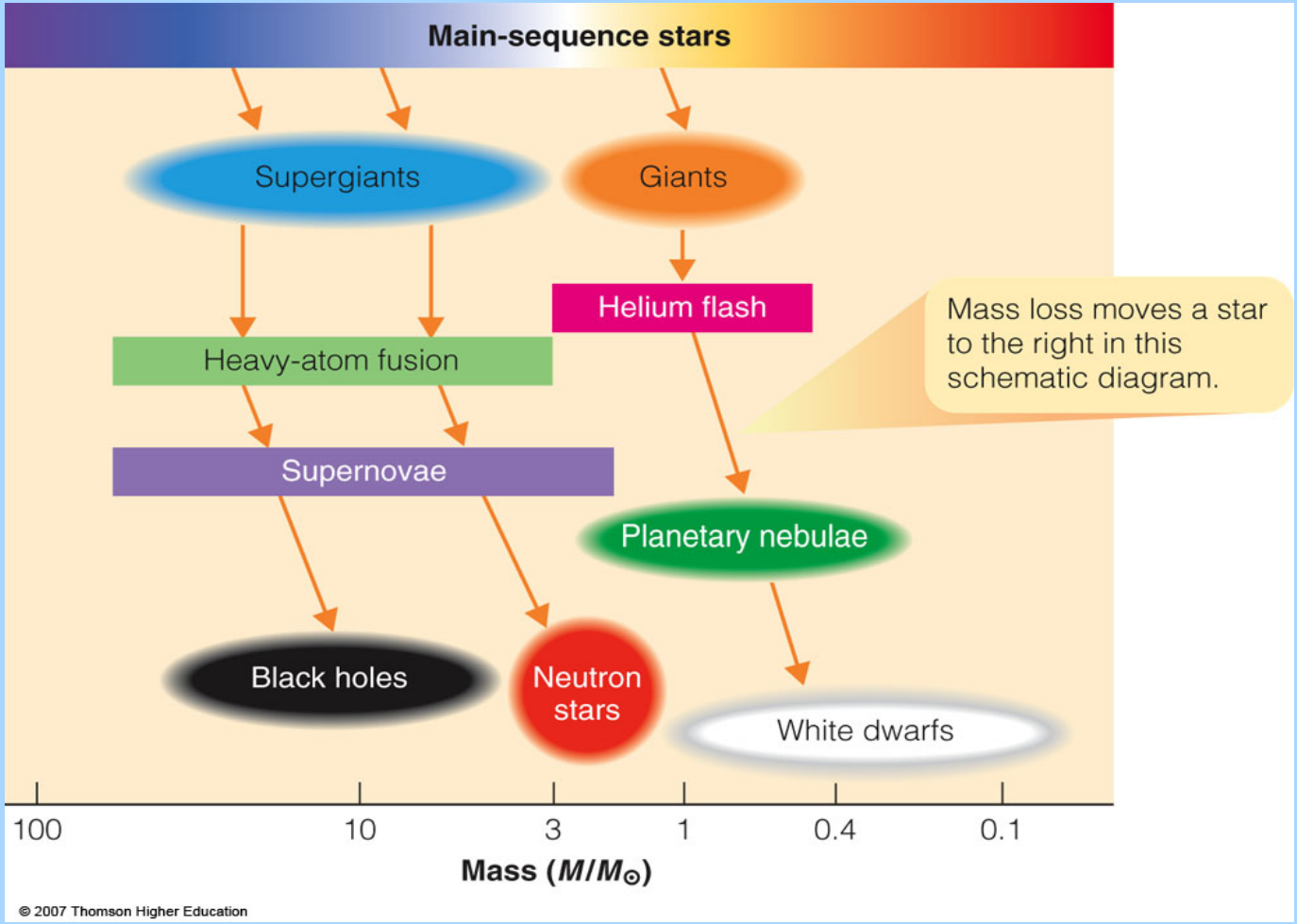
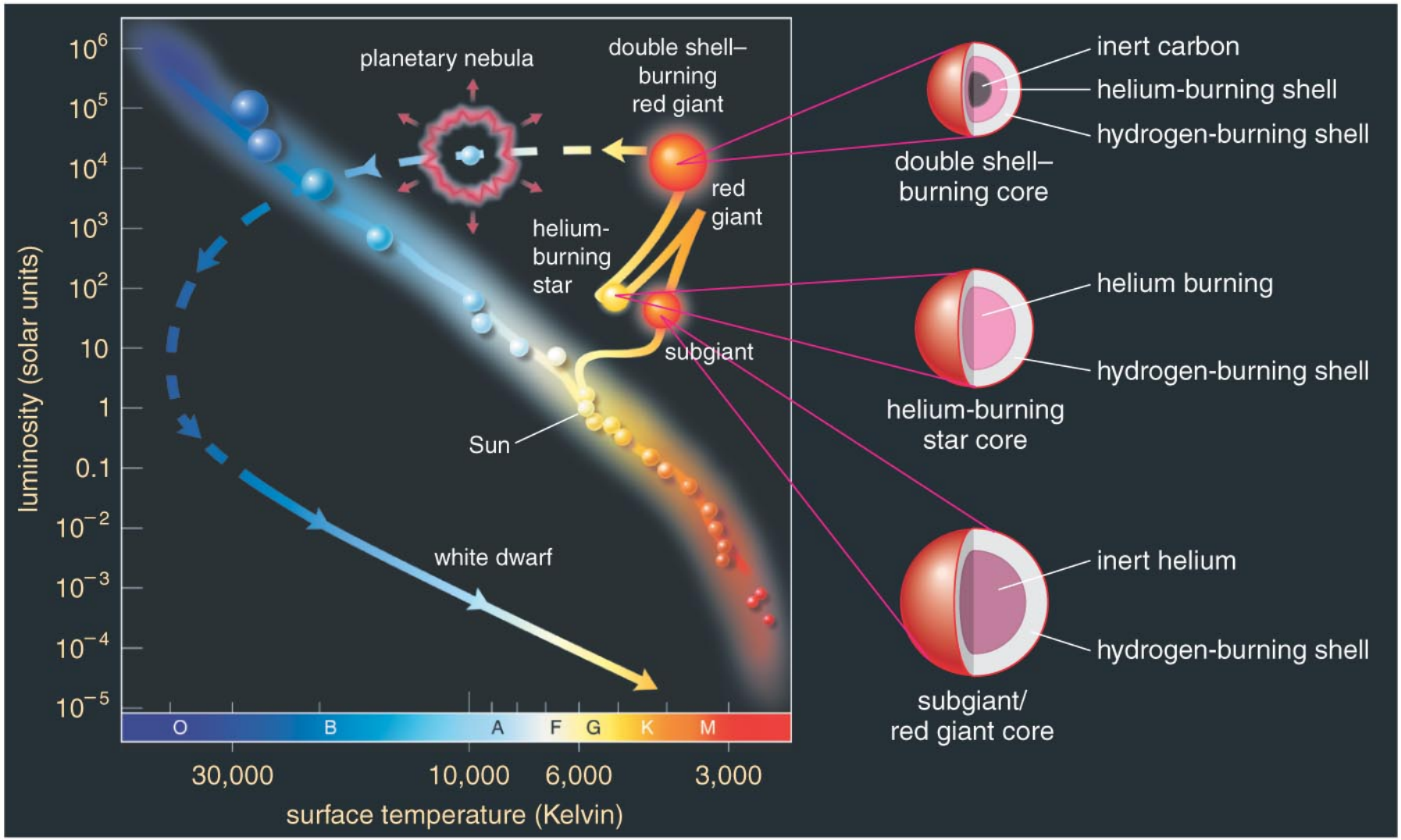
Stellar Evolution



Stages of the Sun's life:

