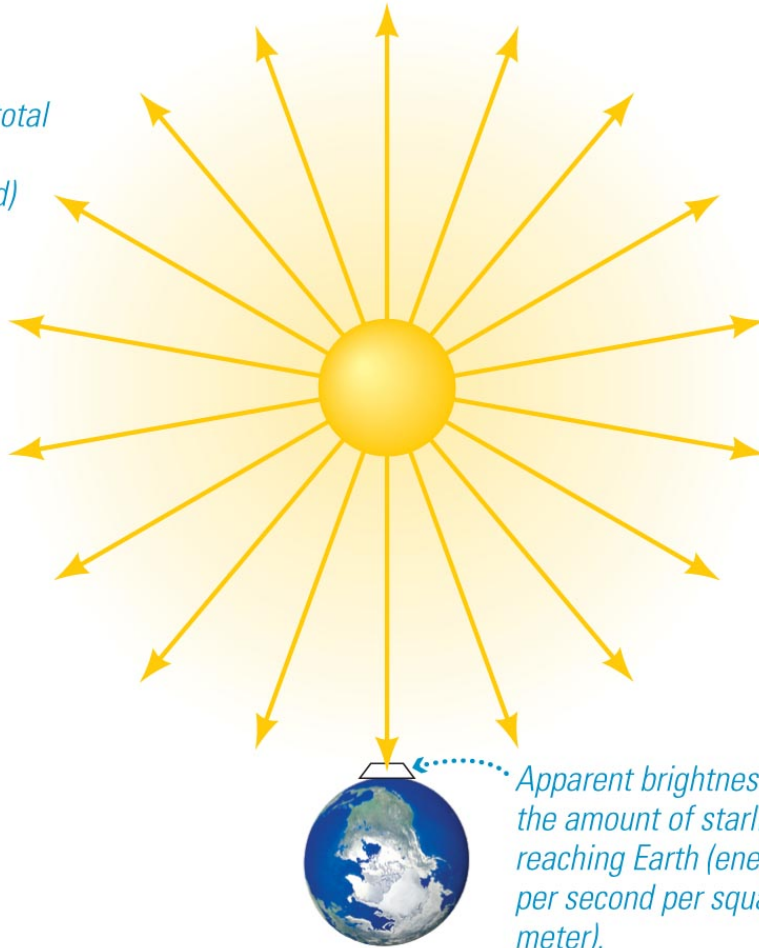


Surveying the Stars



Luminosity is the total amount of power (energy per second) the star radiates into space.



Not to scale!

Apparent brightness is the amount of starlight reaching Earth (energy per second per square meter).

Luminosity:

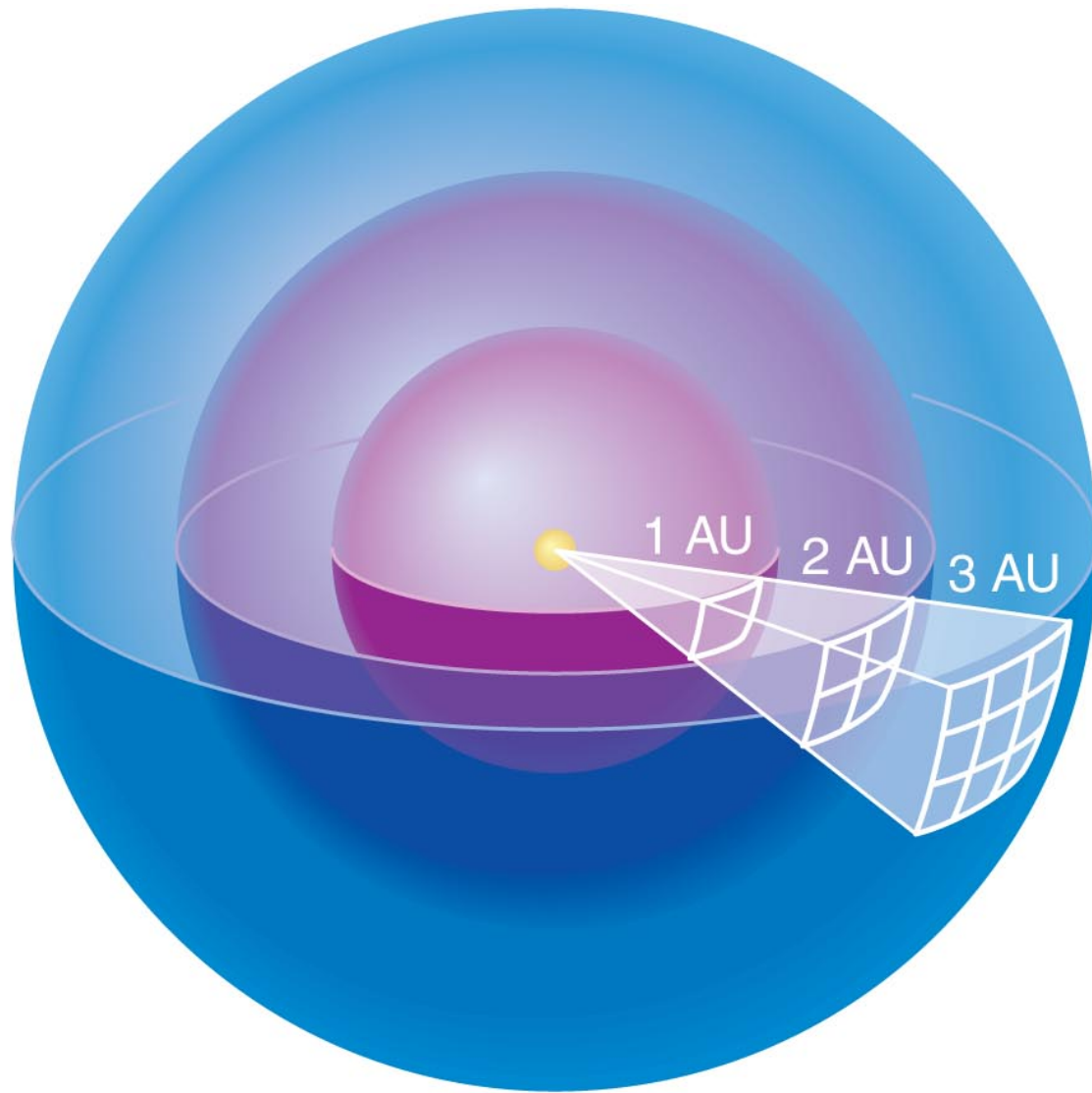
Amount of power a star radiates

(energy per second = watts)

Apparent brightness:

Amount of starlight that reaches Earth

(energy per second per square meter)



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:

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

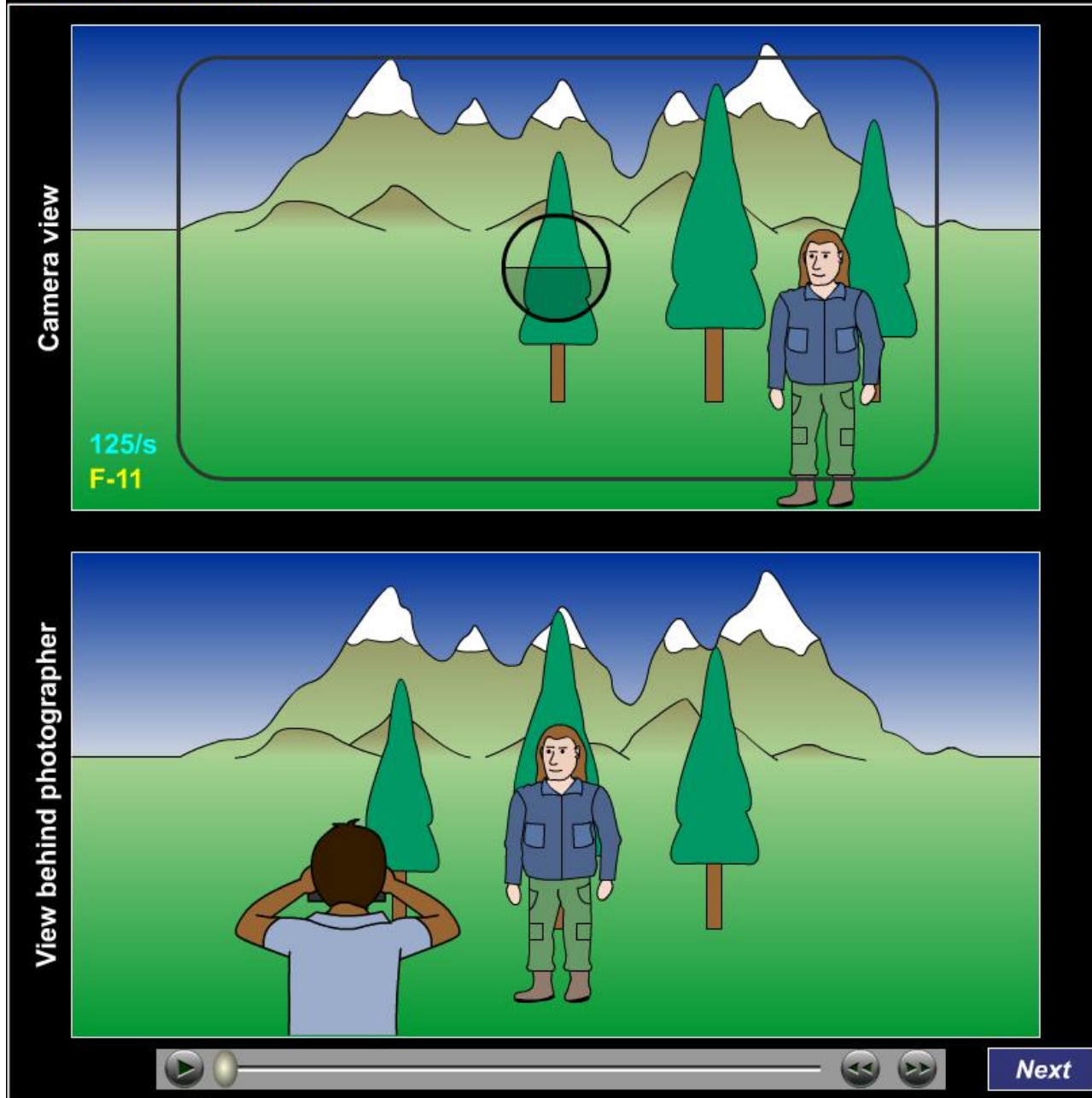
We can determine a star's luminosity if we can measure its distance and apparent brightness:

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



Distances to stars

Introduction to Parallax



Parallax

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

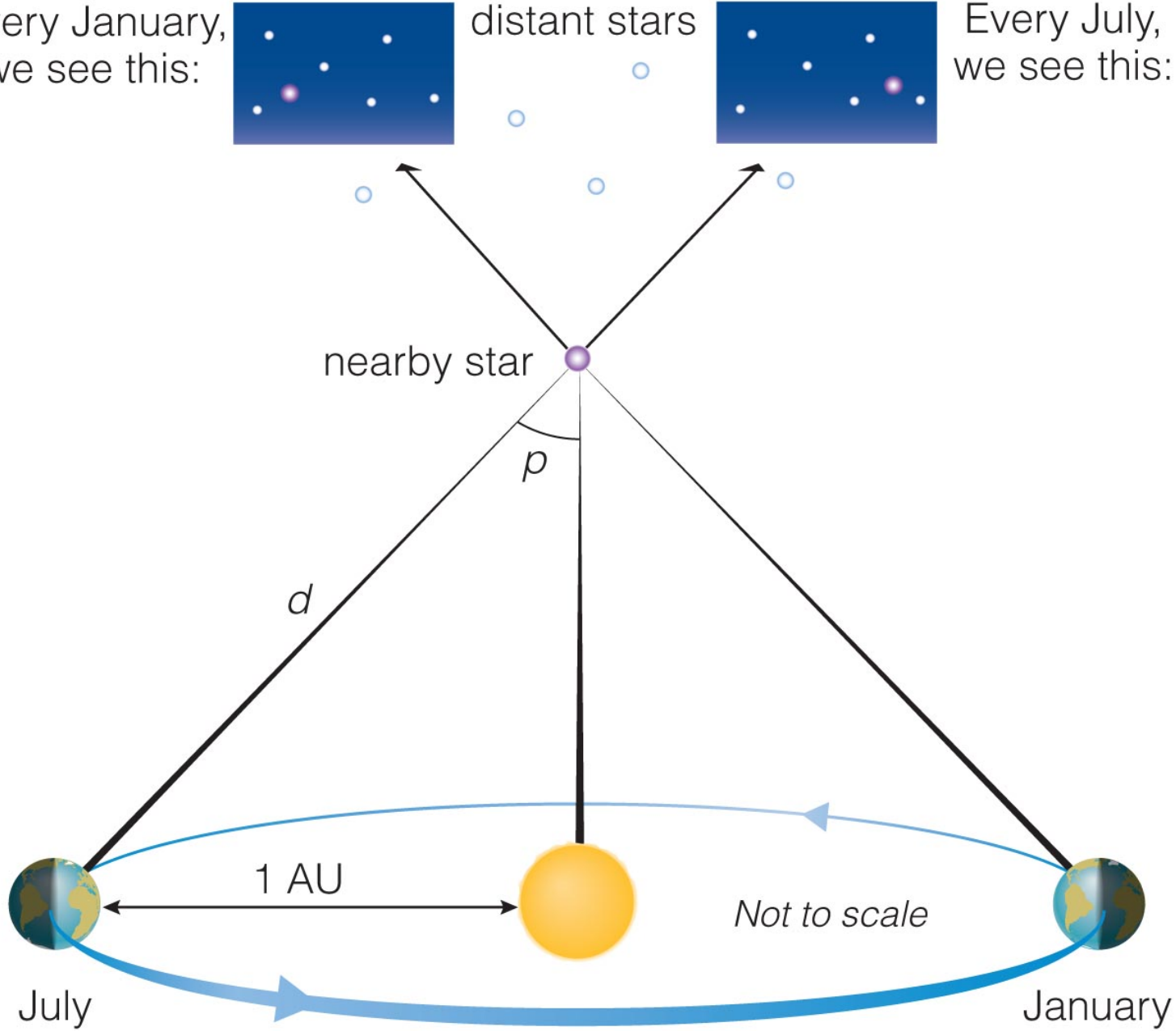
Every January,
we see this:



distant stars



Every July,
we see this:



Parallax and Distance

p = parallax angle

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

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

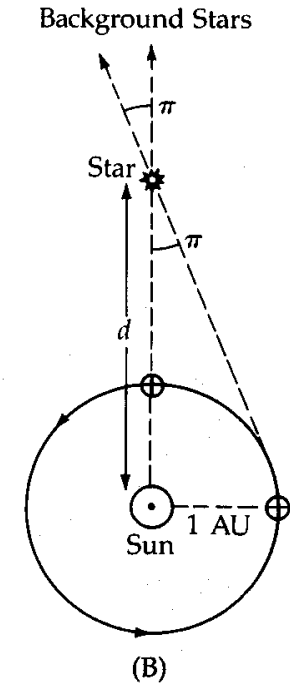
Parallax

- (Bessel 1838)

- $\pi ["] = 1 / d [\text{pc}]$ from $\pi [\text{rad}] = 1 / d [\text{AU}]$

where $1 \text{ pc} = 206265 \text{ AU}$ ($1 \text{ AU} = 1.5 \times 10^8 \text{ km}$)
 $= 3.26 \text{ light yr}$
 $= 3.1 \times 10^{13} \text{ km}$

- 1 parsec = “that distance at which parallax is 1 arcsec”
- measured w.r.t. sun!
- parallactic orbits – ellipse in sky
- nearest star - $\pi = 0.76 \text{ arcsec}$ (Proxima Centauri), $d = ???$
- Limits: $\pm 0.001 \text{ arcsec}$





Most luminous
stars:

$$10^6 L_{\text{Sun}}$$

Least luminous
stars:

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

(L_{Sun} is luminosity
of Sun)

Magnitudes and Fluxes

$$m_1 - m_2 = 2.5 \log_{10}(\ell_2 / \ell_1)$$

$$\ell_2 / \ell_1 = 10^{0.4(m_1 - m_2)}$$

- Backwards, logarithmic, no zeropoint
 - Mag differences correspond to flux ratios
- Origins - Hipparchos “1st-6th mags”
 - Herschel - factor of 100x in brightness
- Each mag is a factor of 2.512...x in brightness
 - 2.5 mag = 10x, 5 mag = 100x, 10mag = 10⁴x, ...
- Combining mags: convert to flux first
- Small Δm :

$$\Delta \ell / \ell \cong \Delta m$$

- *Apparent vs. Absolute magnitude:*

- abs mag is apparent magnitude if the object were at a distance of 10pc
- From inverse square law (Euclidean space):

$$m - M = 5 \log_{10} d_{pc} - 5 = \text{"distance modulus"}$$

App mag

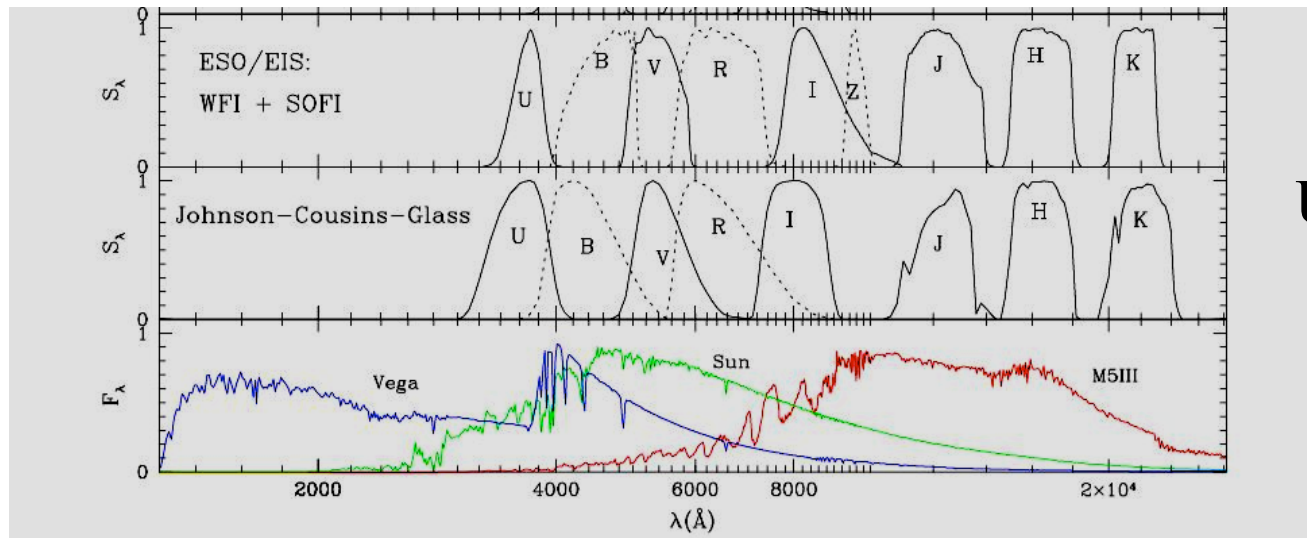
Abs mag

Must be in parsecs, not kpc or Mpc

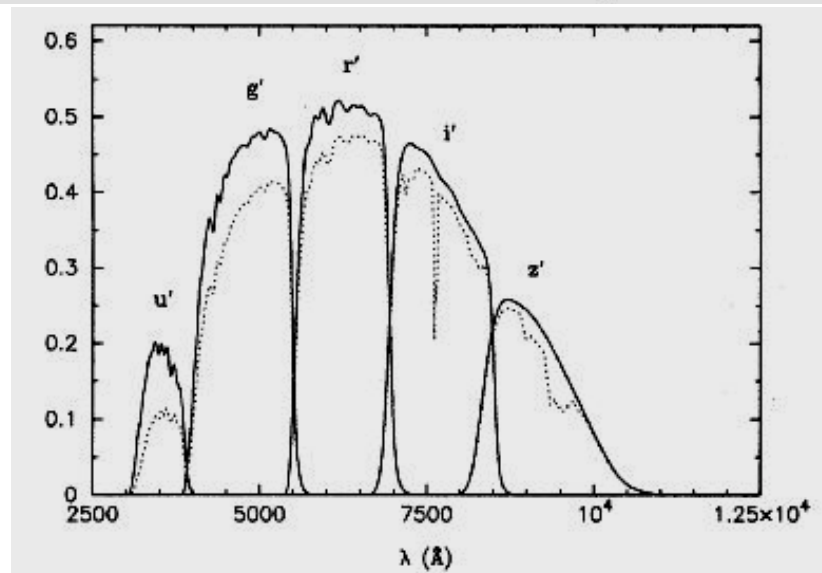
- *Magnitude systems* - examples:

- UBVRIJHK...
- griz
- ...

Photometric band-passes



UBVRIJHK



Sloan Digital Sky Survey

- Zero points
 - Vega system for UBVRIJK

Table 7.5. Filter wavelengths, bandwidths, and flux densities for Vega.^a

Filter name	λ_{iso}^b (μm)	$\Delta\lambda^c$ (μm)	F_λ ($\text{W m}^{-2} \mu\text{m}^{-1}$)	F_V (Jy)	N_ϕ (photons $\text{s}^{-1} \text{m}^{-2} \mu\text{m}^{-1}$)
V	0.5556 ^d	...	3.44×10^{-8}	3 540	9.60×10^{10}
J	1.215	0.26	3.31×10^{-9}	1 630	2.02×10^{10}
H	1.654	0.29	1.15×10^{-9}	1 050	9.56×10^9
K_s	2.157	0.32	4.30×10^{-10}	667	4.66×10^9
K	2.179	0.41	4.14×10^{-10}	655	4.53×10^9
L	3.547	0.57	6.59×10^{-11}	276	1.17×10^9
L'	3.761	0.65	5.26×10^{-11}	248	9.94×10^8
M	4.769	0.45	2.11×10^{-11}	160	5.06×10^8
8.7	8.756	1.2	1.96×10^{-12}	50.0	8.62×10^7
N	10.472	5.19	9.63×10^{-13}	35.2	5.07×10^7
11.7	11.653	1.2	6.31×10^{-13}	28.6	3.69×10^7
Q	20.130	7.8	7.18×10^{-14}	9.70	7.26×10^6

Notes

^aCohen et al. [1] recommend the use of Sirius rather than Vega as the photometric standard for $\lambda > 20 \mu\text{m}$ because of the infrared excess of Vega at these wavelengths. The magnitude of Vega depends on the photometric system used, and it is either assumed to be 0.0 mag or assumed to be 0.02 or 0.03 mag for consistency with the visual magnitude.

^bThe infrared isophotal wavelengths and flux densities (except for K_s) are taken from Table 1 of [1], and they are based on the UKIRT filter set and the atmospheric absorption at Mauna Kea. See Table 2 of [1] for the case of the atmospheric absorption at Kitt Peak. The isophotal wavelength is defined by $F(\lambda_{\text{iso}}) = \int F(\lambda)S(\lambda)d\lambda / \int S(\lambda)d\lambda$, where $F(\lambda)$ is the flux density of Vega and $S(\lambda)$ is the (detector quantum efficiency) $\times$ (filter transmission) $\times$ (optical efficiency) $\times$ (atmospheric transmission) [2]. λ_{iso} depends on the spectral shape of the source and a correction must be applied for broadband photometry of sources that deviate from the spectral shape of the standard star [3]. The flux density and λ_{iso} for K_s were calculated here. For another filter, K' , at $2.11 \mu\text{m}$, see [4].

^cThe filter full width at half maximum.

^dThe wavelength at V is a monochromatic wavelength; see [5].

References

1. Cohen, M. et al. 1992, *AJ*, **104**, 1650
2. Golay, M. 1974, *Introduction to Astronomical Photometry* (Reidel, Dordrecht), p. 40
3. Hanner, M.S., et al. 1984, *AJ*, **89**, 162
4. Wainscoat, R.J., & Cowie, I.L. 1992, *AJ*, **103**, 332
5. Hayes, D.S. 1985, in *Calibration of Fundamental Stellar Quantities*, edited by D.S. Hayes, et al., Proc. IAU Symp. No. 111 (Reidel, Dordrecht), p. 225

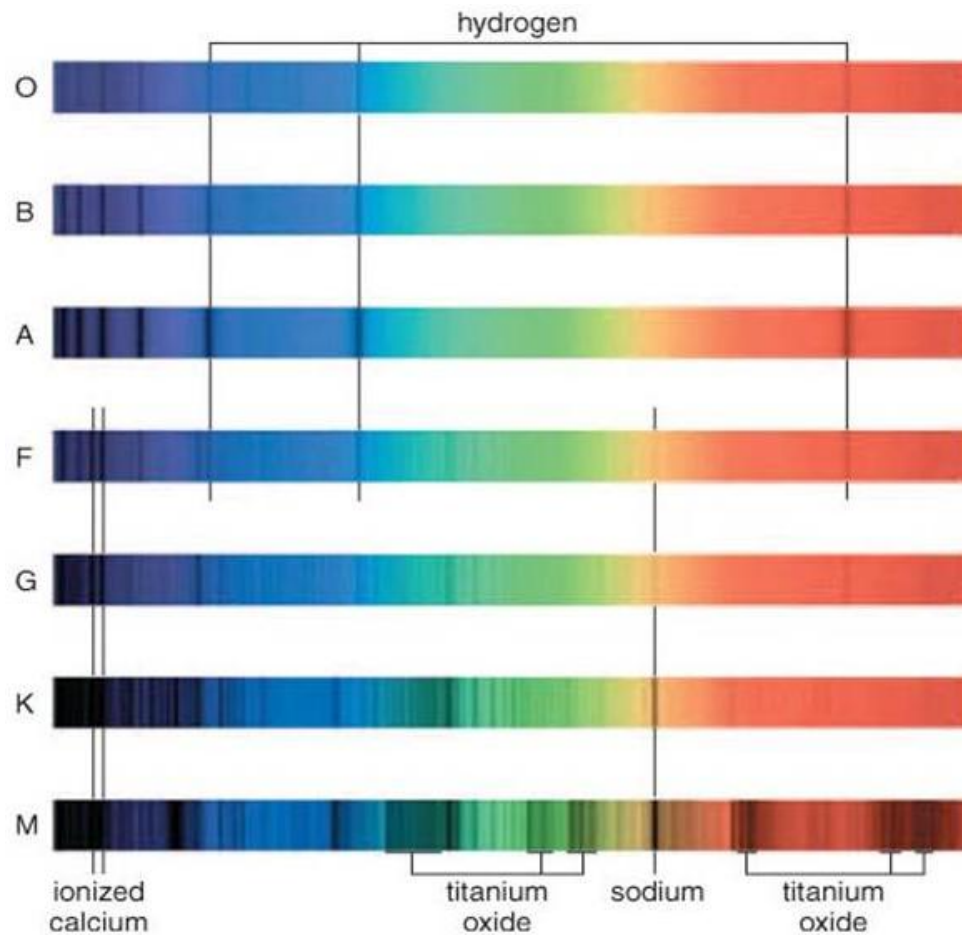
- AB system for griz...

