ELEMENTS OF ASTRONOMY

PHYS 1311

Lecture Slides
Prepared by Prof. Stephen Sekula
SMU-in-Taos, August Term, 2016

Lecture 7:
The Lives and Deaths of Stars

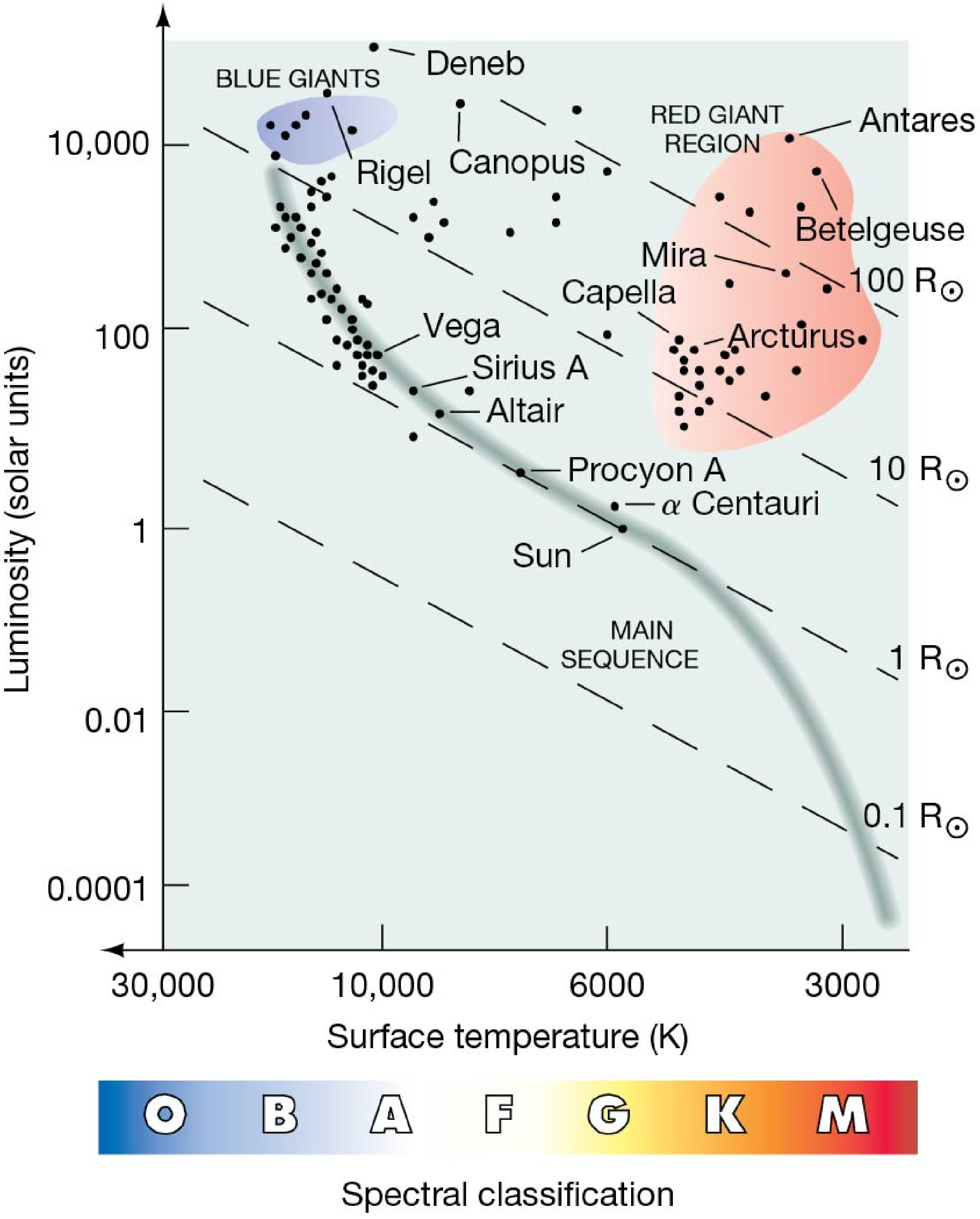
Announcements

- For Today:
  - Chapter 12, Lab 8
  - Homework 6 is due
- For Monday:
  - Homework 7
  - Read Chapter 13 and Lab 10
- Friday + Weekend Stuff
  - Will do a viewing night tonight – forecast looks reasonable
  - Movie night tomorrow: “Interstellar”, 7pm, Media Room

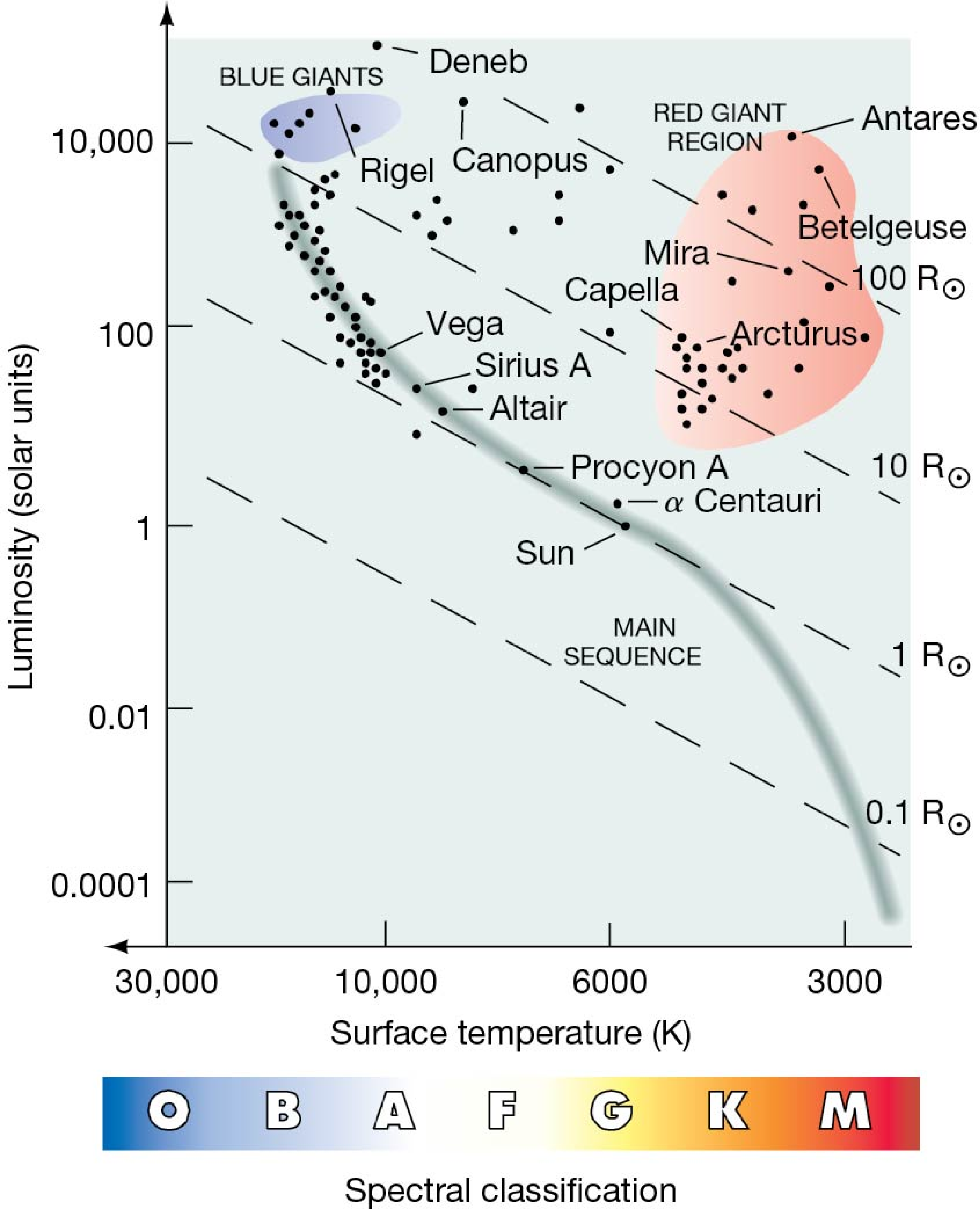
Programme

- When a star leaves the Main Sequence
- The fate of stars
  - low-mass stars (like our own Sun)
    - red giants
    - white dwarves
    - novae
  - high-mass stars (like some in our stellar neighborhood)
    - supergiants
    - supernovae explosions

LEAVING THE MAIN SEQUENCE



Once a star is born, its luminosity and surface temperature are fixed by its original mass. This determines where it lands in the H-R diagram on the “Main Sequence”. There it remains, for nearly all of its lifetime, until its fate is sealed by both its mass and the very thing that gives us sunlight in the first place: its core’s nuclear reactions.



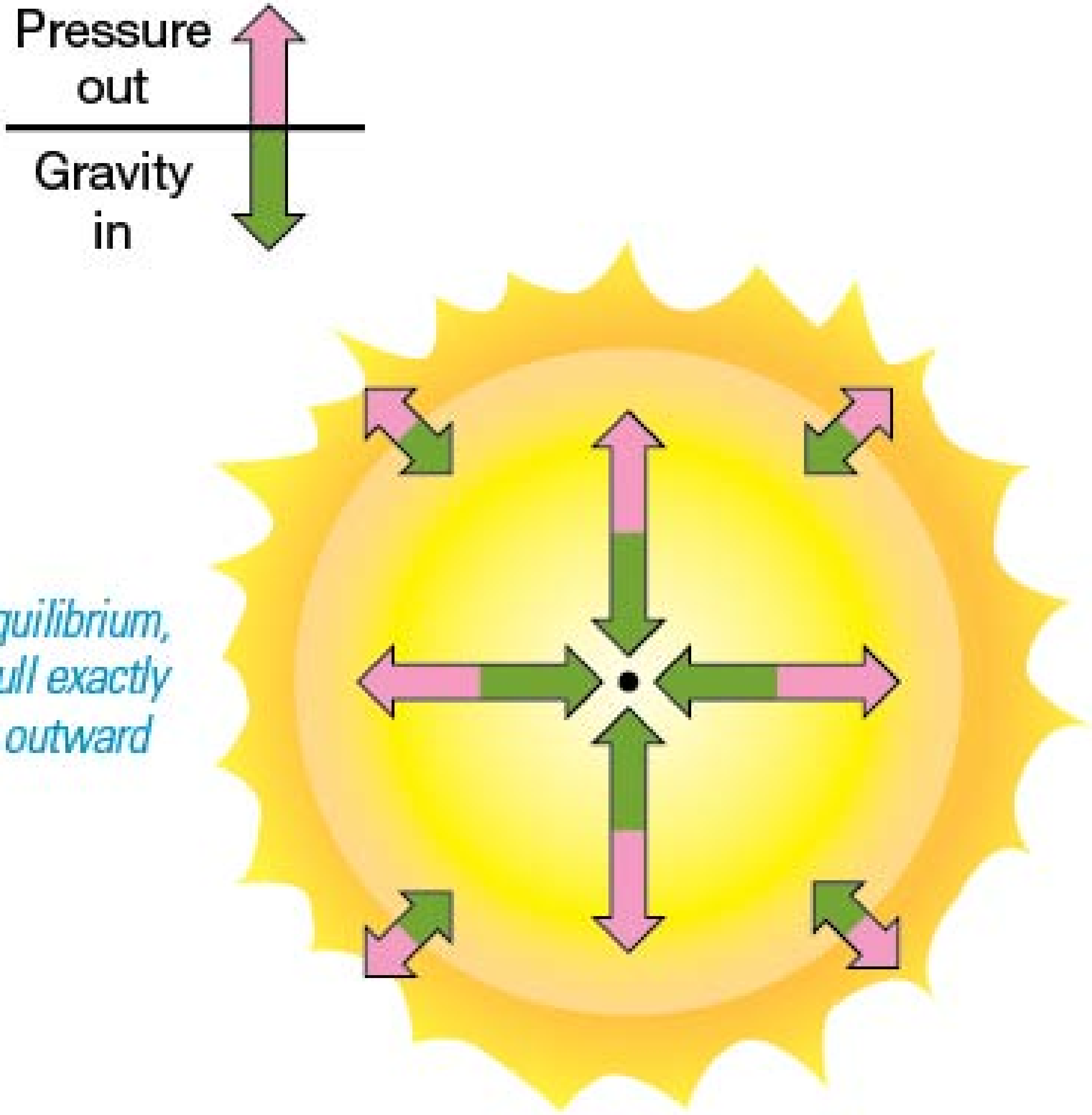
For example, our own Sun probably spent a few 10s of millions of years going through its formation process before landing on the Main Sequence. There it should remain for about 10 billion years... before evolving into something else.

Let’s see what Main Sequence stars become.