1) initial collapse from interstellar gas (5 million yrs)
2) onset of nuclear reactions to start of main sequence phase (30 million yrs)
3) main sequence (10 billion years)
4) red giant phase (roughly 1 billion years)
5) production of planetary nebula (50,000 yrs)
6) white dwarf phase (will last for billions and billions of years, as the only the thing the Sun can do is to cool down; Sun's mass will be about 0.6 of its present mass)



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How long does a star of 4 solar masses last as a main sequence star?

a. The same amount of time as the Sun
b. 4 times as long as the Sun
c. ¼ as long as the Sun
d. $4^{-2.5}$ times as long as the Sun

The mass-luminosity relation revisited

total energy produced converting H to He =

luminosity (in Joules/sec) X number of seconds in MS lifetime =

E_{tot} (Joules) = m c^2 =

[mass of star X fraction converted to energy] X c^2

So $L * T_{MS}$ proportional to M, or

T_{MS} proportional to M/L

From measures of the masses of binary stars, we find that for a great range of masses,

$$L \sim M^{3.5}$$

Combining the last two proportionalities,

$$T_{MS} \sim M/L \sim M/M^{3.5} \sim M^{-2.5}$$

The bottom line is that massive stars evolve very quickly, and low mass stars evolve very slowly.

mass of Sun = 2×10^{30} kg

0.007 of mass of hydrogen is converted into energy

0.1 of mass of Sun (the core) is converted in He

Total energy liberated by Sun during main sequence phase is $(2 \times 10^{30}) \times 0.007 \times 0.1 \times c^2 = 1.26 \times 10^{44}$ J.

Luminosity of Sun = 3.8×10^{26} Joules/sec

main sequence lifetime = $1.26 \times 10^{44} / 3.8 \times 10^{26} = 3.32 \times 10^{17}$ sec = 10.5 billion years

Table 12-2 | Main-Sequence Stars

Spectral Type	Mass (sun = 1)	Luminosity (sun = 1)	Approximate Years on Main Sequence
O5	40	405,000	1×10^6
B0	15	13,000	11×10^6
A0	3.5	80	440×10^6
F0	1.7	6.4	3×10^9
G0	1.1	1.4	8×10^9
K0	0.8	0.46	17×10^9
M0	0.5	0.08	56×10^9

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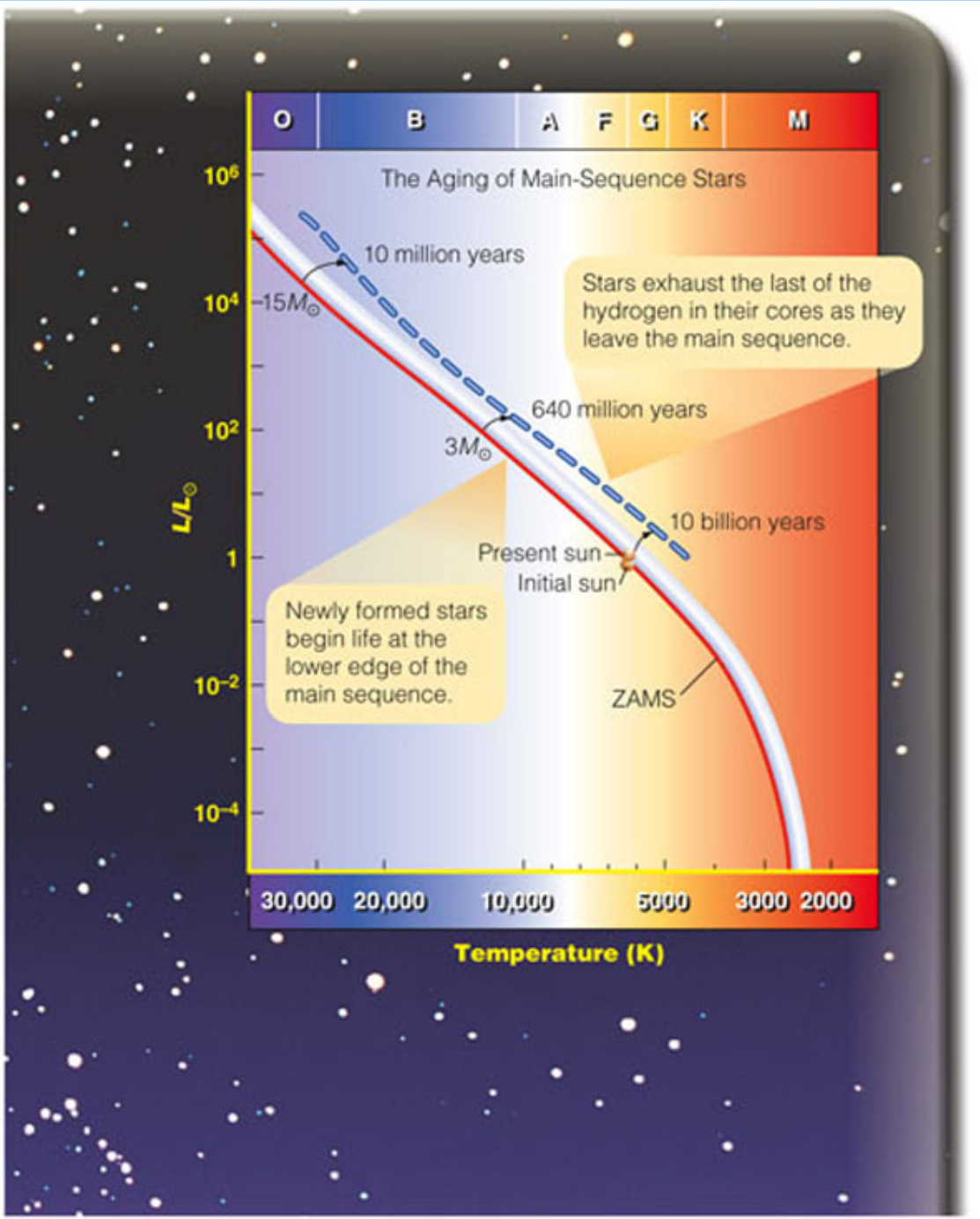
More massive main sequence stars have hotter cores because the weight of all the layers presses down on the core more than the layers in less massive stars.

The hotter the core, the faster the nuclear reactions run.

The faster the nuclear reactions run, the more luminosity the star has. This explains why more massive stars have greater luminosity, and why more massive stars use up their core hydrogen at a much faster rate.