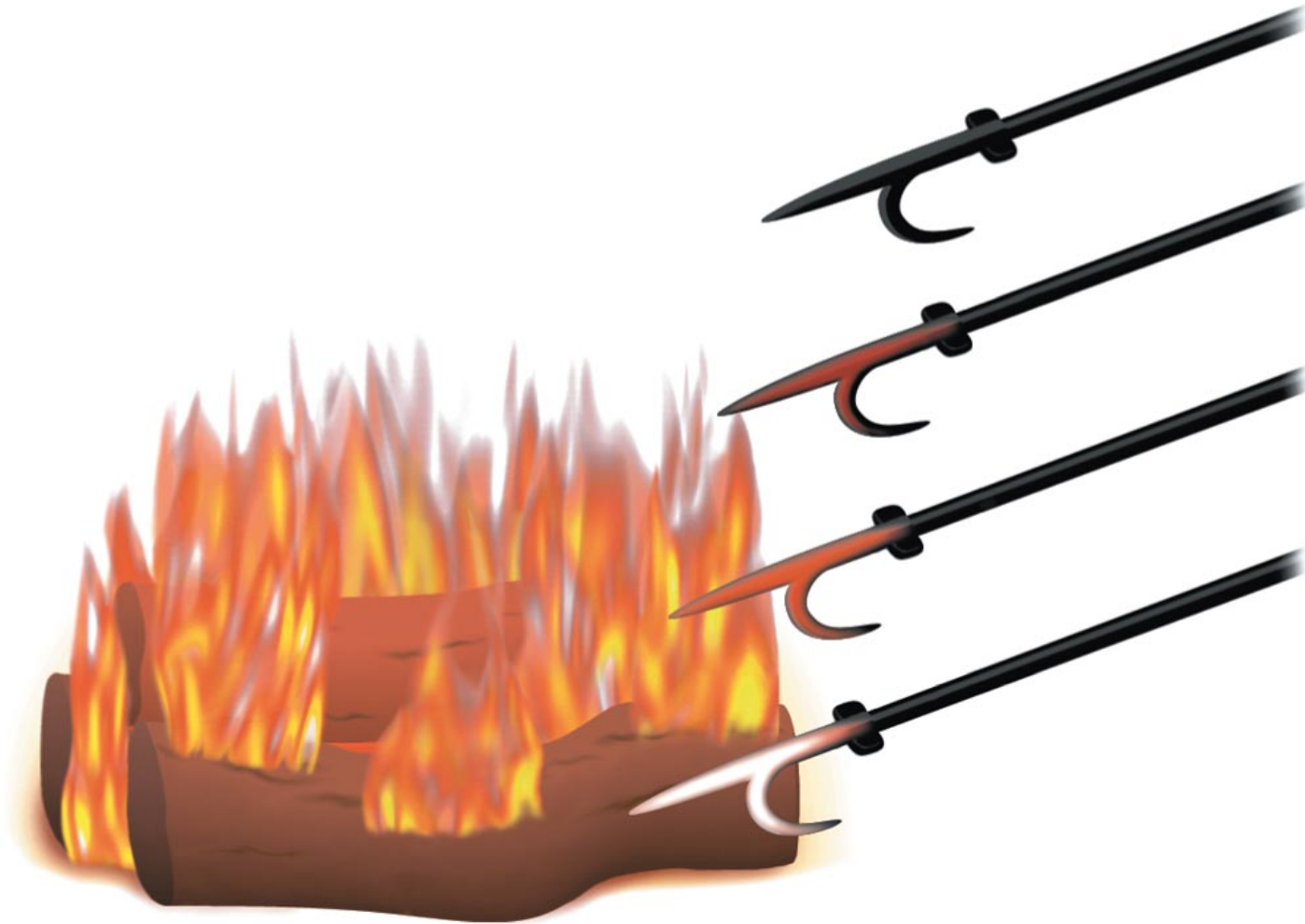
– $m_{\text{AB}}=0$ corresponds to $3.63 \times 10^{-20} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1}$

$$m_{\text{AB}} = -2.5 \log_{10} f_\nu [\text{erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1}] - 48.60$$

- Warning: sometimes UBVRIJHK is in the AB system!!

How do we measure stellar temperatures?

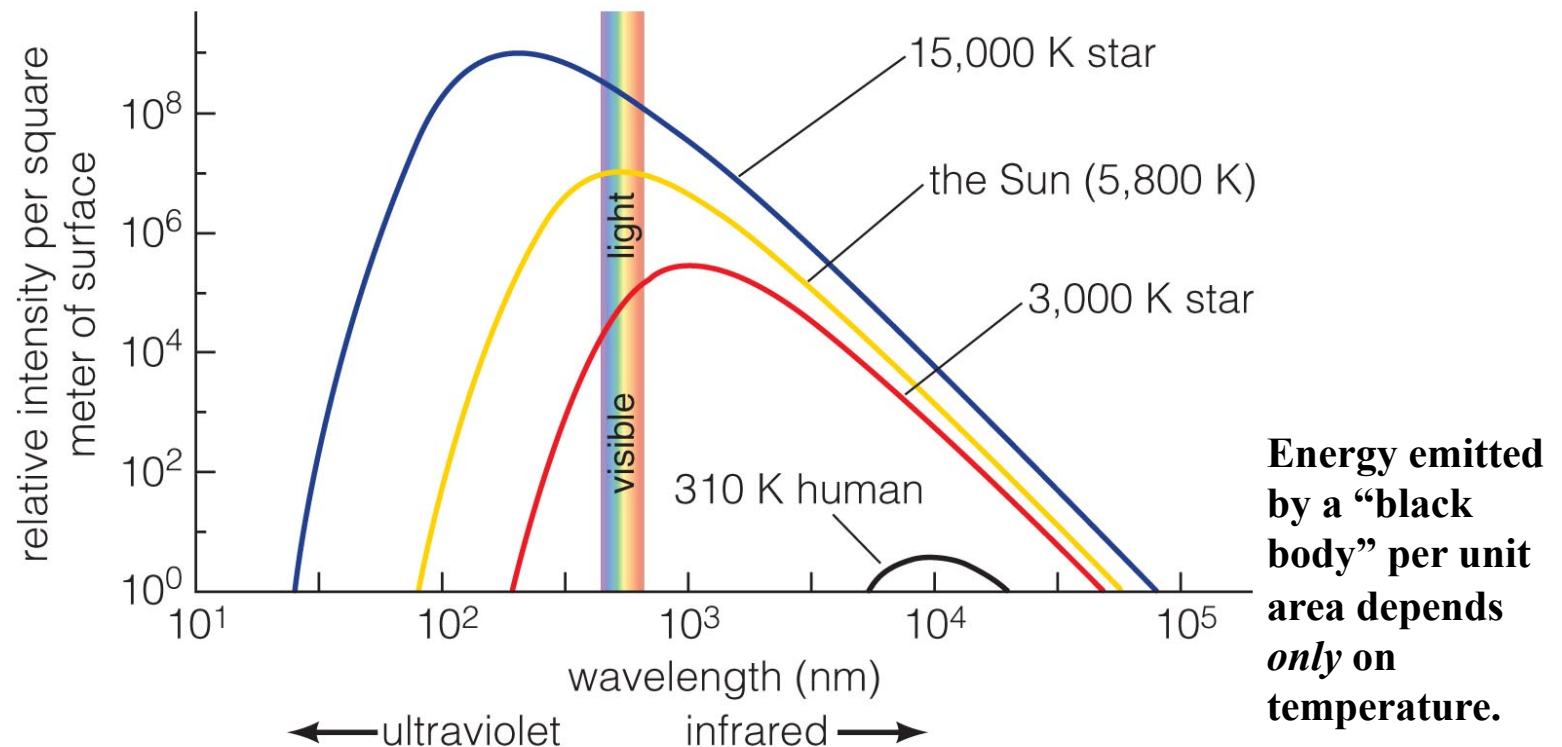




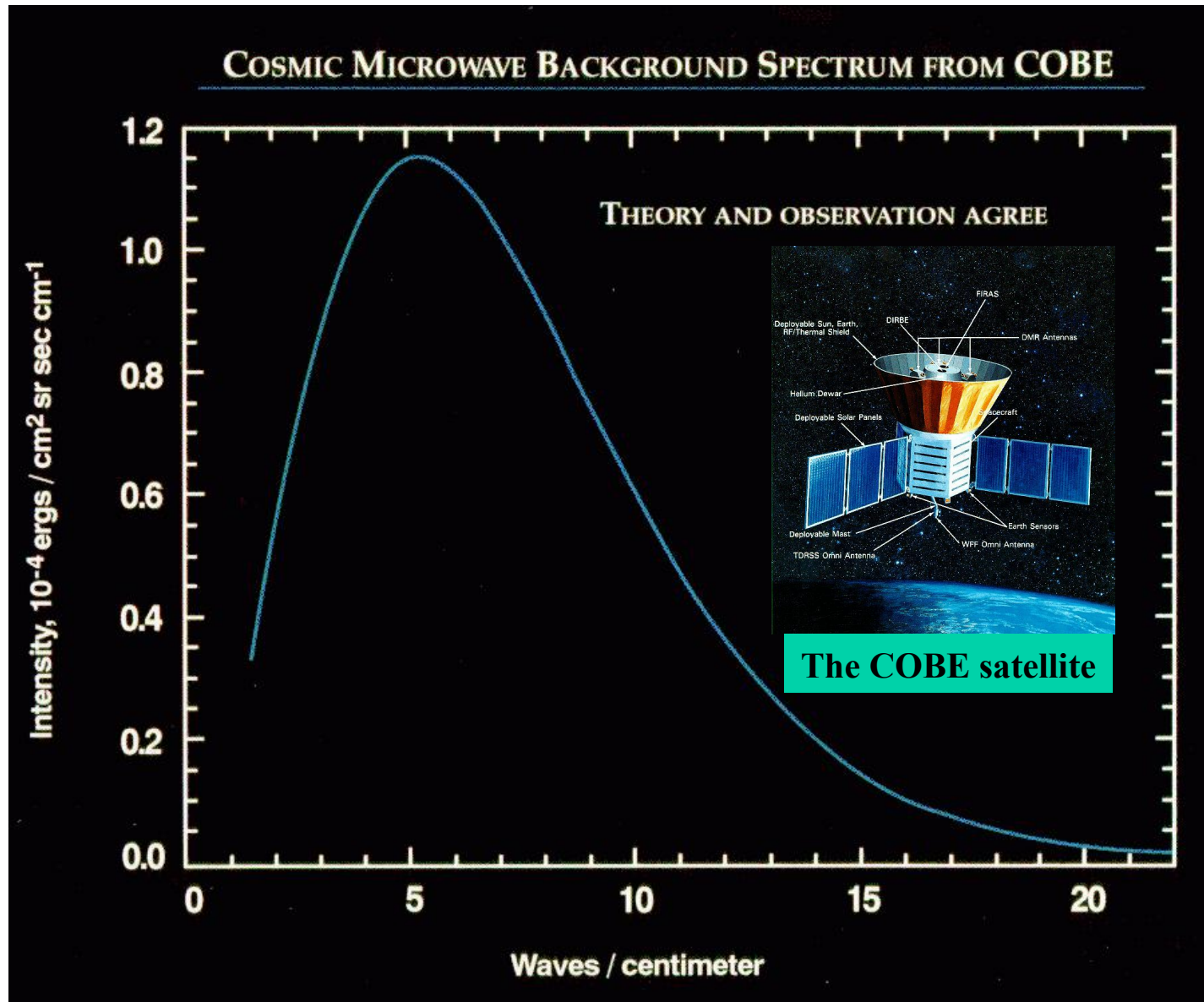
Every object emits *thermal radiation* with a spectrum that depends on its temperature

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.



The Perfect Black Body



$$\lambda_{\text{max}} = (2.9/T_K) \text{mm}$$

**Wien's
displacement law**

**The Universe has
a well-defined
temperature:
2.7K**



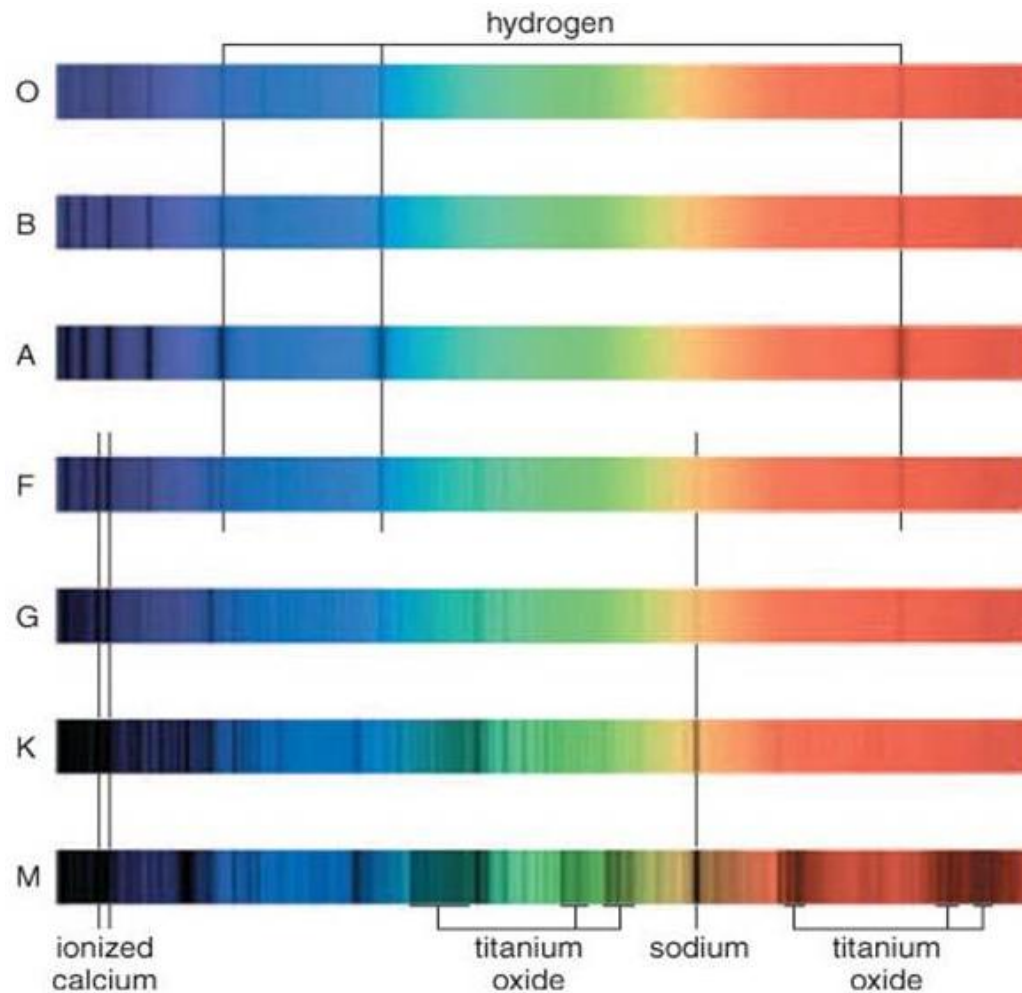
Hottest stars:

50,000 K

Cooler stars:

3,000 K

(Sun's surface
is 5,800 K)



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

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

Pioneers of Stellar Classification



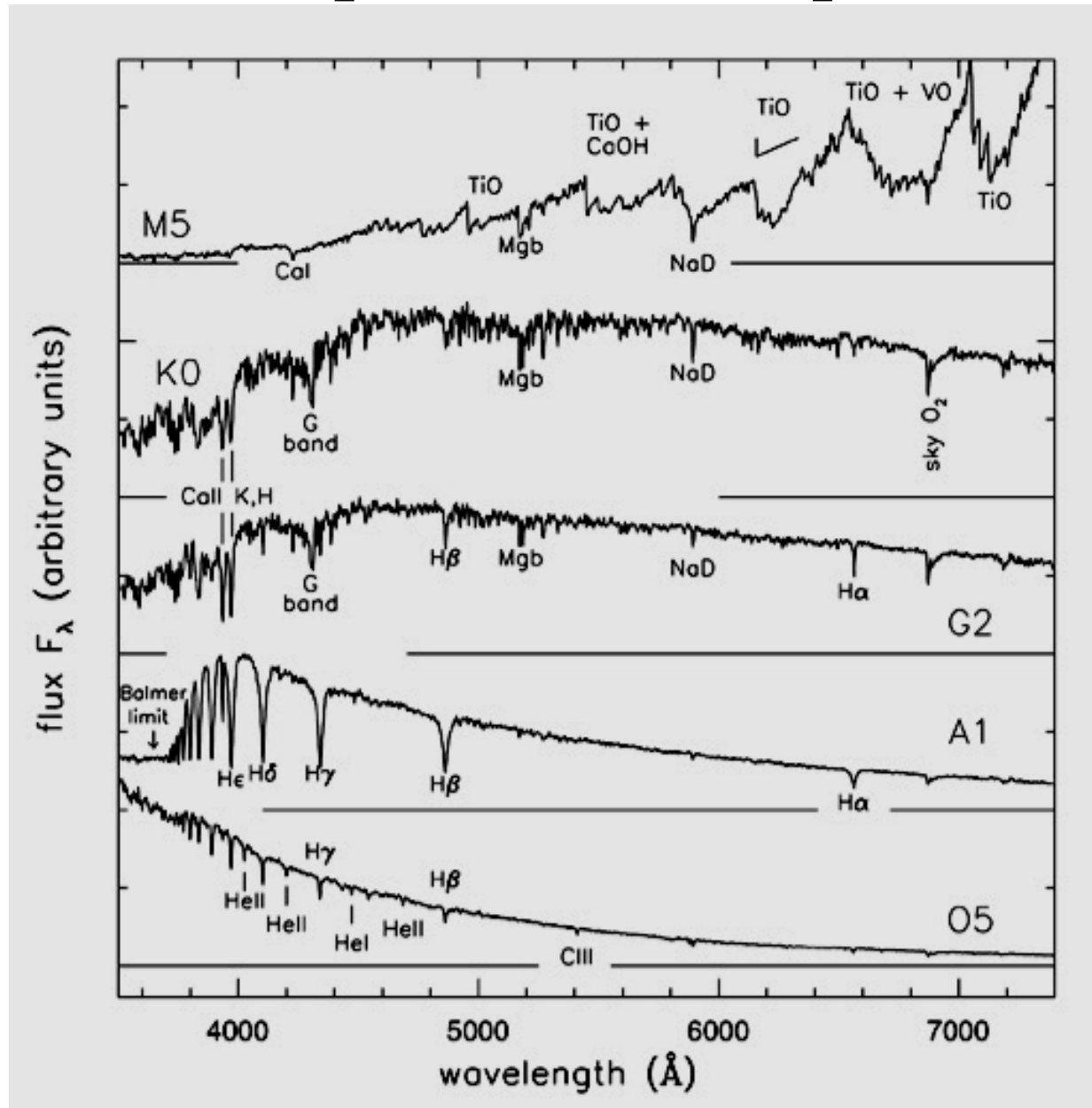
- Annie Jump Cannon and the “computers” at Harvard laid the foundation of modern stellar classification

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

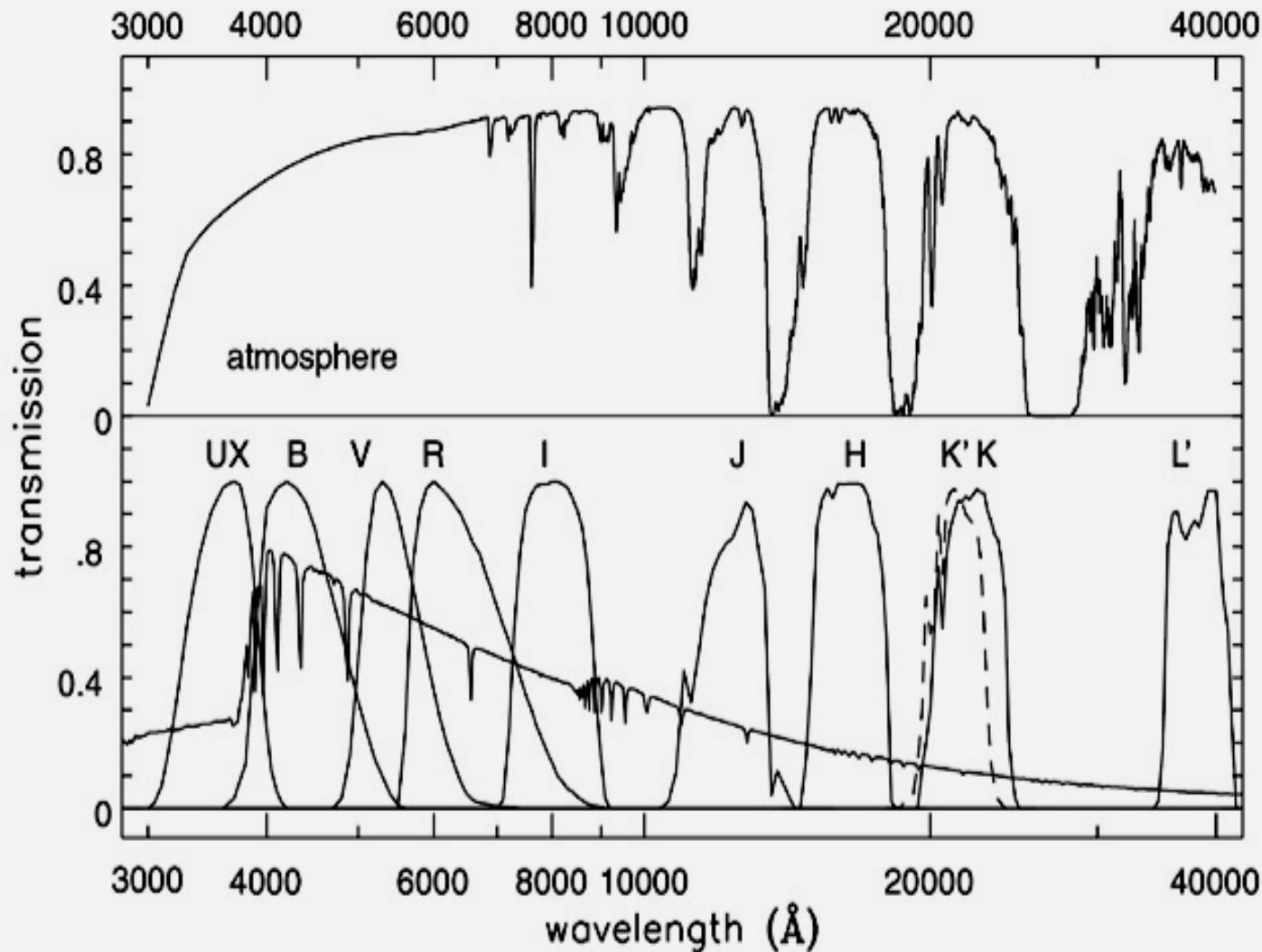
Temperature and Spectral Classification



The shape of the spectrum and its features correlate strongly with the star's temperature.

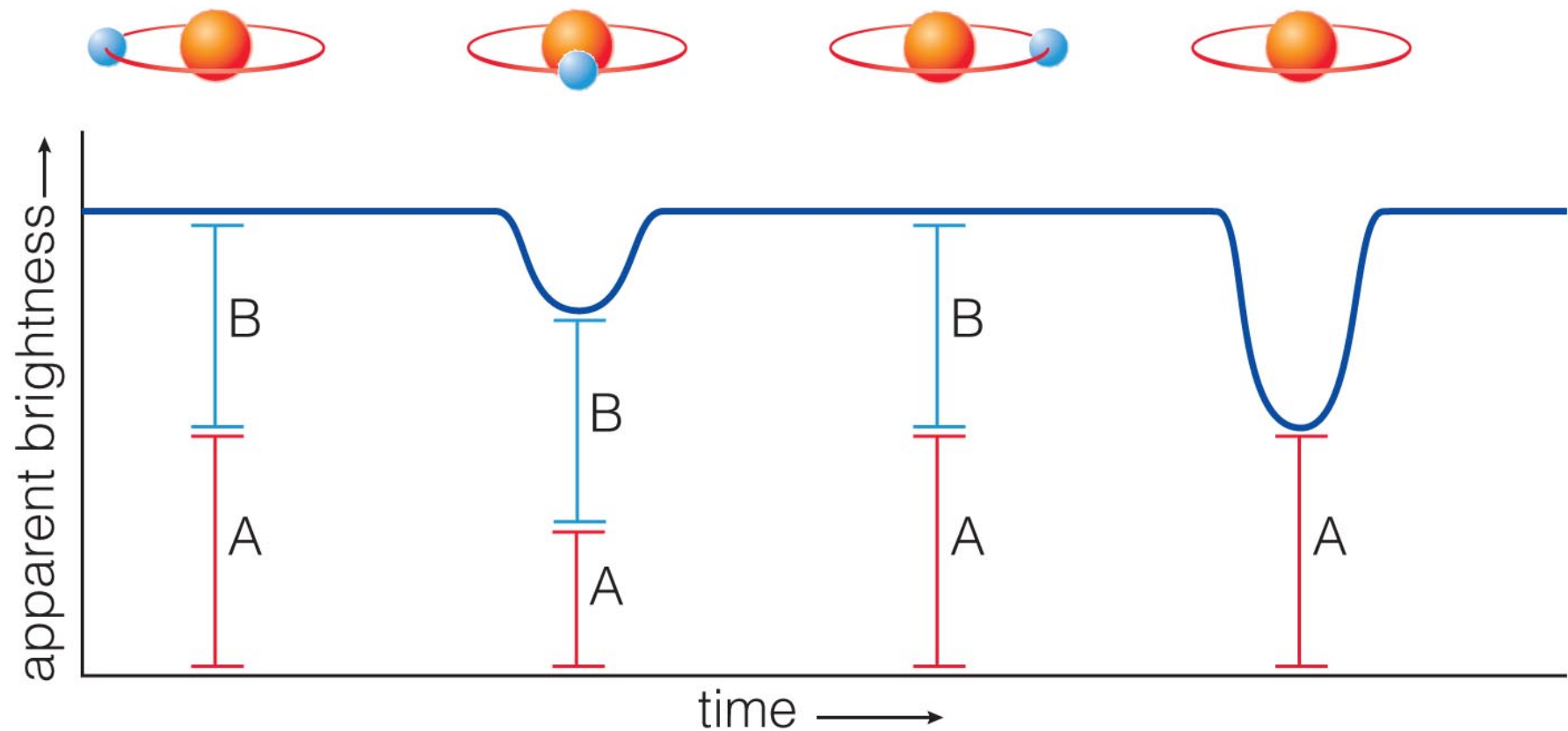
They also depend on a star's composition

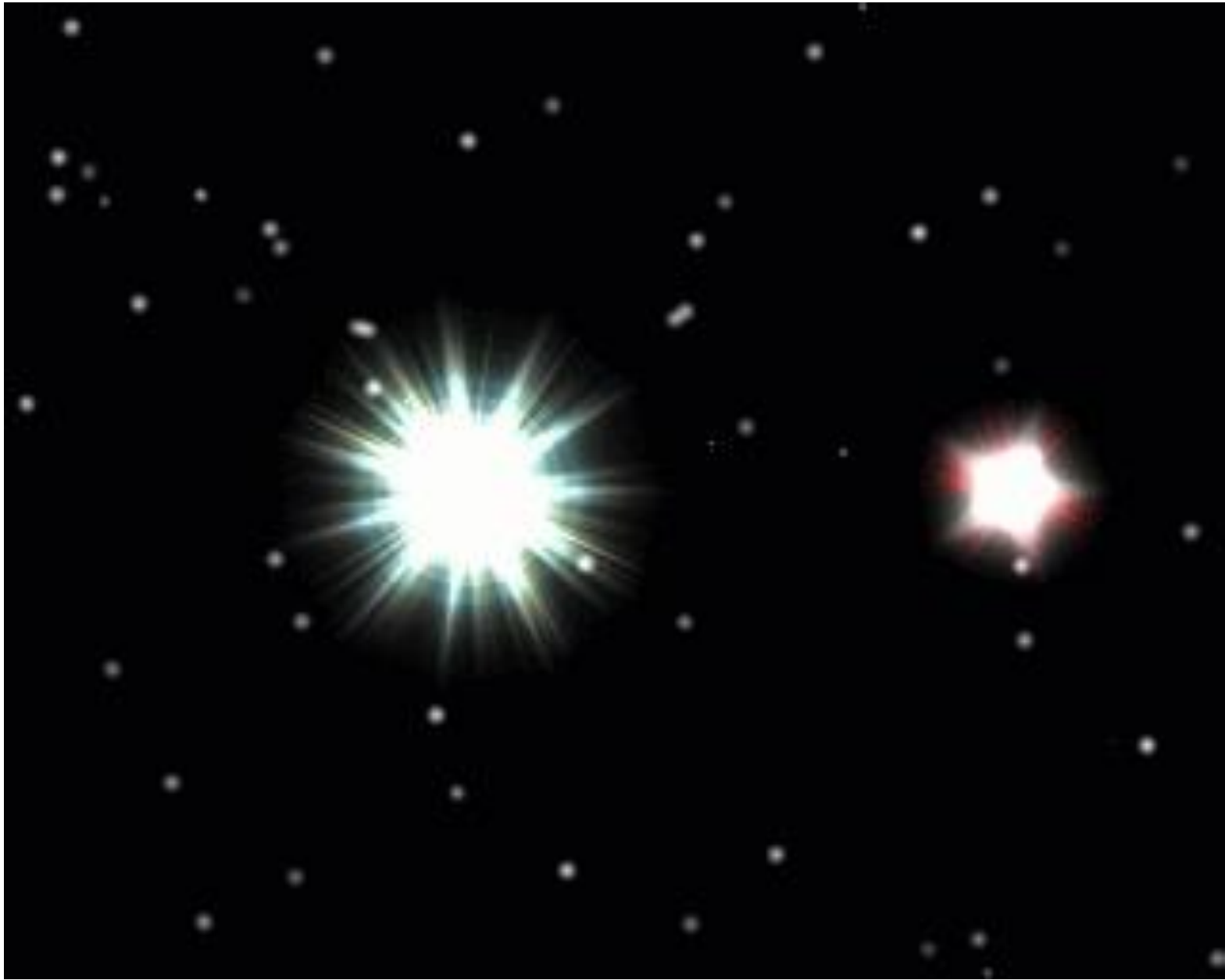
Spectral Classification and Photometric Bandpasses



Bandpasses are chosen to either bracket features in a star's spectrum or to track portions of the spectrum where the Earth's atmosphere is transparent.

