars are giant?

It is NOT because we have measured their diameters!

We know it because of their location in the L-T diagram TOGETHER with $L = 4\pi\sigma R^2T^4$

suppose you have 2 stars at the same temperature T

one has a luminosity L larger by a factor of 10^4

how can that be?

→ it must have a radius R larger by a factor of 10^2

L and T are related since stars are well approximated by spherical blackbodies

Luminosity = Area x Flux

L = A F

Area = $4\pi R^2$ for sphere

Flux = $\sigma_{SB} T^4$ for "blackbody" source

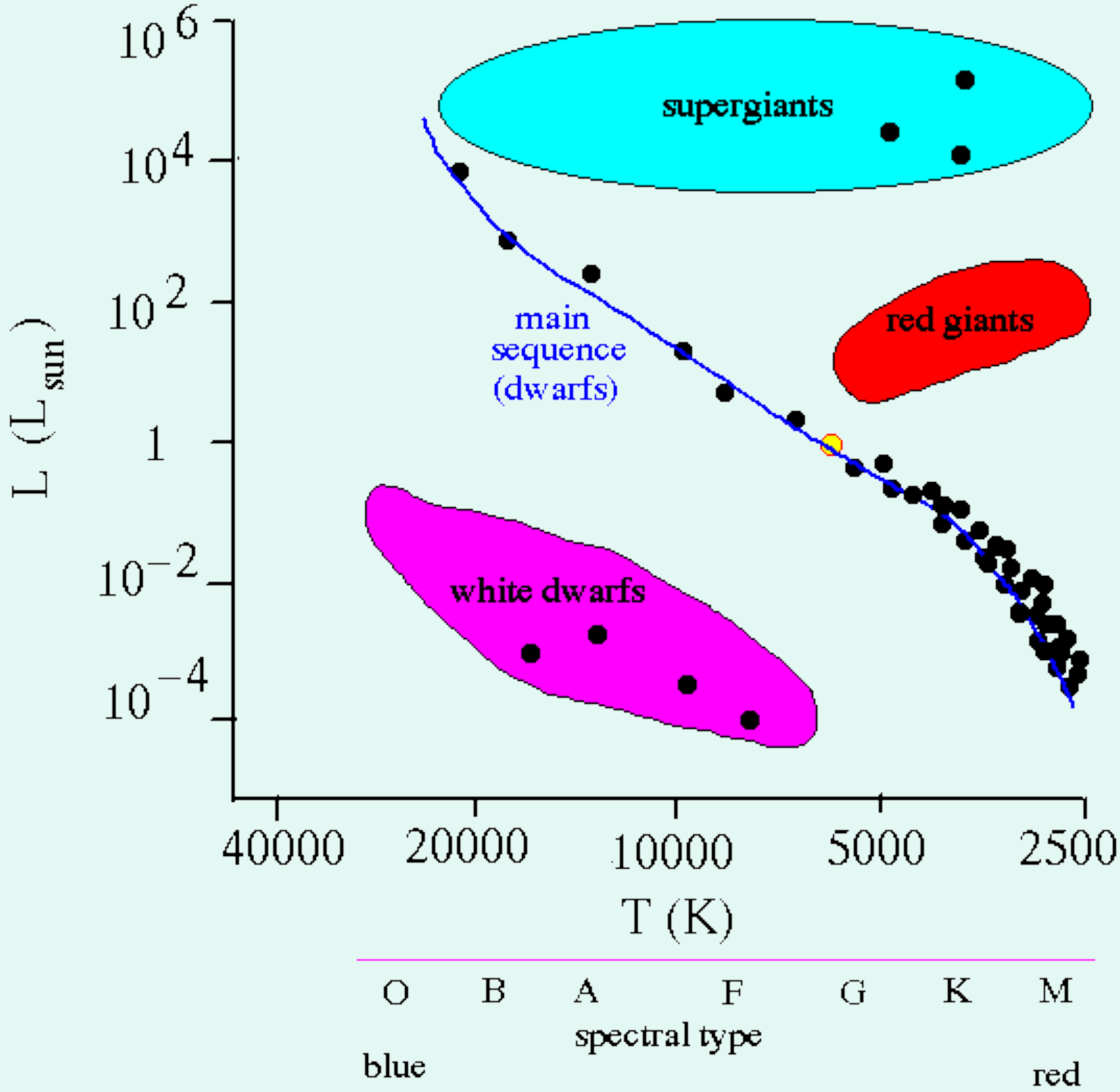
L luminosity : rate of energy output (in form of EM radiation) in all directions, integrated over all wavelengths (erg s^{-1})

$L = 4\pi R^2 \sigma_{SB} T^4$ for stars

at a given T in the HR diagram, MS stars all have the same luminosity since they have the same radius R

at the same T, giant stars all have a greater luminosity since they have a much greater radius R

HR diagram – schematic with types of stars



The word “sequence” implies that stars on the main sequence of the HR diagram can be put in some sort of order. Which of the following is not ordered as one goes along the main sequence?