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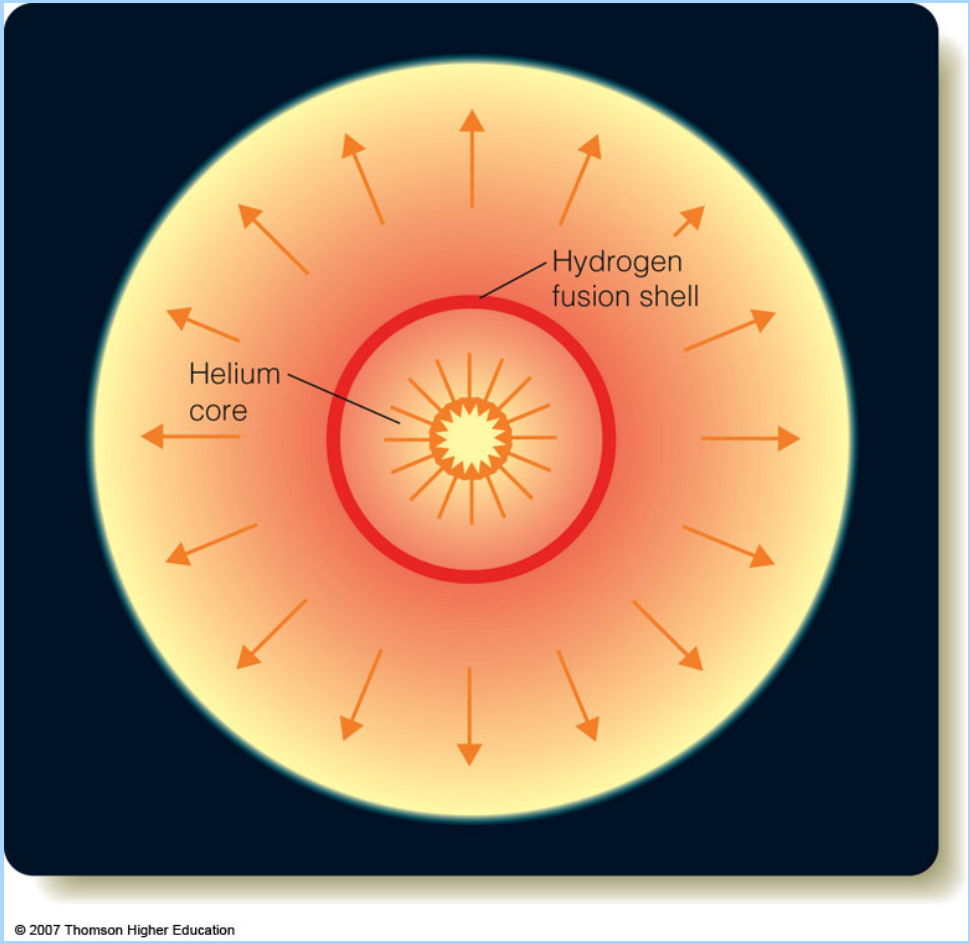

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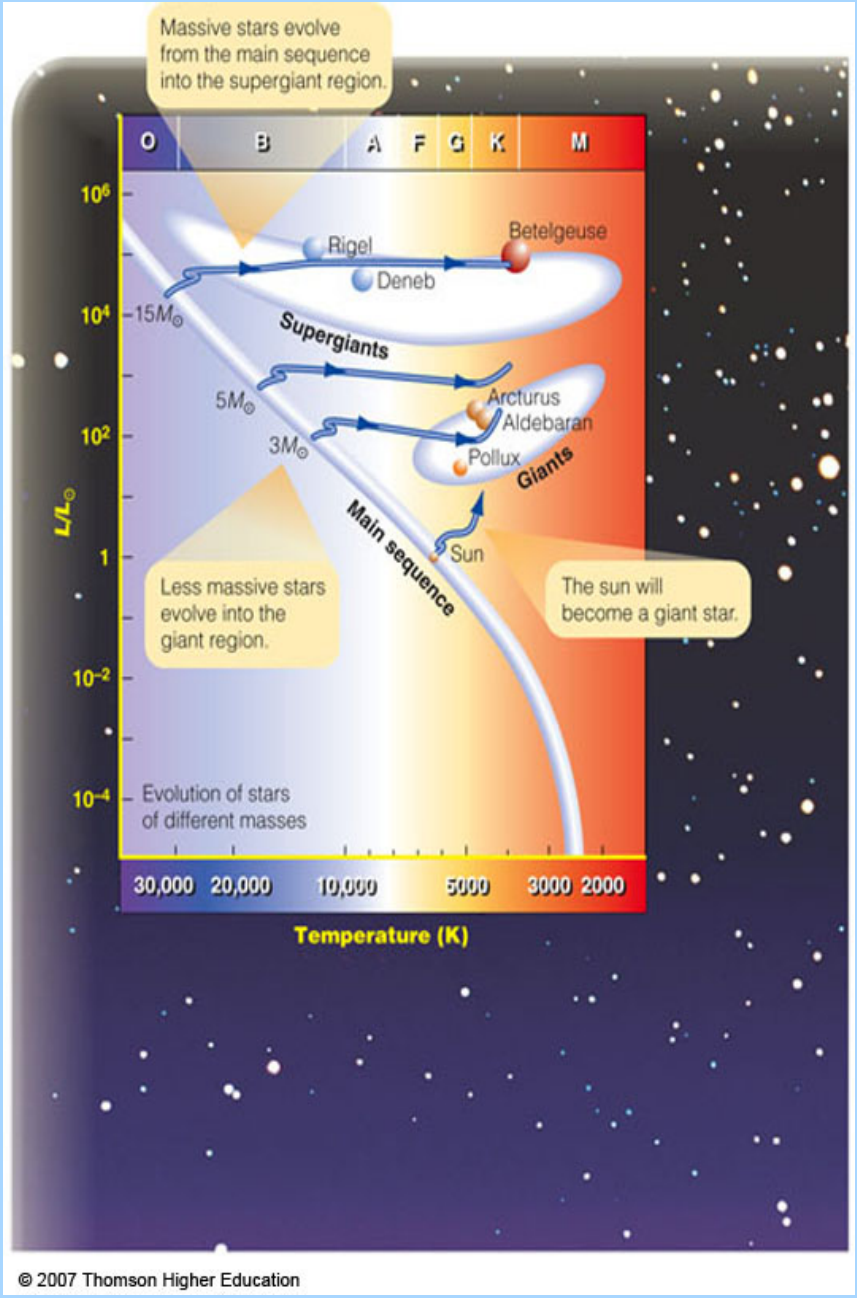
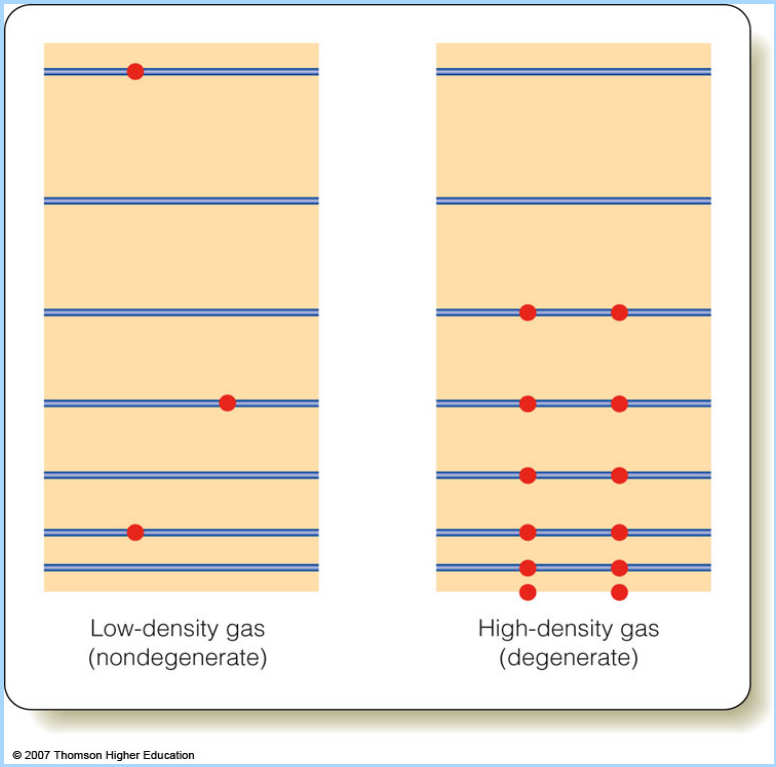
When a star runs out of H in its core, it ignites a hydrogen burning shell. The helium core contracts and heats up. The envelope expands and cools.