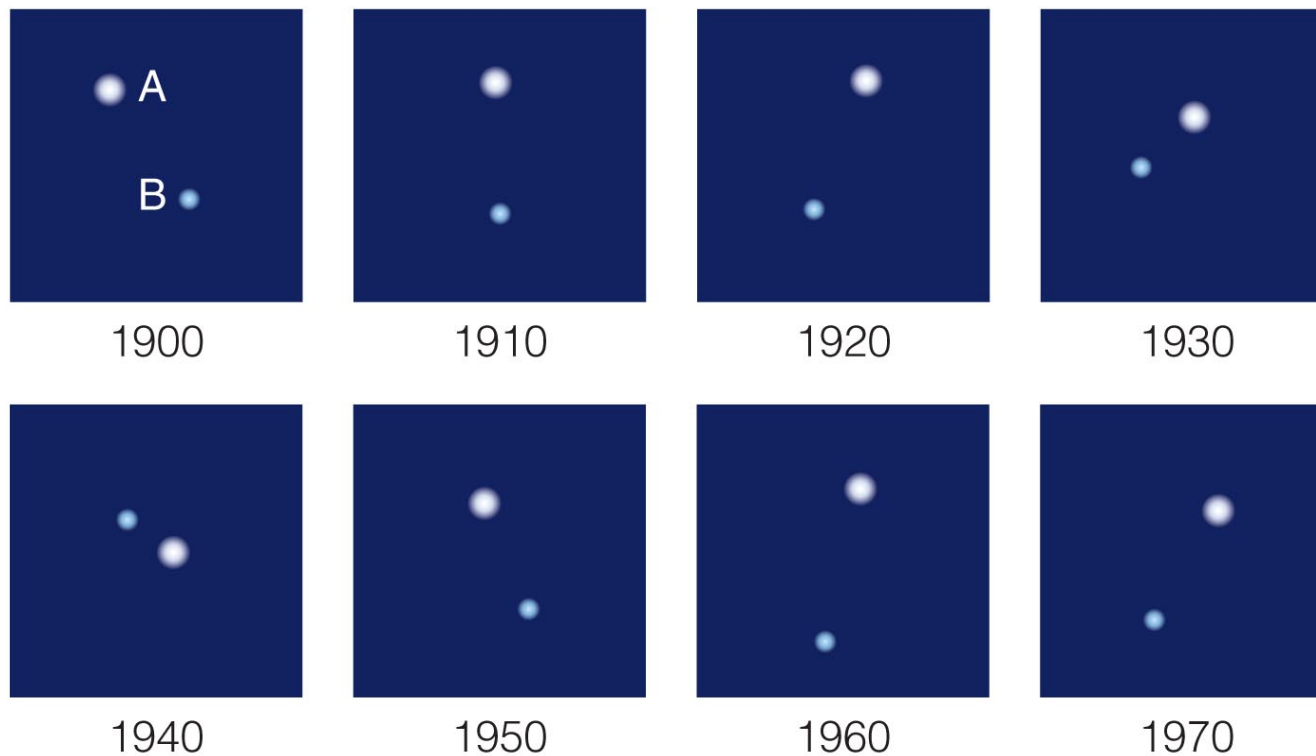
How do we measure stellar masses?





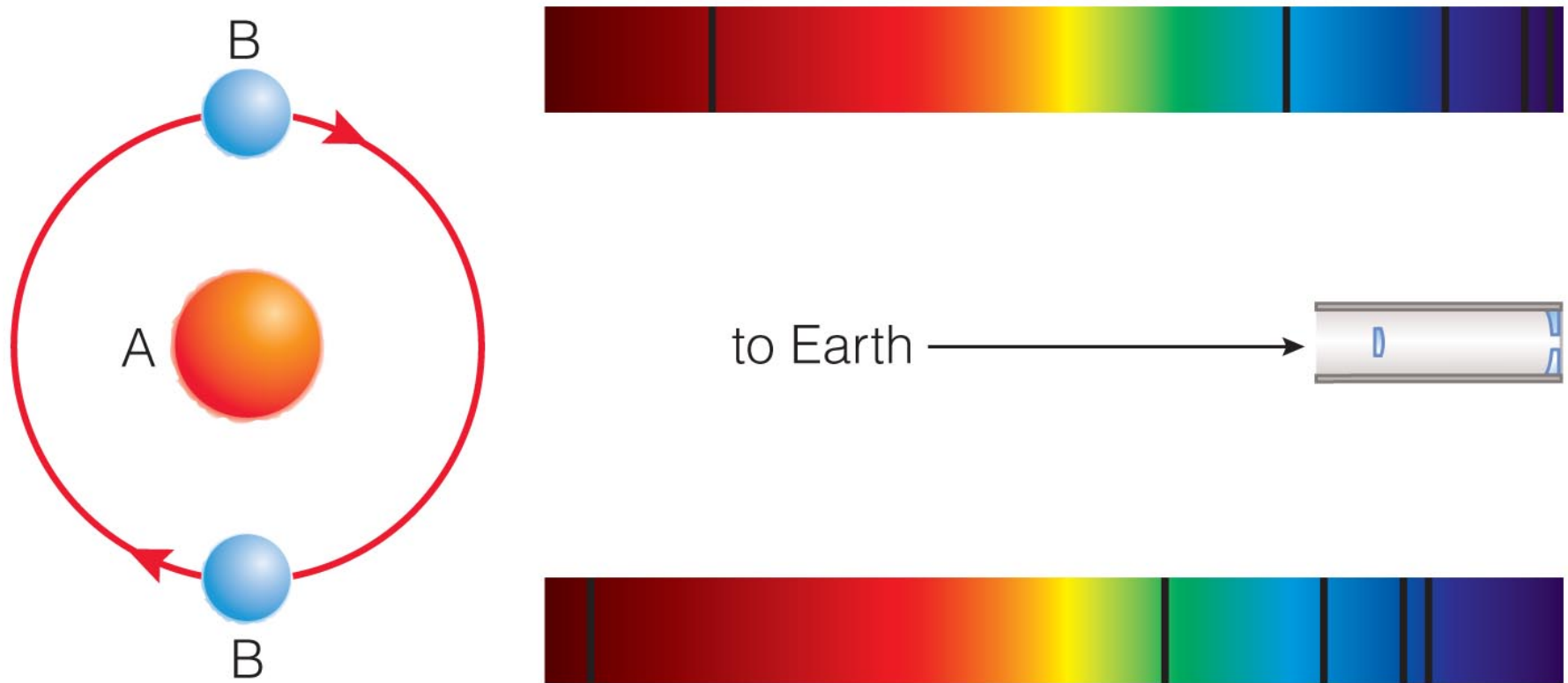
The orbit of a binary star system depends on strength of gravity

Visual Binary



We can directly observe the orbital motions of these stars

Spectroscopic Binary



We determine the orbit by measuring Doppler shifts



Sir Isaac Newton (1642–1727)

We measure mass using gravity

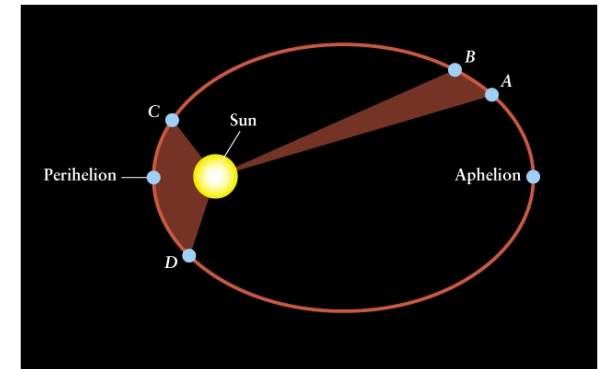
Direct mass measurements are possible only for stars in binary star systems

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

p = period

a = average separation

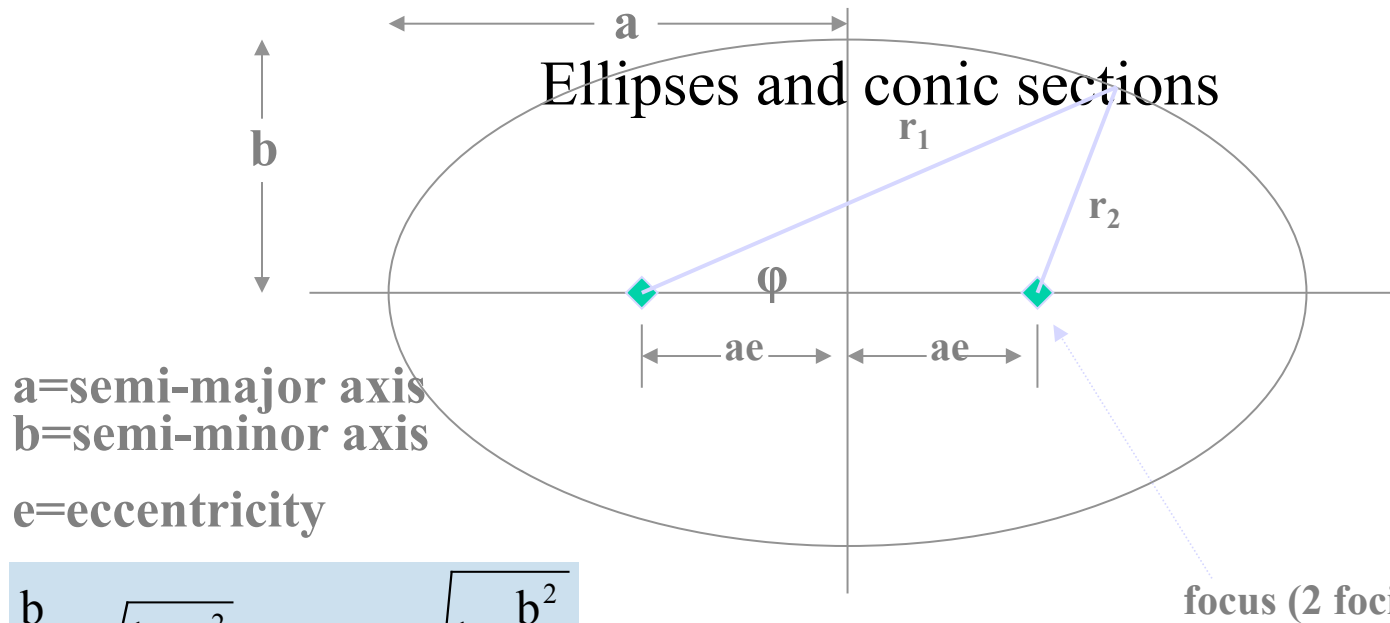
Gravity & Kepler's Laws



From Tycho Brahe's observations ...

- I. Planets move in elliptical orbits with the sun at one focus.
- II. Radius vector between the sun and a planet sweeps out equal areas in equal time.
- III. P^2 prop. to a^3 for orbit (P =period, a =semimajor axis)

Ellipses and conic sections



a =semi-major axis
 b =semi-minor axis
 e =eccentricity

$$\frac{b}{a} = \sqrt{1 - e^2} \quad \text{or} \quad e = \sqrt{1 - \frac{b^2}{a^2}}$$

$$r_1 + r_2 = 2a$$

Ellipse in x-y:

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$$

$$r = \frac{a(1 - e^2)}{1 + e \cos \phi}$$

r =distance from focus
 ϕ =angle from x-axis in r direction

- Kepler's 3rd Law: centripetal force = gravitational force

$$\frac{mv^2}{r} = \frac{GMm}{r^2}, \quad v = 2\pi r/P$$

$$\therefore \frac{4\pi^2 r^2}{r P^2} = \frac{GM}{r^2}$$

$$\therefore P^2 = \left(\frac{4\pi^2}{GM} \right) r^3 \quad \text{or} \quad P^2 \propto a^3$$

for circular
orbits

P in yr, a in AU, M in solar masses:

$$P^2 = a^3 / M$$

$$M = m_1 + m_2 \cong M_{\text{sun}} \text{ for solar system}$$

Energy Considerations

- Total energy of orbit:

$$E_{\text{tot}} = -\frac{GMm}{2a}$$

Why is
energy
conserved?

- Energy in orbit

$$E_{\text{tot}} = -\frac{GMm}{2a} = \frac{mv^2}{2} - \frac{GMm}{r} \quad \text{at any point in orbit}$$

A little algebra gives:
$$v^2 = GM \left(\frac{2}{r} - \frac{1}{a} \right)$$



Most massive
stars:

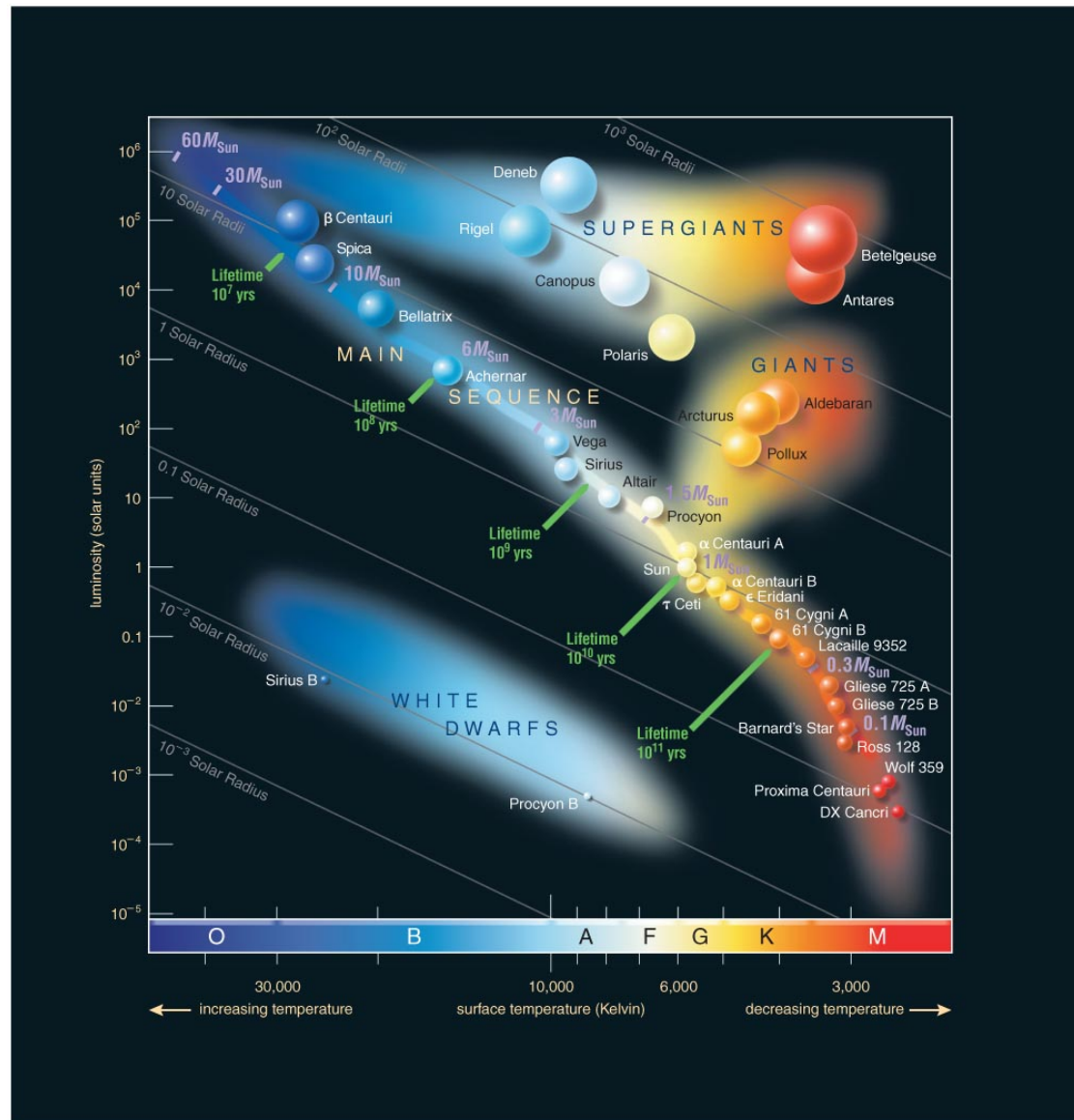
$$100 M_{\text{Sun}}$$

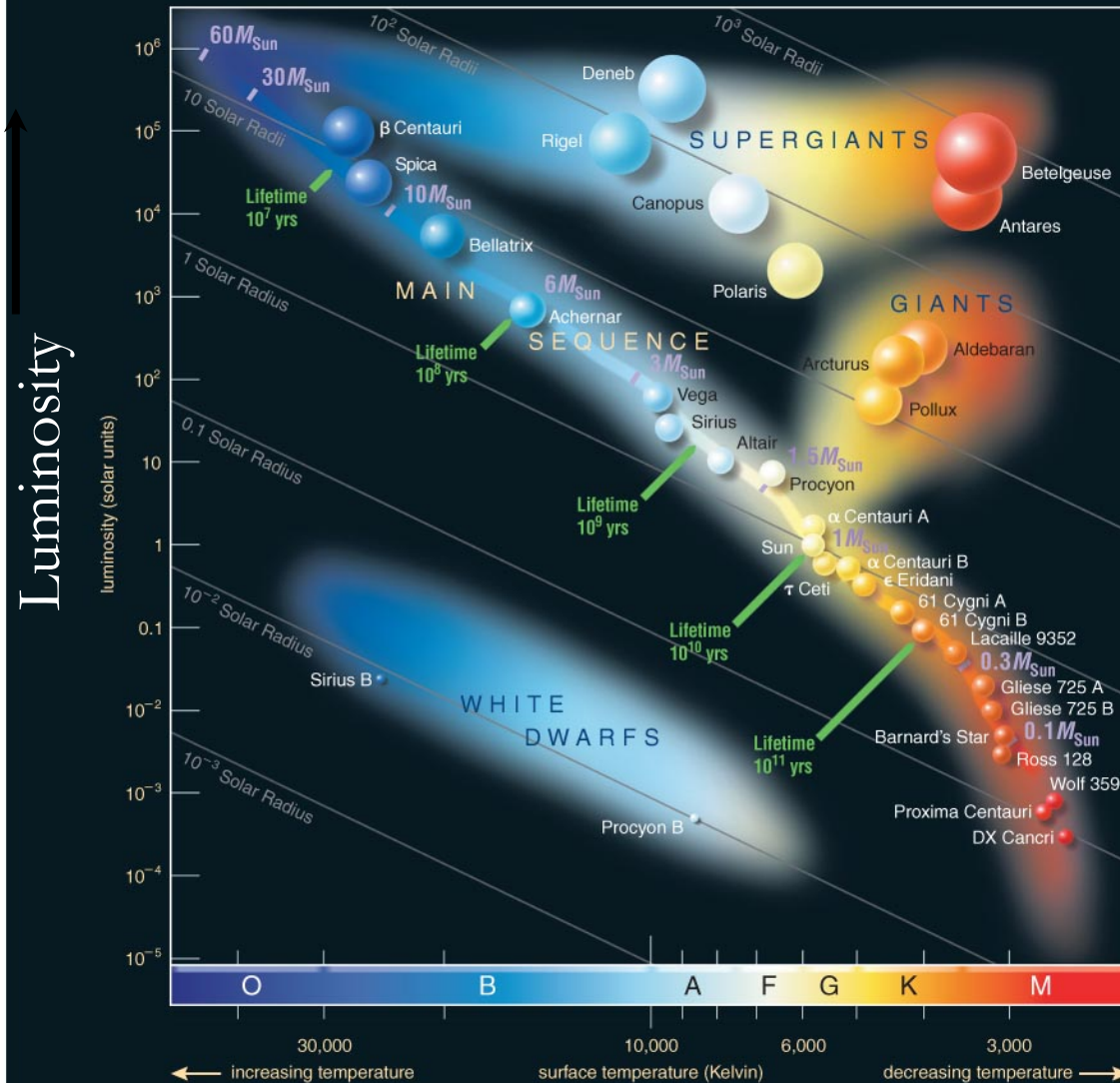
Least massive
stars:

$$0.08 M_{\text{Sun}}$$

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

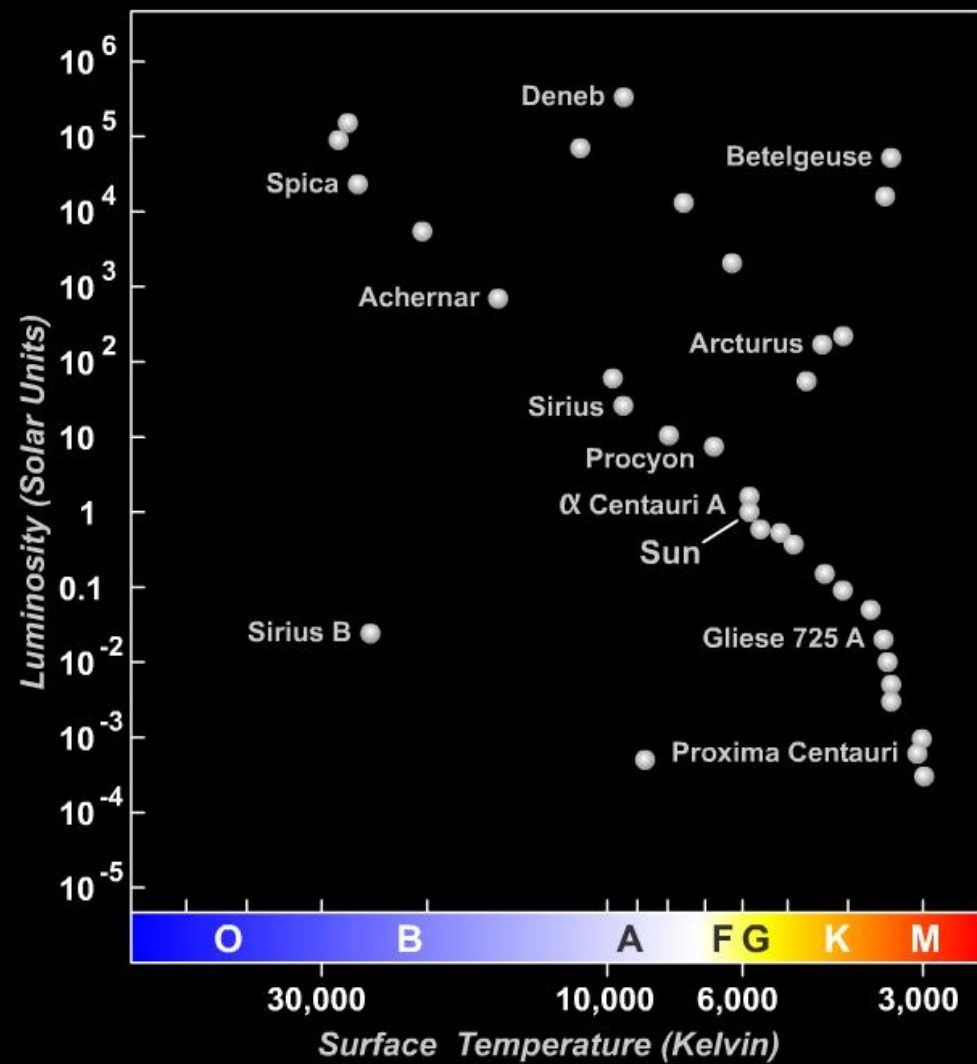
Patterns among stars





A Hertzsprung-Russell diagram plots the luminosity and temperature of stars

Generating an H-R Diagram



Groups

Reset

Star

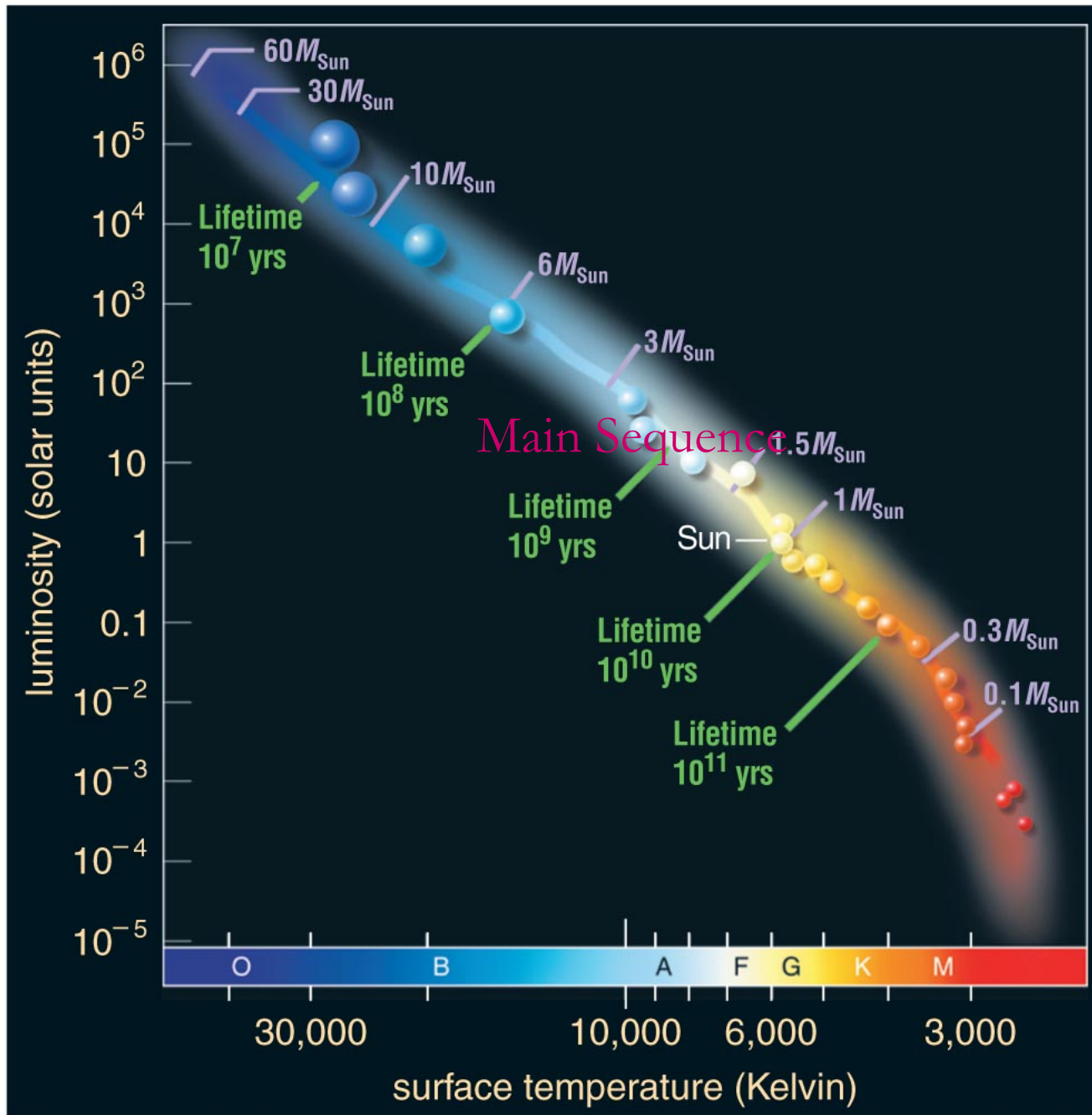
Lacaille 9532

Luminosity
(L_{Sun})