Some Terminology

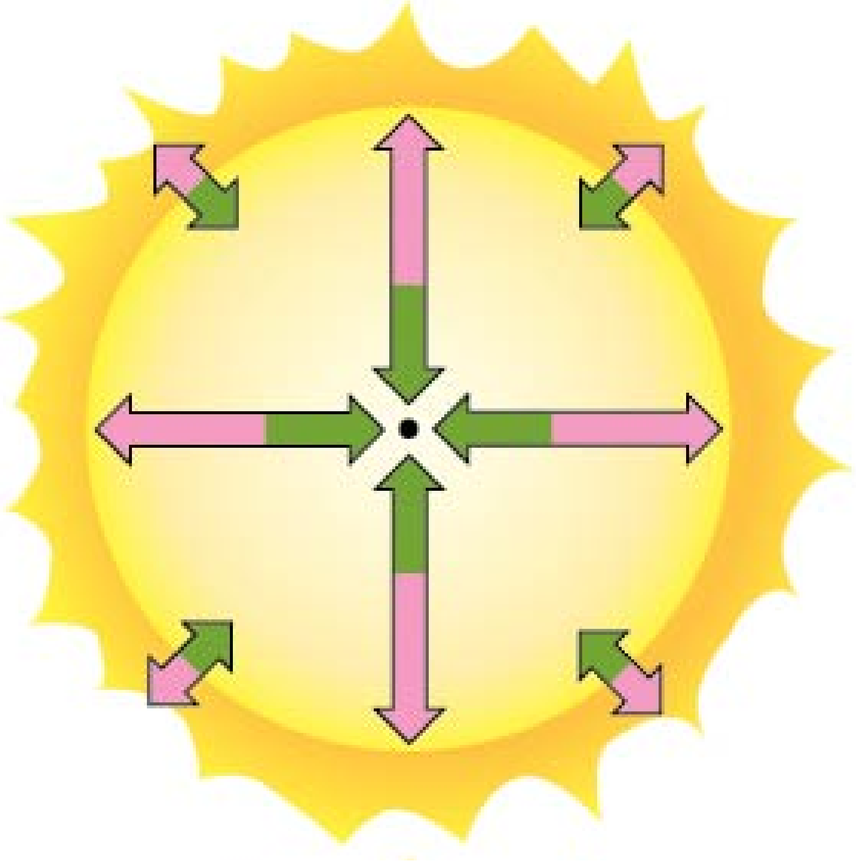
- Once on the Main Sequence, a star remains at its place there until it reaches the end of its life.
  - At that point, it moves OFF the Main Sequence and becomes something else.
- "Stellar Evolution" refers to the changes that a star goes through once it moves off the Main Sequence.
  - A single star can evolve through various stages. These stages depend on its original mass.
- No one has ever watched a star from birth to death. Rather, we employ the scientific method again to test hypotheses about stellar physics (e.g. based on nuclear physics, electromagnetism, thermal physics, gravitation) and check those against observations of stars.

Stellar Equilibrium
A long balancing act



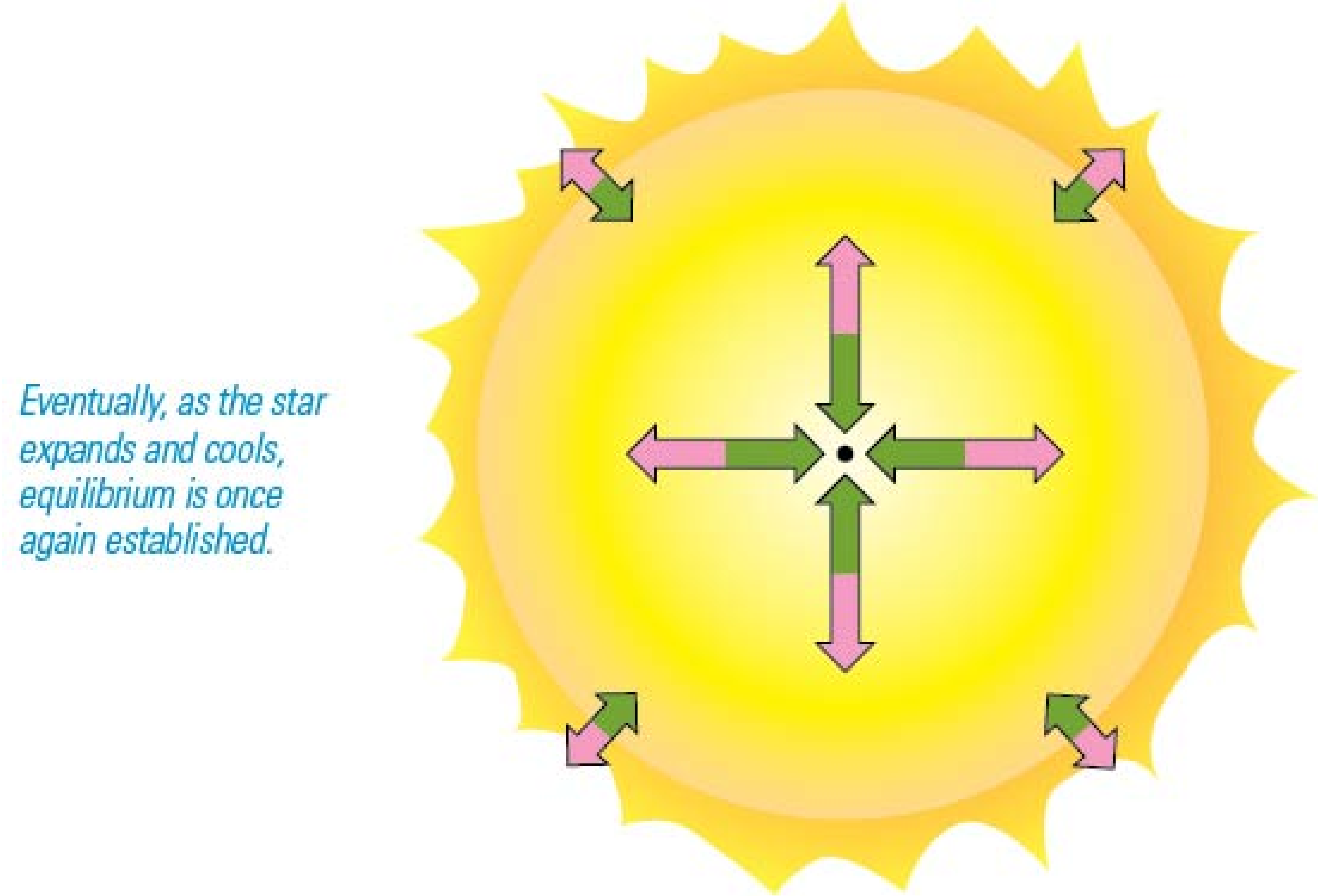
Normally, a star is in equilibrium, with gravity's inward pull exactly balanced by pressure's outward push.

Stellar Equilibrium
A long balancing act



If the star's interior gets hotter, pressure temporarily wins the battle against gravity and the star expands.

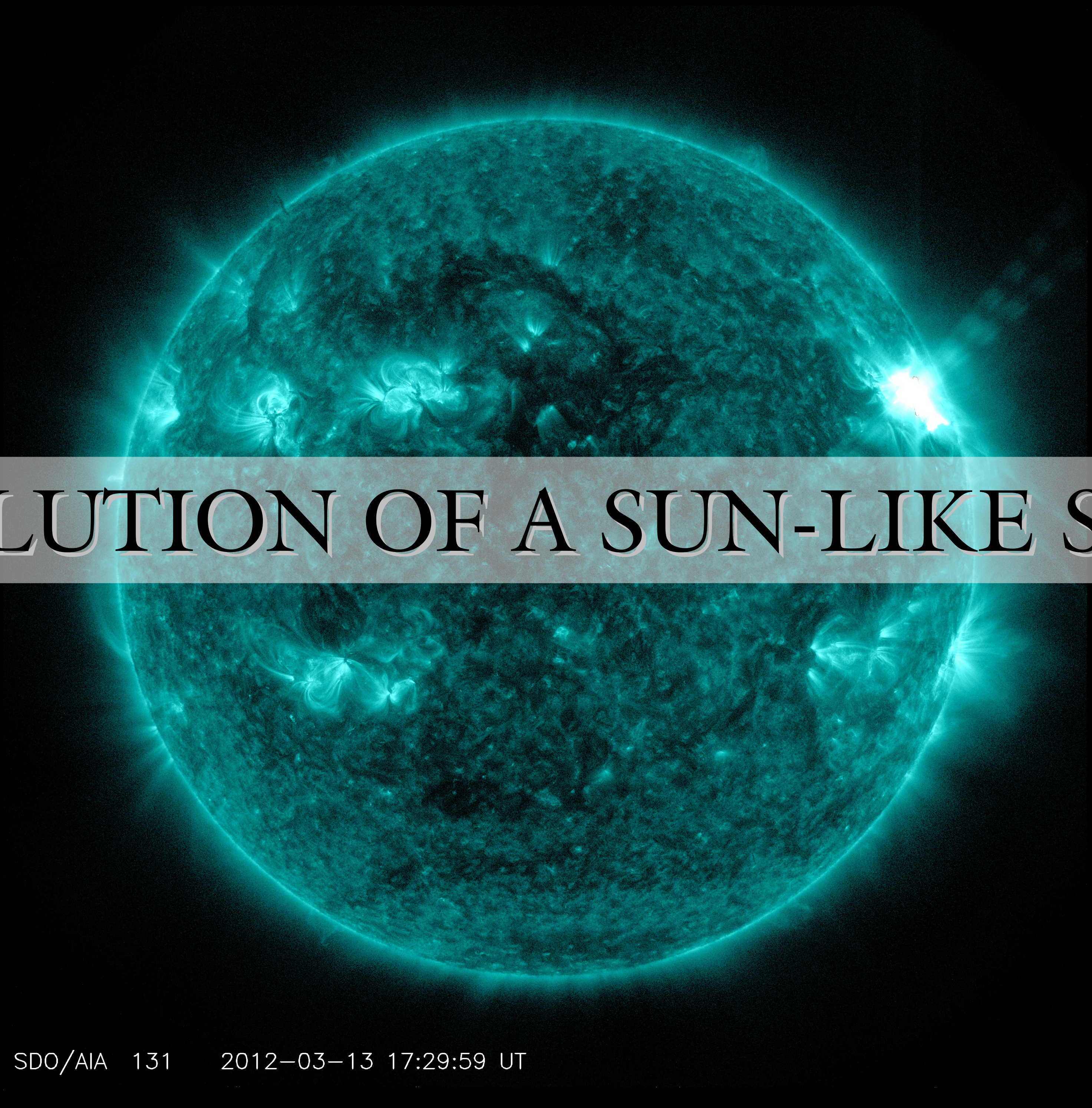
Stellar Equilibrium
A long balancing act


Eventually, as the star expands and cools, equilibrium is once again established.

Principles

- A star wants to expand, driven by the heat of its nuclear core hydrogen burning.
- A star wants to collapse, driven by the gravitational pull of its own mass
- These are kept in equilibrium, as illustrated on the previous page, so long as nothing changes to alter the balance
- Of course… nothing lasts forever…
- The relationship between Luminosity (brightness), the radius of the star, and its Temperature, is: $\mathbf{L = 4\pi R^2(\sigma T^4)}$.
  - From this we can see that it's possible for the temperature of a star to, for instance, increase, but if it also contracts in size (shrinks) its luminosity can remain constant.