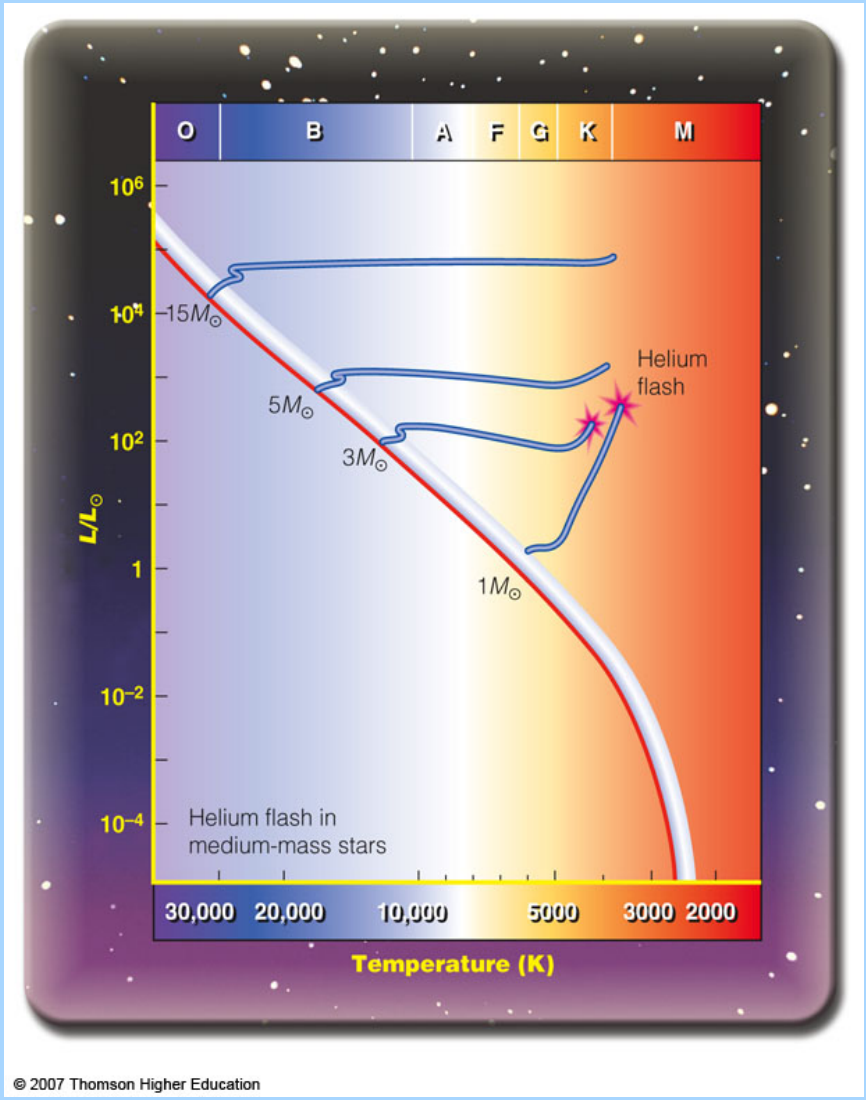
Massive stars become supergiants.

Not so massive stars become red giants.

As the hydrogen in the core of a star is transformed into helium, the matter in the core becomes **degenerate**. In a low density gas many possible energy levels of the electrons are open, but as the gas become denser all the lower energy levels are filled.



The Pauli exclusion principle states that each energy level can only contain one spin up electron and one spin down electron.



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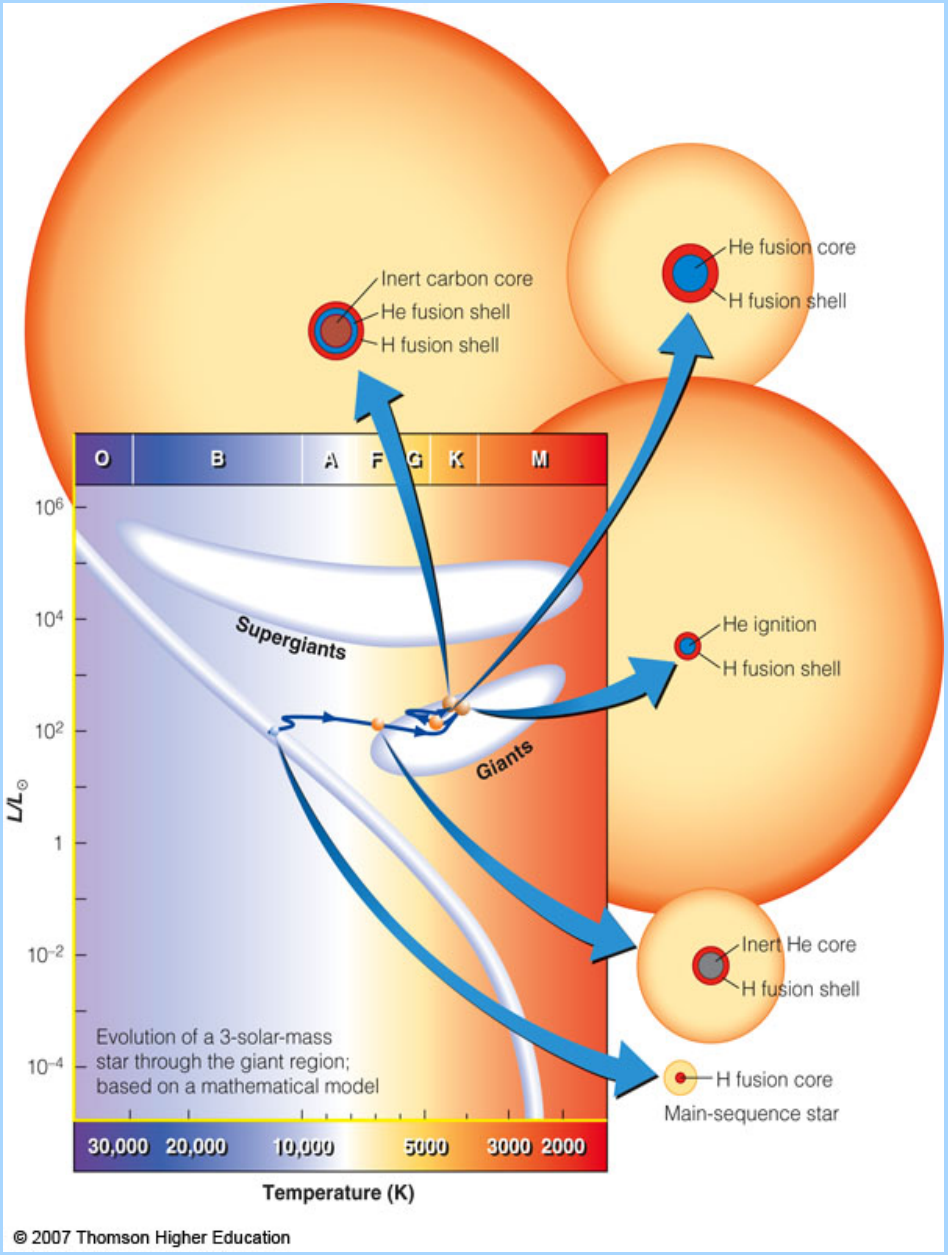
Stars in between 0.4 and 3 solar masses begin helium burning with a **flash**. For a few minutes these stars produce 10^{14} times more energy than the Sun – more energy than an entire galaxy!