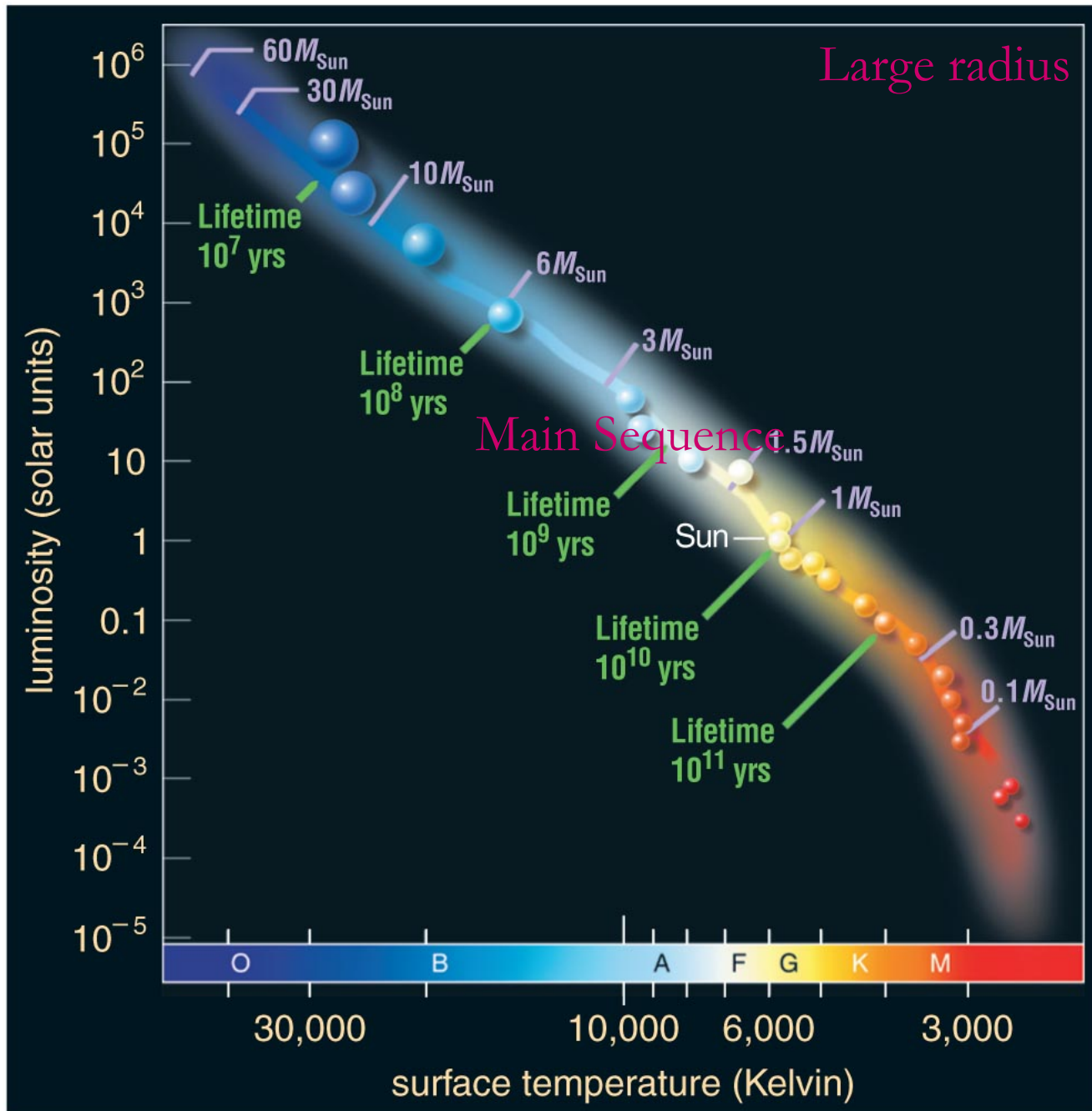
0.05

Temperature
(K)

3,650

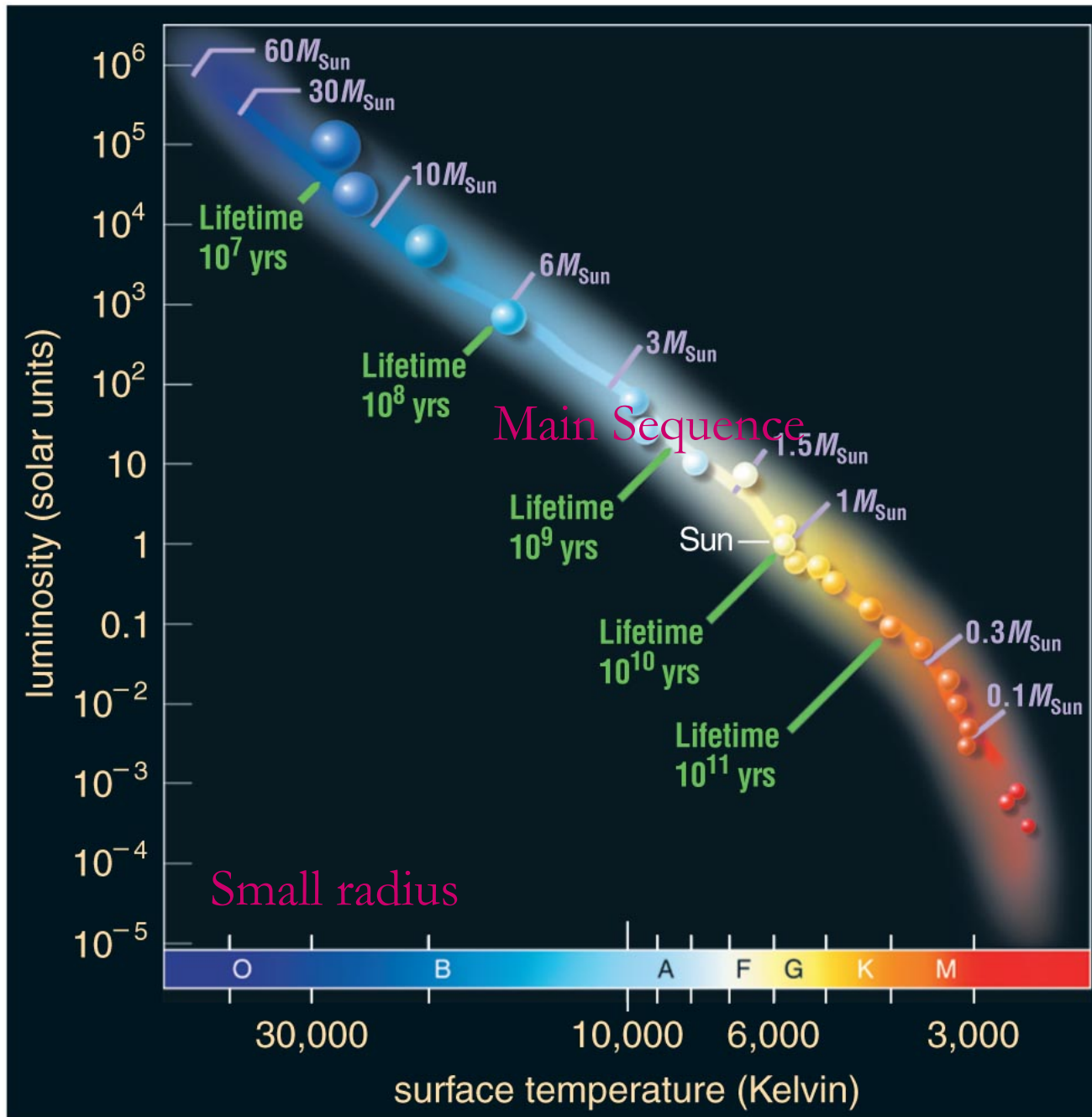


Most stars fall somewhere on the *main sequence* of the H-R diagram



Stars with lower T and higher L than main-sequence stars must have larger radii:

giants and supergiants



Stars with higher T and lower L than main-sequence stars must have smaller radii:

white dwarfs

H-R diagram depicts:

Temperature

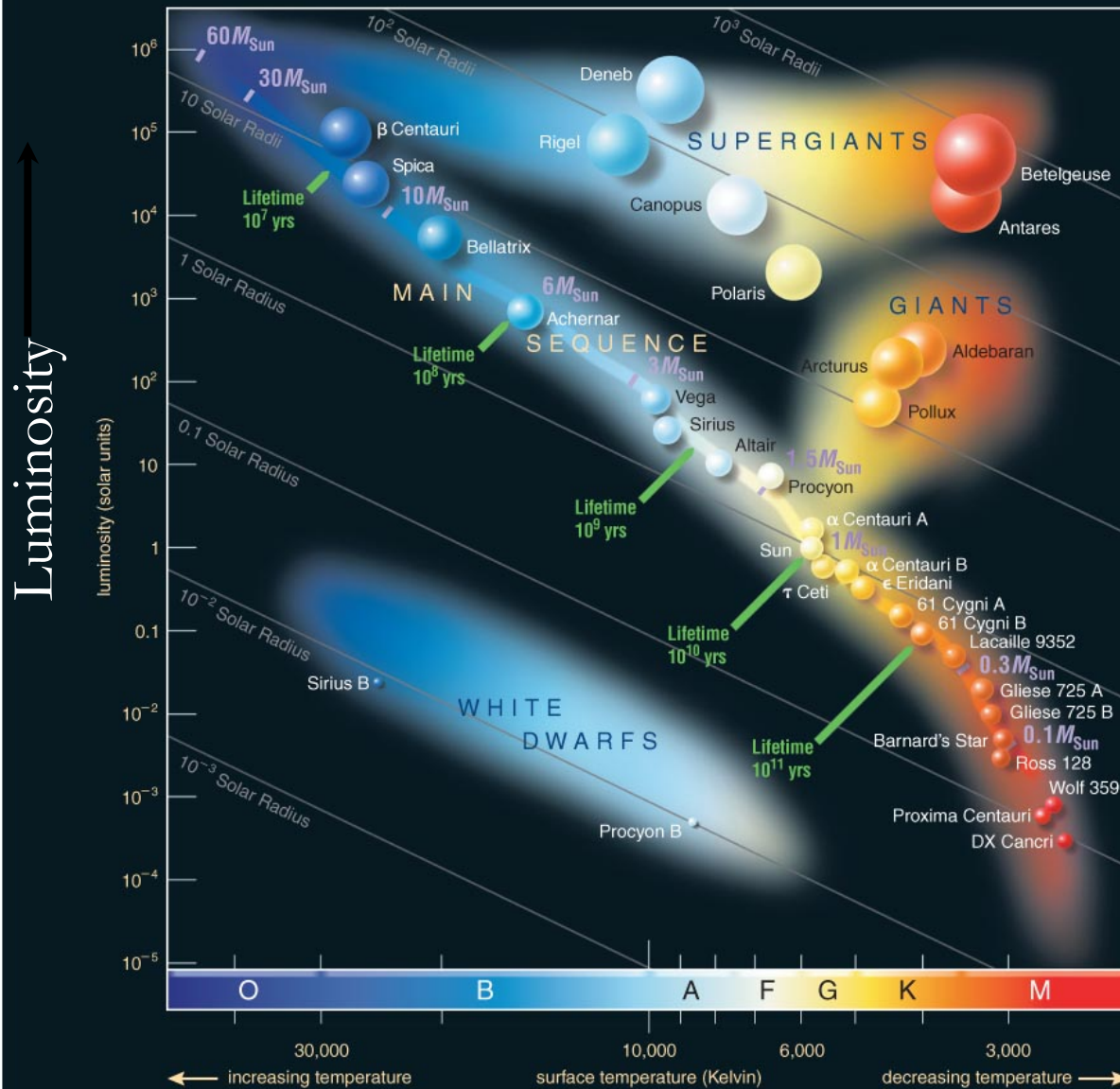
Color

Spectral Type

Luminosity

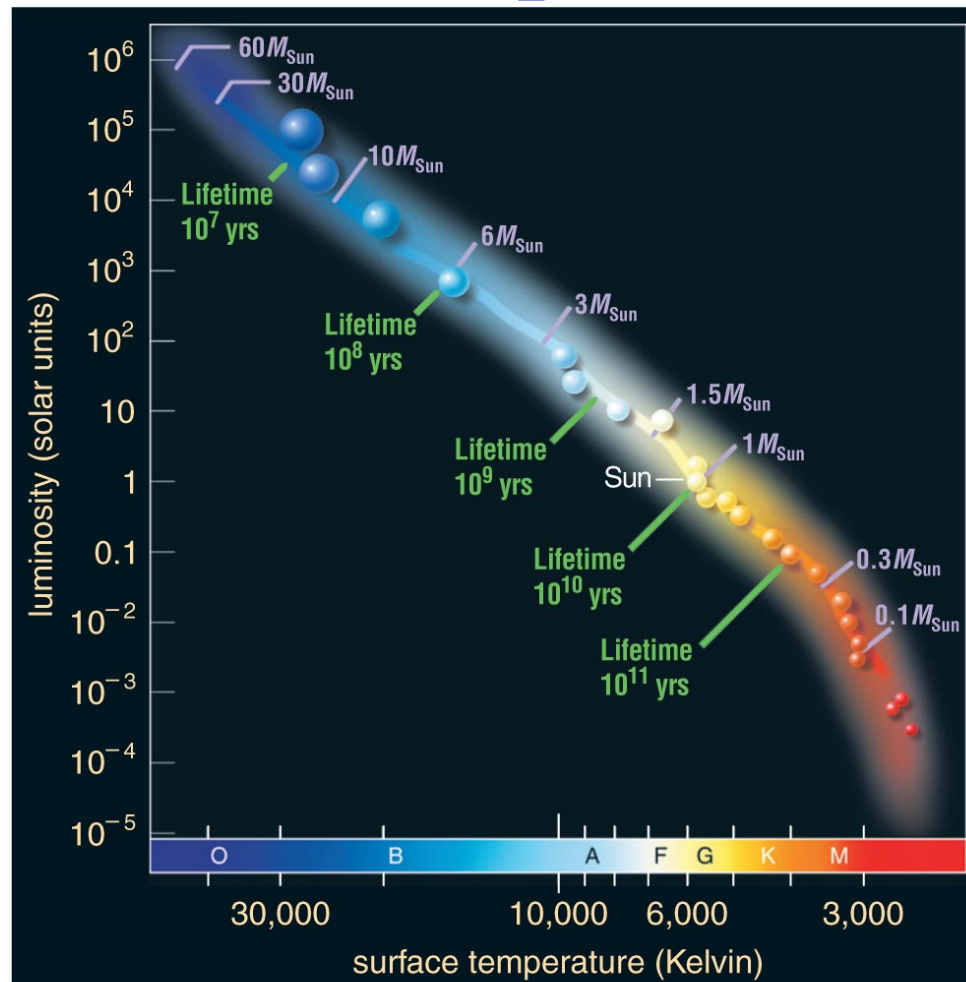
Radius

$$L \propto r^2 T^4$$



Temperature

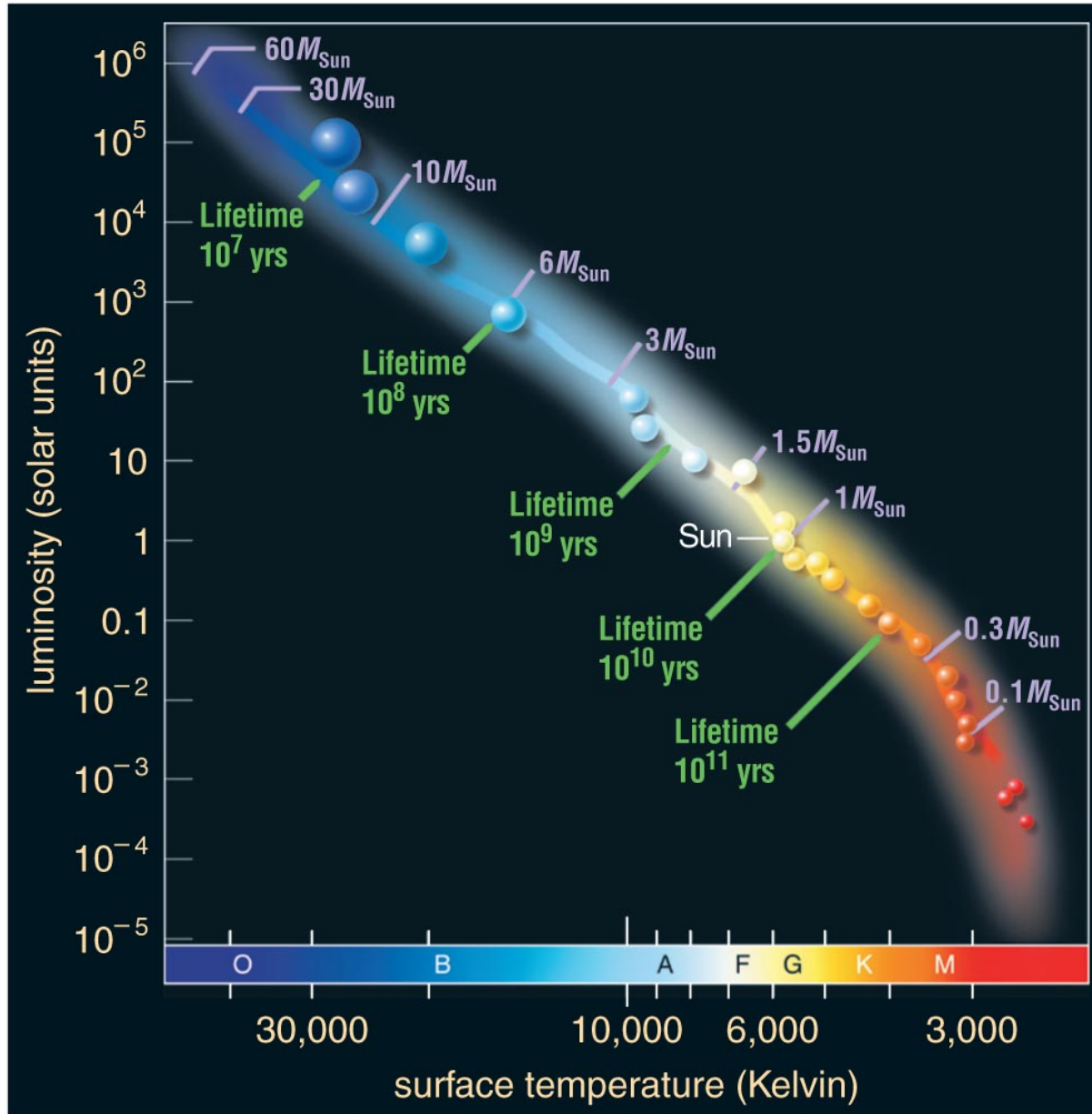
What is the significance of the main sequence?



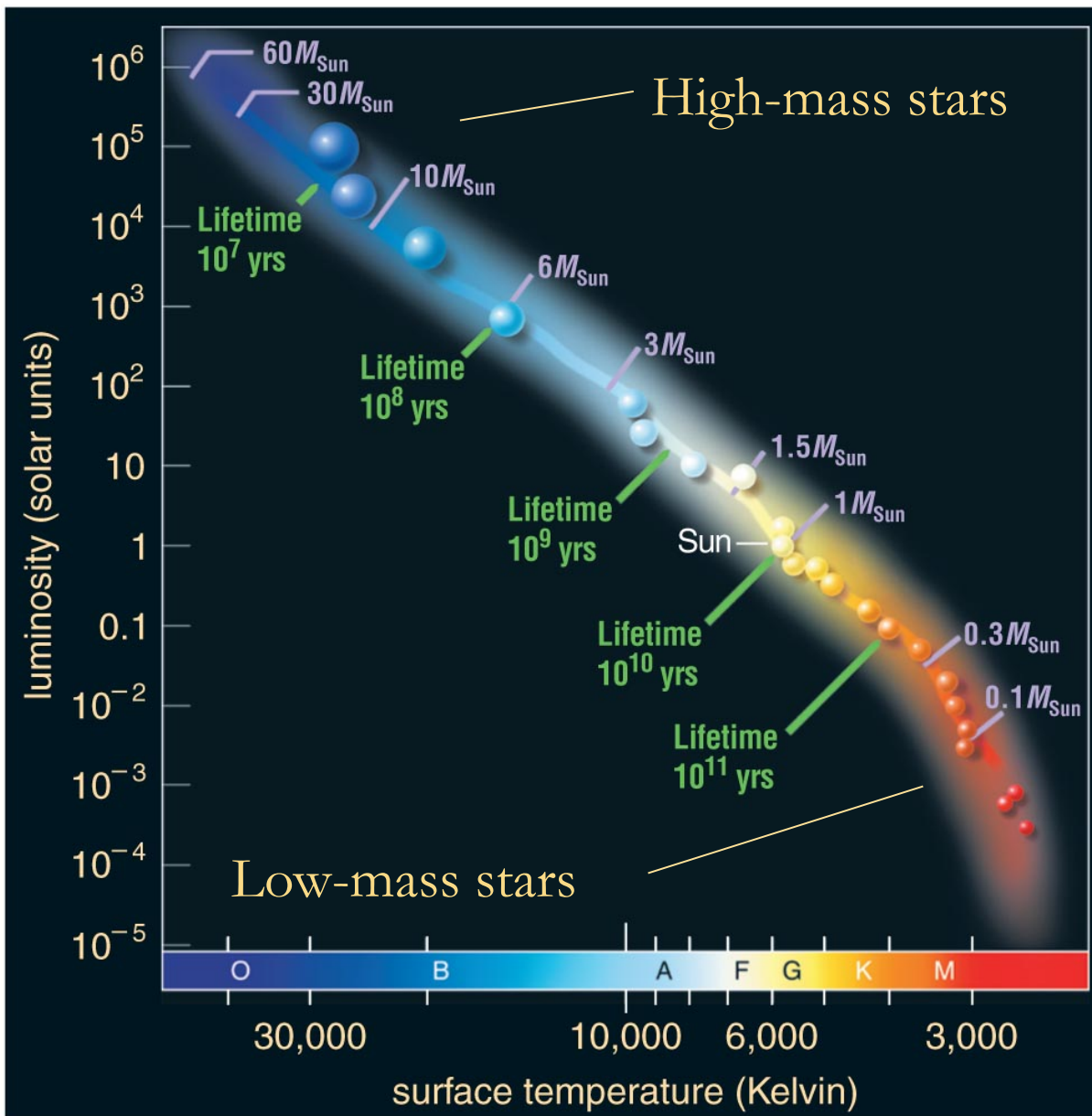
Main-sequence stars
are fusing
hydrogen into
helium in their
cores like the Sun

Luminous main-
sequence stars are
hot (blue)

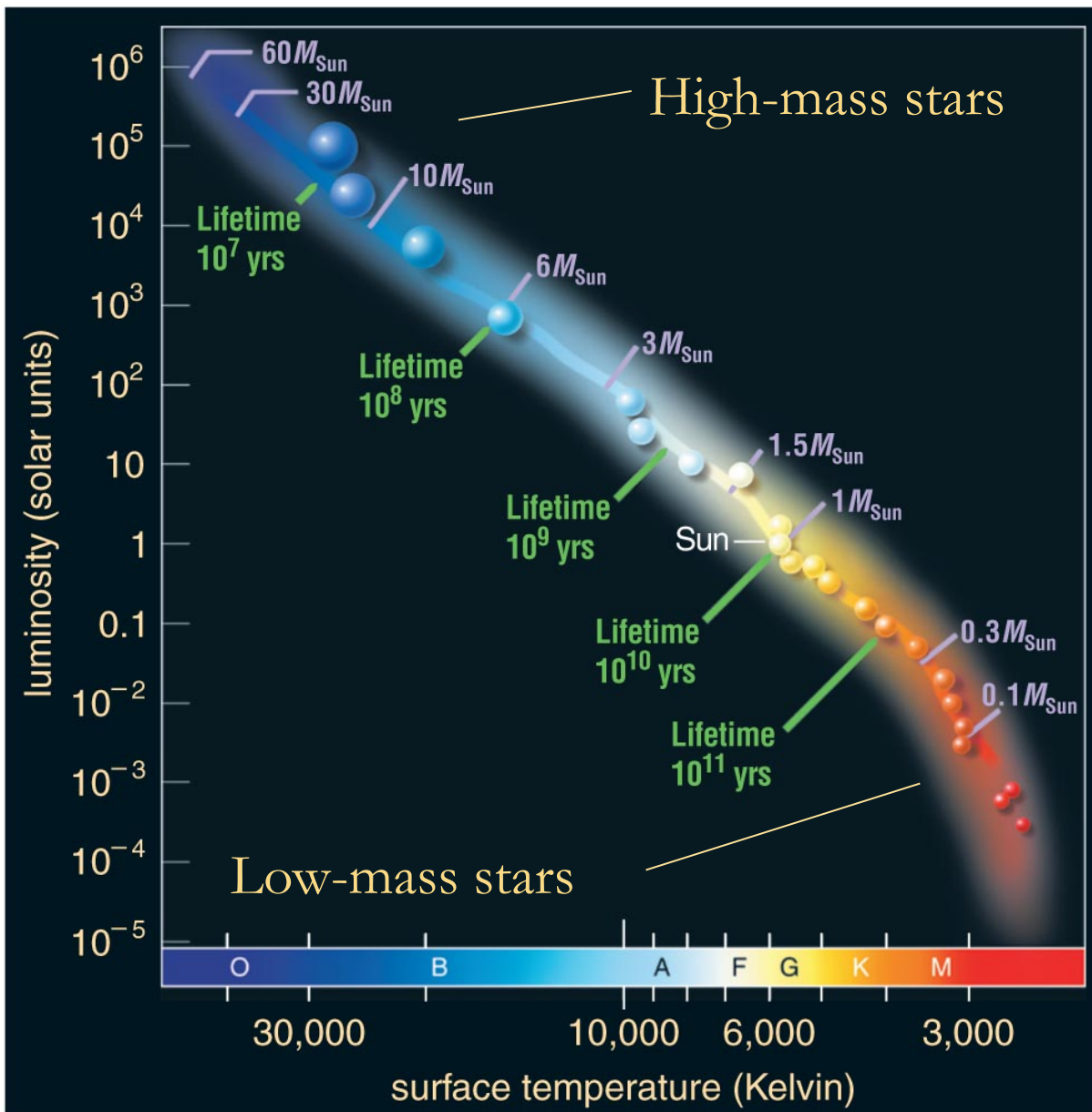
Less luminous
ones are cooler
(yellow or red)



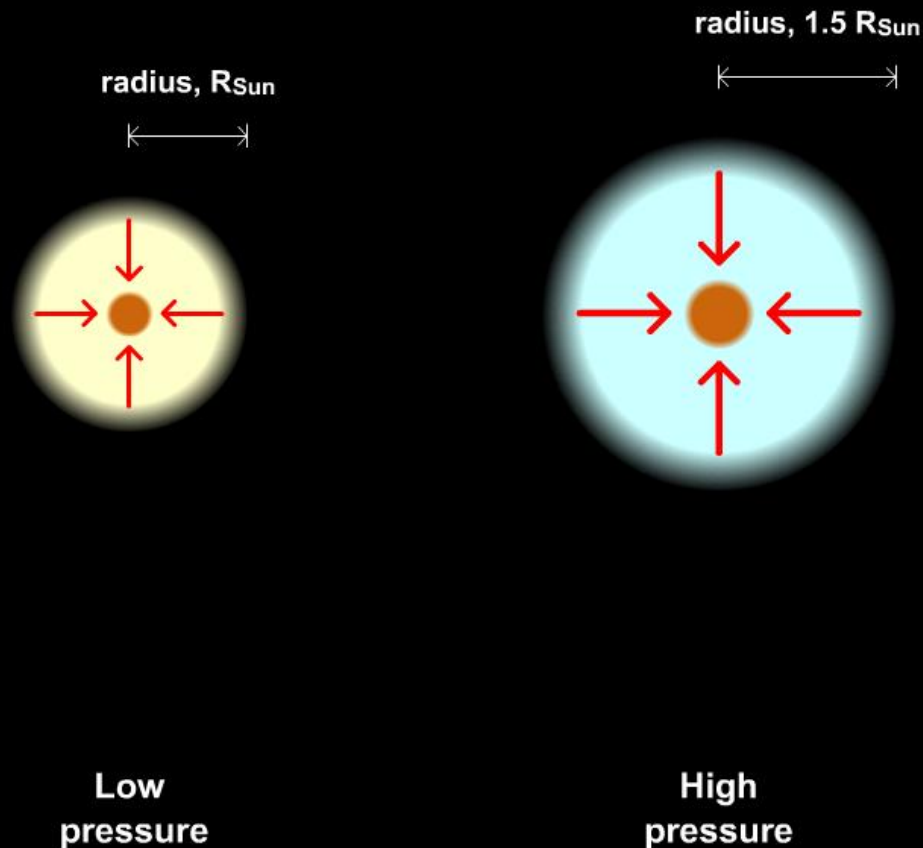
Mass measurements of main-sequence stars show that the hot, blue stars are much more massive than the cool, red ones