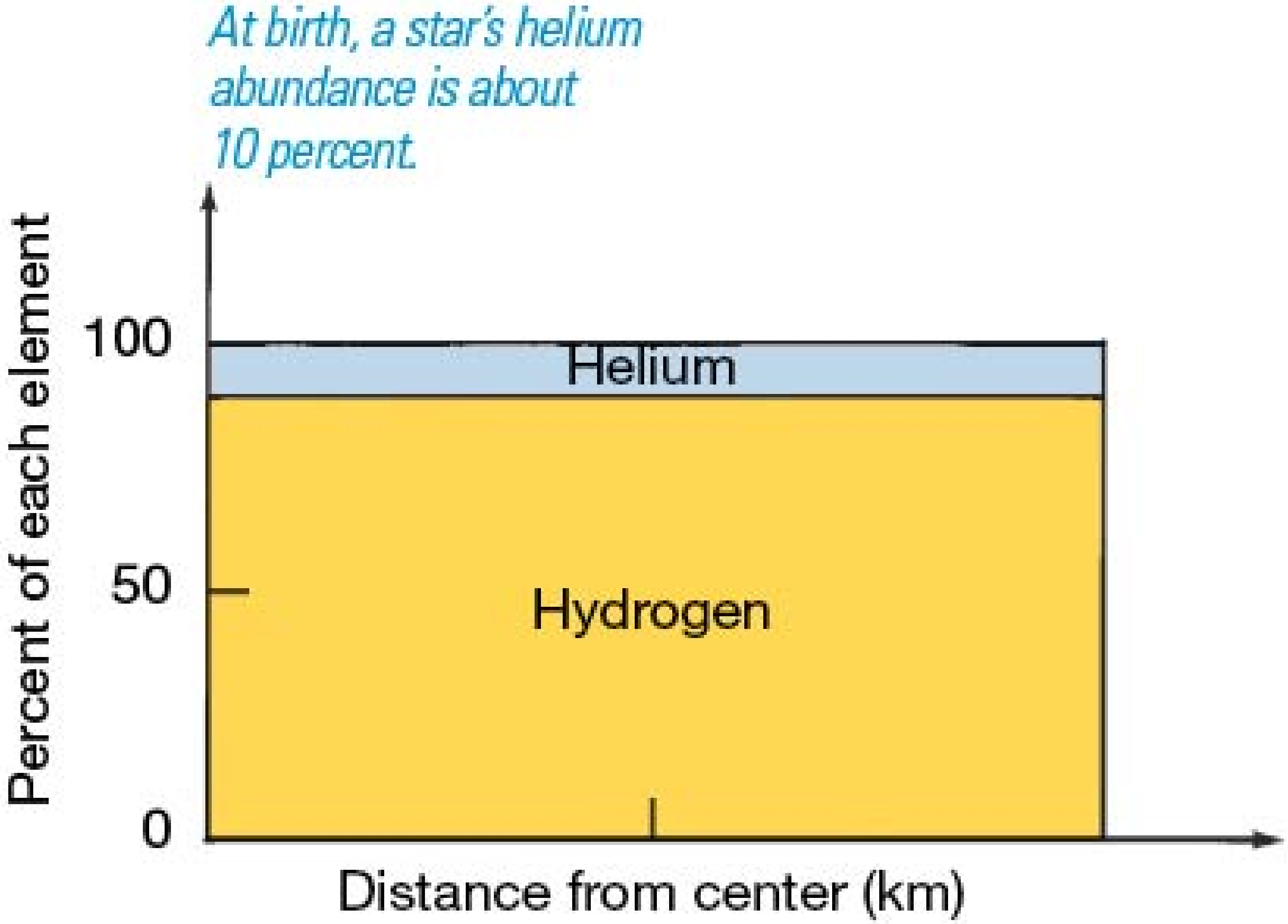
EVOLUTION OF A SUN-LIKE STAR



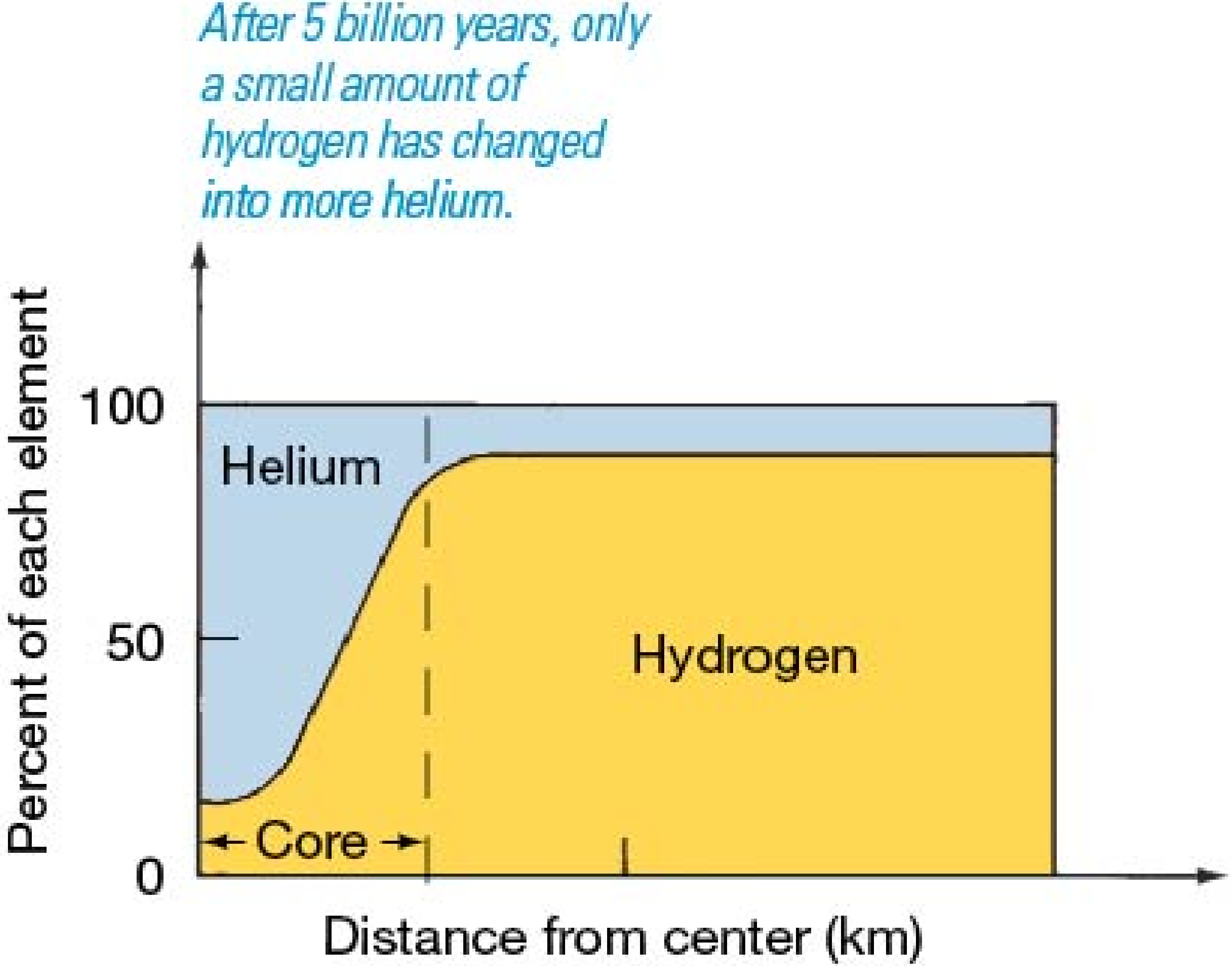
A "Sun-Like" Star

- Spends a few 10s of millions of years in the formation stages (Stages 1-6)
- Spends about 10 billion years on the Main Sequence
- Burns Hydrogen for most of its life…
  - As the star nears the end of its life, this fact changes and trigger a host of events that lead to a fork in the road – a final set of paths that, so far as we know, decides the final fate of a Sun-like star.

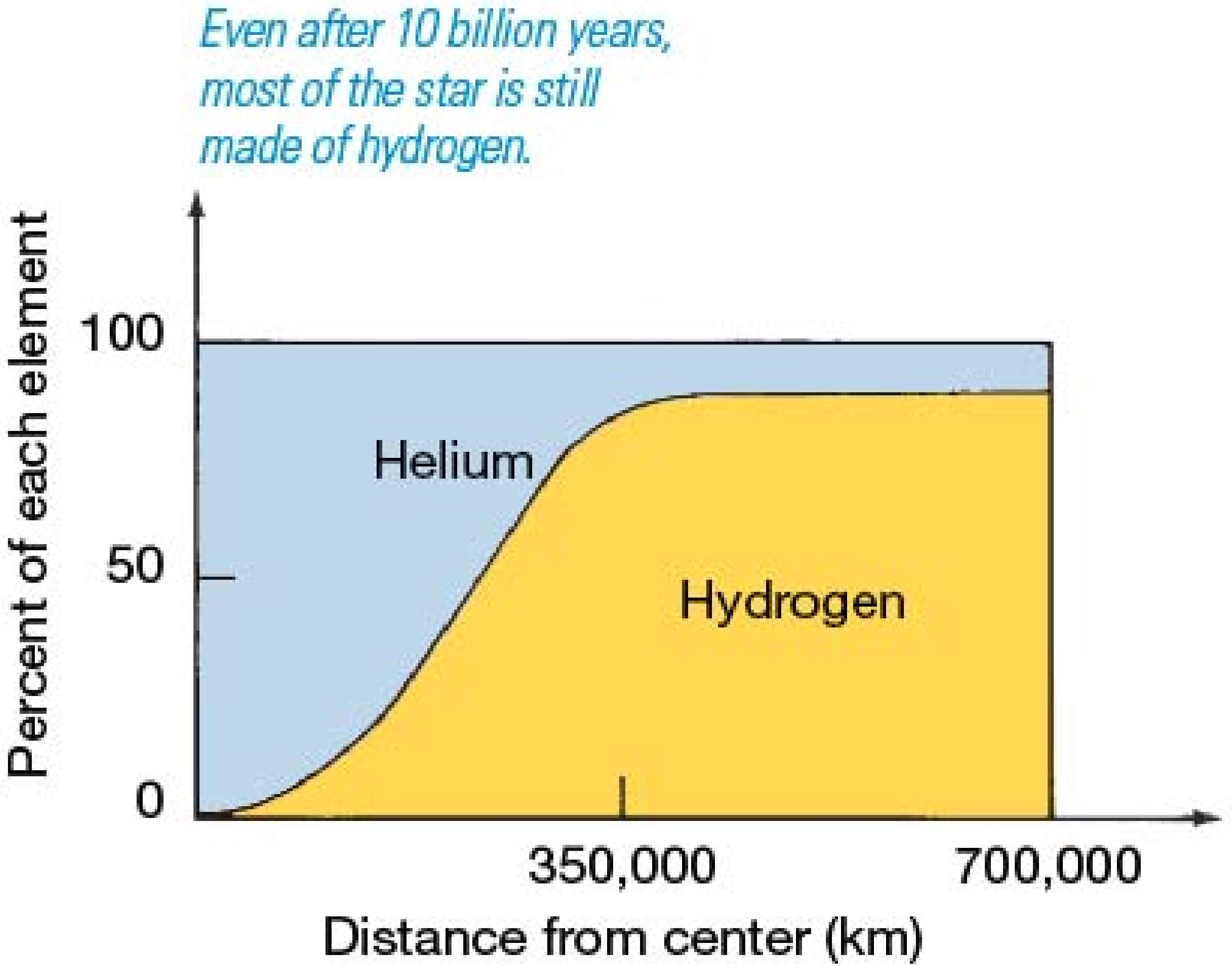
Hydrogen Burning and Aging

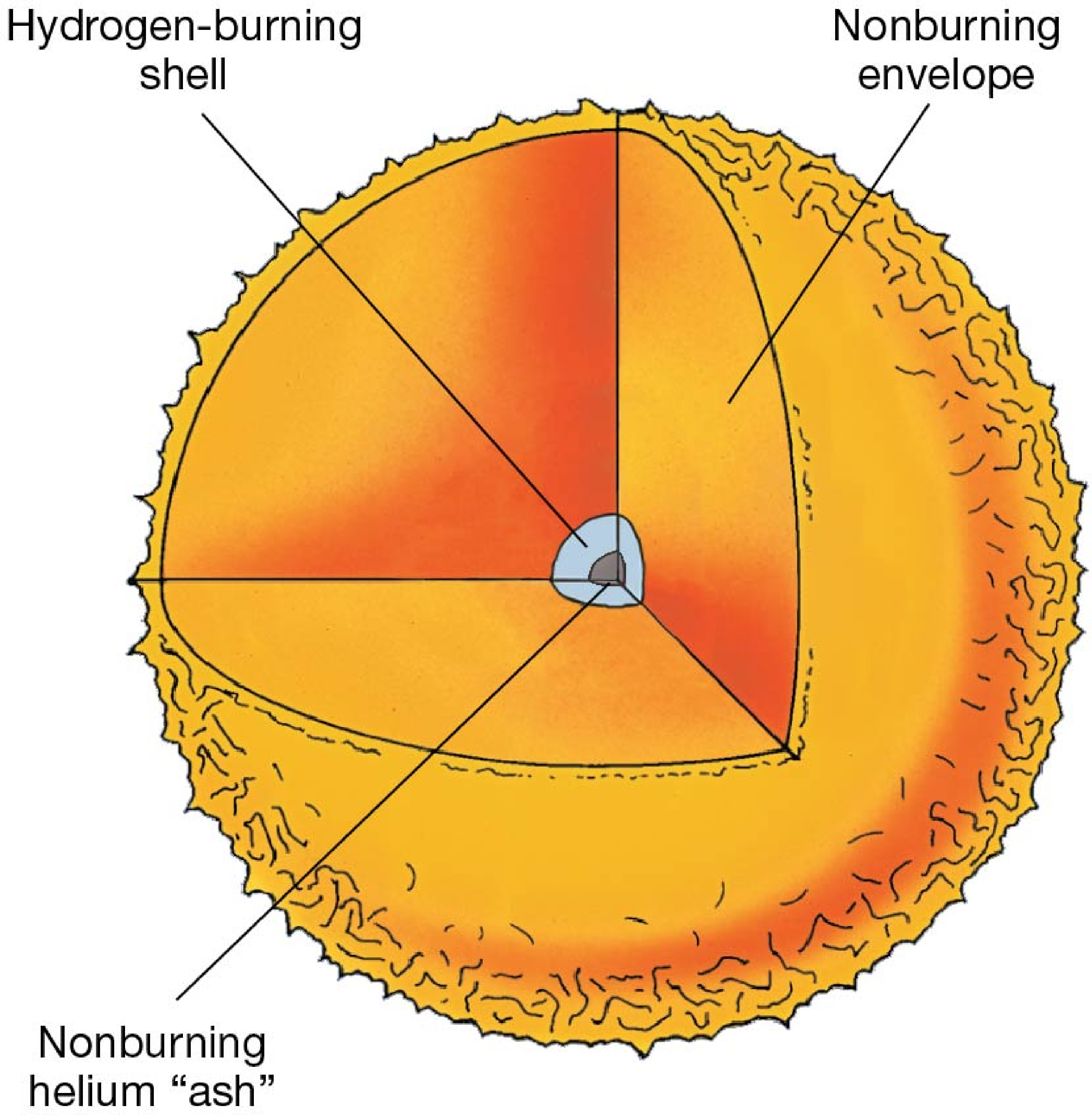


Hydrogen Burning and Aging



Hydrogen Burning and Aging

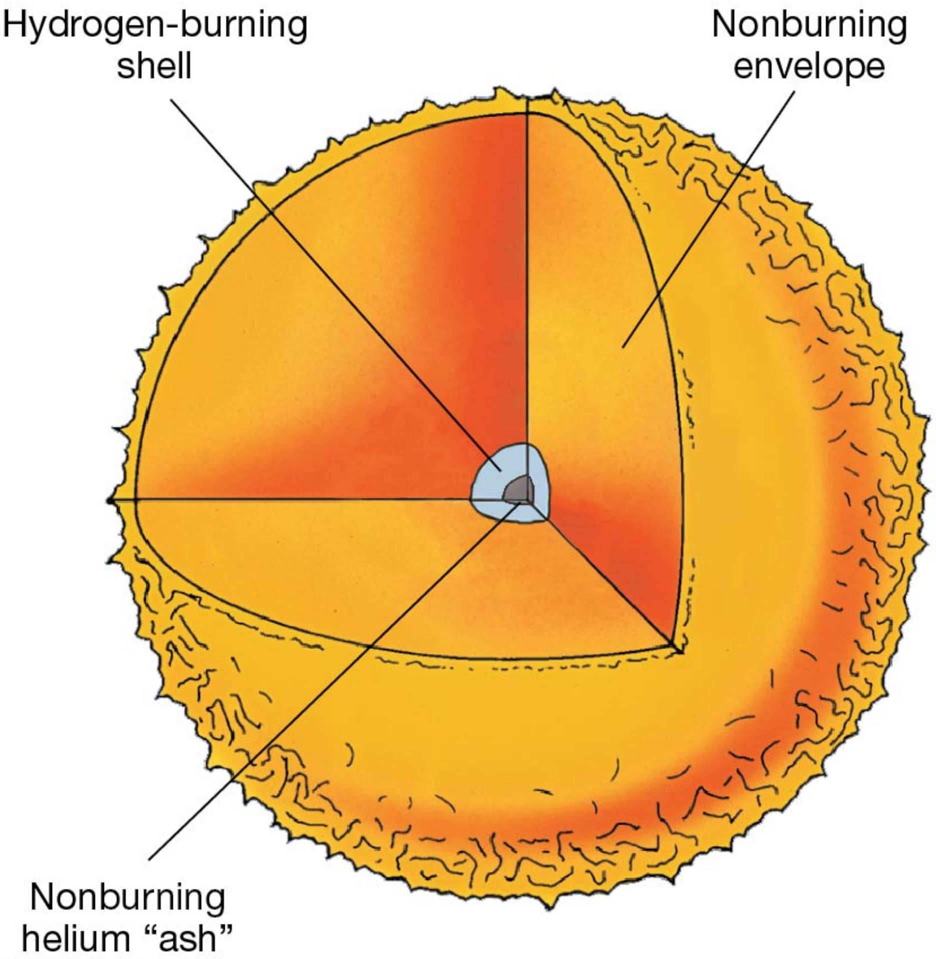




- Helium accumulates in the core, where H is converted to He the fastest.
- Helium can fuse, but only at 100,000,000K – 10× hotter than the core at this point.
- A non-burning “Helium Ash” builds up.