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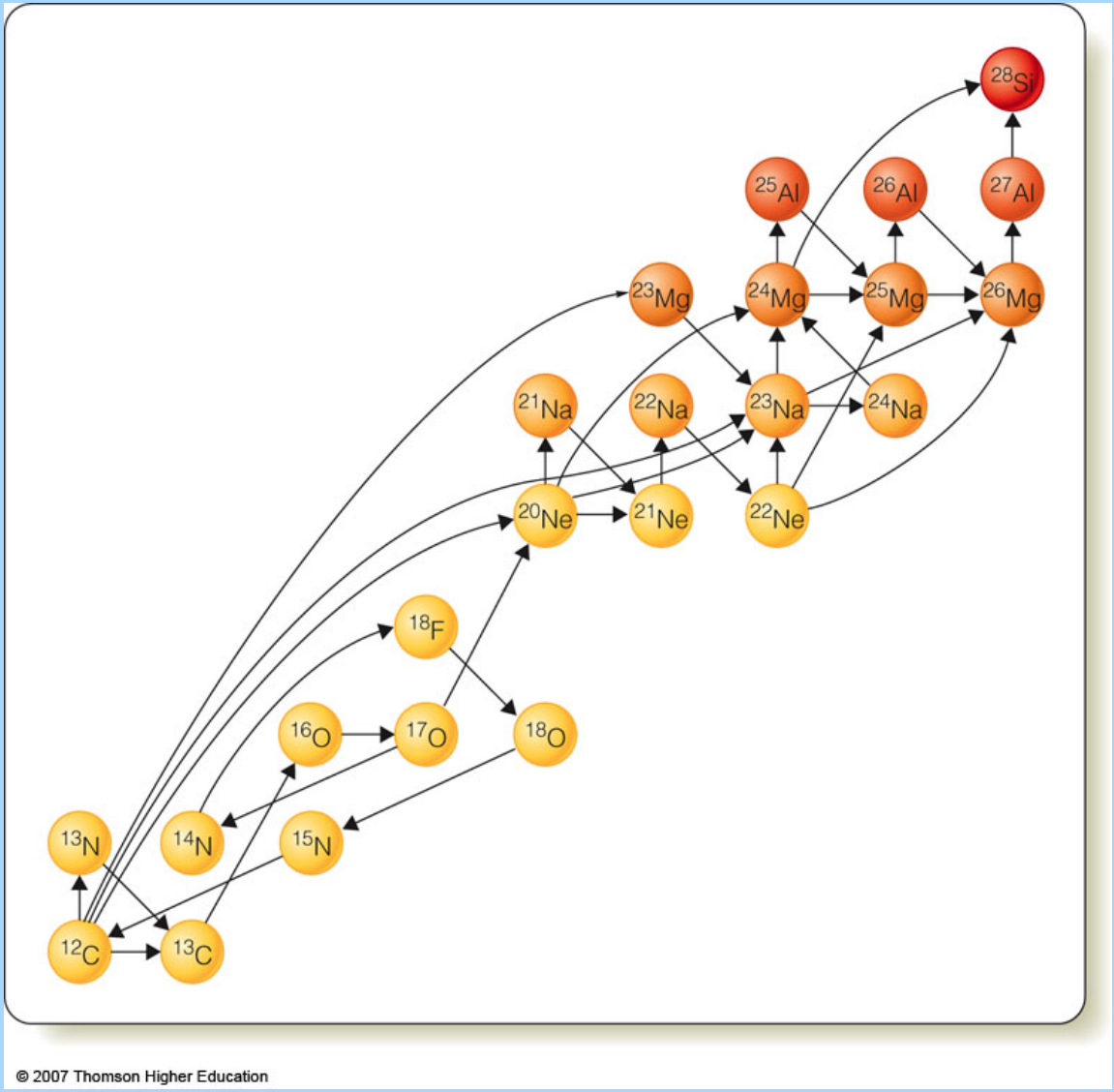
As hydrogen in the core is used up, it is burned in a shell. The star swells up to be a cool giant. As helium starts being transformed into carbon in the core, the star contracts and heats up slightly. When He shell burning occurs, the star swells up again.



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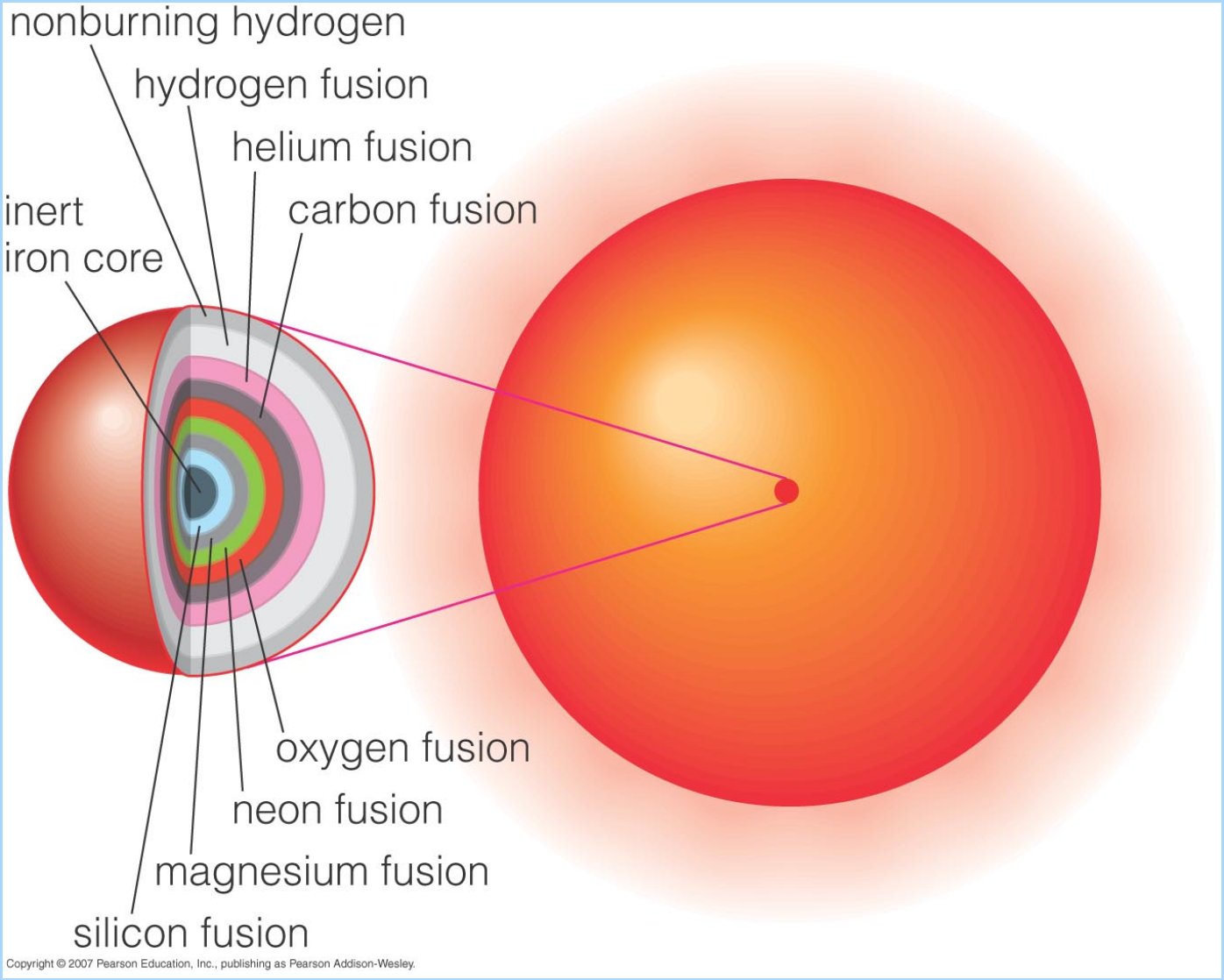
Massive stars can fuse elements up to ^{56}Fe (iron 56).