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



Hydrostatic Equilibrium



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

Mass & Lifetime

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

Sun's life expectancy: 10 billion years

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

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

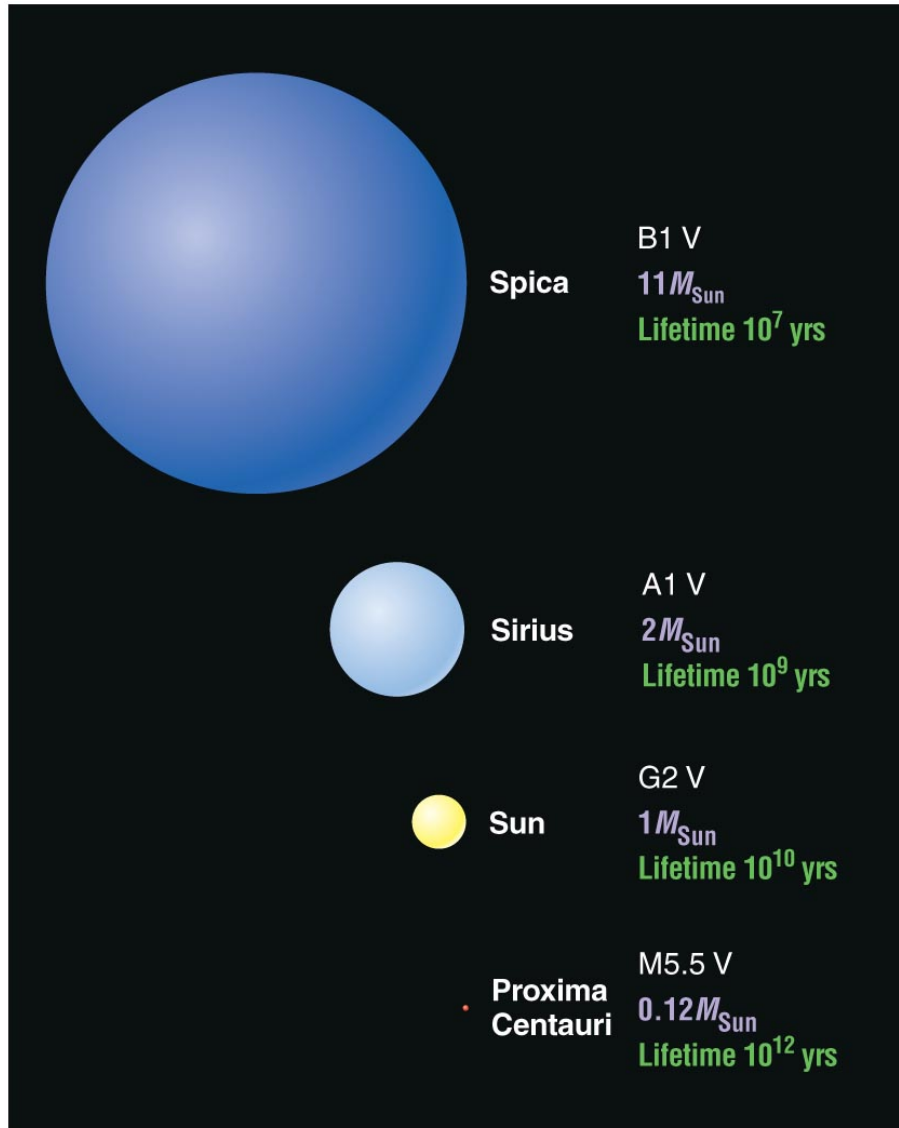
10 million years $\sim$ 10 billion years $\times$ $10 / 10^4$

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

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

100 billion years $\sim$ 10 billion years $\times$ $0.1 / 0.01$

Main-Sequence Star Summary



High Mass:

High Luminosity

Short-Lived

Large Radius

Blue

Low Mass:

Low Luminosity

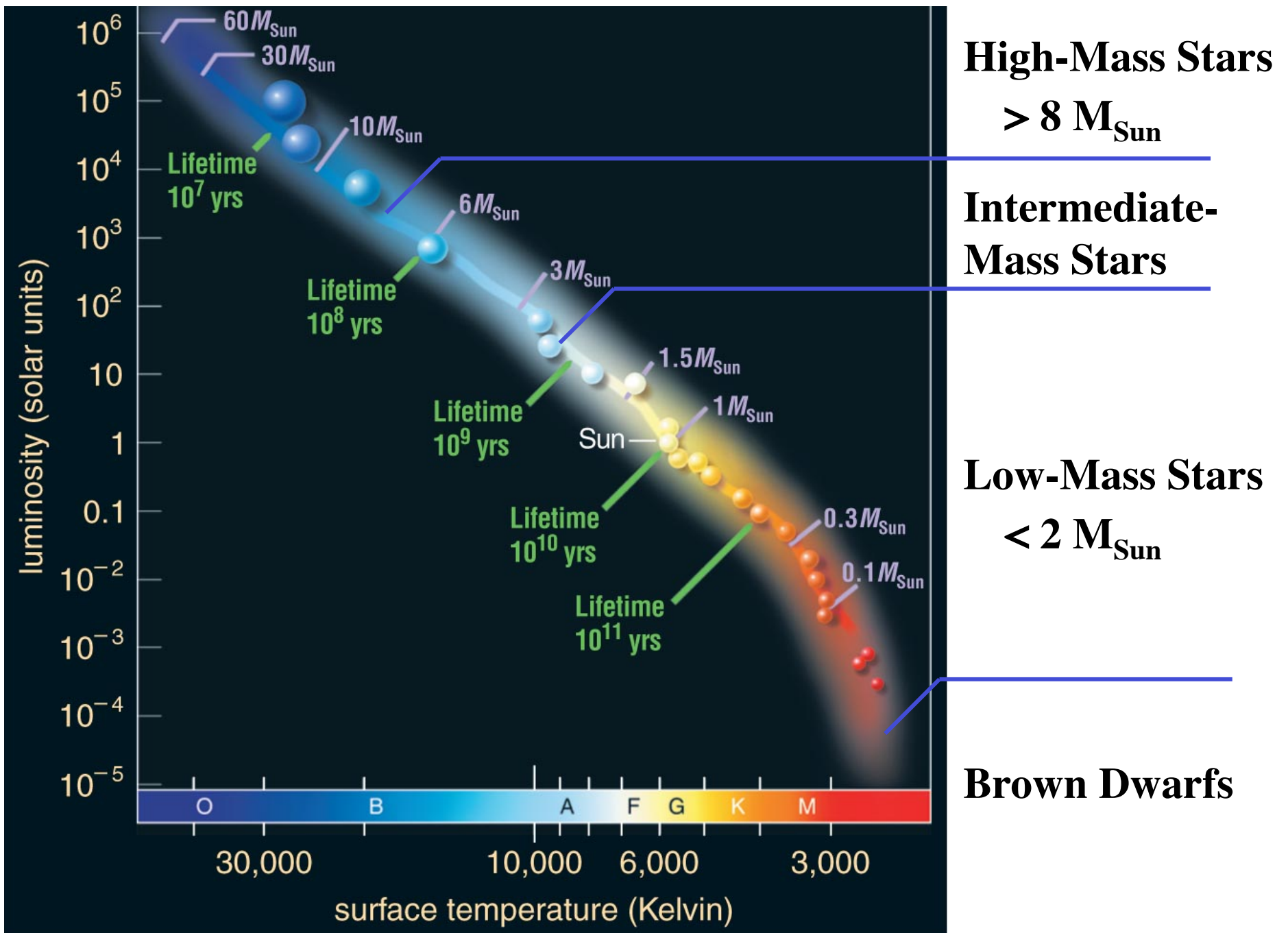
Long-Lived

Small Radius

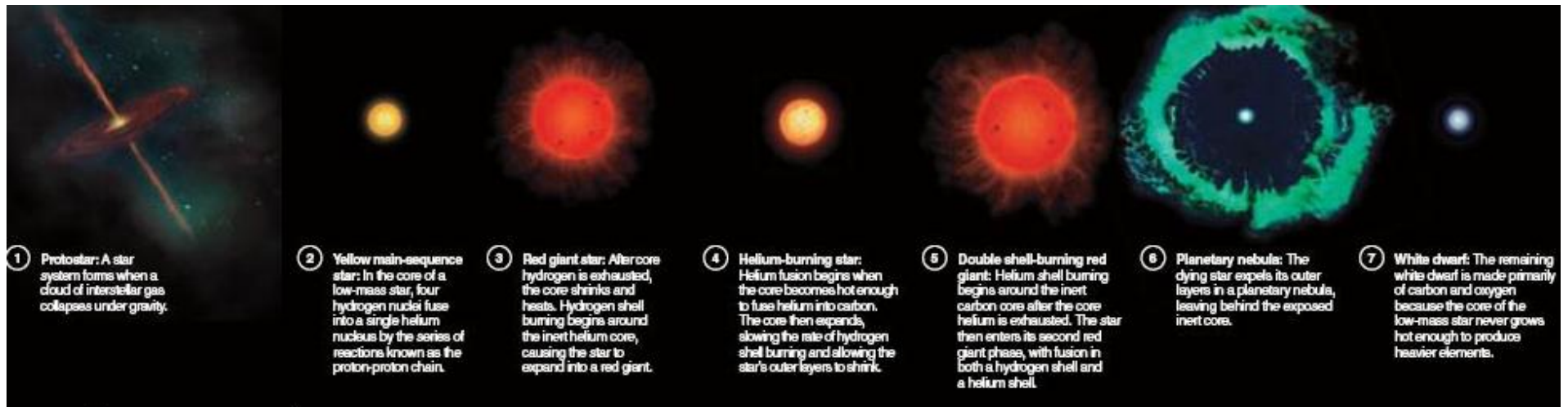
Red

Stellar Mass and Fusion

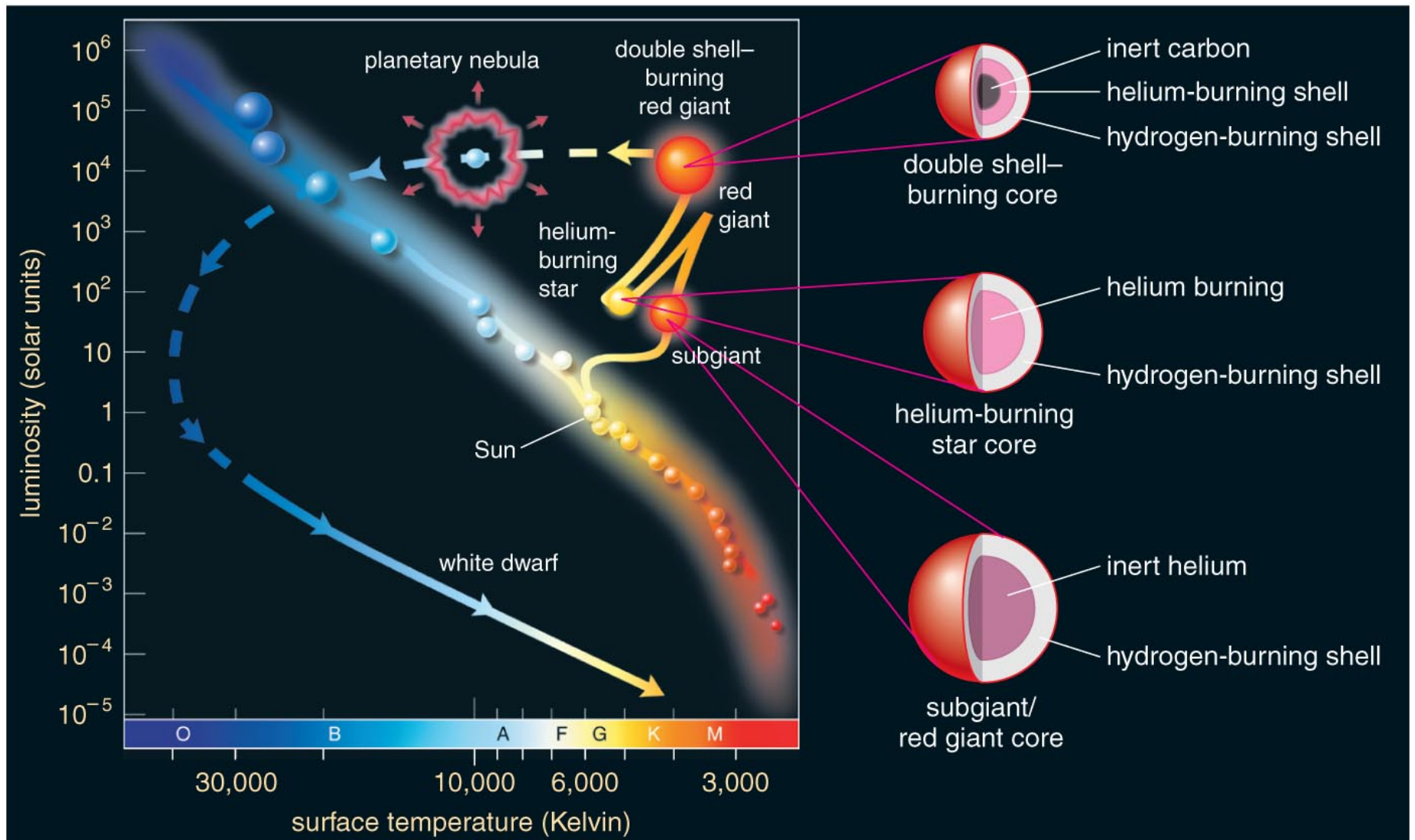
- The mass of a main sequence star determines its core pressure and temperature
- Stars of higher mass have higher core temperature and more rapid fusion, making those stars both more luminous and shorter-lived
- Stars of lower mass have cooler cores and slower fusion rates, giving them smaller luminosities and longer lifetimes



What are the life stages of a low-mass star?



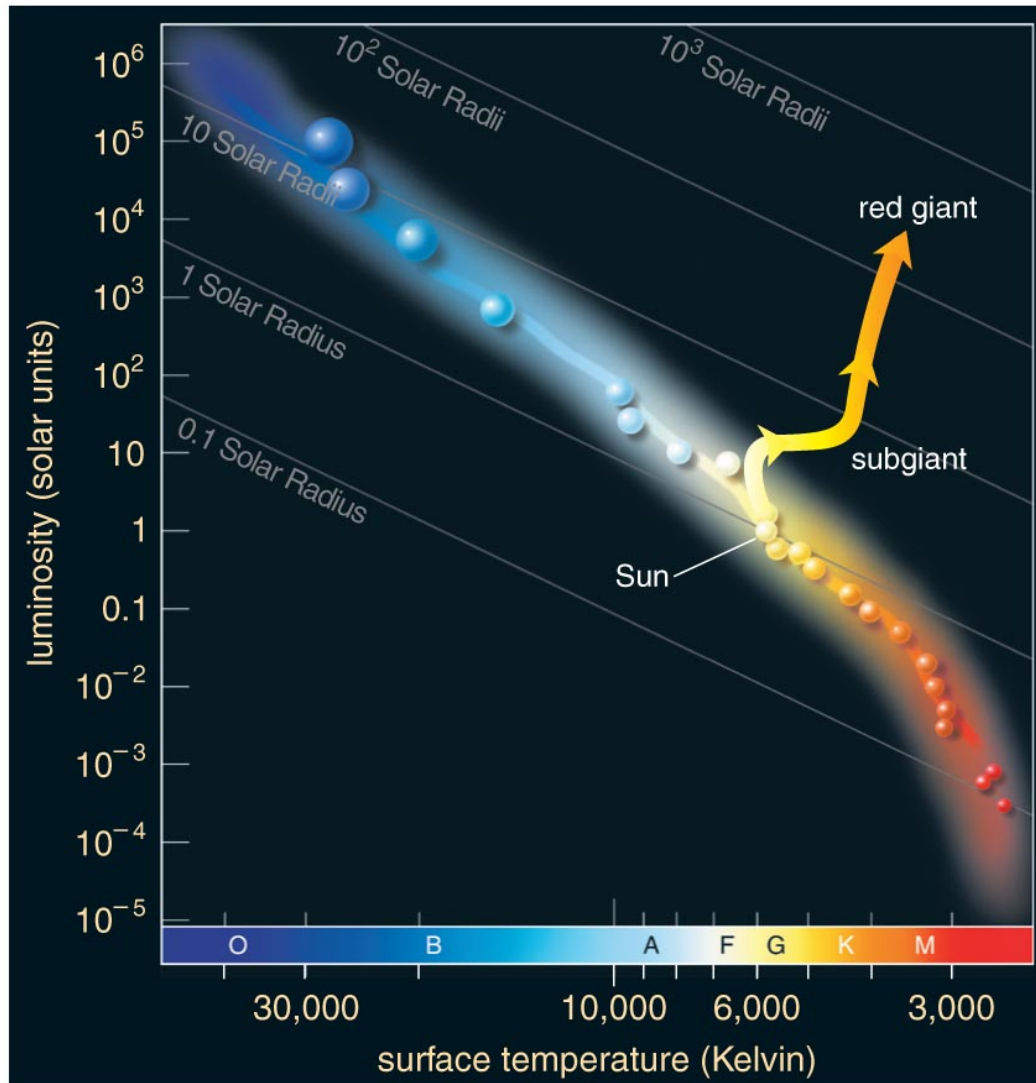
Life Track of a Sun-Like Star



Off the Main Sequence

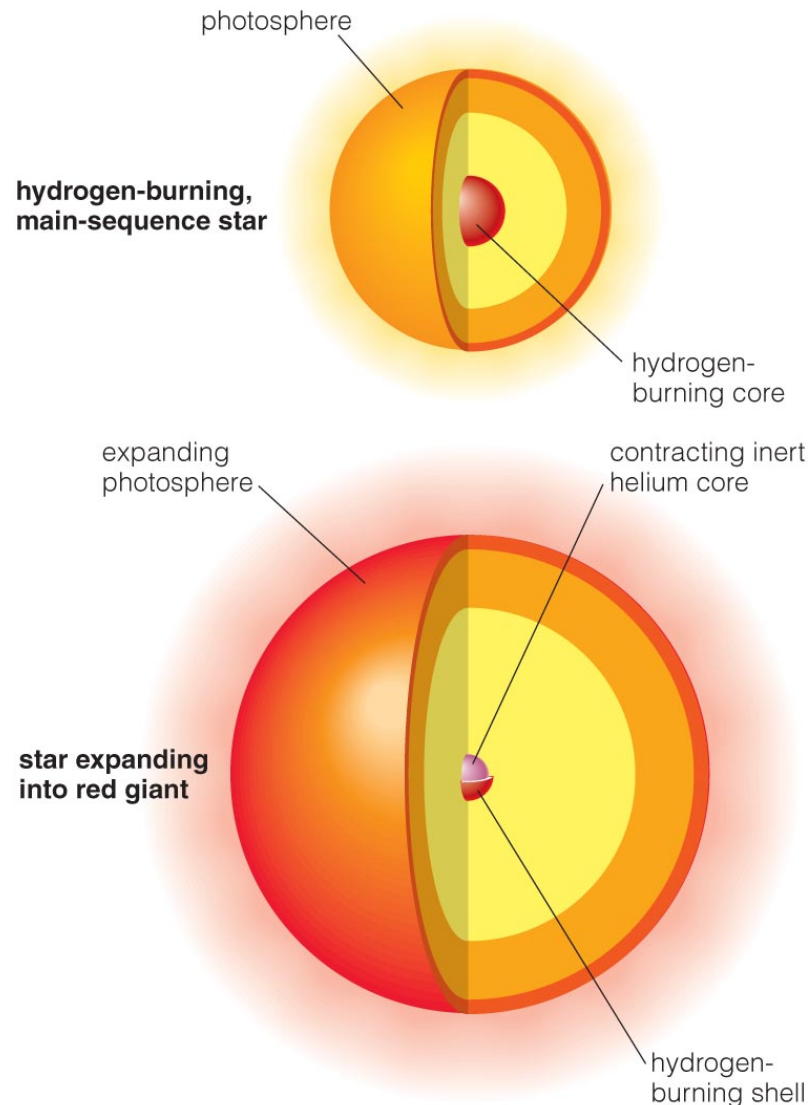
- Stellar properties depend on both mass and age: those that have finished fusing H to He in their cores are no longer on the main sequence
- All stars become larger and redder after exhausting their core hydrogen: **giants** and **supergiants**
- Most stars end up small and white after fusion has ceased: **white dwarfs**

Life Track After Main Sequence

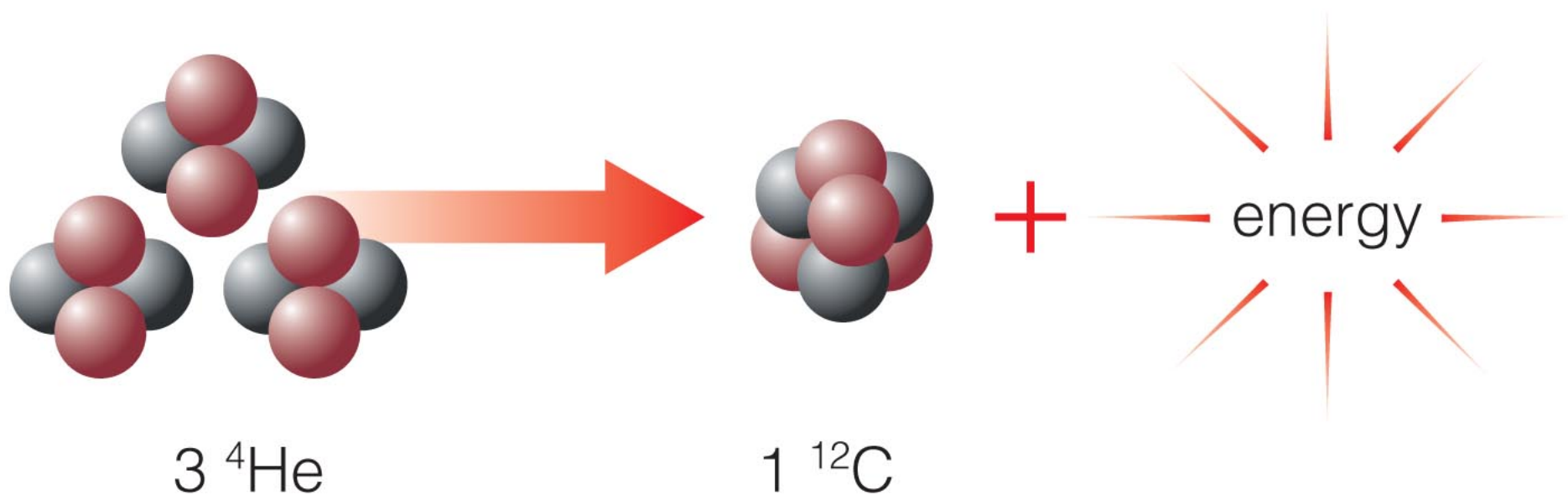


- Observations of star clusters show that a star becomes larger, redder, and more luminous after its time on the main sequence is over

Broken Thermostat Degenerate Cores



- As the core contracts, H begins fusing to He in a shell around the core
- Luminosity increases because the core thermostat is broken—the increasing fusion rate in the shell does not stop the core from contracting

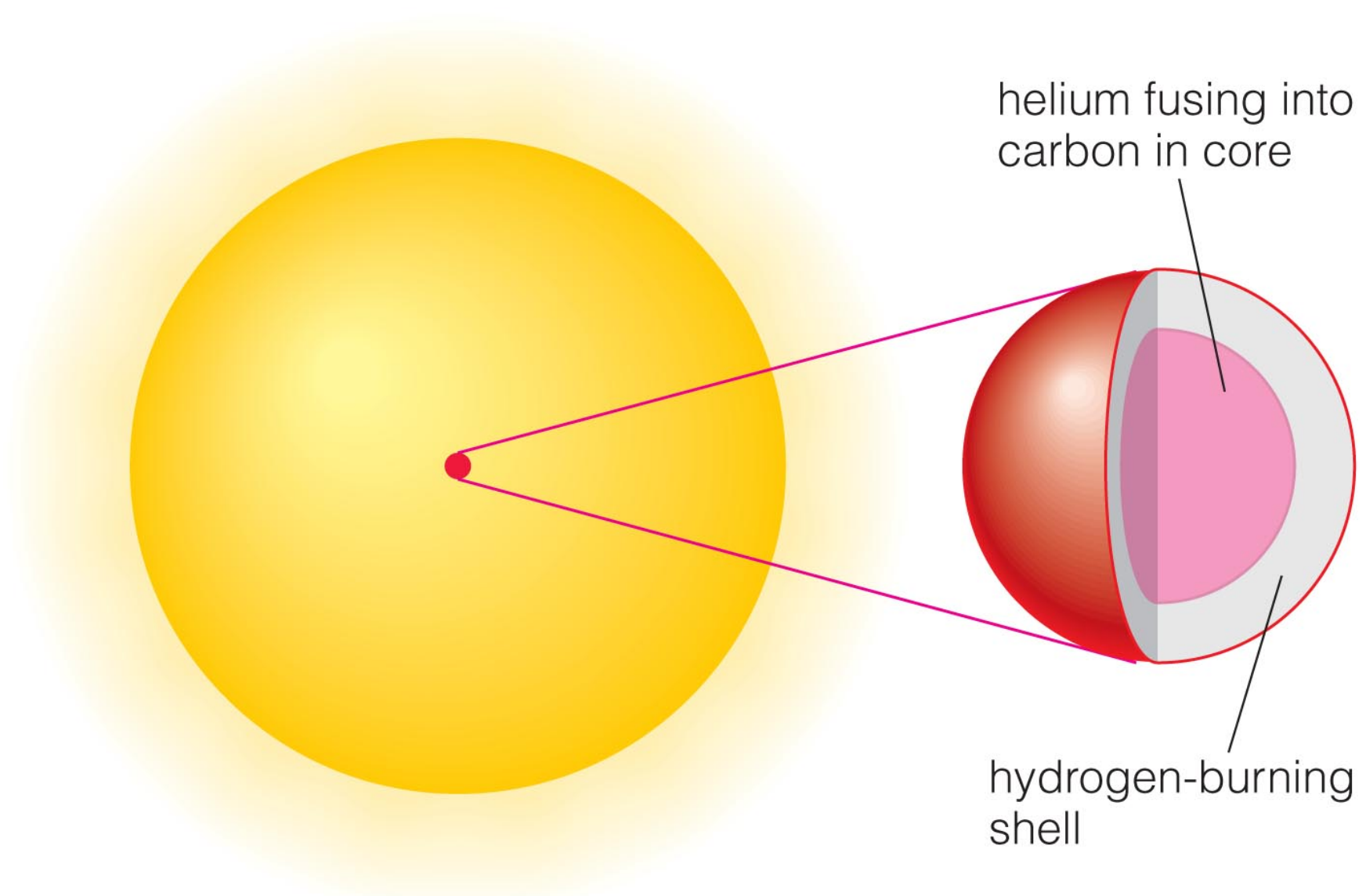


Helium fusion does not begin right away because it requires higher temperatures than hydrogen fusion—larger charge leads to greater repulsion