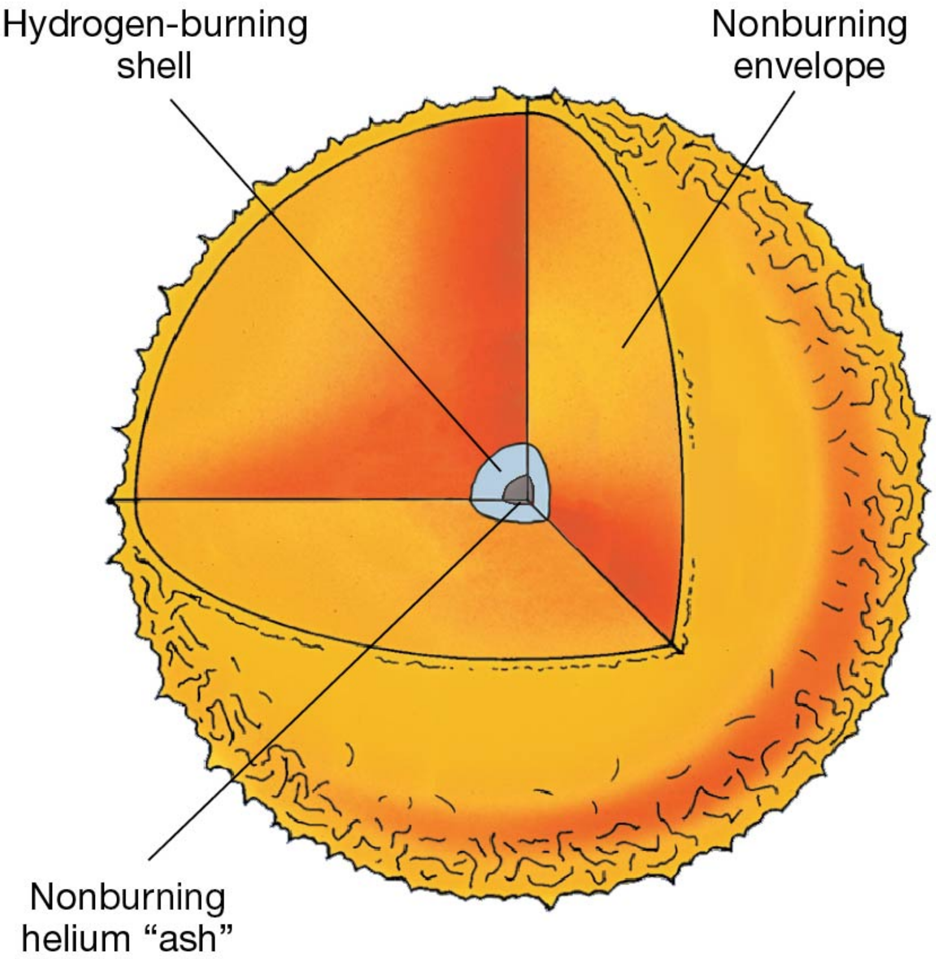
Stages 8 and 9

- Recall from the lecture on the Sun that the radiation pressure exerted by the core balances with the gravitational self-attracting that wants to collapse the star.
- As non-burning Helium accumulates in the core, the outward radiation pressure lessens.
- What happens next, do you think?
  - *The star begins to shrink*
- What happens to the temperature at the core of the star as it compresses under gravitational pressure?
  - *It heats up – very fast – and the shell of Hydrogen around the core begins to burn VERY FAST.*



Stages 8 and 9

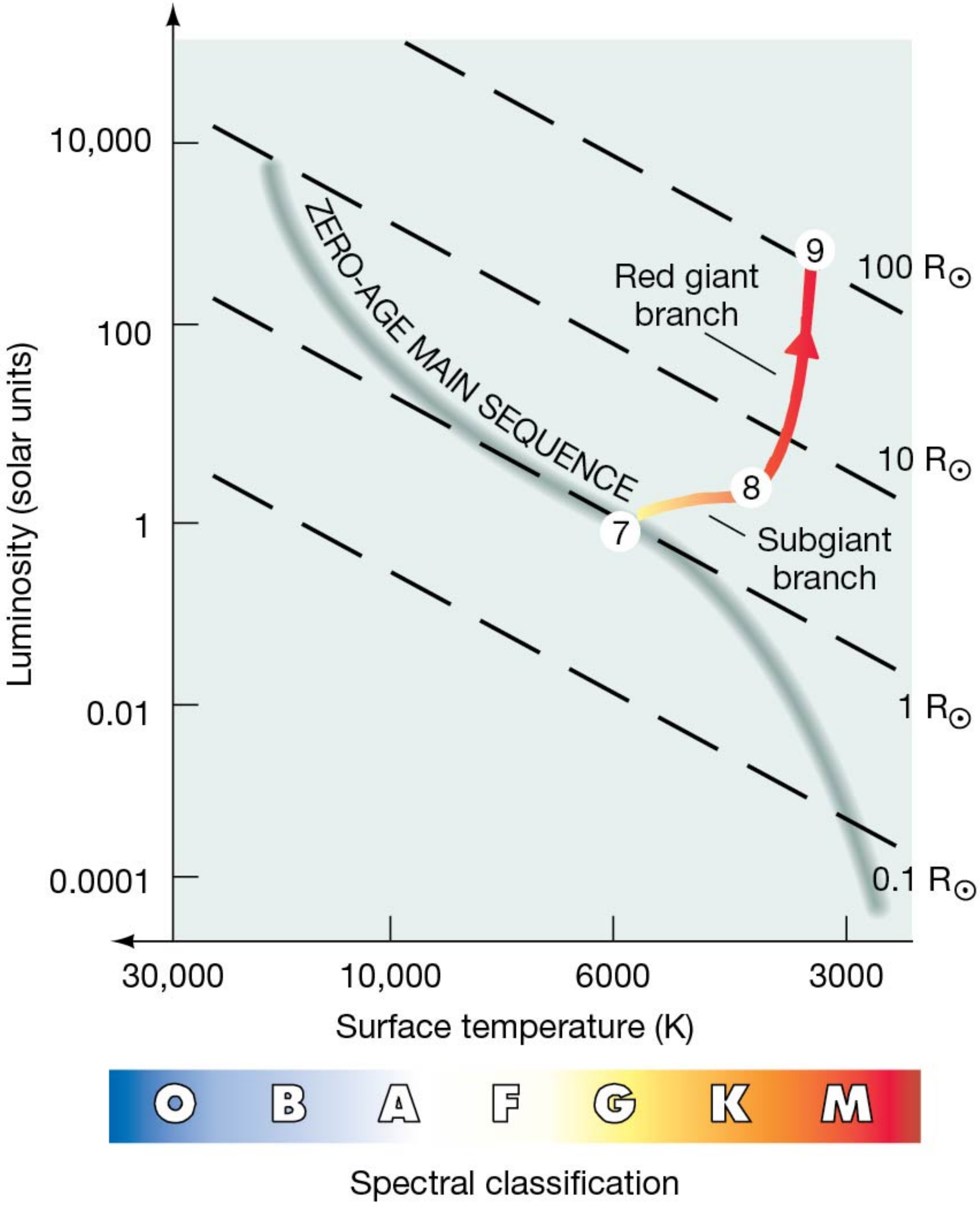
- The core is now burning Hydrogen faster than ever.
- What happens next as a result of all that new and increased Hydrogen burning?
  - *The star begins to expand – radiation pressure beats gravitational inward pressure and the star's size expands to about 3 times its original radius.*
- At this stage (Stage 8) it is a subgiant star – its temperature is lower at the surface as it expands and cools there, but its brightness is about the same owing to a higher rate of Hydrogen burning.
- Over 100 million years, the star continues to expand (Stage 9) to as much as 100-times its original size. It grows brighter, though its surface temp. is constant.



Stage 9: Red Giant

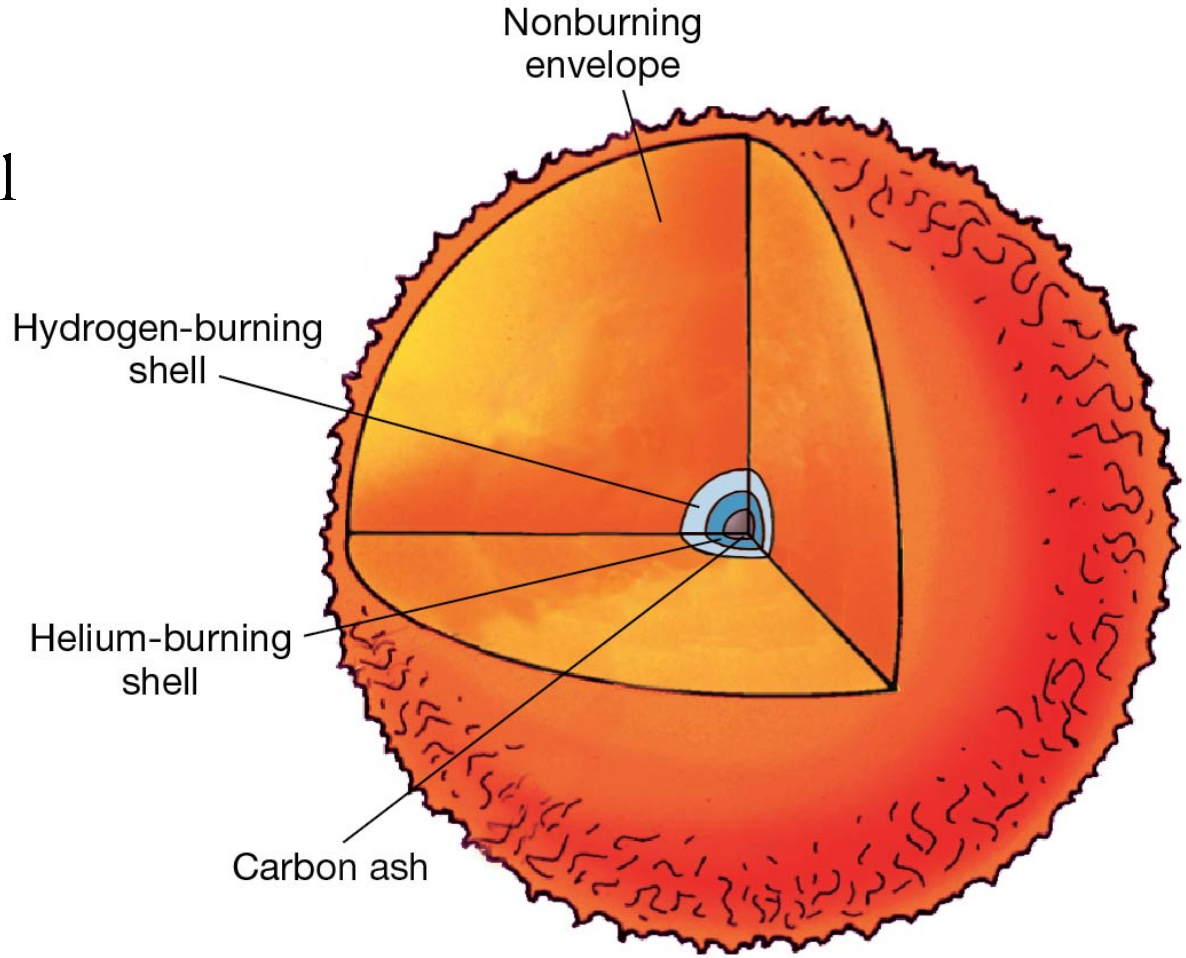
- Meet Arcturus, 37 light-years from Earth and currently visible from Taos above McGaffey Ridge in the western sky. It is bright... very bright. It’s one of the first stars you can see at night after the sun sets.
- It is presently in its Red Giant phase. Its present mass is 1.5 times that of our own Sun. Its radius is presently 21 times that of the Sun. It emits 160 times more energy than the Sun, much in the infrared.