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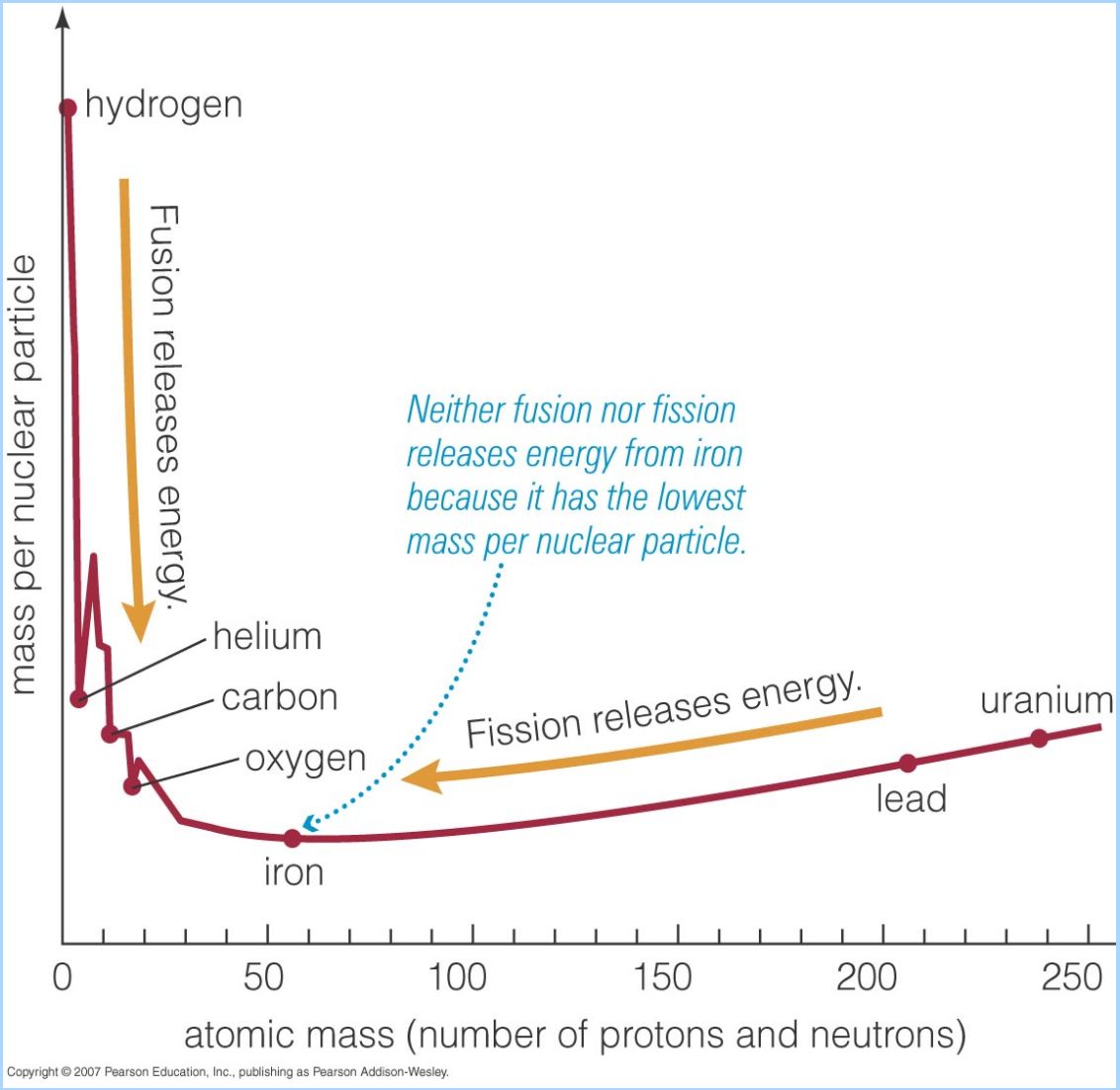
Eventual structure of a star with more than 8 solar masses.



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Once an iron core develops in a massive star, the nuclear reactions can no longer push up on the upper layers and keep them there. The outer layers squeeze down on the star, and it explodes.

Table 12-3 | Nuclear Reactions in Massive Stars

Nuclear Fuel	Nuclear Products	Minimum Ignition Temperature	Main-Sequence Mass Needed to Ignite Fusion	Duration of Fusion in a 25-$M_\odot$ Star
H	He	4×10^6 K	0.1 $M_\odot$	7×10^6 yr
He	C, O	120×10^6 K	0.4 $M_\odot$	0.5×10^6 yr
C	Ne, Na, Mg, O	0.6×10^9 K	4 $M_\odot$	600 yr
Ne	O, Mg	1.2×10^9 K	~8 $M_\odot$	1 yr
O	Si, S, P	1.5×10^9 K	~8 $M_\odot$	~ 0.5 yr
Si	Ni to Fe	2.7×10^9 K	~8 $M_\odot$	~ 1 day

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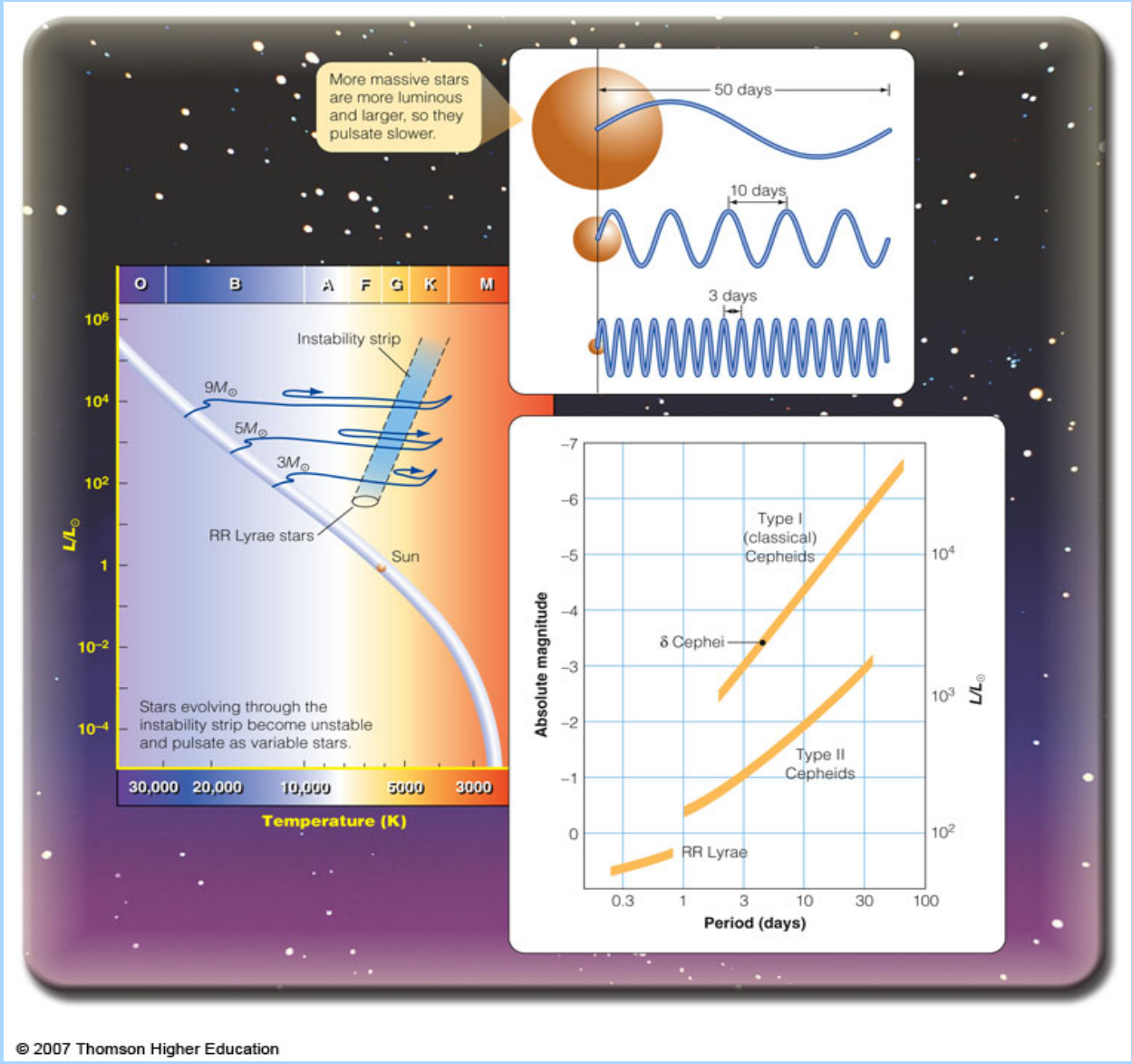
Eventually, the core of the Sun will be made of carbon and oxygen. Once the outer layers are exhaled as a planetary nebula, the remant of the Sun will be a C-O white dwarf star.