Fusion of two helium nuclei doesn't work, so helium fusion must combine three He nuclei to make carbon

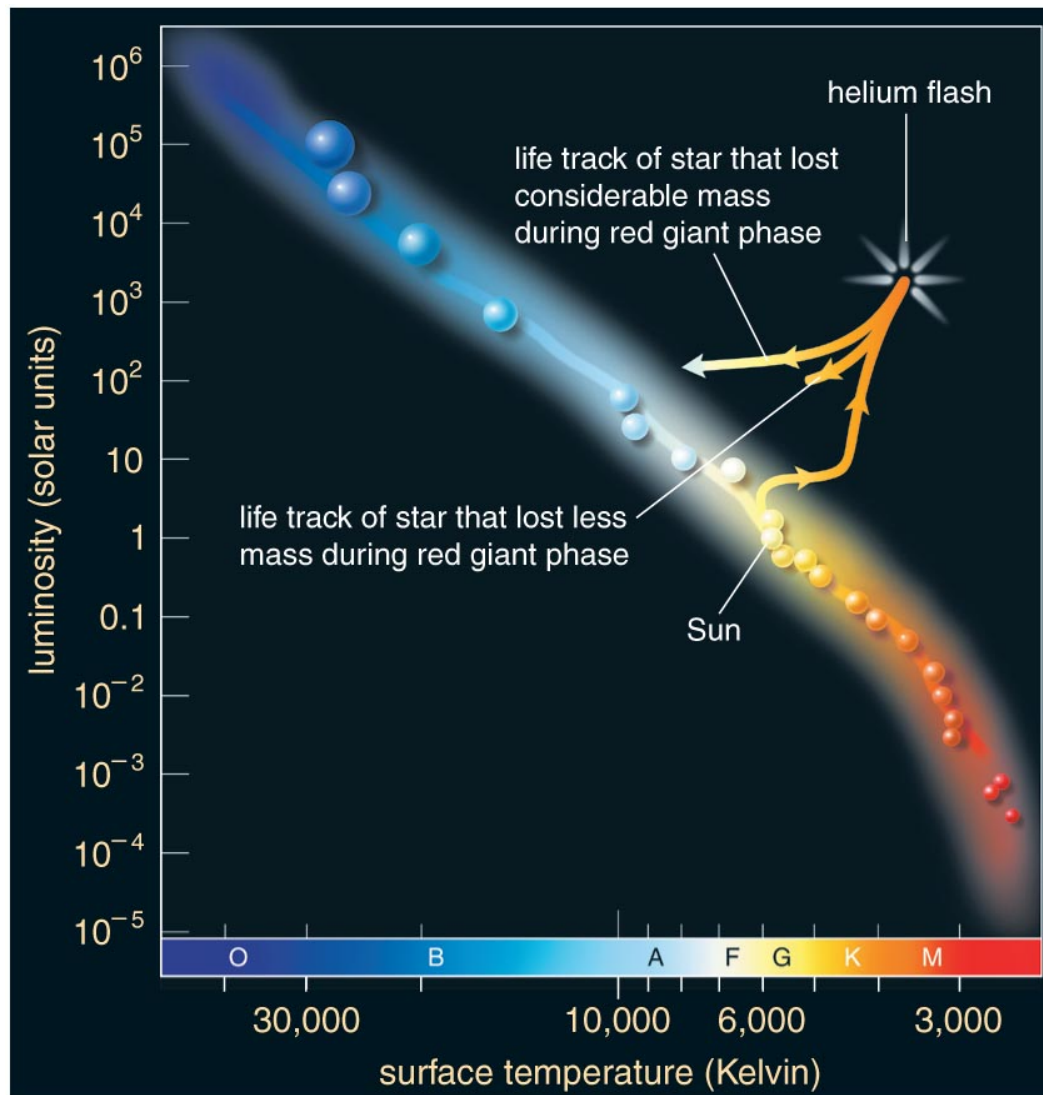
Helium Flash

- Thermostat is broken in low-mass red giant because degeneracy pressure supports core
- Core temperature rises rapidly when helium fusion begins
- Helium fusion rate skyrockets until thermal pressure takes over and expands core again



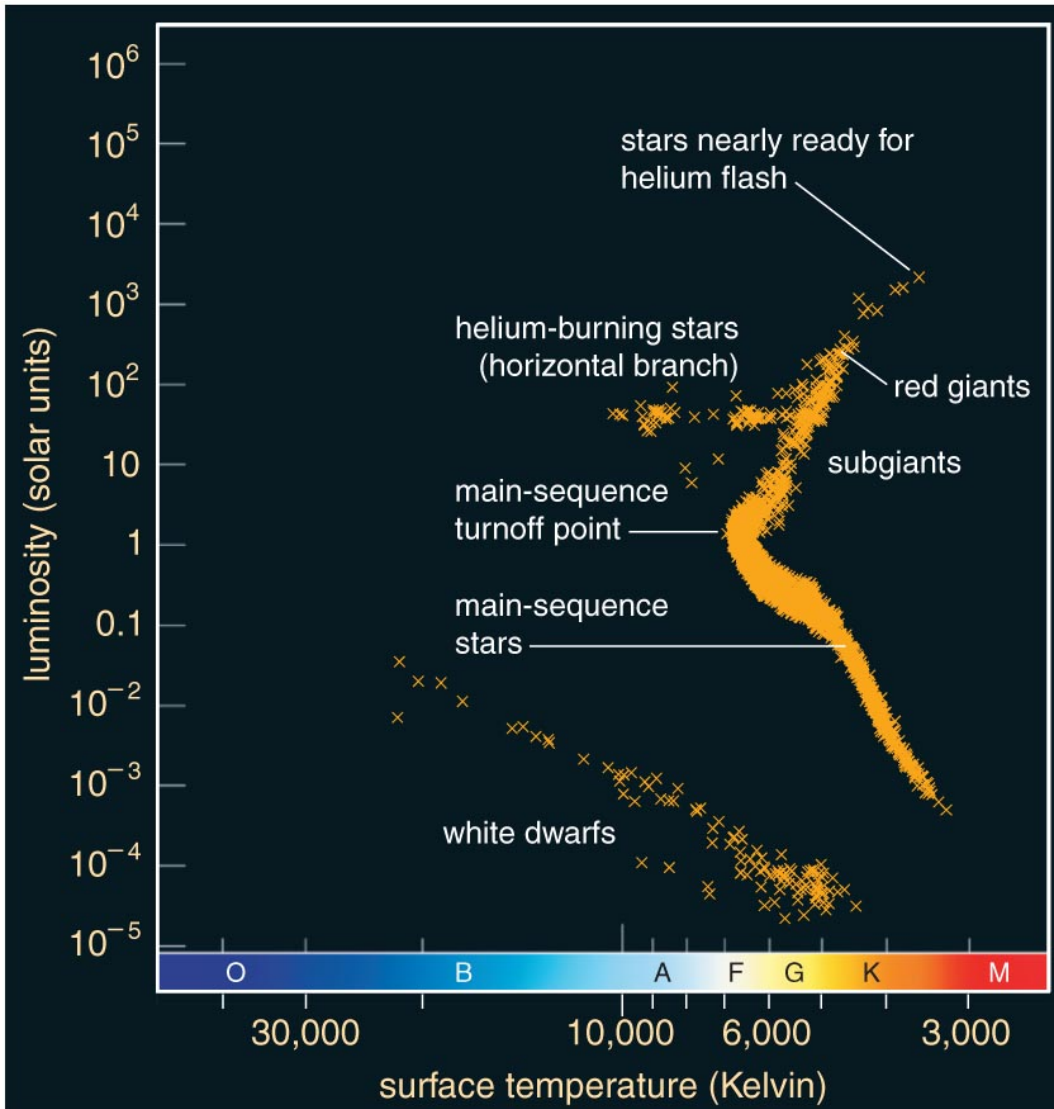
Helium burning stars neither shrink nor grow because core thermostat is temporarily fixed.

Life Track after Helium Flash



- Models show that a red giant should shrink and become less luminous after helium fusion begins in the core

Life Track after Helium Flash

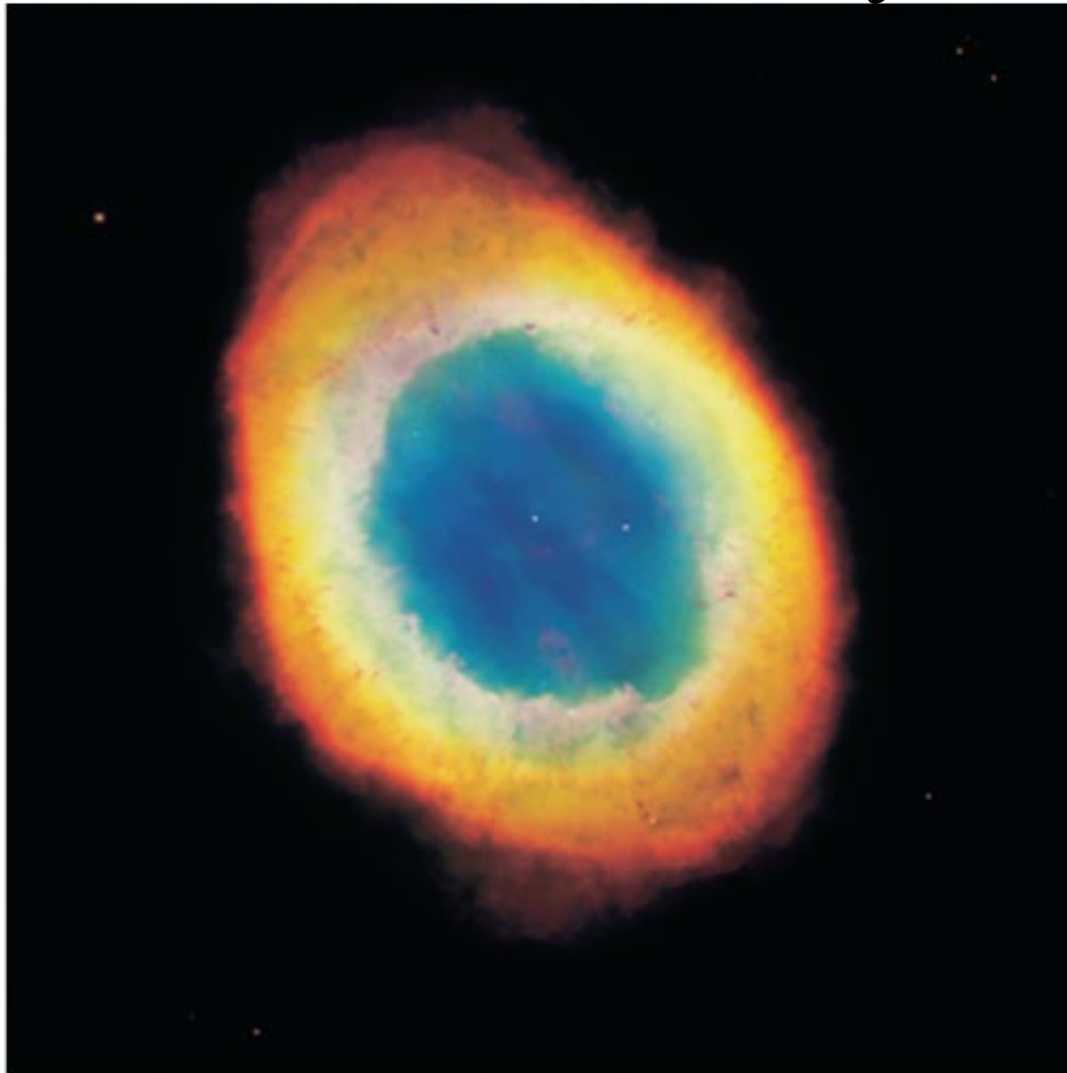


- Observations of star clusters agree with those models
- Helium-burning stars are found in a *horizontal branch* on the H-R diagram

Double Shell Burning

- After core helium fusion stops, He fuses into carbon in a shell around the carbon core, and H fuses to He in a shell around the helium layer
- This double-shell burning stage never reaches equilibrium—fusion rate periodically spikes upward in a series of *thermal pulses*
- With each spike, convection dredges carbon up from core and transports it to surface

Planetary Nebulae



- Double-shell burning ends with a pulse that ejects the H and He into space as a *planetary nebula*
- The core left behind becomes a white dwarf

Planetary Nebulae



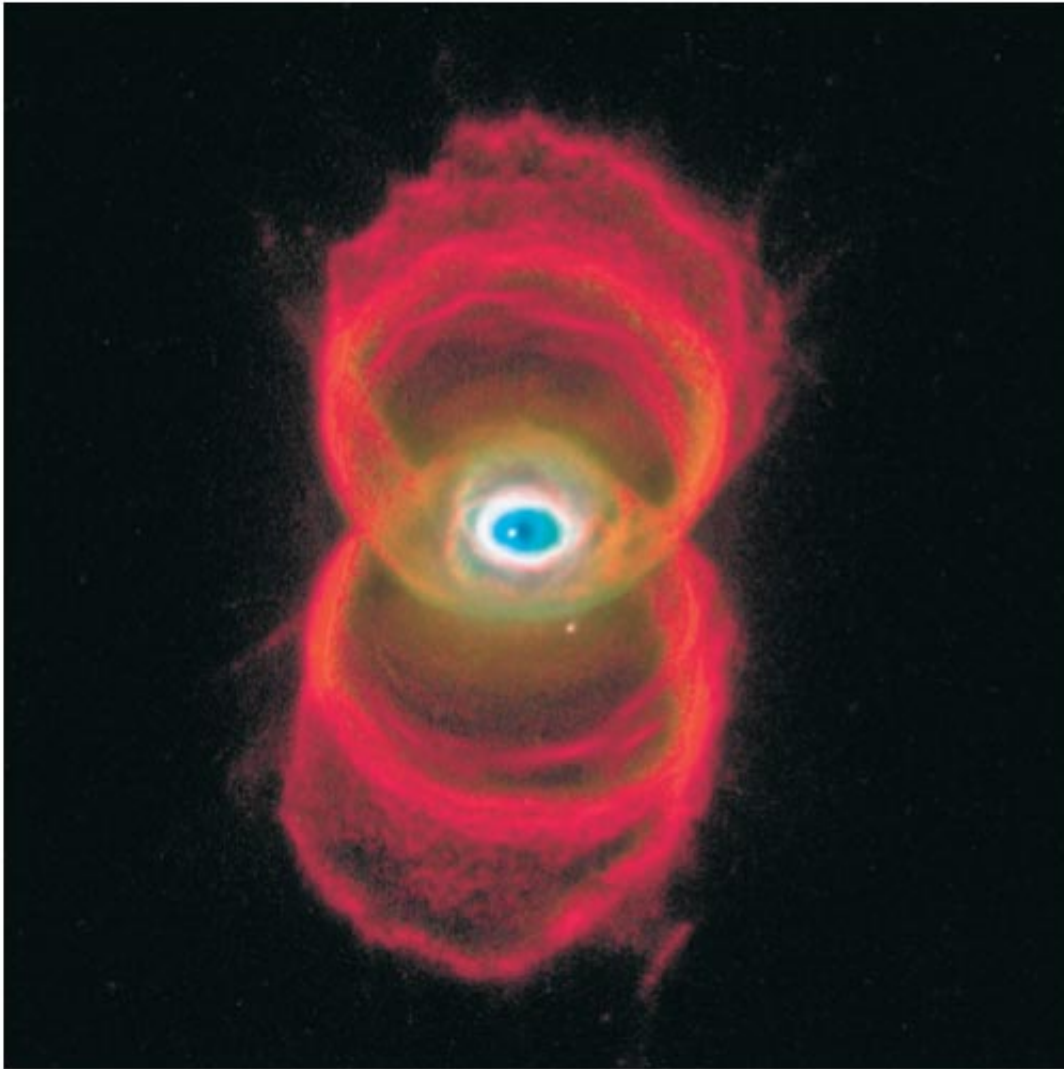
- Double-shell burning ends with a pulse that ejects the H and He into space as a *planetary nebula*
- The core left behind becomes a white dwarf

Planetary Nebulae



- Double-shell burning ends with a pulse that ejects the H and He into space as a *planetary nebula*
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Planetary Nebulae



- Double-shell burning ends with a pulse that ejects the H and He into space as a *planetary nebula*
- The core left behind becomes a white dwarf

End of Fusion

- Fusion progresses no further in a low-mass star because the core temperature never grows hot enough for fusion of heavier elements (some He fuses to C to make oxygen)
- Degeneracy pressure supports the white dwarf against gravity

Stellar Lives



Star Clusters





Open cluster: A few thousand loosely packed stars



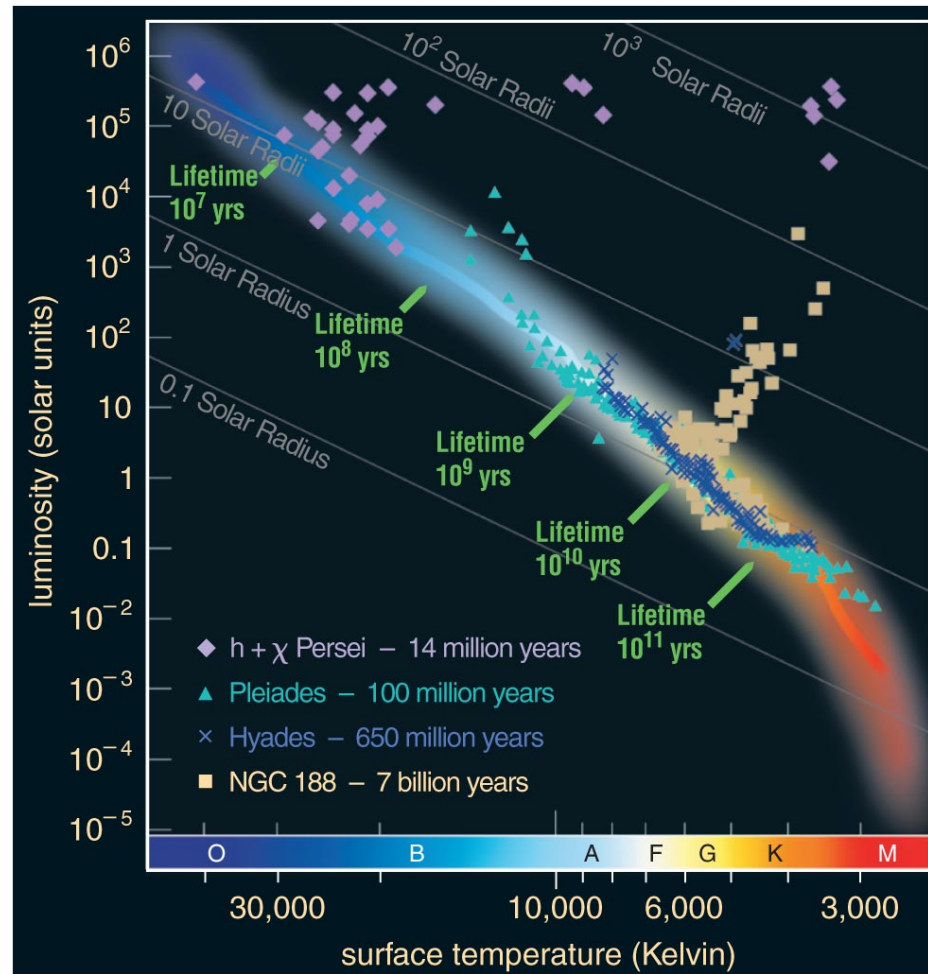
Globular cluster: Up to a million or more stars in a dense ball bound together by gravity

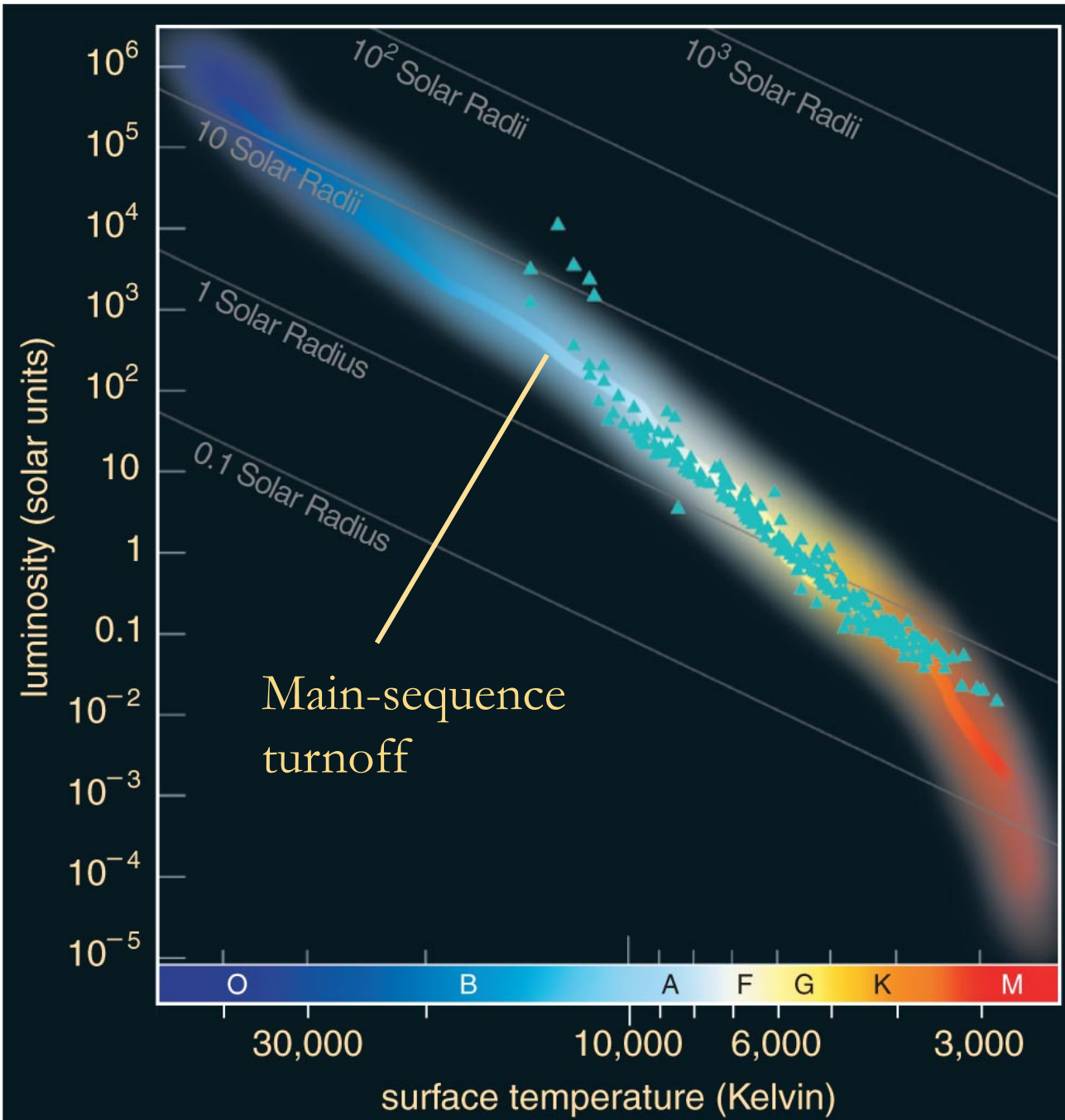
Star Clusters and Stellar Lives



- Our knowledge of the life stories of stars comes from comparing mathematical models of stars with observations
- Star clusters are particularly useful because they contain stars of different mass that were born about the same time

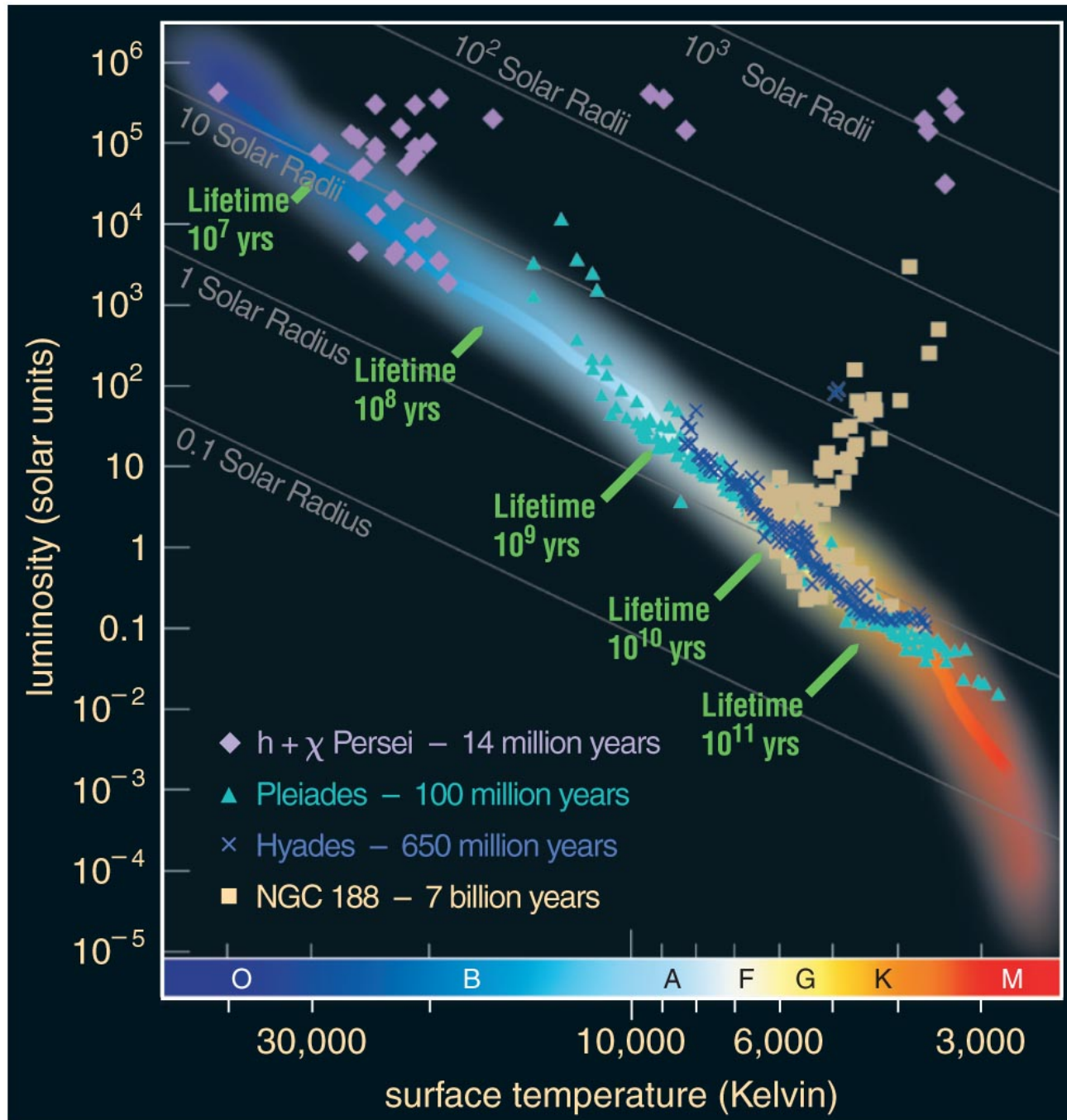
Star Cluster Ages



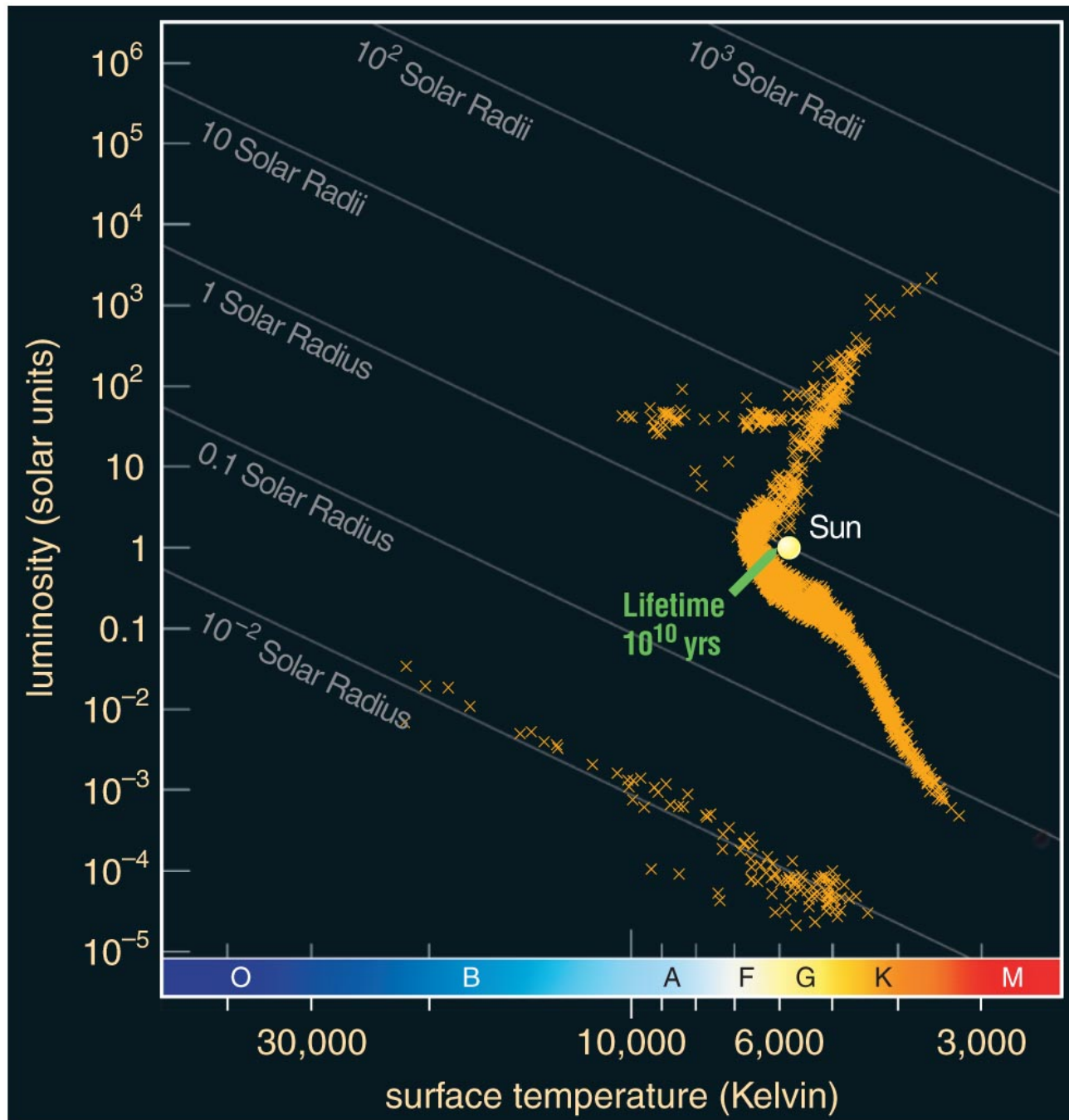


Pleiades now
has no stars
with life
expectancy
less than
around 100
million years