Main Sequence → Stages 8+9



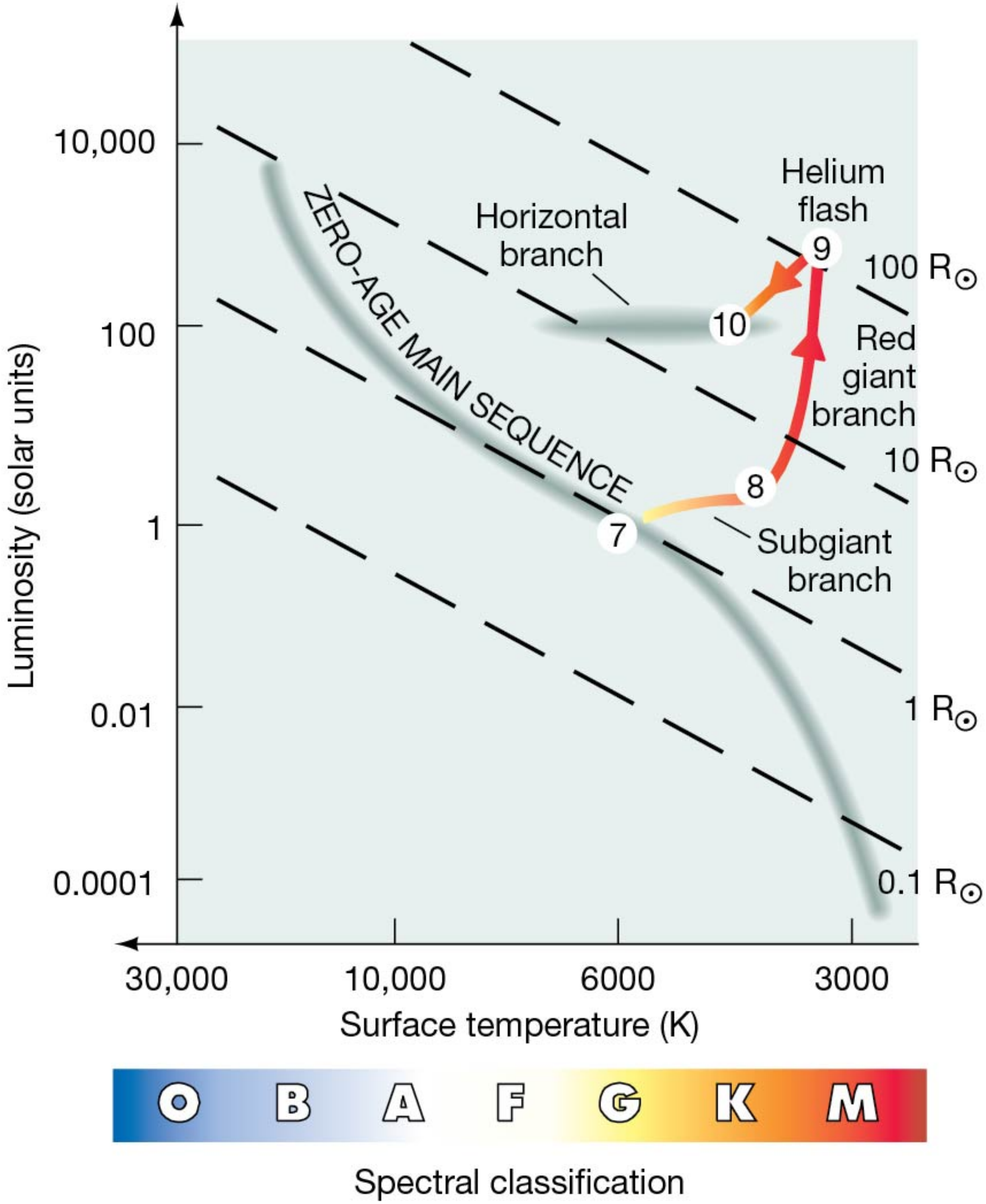
Stage 10: Helium Fusion

- While all of this expansion has been going on, the heavy Helium core has been contracting, growing smaller and hotter under gravitational inward pressure
- 100 million years after leaving the Main Sequence, the temperature in the core becomes hot enough to fuse Helium – this leads to "Helium Flash", a runaway explosion that lasts a few hours and causes the core to expand.



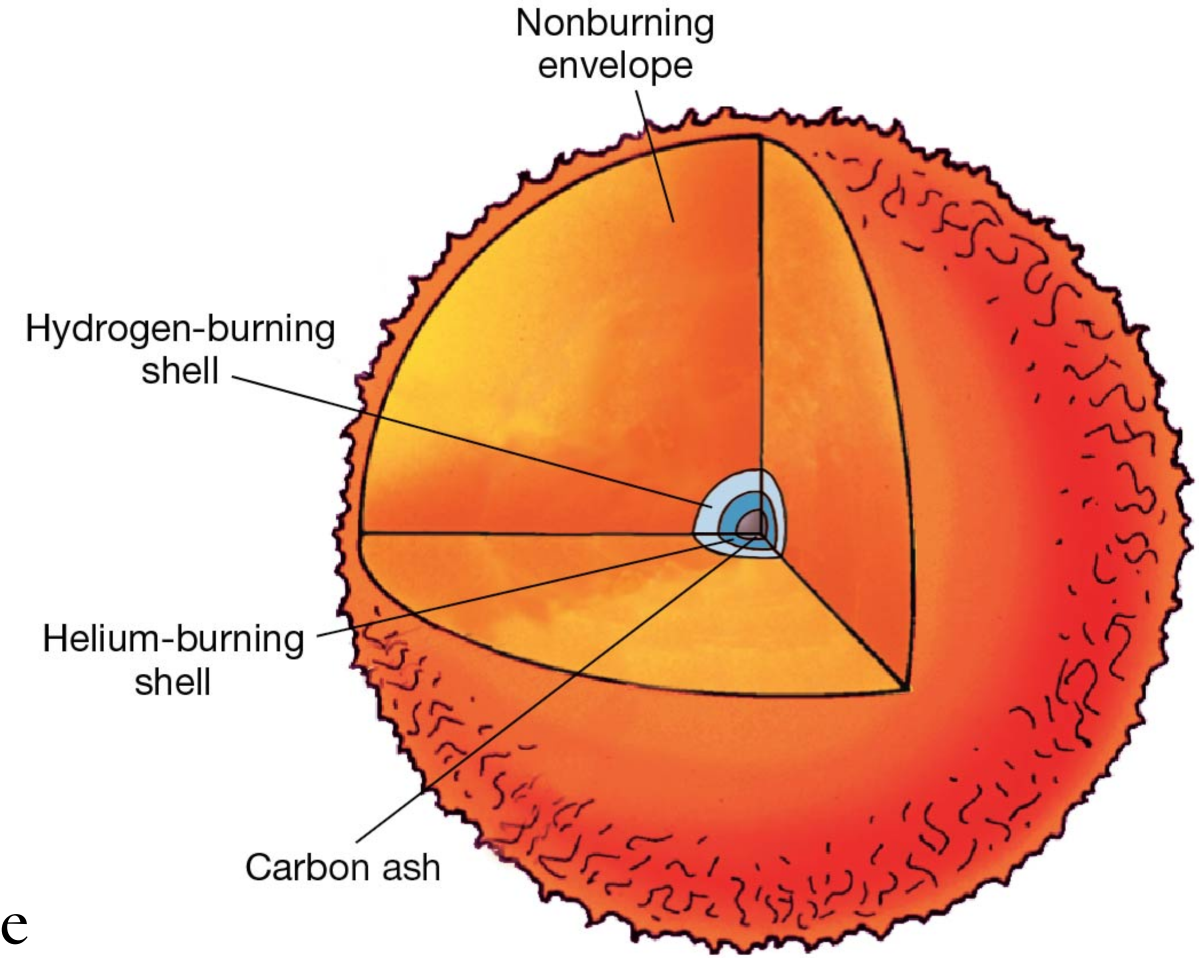
Stage 10: Helium Fusion

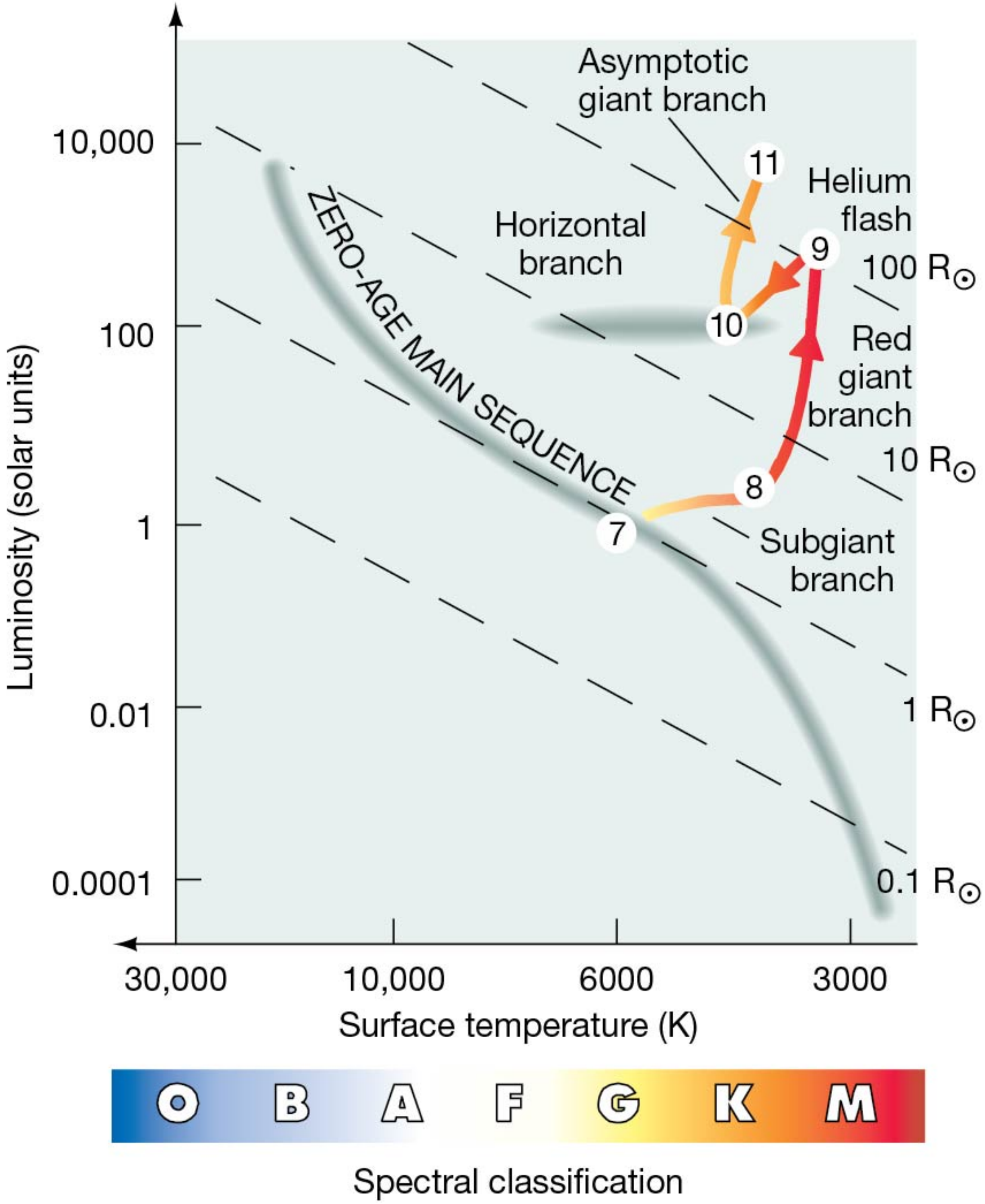
- Helium flash and then steady Helium burning thereafter increases the temperature of the star (it becomes more blue in appearance). The core expands under this pressure and overall energy output drops.
- This puts it on something called the "horizontal branch" of the H-R Diagram, where a Helium-burning star will remain for a long time.
- At this stage, a star can shed 20-30% of its mass due to strong solar winds.



Stage 11: Red Giant (Again)

- Helium burning yields Carbon. A non-burning Carbon core develops, contracting as it grows in quantity. The cycle repeats again.
- Helium burning increases in the shell around the carbon core, achieving burning rates that are MUCH FASTER than in the original H → He process. The star expands again.
- This leads the star up to Stage 11 – a Red Giant once more.




Asymptotic giant branch
11
Helium flash
9
100 R⊙
Horizontal branch
10
Red giant branch
10 R⊙
ZERO-AGE MAIN SEQUENCE
8
7
Subgiant branch
1 R⊙
0.1 R⊙
10,000
100
1
0.01
0.0001
Luminosity (solar units)
30,000
10,000
6000
3000
Surface temperature (K)
O
B
A
F
G
K
M
Spectral classification

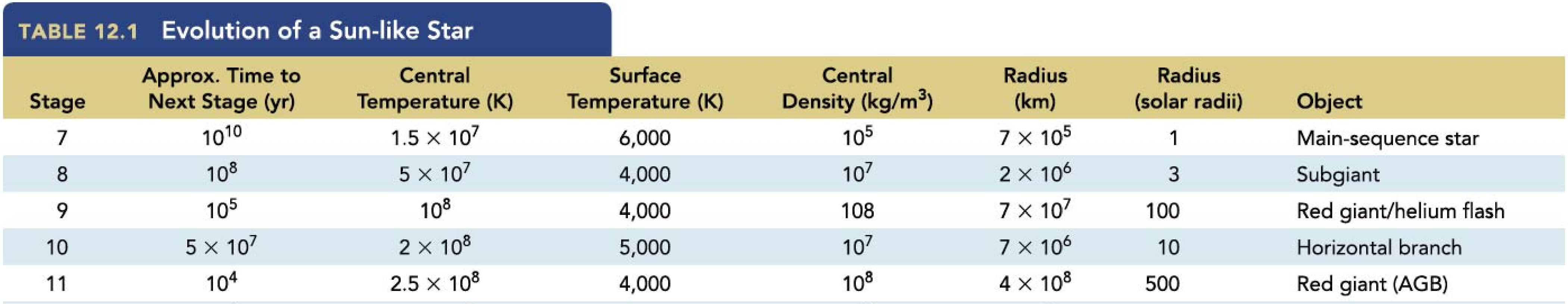
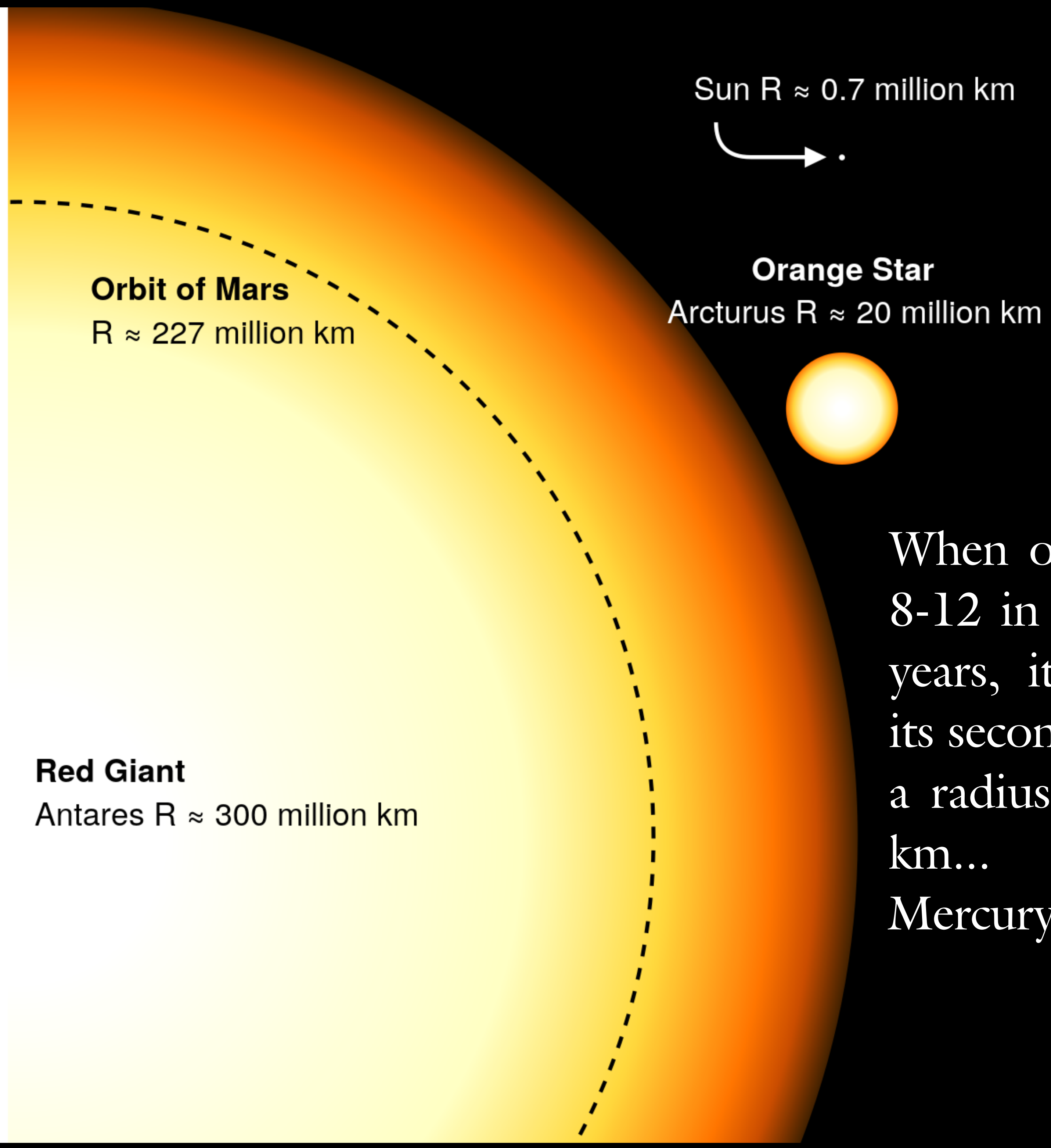