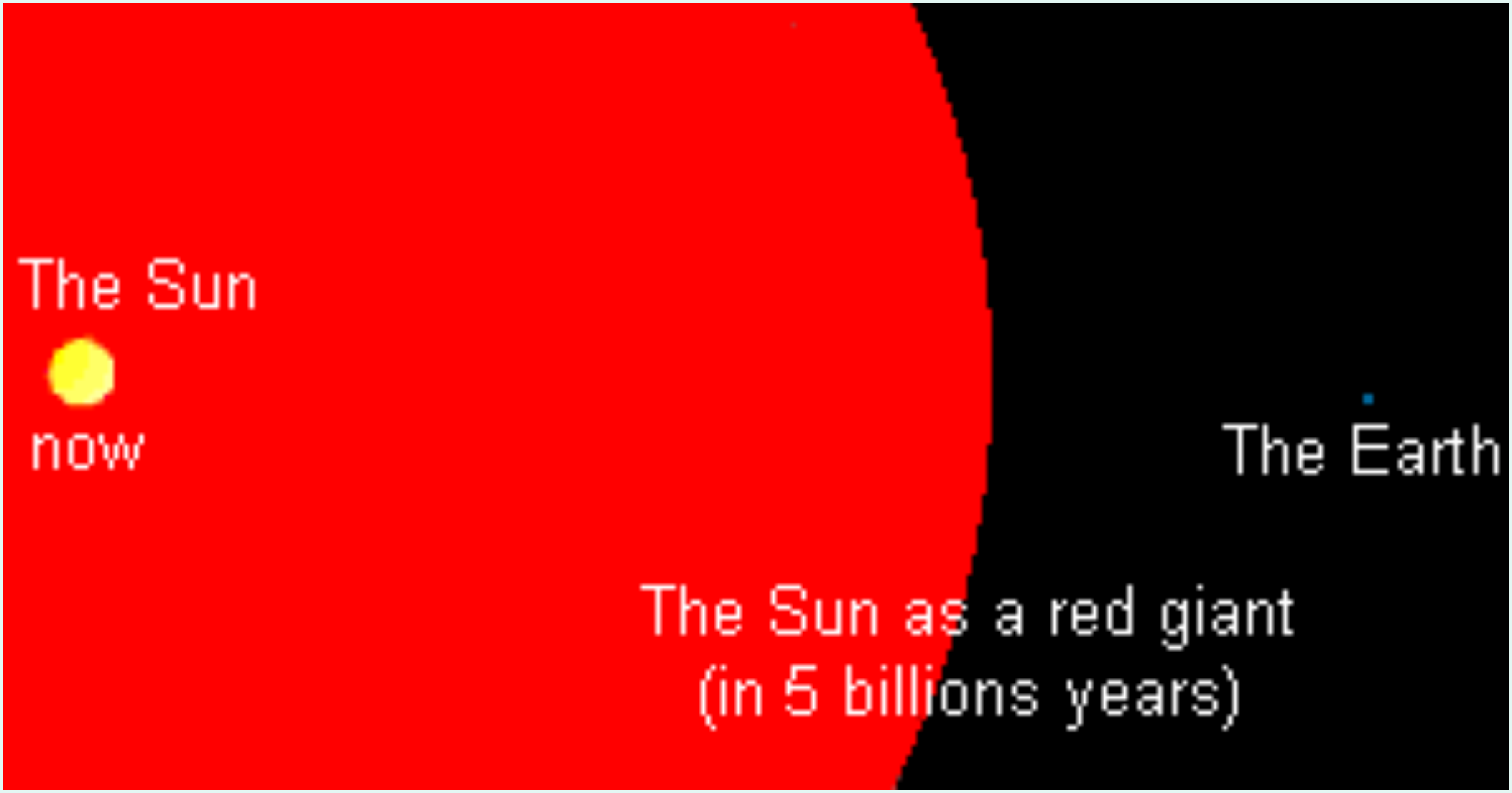
A. Mass
B. Age
C. Color
D. Luminosity
E. Lifetime