Though the time scale for evolution of stars is typically much, much longer than a human lifetime, during some stages of a star's life we can measure changes in its structure. Stars that pulsate may change their pulsational periods, indicating that the star is getting cooler or hotter.



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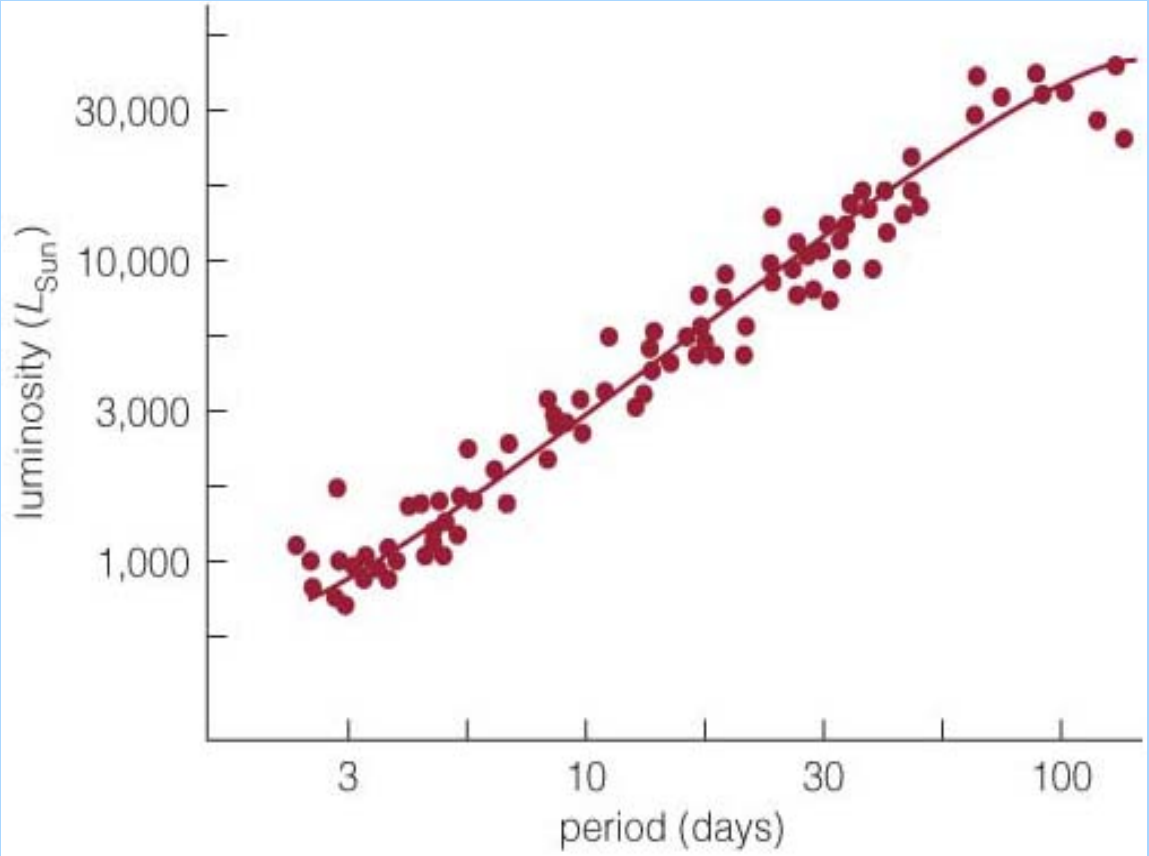
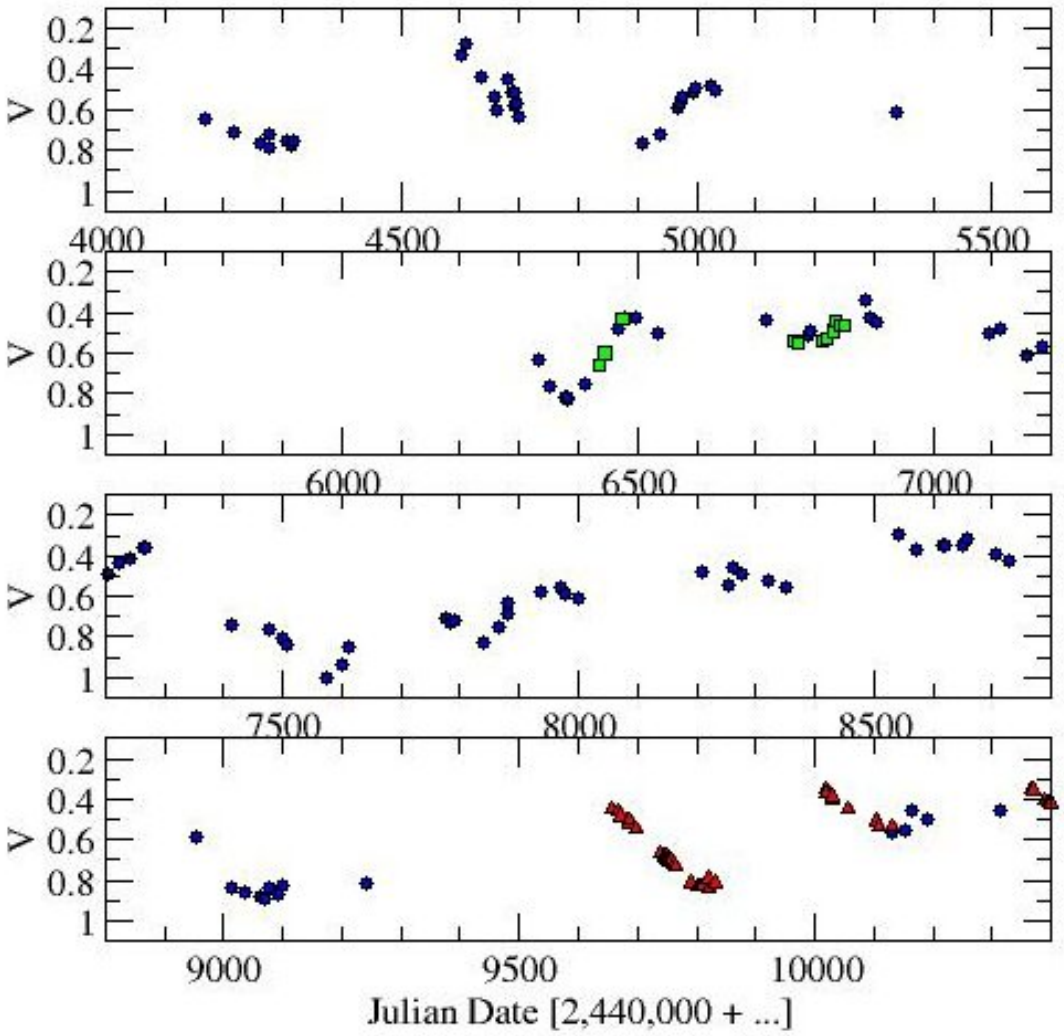
When the evolutionary track of a star places it in the instability strip, it will pulsate.