TABLE 12.1 Evolution of a Sun-like Star

Stage	Approx. Time to Next Stage (yr)	Central Temperature (K)	Surface Temperature (K)	Central Density (kg/m^3)	Radius (km)	Radius (solar radii)	Object
7	10^{10}	1.5×10^7	6,000	10^5	7×10^5	1	Main-sequence star
8	10^8	5×10^7	4,000	10^7	2×10^6	3	Subgiant
9	10^5	10^8	4,000	108	7×10^7	100	Red giant/helium flash
10	5×10^7	2×10^8	5,000	10^7	7×10^6	10	Horizontal branch
11	10^4	2.5×10^8	4,000	10^8	4×10^8	500	Red giant (AGB)

The table above from the textbook summarizes the details of the transition from Stage 7 to Stage 11:

- Stage 7: a long, 10-billion year life as a Main Sequence Star
- Stage 8: a contracting Helium-rich core speeds burning of Hydrogen around the core, and the star expands to a Subgiant, about 3× the size of our Sun. This takes 100 million years.
- Stage 9: expansion continues for 10,000 more years as the star enters its Red Giant phase, expanding to 100 Solar radii.
- Stage 10: The Helium core kept contracting, and heats – Helium fusion begins first in a violent flash that ends the Red Giant phase. The star contracts to only 10 Solar radii. This process takes 50 million years.
- Stage 11: A carbon core develops from Helium burning. As it contracts, Helium burning increases and the star expands into a second Red Giant phase. This takes 25 million years.

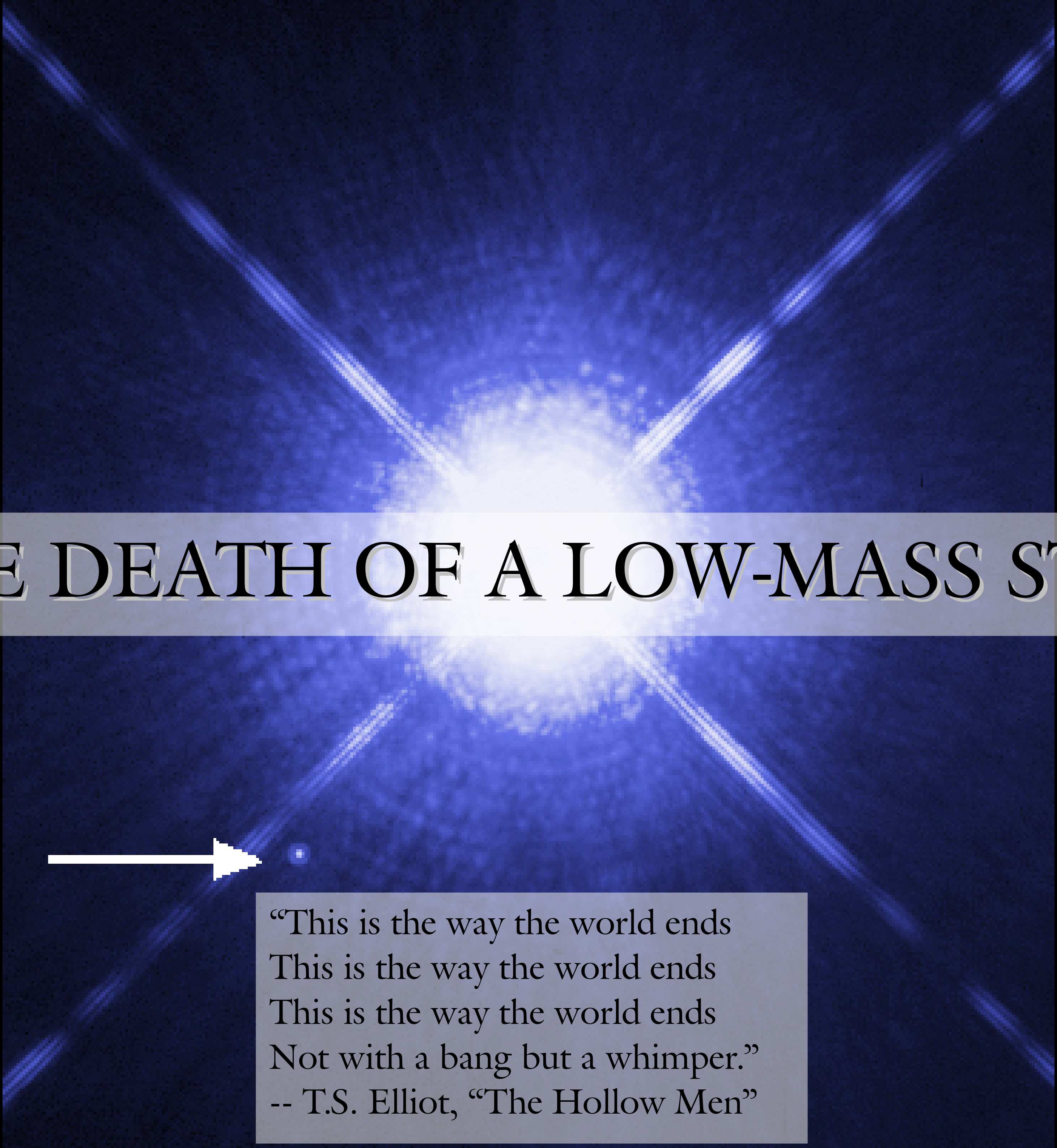


When our Sun enters Stages 8-12 in about 5 billion more years, it will expand during its second Red Giant phase to a radius of about 70 million km… this will engulf Mercury.

What Happens Next?

- Determined by its mass.
- A “**Low-Mass**” **Star** (like our Sun) is determined by having a mass that is about **8 times the Sun or LESS**.
- A “**High-Mass**” **Star** is the complement – having a mass that is **8 times the Sun or MORE**
  - It’s important to note that we’re talking about the mass the Sun has when it leaves the Main Sequence, and not afterward. This is important for reasons we’ll discuss later.

THE DEATH OF A LOW-MASS STAR

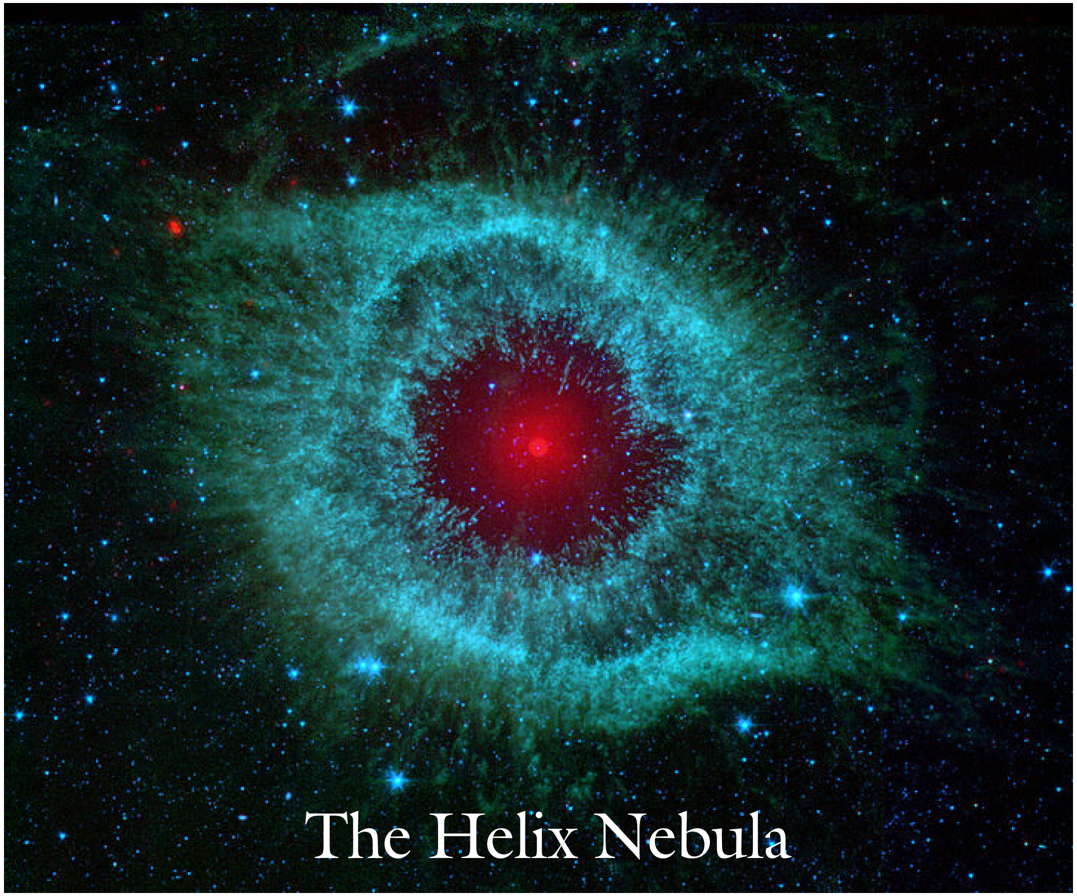


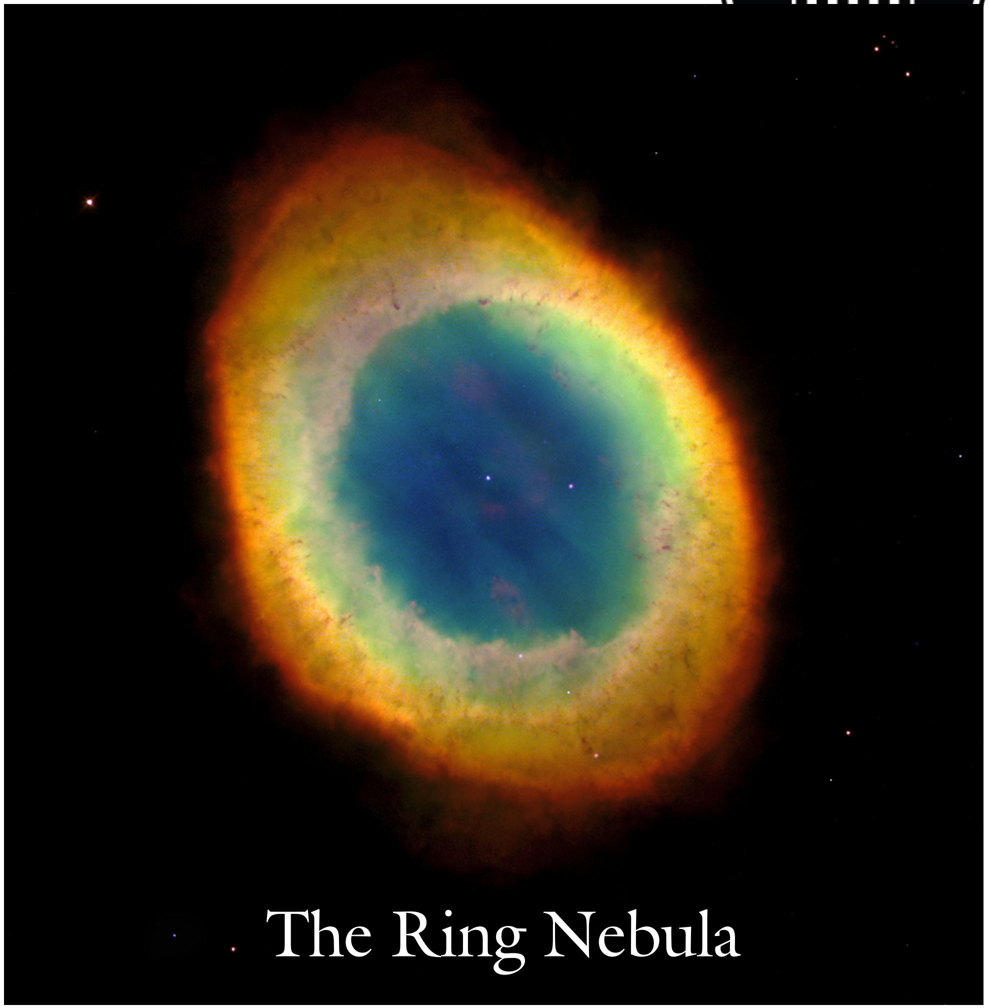
“This is the way the world ends
This is the way the world ends
This is the way the world ends
Not with a bang but a whimper.”
-- T.S. Elliot, “The Hollow Men”

The Next Stages

- You might think that the carbon core will now contract, and a new cycle of fusion burning of carbon will begin. Alas, for a low-mass star, it is not to be – the masses are just not high enough to trigger this.
- Final Stages:
  - Stage 12 – A Planetary Nebula
  - Stage 13 – A White Dwarf
- These will be the likely fate of the Sun.