The main sequence

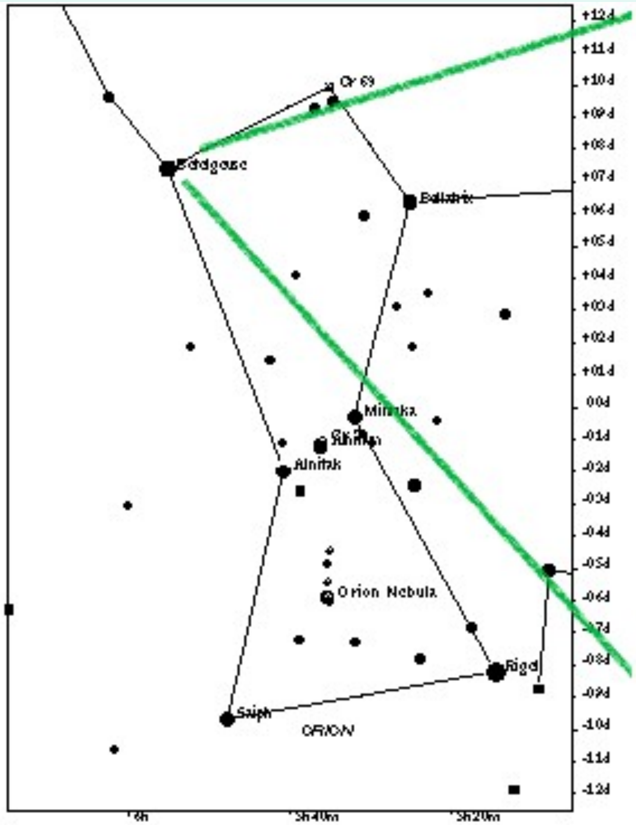
- While a star is **burning H in its core**, it lies along a curve in the LT diagram referred to as the "**main sequence**"

- The Main sequence is a mass sequence!

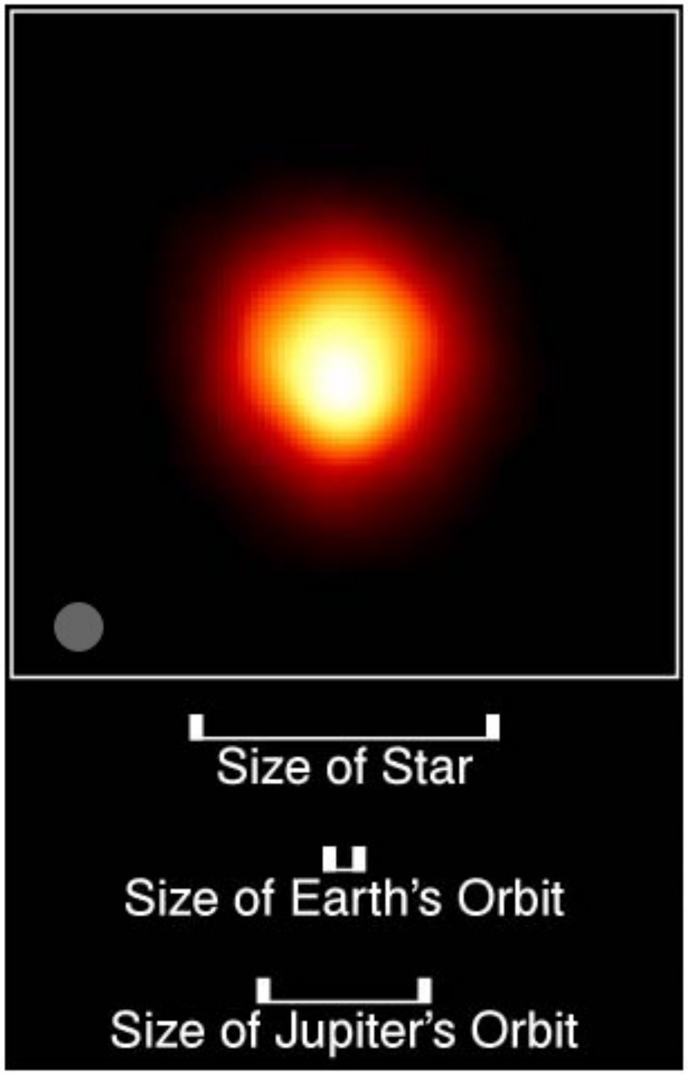
- After it consumes all H in the core, the star "evolves off the main sequence"


The Sun
now
The Earth
The Sun as a red giant
(in 5 billions years)

The Red Giant Betelgeuse



HST view of Betelgeuse in the ultraviolet. Even though Betelgeuse is very large, its distance is too great to resolve details smaller than about 1/4th of its diameter (small gray circle).



Planetary Nebula NGC 3132

PRC98-39 • Space Telescope Science Institute • Hubble Heritage Team