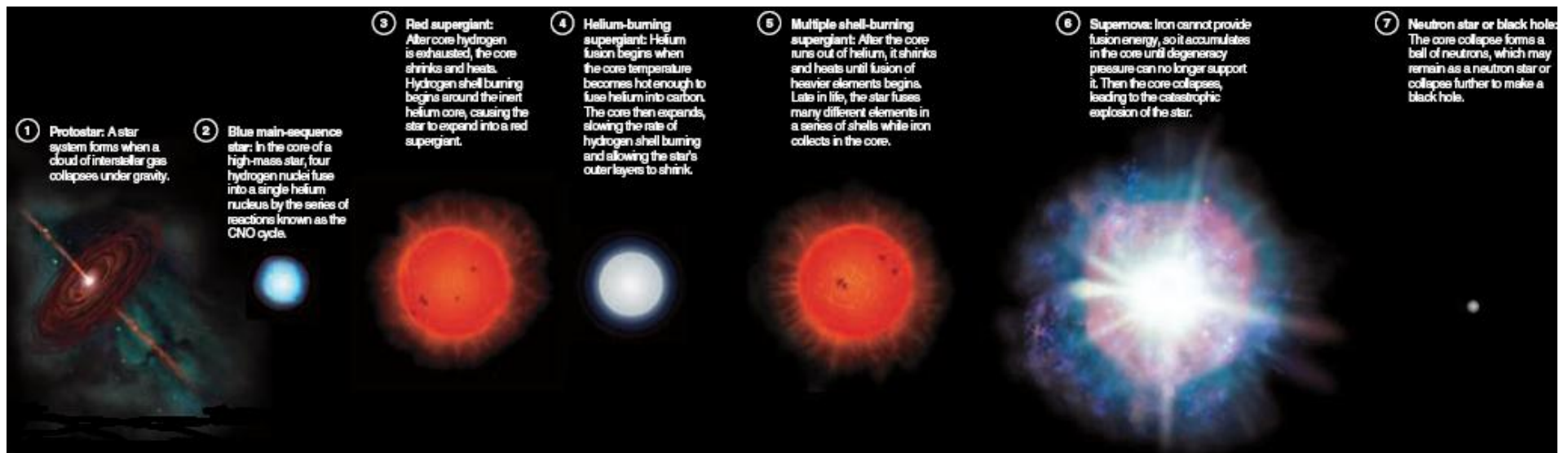
Main-
sequence
turnoff point
of a cluster
tells us its age



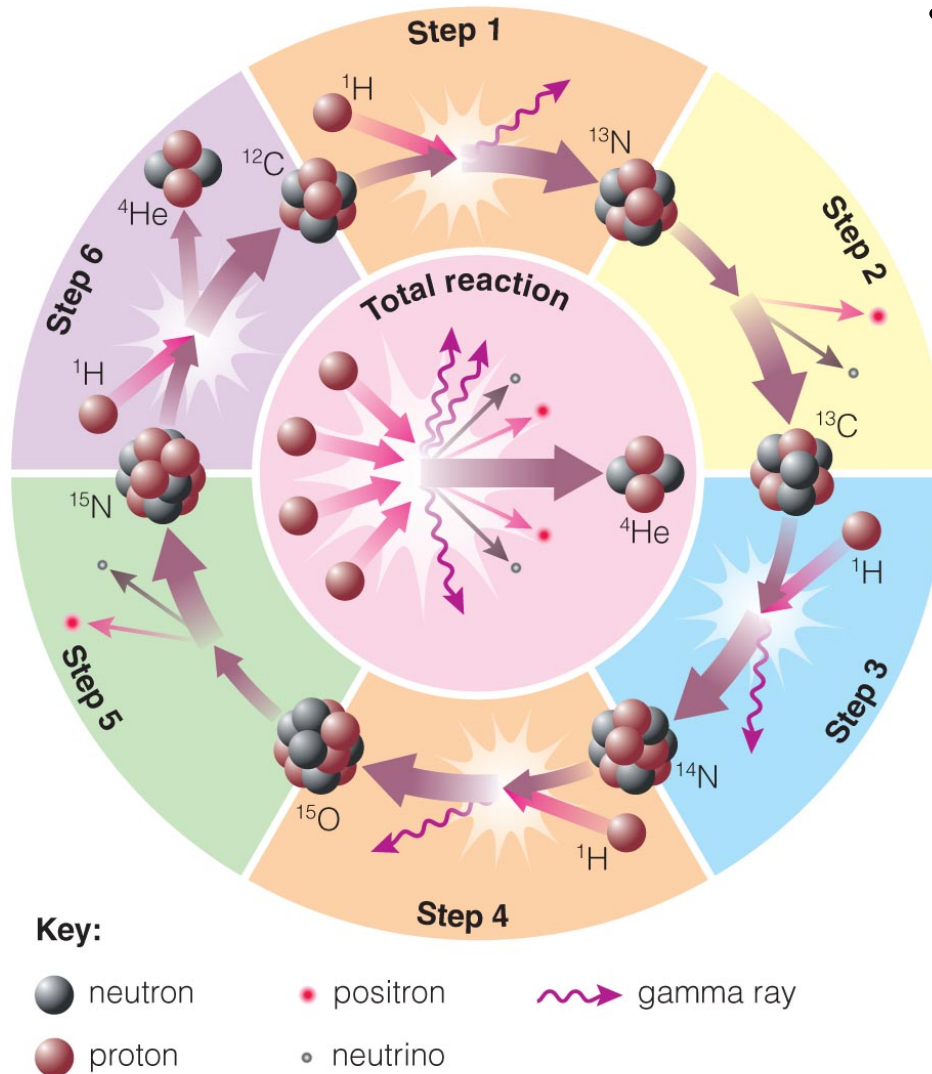
Detailed modeling of the oldest globular clusters reveals that they are about 13 billion years old



What are the life stages of a high-mass star?



CNO Cycle



- High-mass main sequence stars fuse H to He at a higher rate using carbon, nitrogen, and oxygen as catalysts
- Greater core temperature enables H nuclei to overcome greater repulsion

Key

12	Atomic number
Mg	Element's symbol
Magnesium	Element's name
24.305	Atomic mass*

*Atomic masses are fractions because they represent a weighted average of atomic masses of different isotopes—in proportion to the abundance of each isotope on Earth.

1
H
Hydrogen
1.00794

2
He
Helium
4.003

3	4
Li	Be
Lithium	Beryllium
6.941	9.01218

11	12
Na	Mg
Sodium	Magnesium
22.990	24.305

19	20
K	Ca
Potassium	Calcium
39.098	40.08

37	38
Rb	Sr
Rubidium	Strontium
85.468	87.62

55	56
Cs	Ba
Cesium	Barium
132.91	137.34

87	88
Fr	Ra
Francium	Radium
(223)	226.0254

21	22	23	24	25	26	27	28	29	30
Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn
Scandium	Titanium	Vanadium	Chromium	Manganese	Iron	Cobalt	Nickel	Copper	Zinc
44.956	47.88	50.94	51.996	54.938	55.847	58.9332	58.69	63.546	65.39
39	40	41	42	43	44	45	46	47	48
Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd
Yttrium	Zirconium	Niobium	Molybdenum	Technetium (98)	Ruthenium	Rhodium	Palladium	Silver	Cadmium
88.9059	91.224	92.91	95.94	(98)	101.07	102.906	106.42	107.868	112.41
72	73	74	75	76	77	78	79	80	
Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	
Hafnium	Tantalum	Tungsten	Rhenium	Osmium	Iridium	Platinum	Gold	Mercury	
178.49	180.95	183.85	186.207	190.2	192.22	195.08	196.967	200.59	
104	105	106	107	108	109	110	111	112	
Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub	
Rutherfordium	Dubnium	Seaborgium	Bohrium	Hassium	Meitnerium	Ununnilium	Ununium	Ununbium	
(261)	(262)	(263)	(262)	(265)	(266)	(269)	(272)	(277)	

5	6	7	8	9	10
B	C	N	O	F	Ne
Boron	Carbon	Nitrogen	Oxygen	Fluorine	Neon
10.81	12.011	14.007	15.999	18.988	20.179

13	14	15	16	17	18
Al	Si	P	S	Cl	Ar
Aluminum	Silicon	Phosphorus	Sulfur	Chlorine	Argon
26.98	28.086	30.974	32.06	35.453	39.948

31	32	33	34	35	36
Ga	Ge	As	Se	Br	Fr
Gallium	Germanium	Arsenic	Selenium	Bromine	Krypton
69.72	72.59	74.922	78.96	79.904	83.80

49	50	51	52	53	54
In	Sn	Sb	Te	I	Xe
Indium	Tin	Antimony	Tellurium	Iodine	Xenon
114.82	118.71	121.75	127.60	126.905	131.29

81	82	83	84	85	86
Tl	Pb	Bi	Po	At	Rn
Thallium	Lead	Bismuth	Polonium	Astatine	Radon
204.383	207.2	208.98	(209)	(210)	(222)

Lanthanide Series

57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Lanthanum	Cerium	Praseodymium	Neodymium	Promethium (145)	Samarium	Europium	Gadolinium	Terbium	Dysprosium	Holmium	Erbium	Thulium	Ytterbium	Lutetium
138.906	140.12	140.908	144.24	(145)	150.36	151.96	157.25	158.925	162.50	164.93	167.26	168.934	173.04	174.967

Actinide Series

89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr
Actinium	Thorium	Protactinium	Uranium	Neptunium	Plutonium	Americium	Curium	Berkelium	Californium	Einsteinium	Fermium	Mendelevium	Nobelium	Lawrencium
227.028	232.038	231.036	238.029	237.048	(244)	(243)	(247)	(247)	(251)	(252)	(257)	(258)	(259)	(260)

Big Bang made 75% H, 25% He – stars make everything else

1

H

Hydrogen

1.00794

3

Li

Lithium

6.941

4

Be

Beryllium

9.01218

11

Na

Sodium

22.990

12

Mg

Magnesium

24.305

19

K

Potassium

39.098

20

Ca

Calcium

40.08

37

Rb

Rubidium

85.468

38

Sr

Strontium

87.62

55

Cs

Cesium

132.91

56

Ba

Barium

137.34

87

Fr

Francium

(223)

88

Ra

Radium

226.0254

12

Mg

Magnesium

24.305

Atomic number

Element's symbol

Element's name

Atomic mass*

*Atomic masses are fractions because they represent a weighted average of atomic masses of different isotopes—in proportion to the abundance of each isotope on Earth.

5	6	7	8	9	10
B	C	N	O	F	Ne
Boron	Carbon	Nitrogen	Oxygen	Fluorine	Neon
10.81	12.011	14.007	15.999	18.988	20.179
13	14	15	16	17	18
Al	Si	P	S	Cl	Ar
Aluminum	Silicon	Phosphorus	Sulfur	Chlorine	Argon
26.98	28.086	30.974	32.06	35.453	39.948
31	32	33	34	35	36
Ga	Ge	As	Se	Br	Fr
Gallium	Germanium	Arsenic	Selenium	Bromine	Krypton
69.72	72.59	74.922	78.96	79.904	83.80
49	50	51	52	53	54
In	Sn	Sb	Te	I	Xe
Indium	Tin	Antimony	Tellurium	Iodine	Xenon
114.82	118.71	121.75	127.60	126.905	131.29
81	82	83	84	85	86
Tl	Pb	Bi	Po	At	Rn
Thallium	Lead	Bismuth	Polonium	Astatine	Radon
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(261)	(262)	(263)	(262)	(265)	(266)	(269)	(272)	(277)

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La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Lanthanum	Cerium	Praseodymium	Neodymium	Promethium	Samarium	Europium	Gadolinium	Terbium	Dysprosium	Holmium	Erbium	Thulium	Ytterbium	Lutetium
138.906	140.12	140.908	144.24	(145)	150.36	151.96	157.25	158.925	162.50	164.93	167.26	168.934	173.04	174.967

Actinide Series

89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr
Actinium	Thorium	Protactinium	Uranium	Neptunium	Plutonium	Americium	Curium	Berkelium	Californium	Einsteinium	Fermium	Mendelevium	Nobelium	Lawrencium
227.028	232.038	231.036	238.029	237.048	(244)	(243)	(247)	(247)	(251)	(252)	(257)	(258)	(259)	(260)

Helium fusion can make carbon in low-mass stars

Key

12	Atomic number
Mg	Element's symbol
Magnesium	Element's name
24.305	Atomic mass*

*Atomic masses are fractions because they represent a weighted average of atomic masses of different isotopes—in proportion to the abundance of each isotope on Earth.

1 H Hydrogen 1.00794																	2 He Helium 4.003	
3 Li Lithium 6.941	4 Be Beryllium 9.01218																	10 Ne Neon 20.179
11 Na Sodium 22.990	12 Mg Magnesium 24.305																	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.08	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.94	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.847	27 Co Cobalt 58.9332	28 Ni Nickel 58.69	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.72	32 Ge Germanium 72.59	33 As Arsenic 74.922	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80	
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.9059	40 Zr Zirconium 91.224	41 Nb Niobium 92.91	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.41	49 In Indium 114.82	50 Sn Tin 118.71	51 Sb Antimony 121.75	52 Te Tellurium 127.60	53 I Iodine 126.905	54 Xe Xenon 131.29	
55 Cs Cesium 132.91	56 Ba Barium 137.34																	
87 Fr Francium (223)	88 Ra Radium 226.0254																	
		72 Hf Hafnium 178.49	73 Ta Tantalum 180.95	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.2	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.98	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)		
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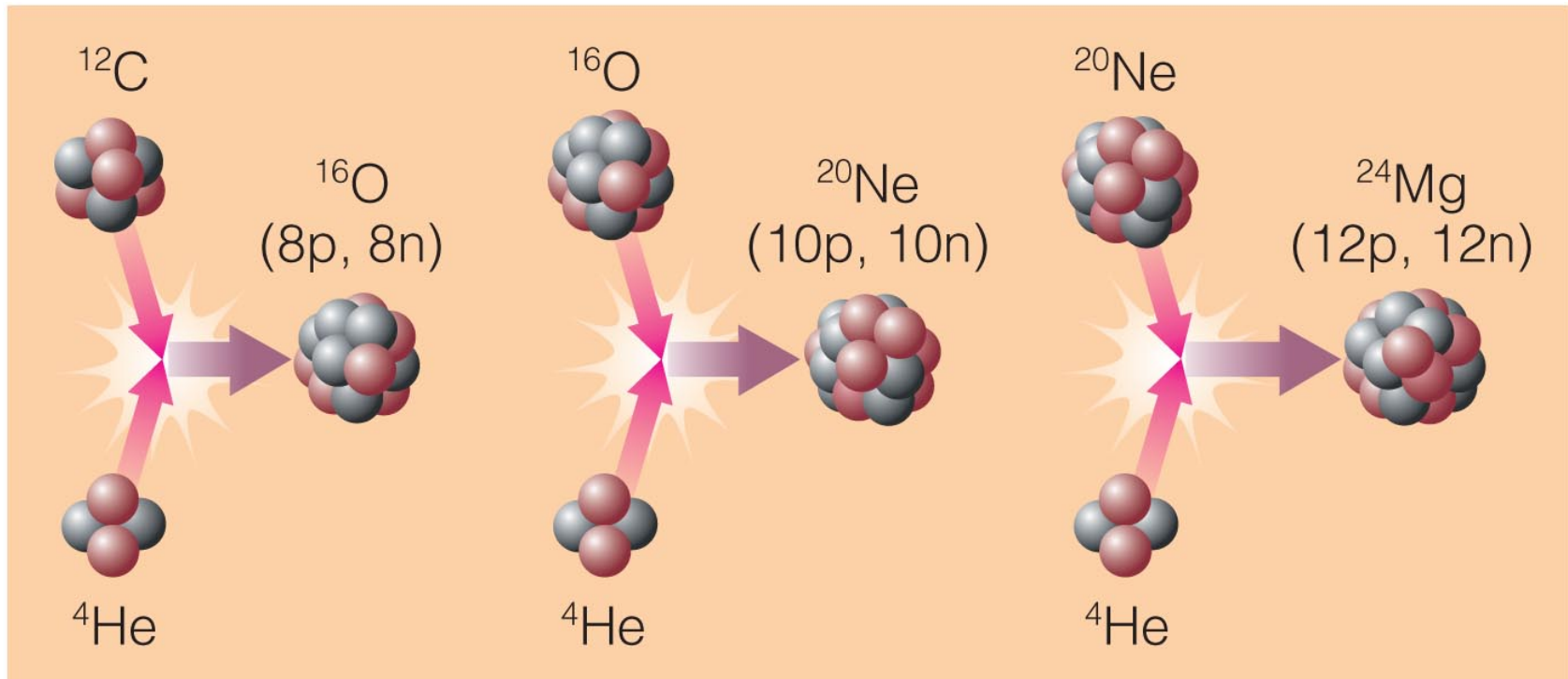
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Actinide Series

89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (260)
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CNO cycle can change C into N and O

Helium Capture



- **High core temperatures allow helium to fuse with heavier elements**

Key

12	Atomic number
Mg	Element's symbol
Magnesium	Element's name
24.305	Atomic mass*

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11 Na Sodium 22.990	12 Mg Magnesium 24.305	13 Al Aluminum 26.98	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.06	17 Cl Chlorine 35.453	18 Ar Argon 39.948	19 K Potassium 39.098	20 Ca Calcium 40.08	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.94	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.847	27 Co Cobalt 58.9332	28 Ni Nickel 58.69	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.72	32 Ge Germanium 72.59	33 As Arsenic 74.922	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Fr Krypton 83.80									
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87 Fr Francium (223)	88 Ra Radium 226.0254	89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (260)	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (263)	107 Bh Bohrium (262)	108 Hs Hassium (265)	109 Mt Meitnerium (266)	110 Uun Ununnilium (269)	111 Uuu Ununium (272)	112 Uub Ununbium (277)	113 Nh Nihonium (284)	114 Fl Flerovium (289)	115 Mc Moscovium (288)	116 Lv Livermorium (293)	117 Ts Tennessine (294)	118 Og Oganesson (294)			

Lanthanide Series

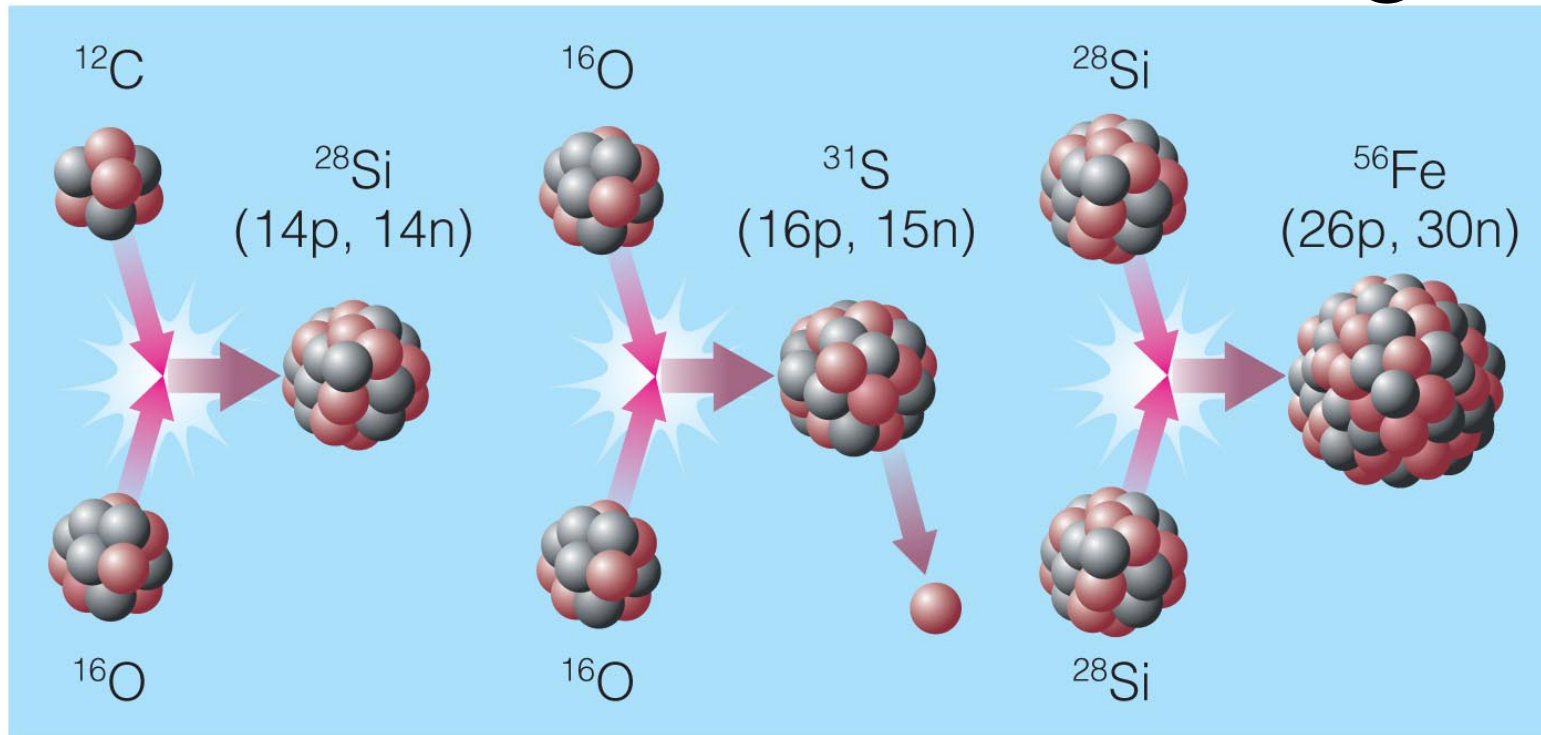
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Actinide Series

89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (260)
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Helium capture builds C into O, Ne, Mg, ...