Stage 12: Planetary Nebula


The Helix Nebula

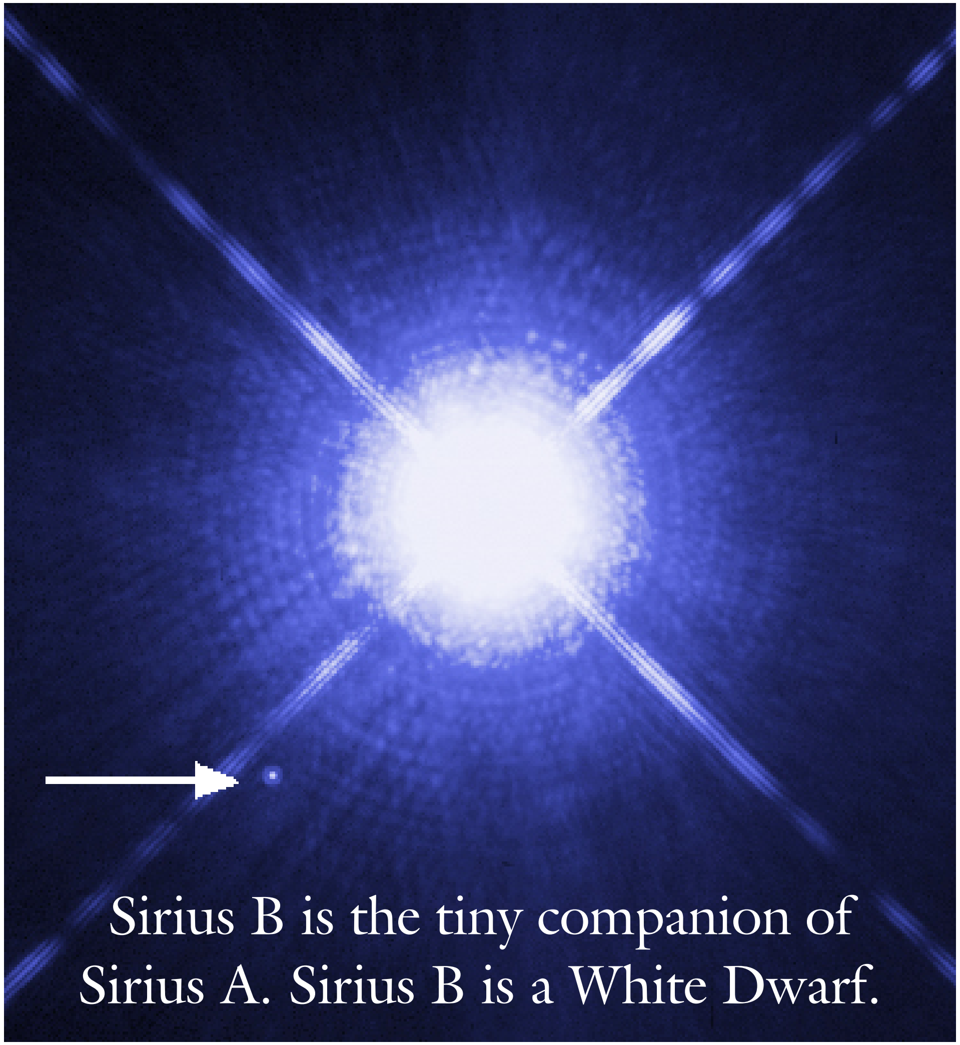

The Ring Nebula

The core contracts, and its intense radiation pushes the outer envelope of the star away. They part ways, resulting in a “planetary nebula”. This is a misnomer – old nomenclature – it has nothing to do with planet formation.

Stage 13: White Dwarf

As the core of the former Red Giant star contracts, it begins to heat – if the core were heavier, owning to having come from a high-mass star, this would have led to Carbon Fusion… but that cannot happen here.

For the low-mass star, a new kind of pressure prevents the collapse of the core and prevents, in turn, carbon-fusion: electrons in the core get so close that they begin to push back hard – no two electrons can be compelled to occupy too confined a space. This ceases the collapse.

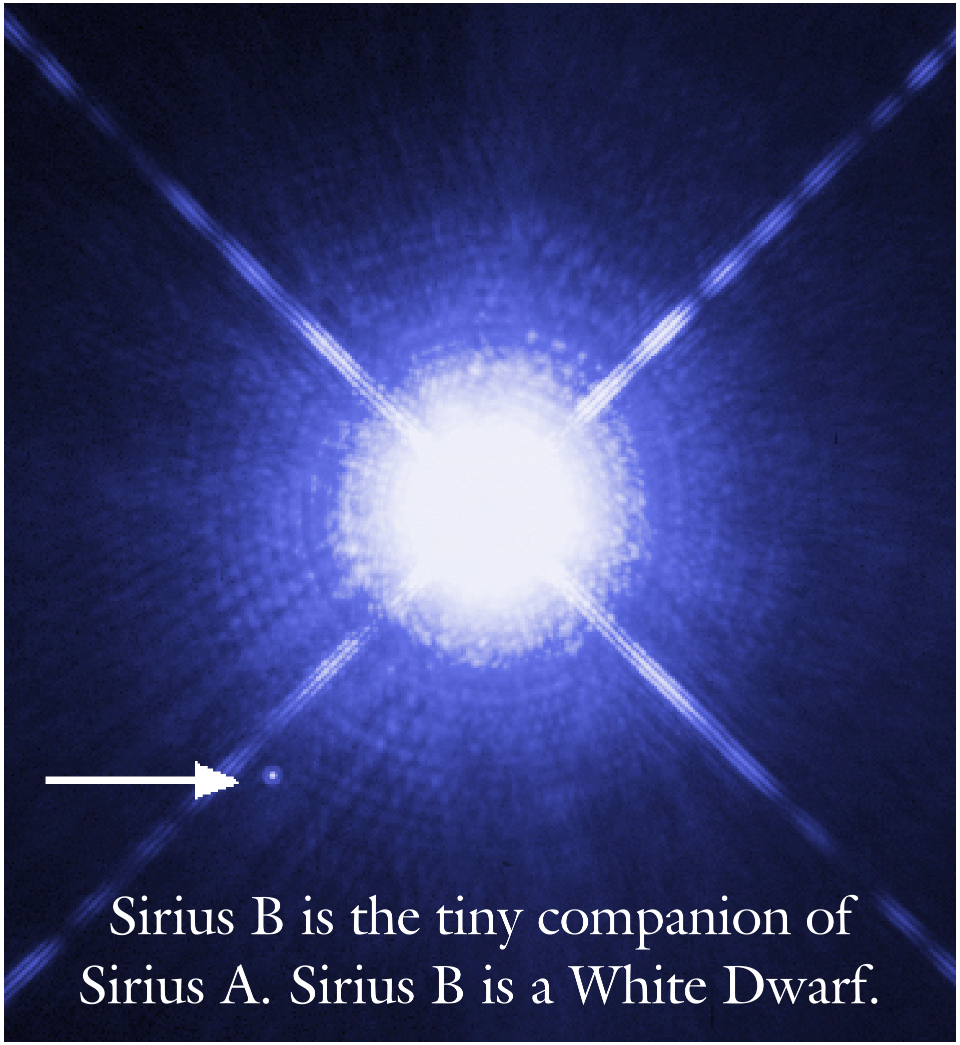


Sirius B is the tiny companion of Sirius A. Sirius B is a White Dwarf.

Stage 13: White Dwarf

The Carbon Core of the star becomes visible as the envelope around it (the nebula) dissipates over time. This core is white-hot when revealed, and is only hard to see because of its extremely small size.

This is now the “White Dwarf” stage of a Sun-like low-mass star. A White Dwarf is nearly the same size as a planet, like Earth. Sirius B is an example of a White Dwarf whose nebula envelope is long gone.

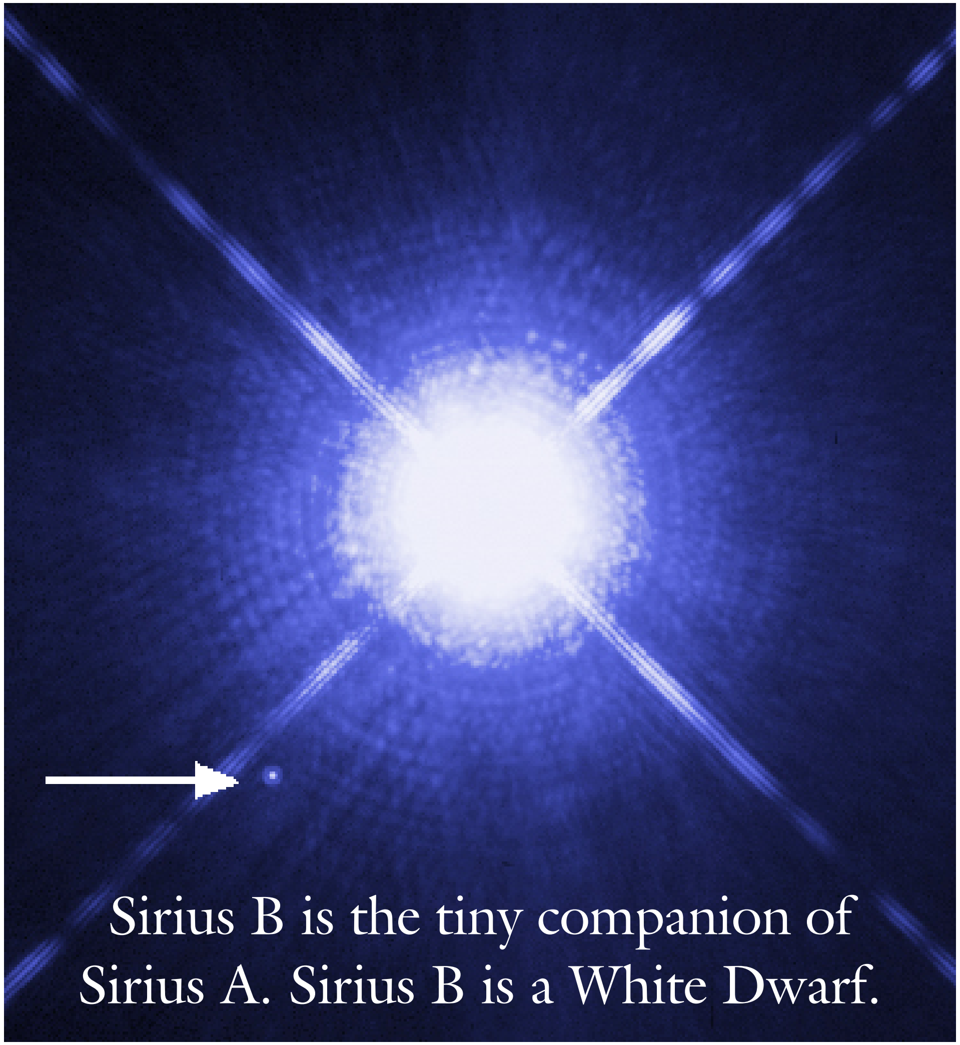


Sirius B is the tiny companion of Sirius A. Sirius B is a White Dwarf.

Stage 13: White Dwarf

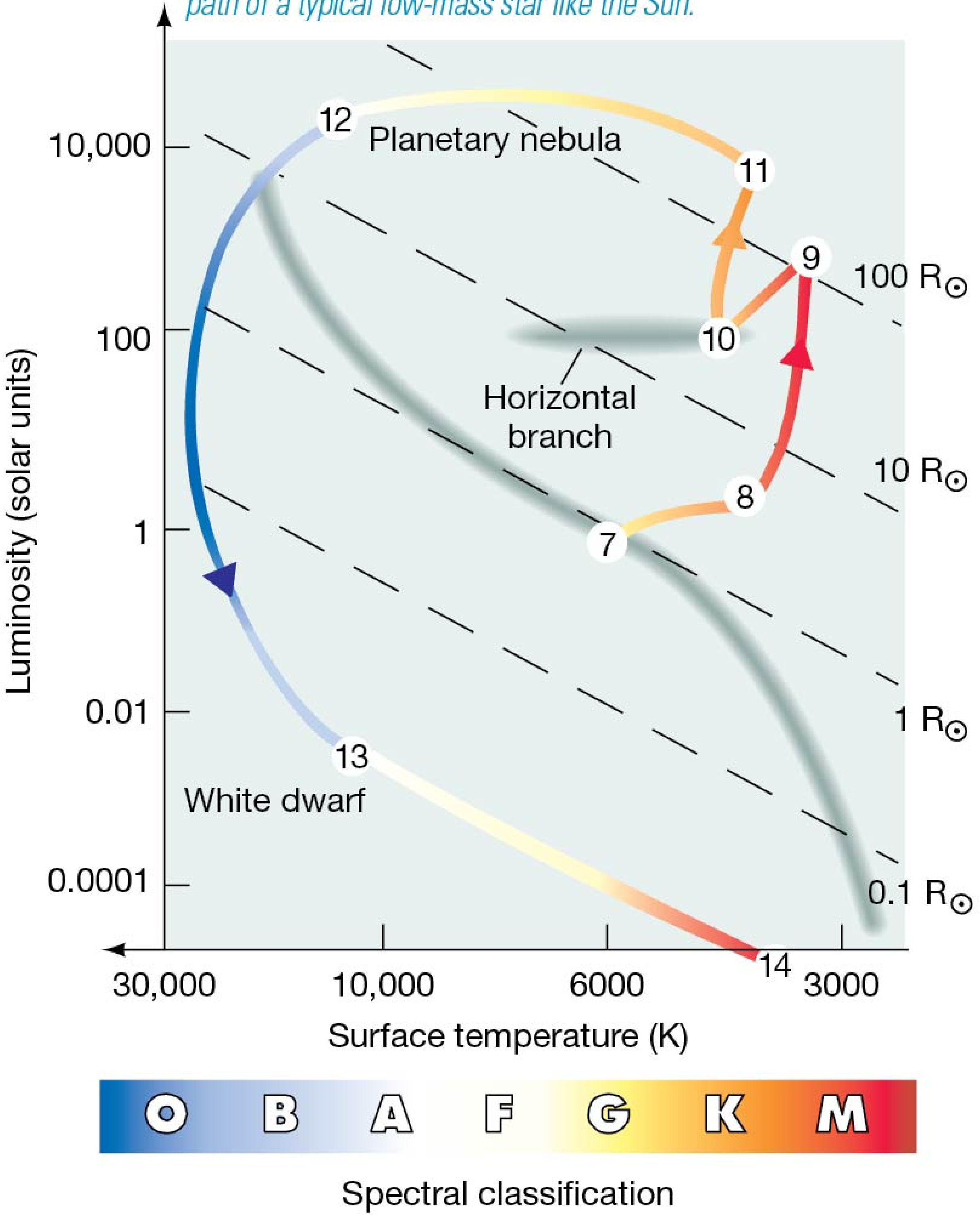
A White Dwarf contains typically carbon and oxygen. It will shine forever, though as it cools its brightness declines along with its temperature. Eventually, after billions of years it can cool to become a "Black Dwarf" - still there, but not visible any longer.