If a Cepheid variable star with a period of 30 days were at a distance of 10 parsecs what would its apparent brightness be?

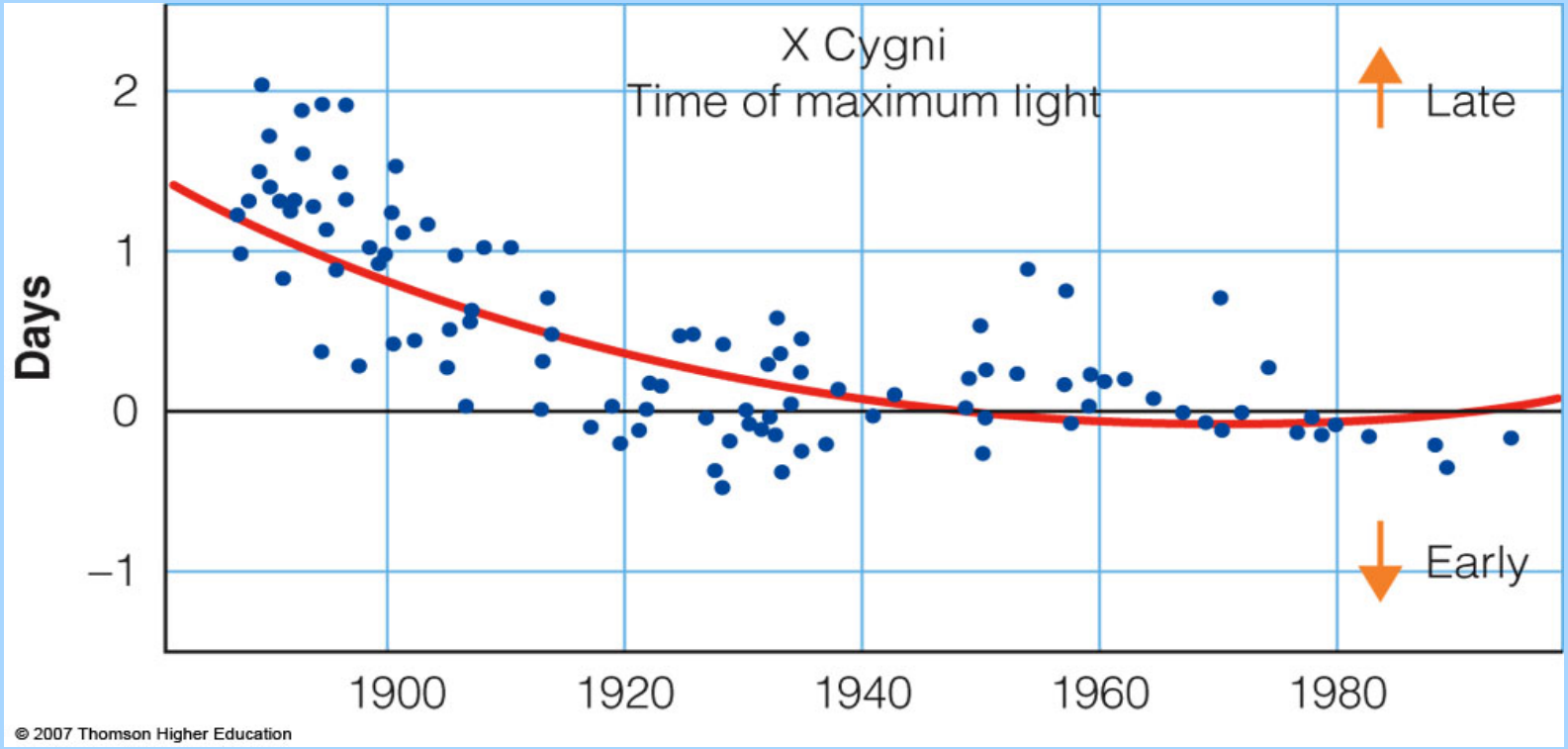
A. as bright as the Sun
B. a bit brighter than the planet Venus
C. just barely visible to the unaided eye
D. only visible in a medium size telescope



A Cepheid with a period of 30 days is 10,000 times more luminous than the Sun. The Sun at d = 10 pc would be just visible to the unaided eye. A 30 day Cepheid would be 10 magnitudes brighter, or a bit brighter than Venus.



Betelgeuse is a red supergiant that pulsates with more than one period. Here is its light curve from October, 1979, through November, 1996. It varied from V = 1.0 to 0.3.

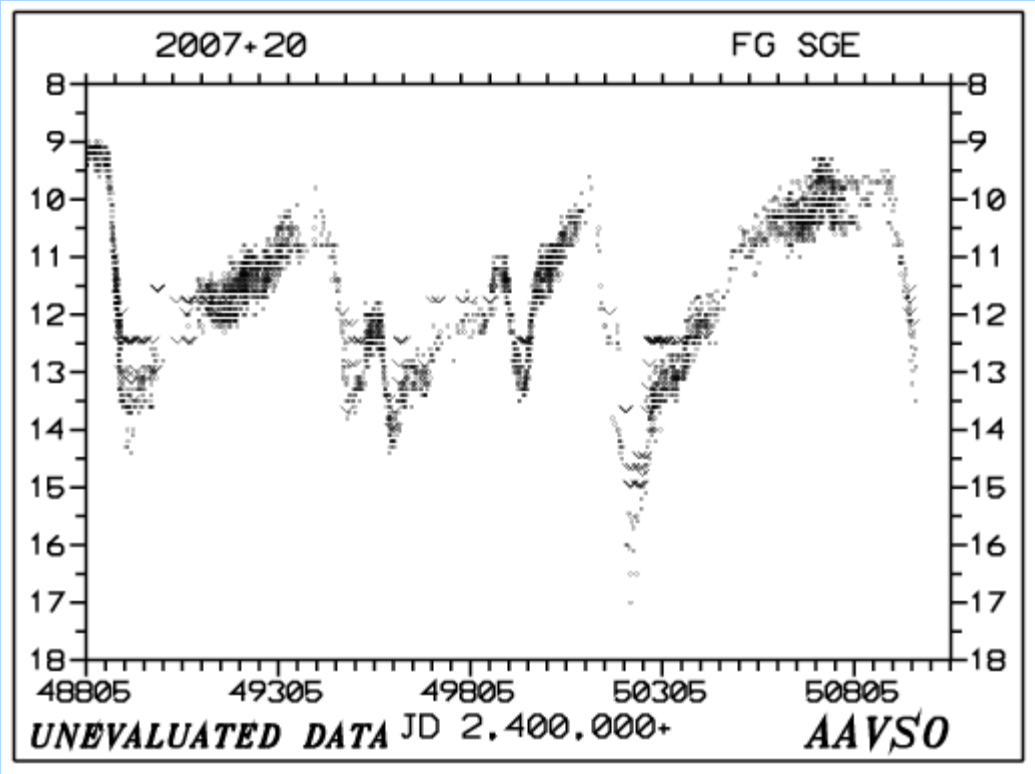


Period changes in a star, which are measurable on times scales of decades, are evidence for changes in stars on human time scales.

The strange case of FG Sagittae

Year	Spectral Type	Temperature (K)
1955	B4Ia	20,000
1967	A5Ia	9,000
1972	F6Ia	7,000
now	K2Ib	4,500

apparent magnitude ~ 13 in 1900, but brightened to 9^{th} mag by 1960



FG Sge from July 1, 1992, to December, 1998.

The canonical wisdom is that FG Sge is going through its helium flash stage.