Advanced Nuclear Burning



- **Core temperatures in stars with $>8M_{\text{Sun}}$ allow fusion of elements as heavy as iron**

Key

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Mg	Element's symbol
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87 Fr Francium (223)	88 Ra Radium 226.0254	104 Rf Rutherfordium (261)		105 Db Dubnium (262)	106 Sg Seaborgium (263)	107 Bh Bohrium (262)	108 Hs Hassium (265)	109 Mt Meitnerium (266)	110 Uun Ununnilium (269)	111 Uuu Unununium (272)	112 Uub Ununbium (277)						

Lanthanide Series

57 La Lanthanum 138.906	58 Ce Cerium 140.12	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.96	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93	68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
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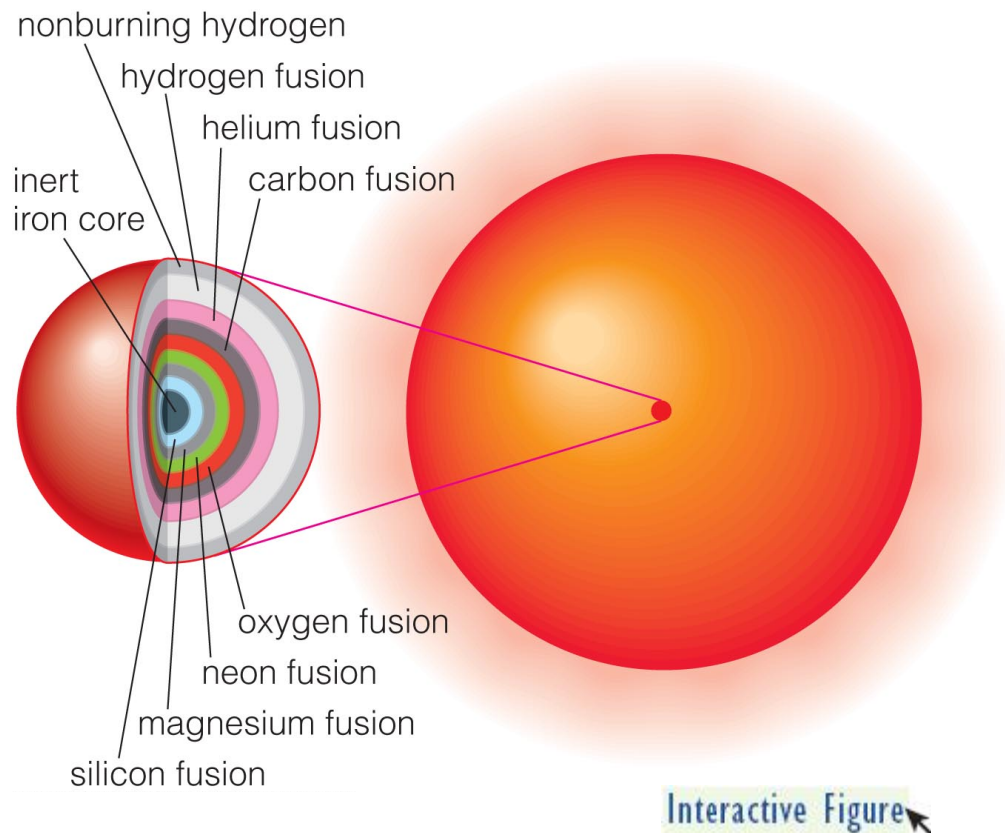
Actinide Series

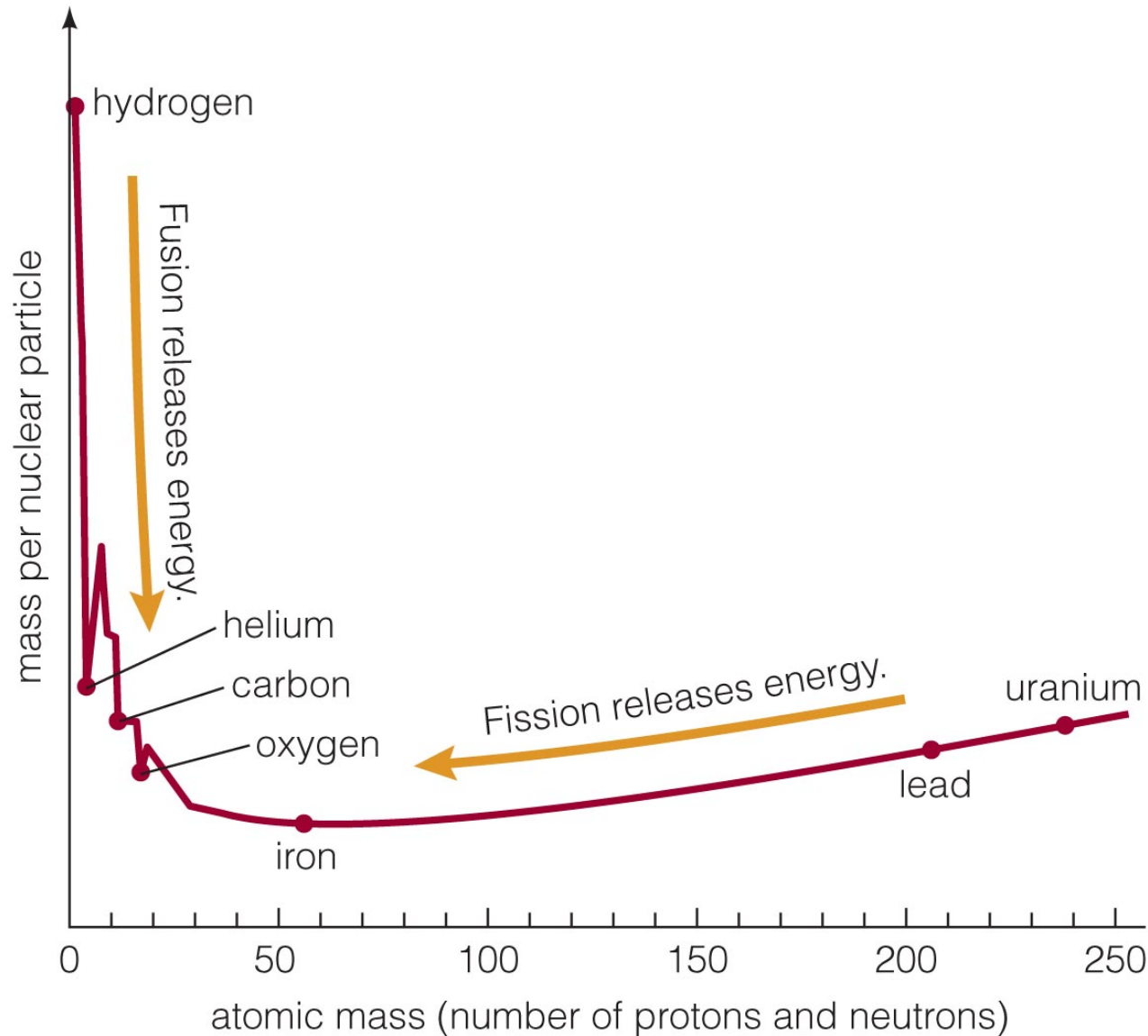
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Advanced reactions in stars make elements like Si, S, Ca, Fe

Multiple Shell Burning

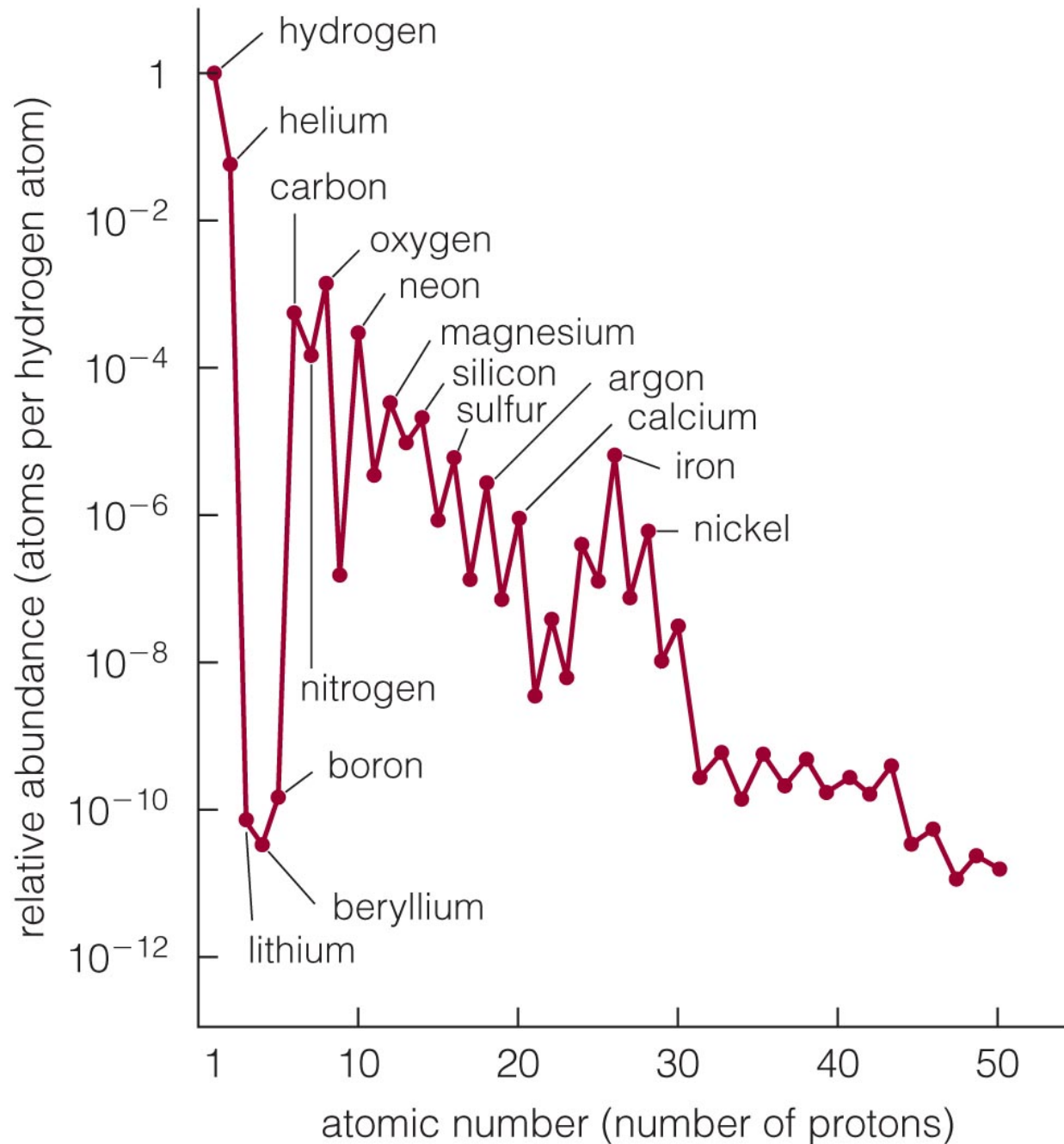
- Advanced nuclear burning proceeds in a series of nested shells





**Iron is dead
end for fusion
because
nuclear
reactions
involving iron
do not release
energy**

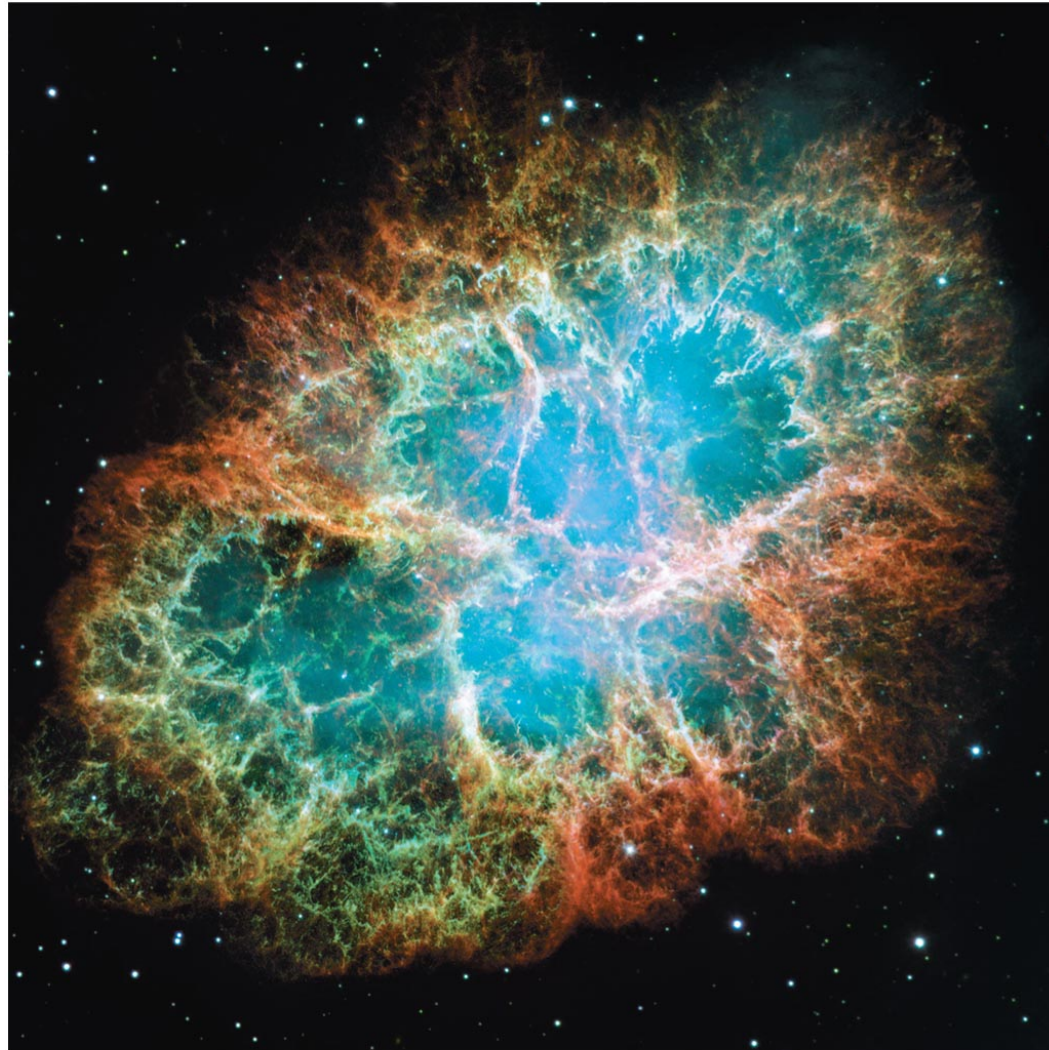
**(Fe has lowest
mass per
nuclear
particle)**



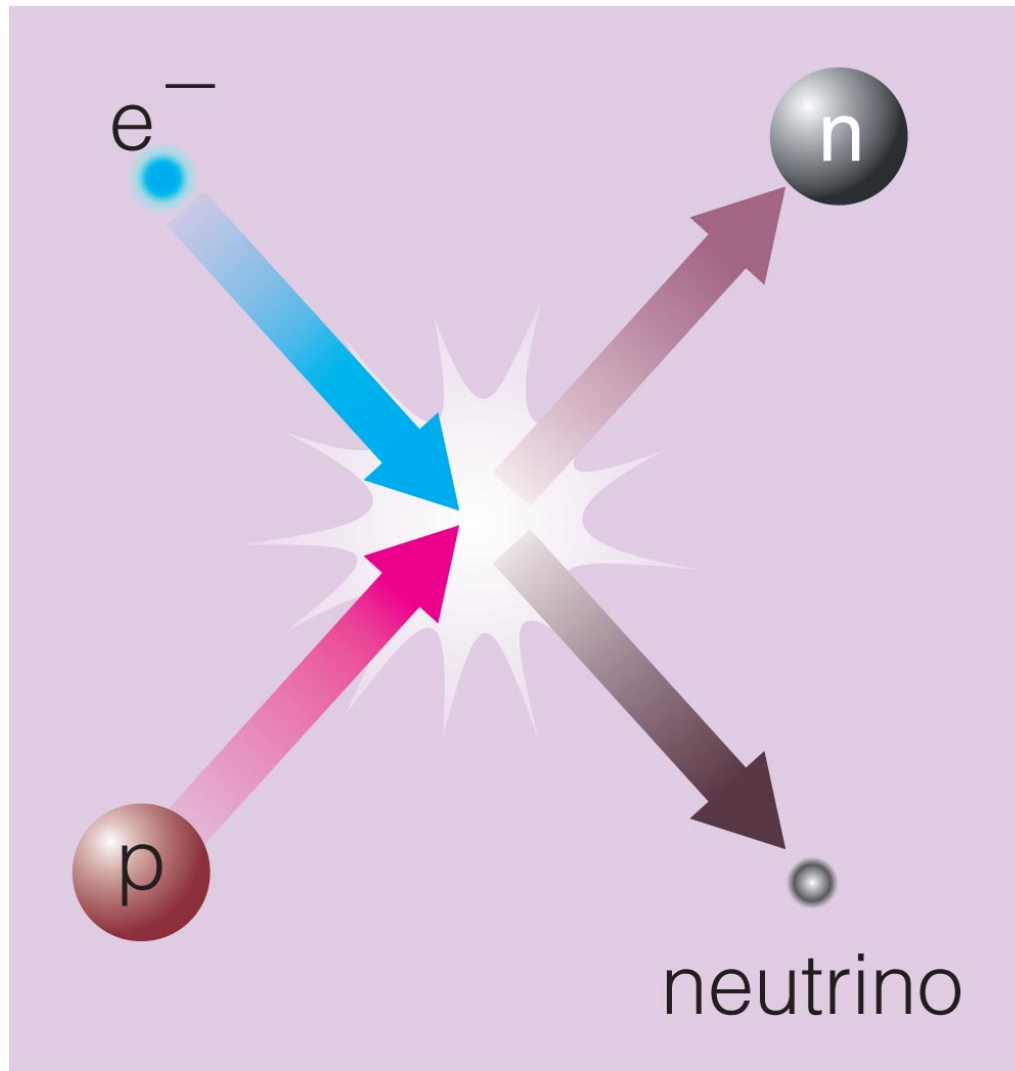
**Evidence for
helium
capture:**

**Higher
abundances
of elements
with even
numbers of
protons**

How does a high-mass star die?



Supernova Explosion



- Core degeneracy pressure goes away because electrons combine with protons, making neutrons and neutrinos
- Neutrons collapse to the center, forming a **neutron star**

Key

12	Atomic number
Mg	Element's symbol
Magnesium	Element's name
24.305	Atomic mass*

*Atomic masses are fractions because they represent a weighted average of atomic masses of different isotopes—in proportion to the abundance of each isotope on Earth.

1 H Hydrogen 1.00794	2 He Helium 4.003																						
3 Li Lithium 6.941	4 Be Beryllium 9.01218	5 B Boron 10.81	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.179																
11 Na Sodium 22.990	12 Mg Magnesium 24.305	13 Al Aluminum 26.98	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.06	17 Cl Chlorine 35.453	18 Ar Argon 39.948																
19 K Potassium 39.098	20 Ca Calcium 40.08	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.94	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.847	27 Co Cobalt 58.9332	28 Ni Nickel 58.69	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.72	32 Ge Germanium 72.59	33 As Arsenic 74.922	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80						
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.9059	40 Zr Zirconium 91.224	41 Nb Niobium 92.91	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.41	49 In Indium 114.82	50 Sn Tin 118.71	51 Sb Antimony 121.75	52 Te Tellurium 127.60	53 I Iodine 126.905	54 Xe Xenon 131.29						
55 Cs Cesium 132.91	56 Ba Barium 137.34																						
72 Hf Hafnium 178.49	73 Ta Tantalum 180.95	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.2	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.98	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)									
87 Fr Francium (223)	88 Ra Radium 226.0254	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (263)	107 Bh Bohrium (262)	108 Hs Hassium (265)	109 Mt Meitnerium (266)	110 Uun Ununnilium (269)	111 Uuu Unununium (272)	112 Uub Ununbium (277)													

Lanthanide Series

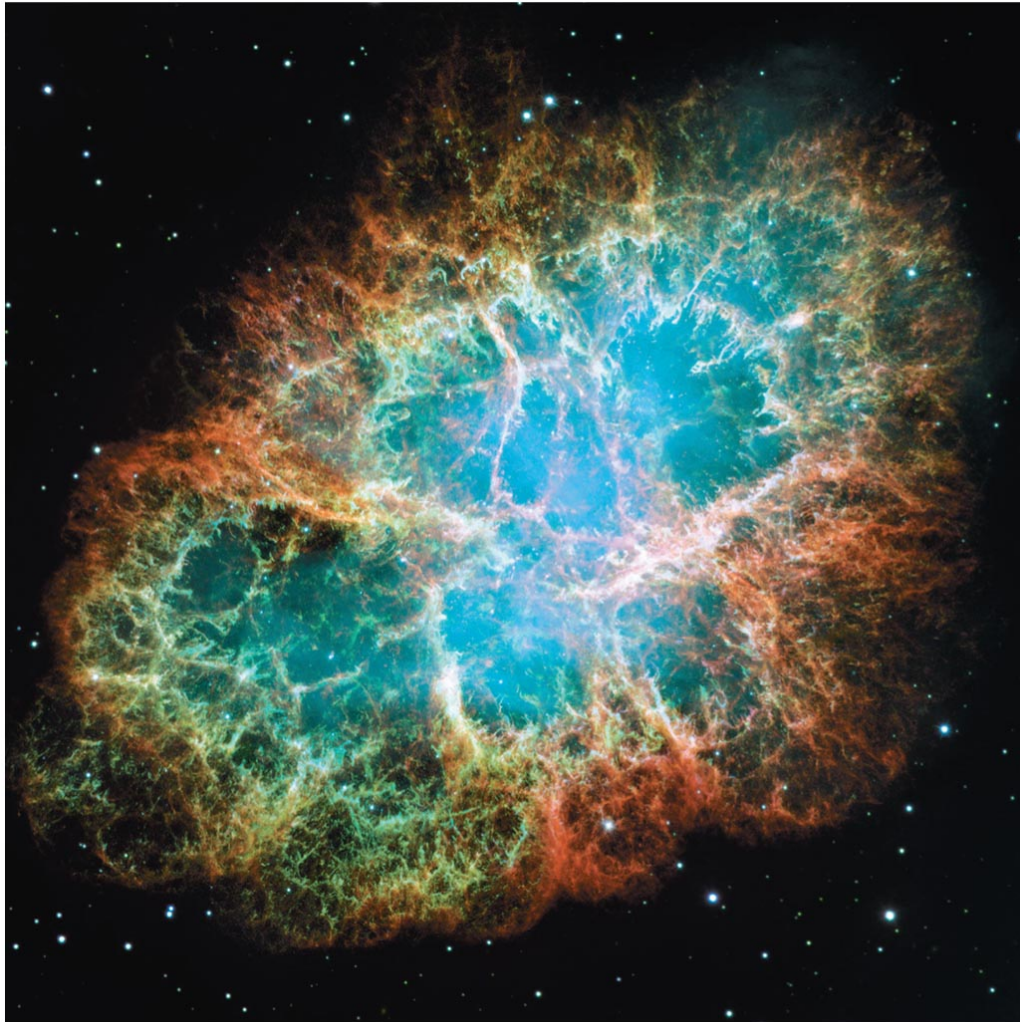
57 La Lanthanum 138.906	58 Ce Cerium 140.12	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.96	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93	68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
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Actinide Series

89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (260)
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Energy and neutrons released in supernova explosion enable elements heavier than iron to form, including Au and U

Supernova Remnant



- Energy released by collapse of core drives outer layers into space
- The Crab Nebula is the remnant of the supernova seen in A.D. 1054

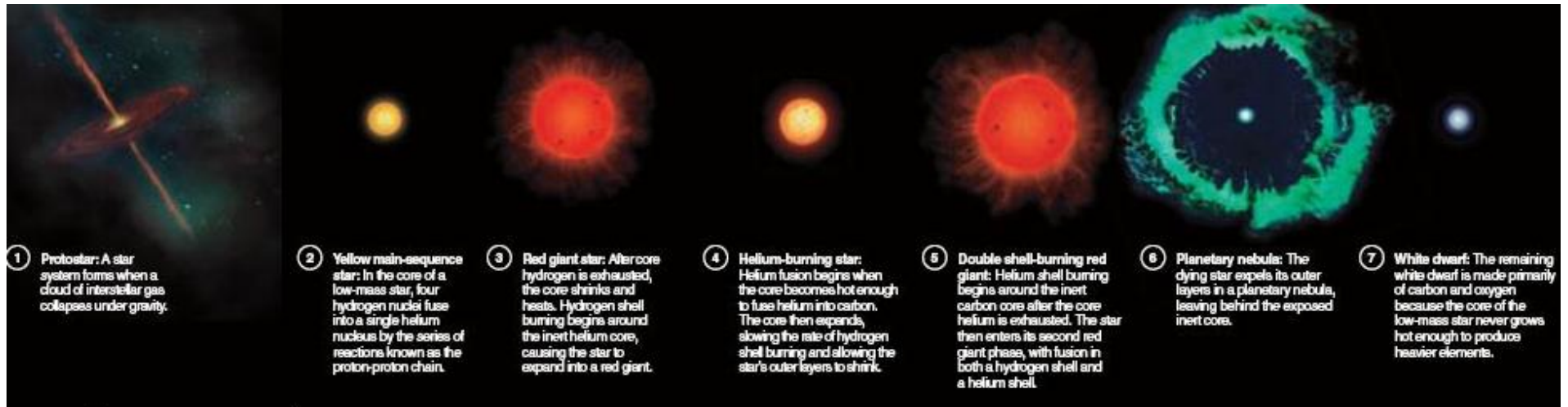
Interactive Figure 

Supernova 1987A



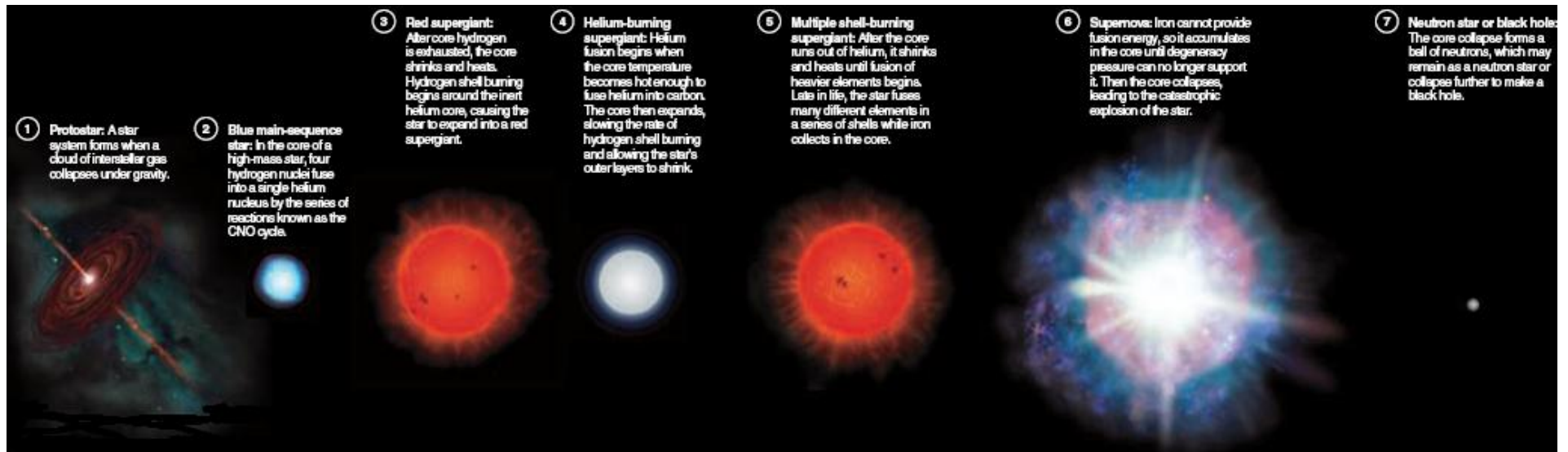
- **The closest supernova in the last four centuries was seen in 1987**

Low-Mass Star Summary



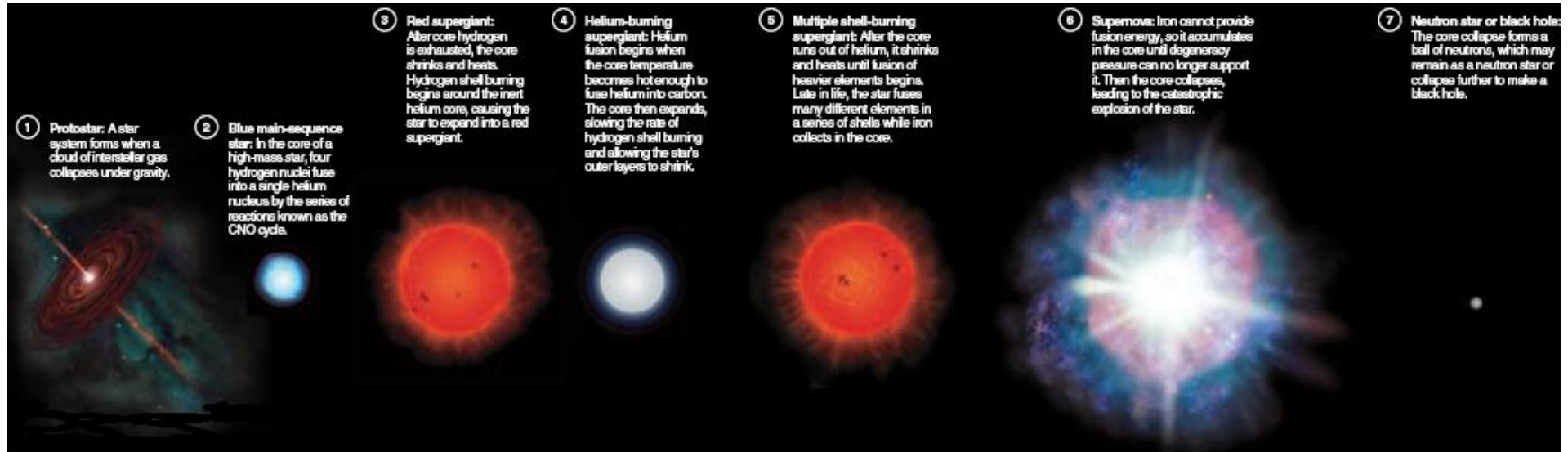
- 1. Main Sequence: H fuses to He in core**
- 2. Red Giant: H fuses to He in shell around He core**
- 3. Helium Core Burning:**
He fuses to C in core while H fuses to He in shell
- 4. Double Shell Burning:**
H and He both fuse in shells
- 5. Planetary Nebula leaves white dwarf behind**

Reasons for Life Stages



- **Core shrinks and heats until it's hot enough for fusion**
- **Nuclei with larger charge require higher temperature for fusion**
- **Core thermostat is broken while core is not hot enough for fusion (shell burning)**
- **Core fusion can't happen if degeneracy pressure keeps core from shrinking**

Life Stages of High-Mass Star



- 1. Main Sequence: H fuses to He in core**
- 2. Red Supergiant: H fuses to He in shell around He core**
- 3. Helium Core Burning:**
He fuses to C in core while H fuses to He in shell
- 4. Multiple Shell Burning:**
Many elements fuse in shells
- 5. Supernova leaves neutron star behind**