There are no more stages for the low-mass star. After a several hundred million year end-of-life drama, it should then remain forever, if undisturbed, cooling until the end of time.

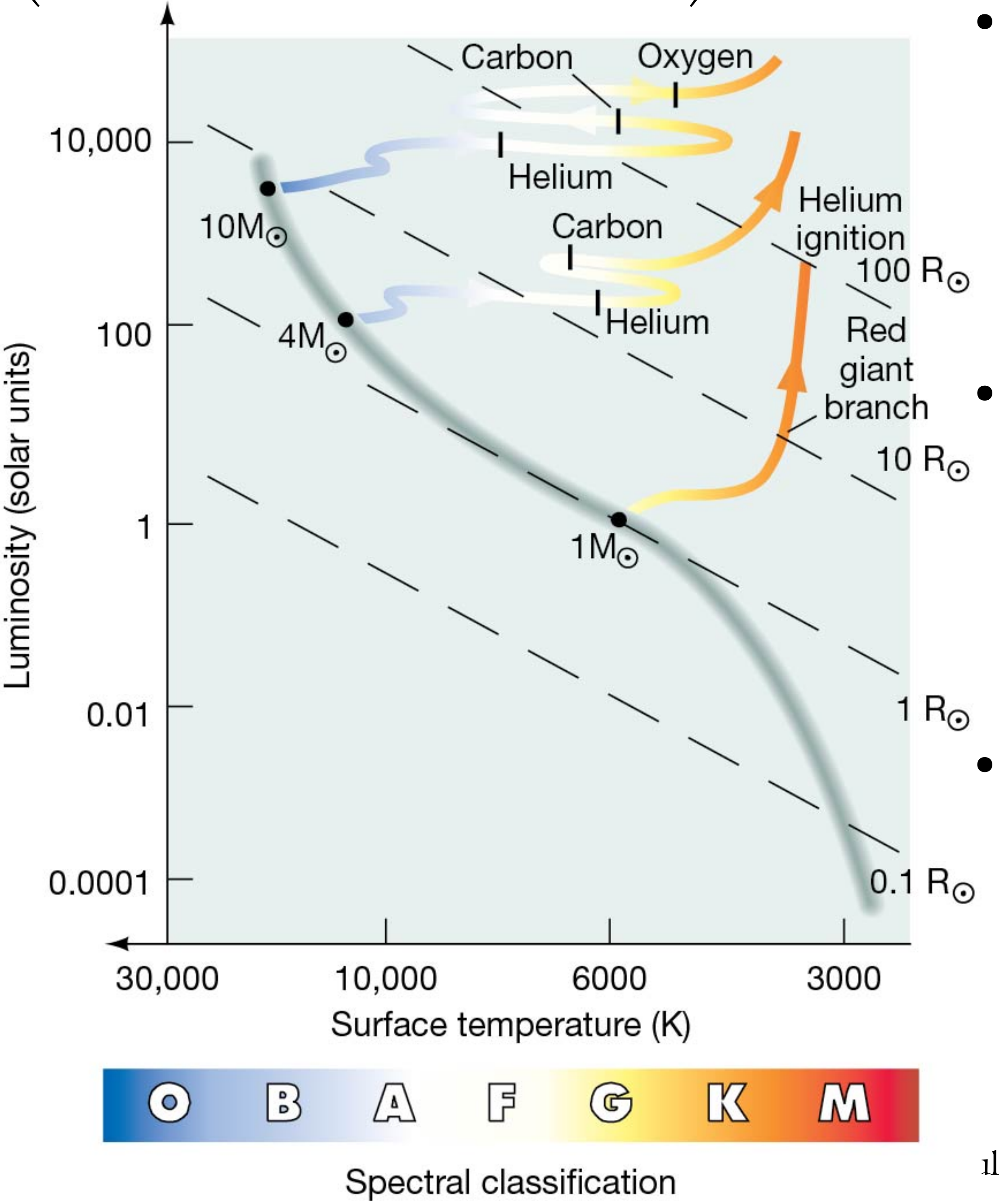


Sirius B is the tiny companion of Sirius A. Sirius B is a White Dwarf.

This diagram illustrates the entire evolutionary path of a typical low-mass star like the Sun.



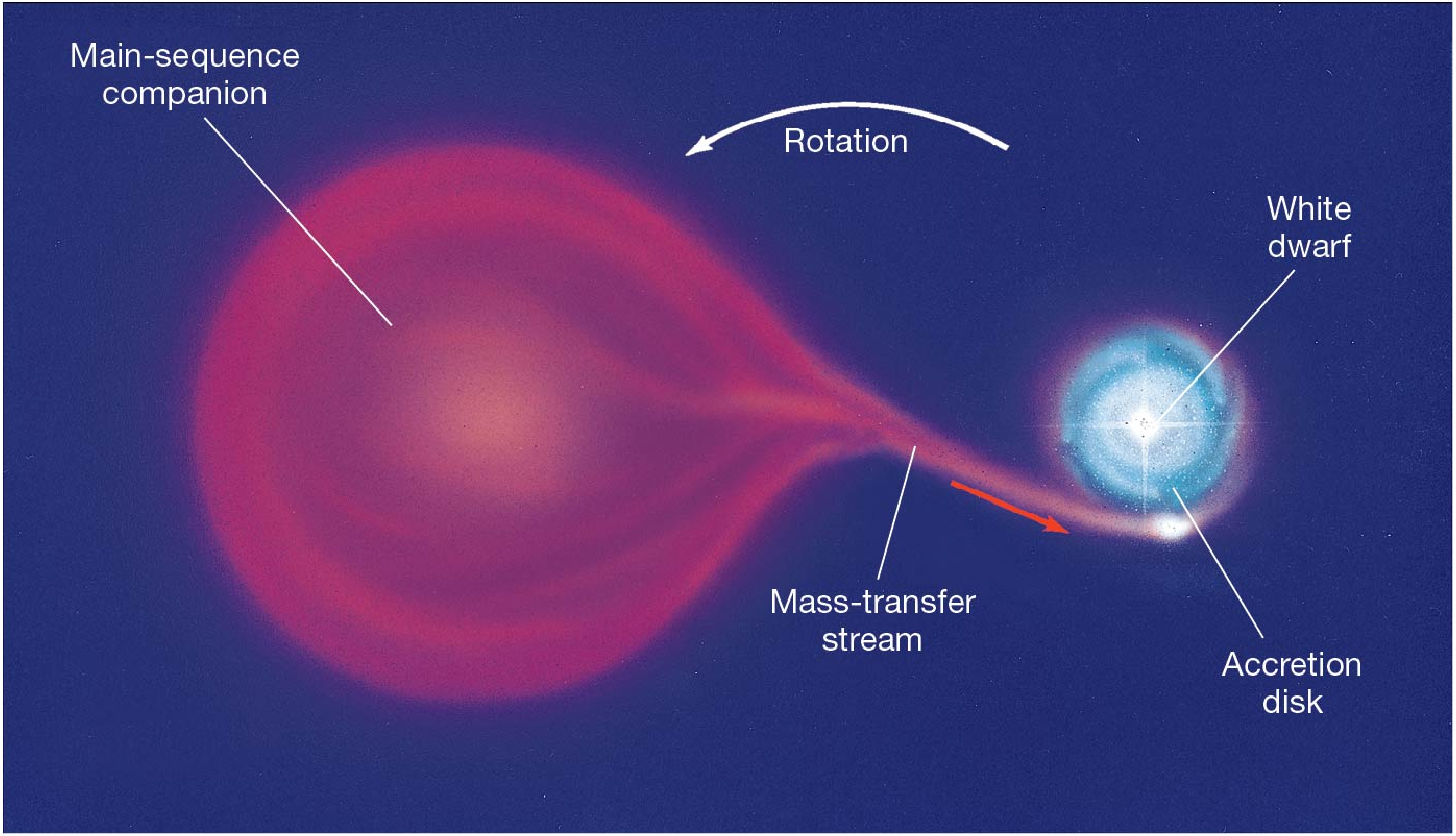
A Star Heavier than the Sun (but still low-mass)



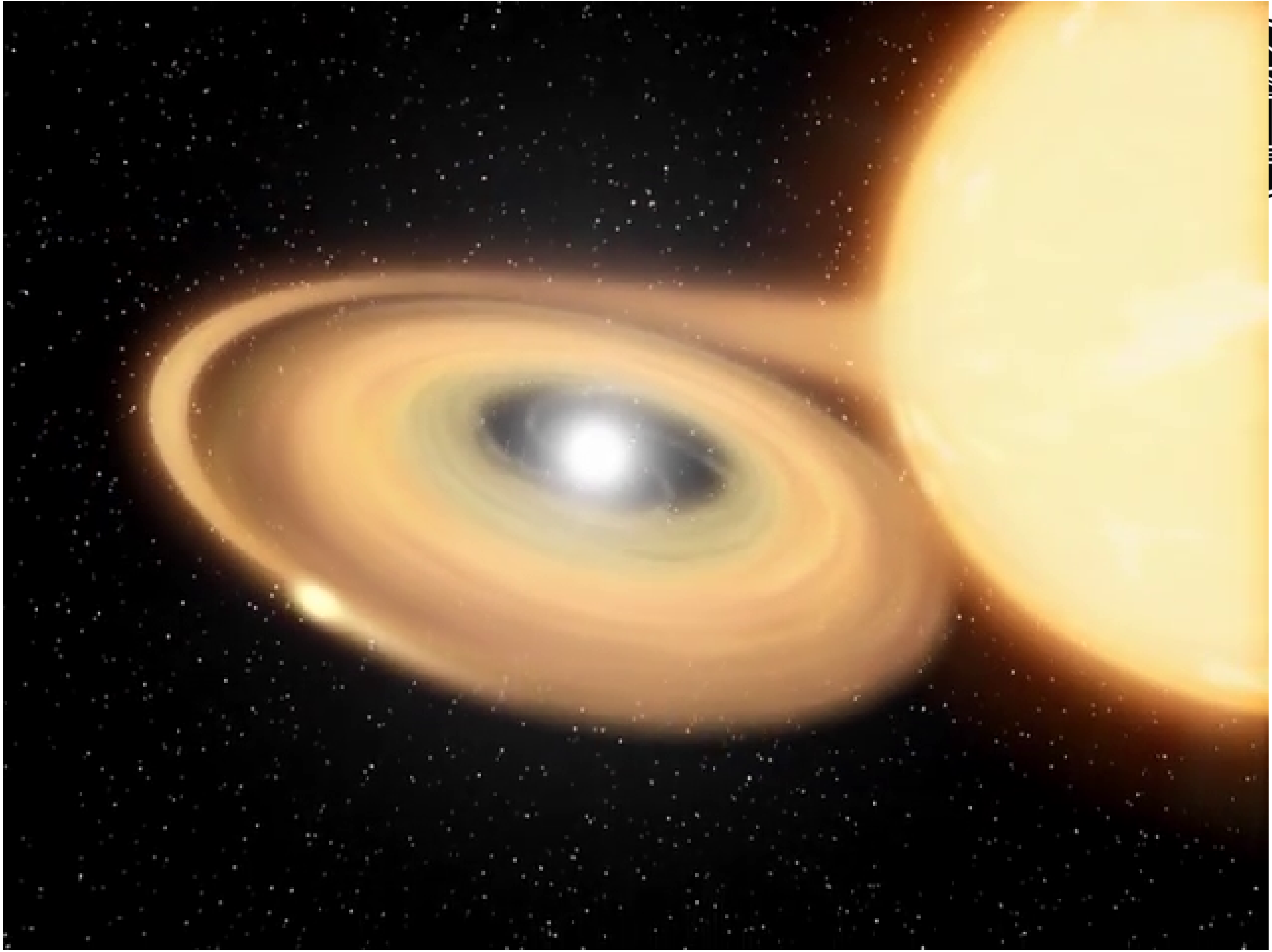
- A star that leaves the Main Sequence with a mass 4× that of the Sun (B-type) is actually heavy enough for Carbon fusion to eventually occur.
- Carbon fuses into Oxygen. However, such a star is not heavy enough, after another cycle to a Red Giant, to then lead to fusion of Oxygen.
- This kind of start then goes into the White Dwarf phase with a core of Carbon and Oxygen ... this leads to a rare Carbon-Oxygen White Dwarf.

A Little More Drama

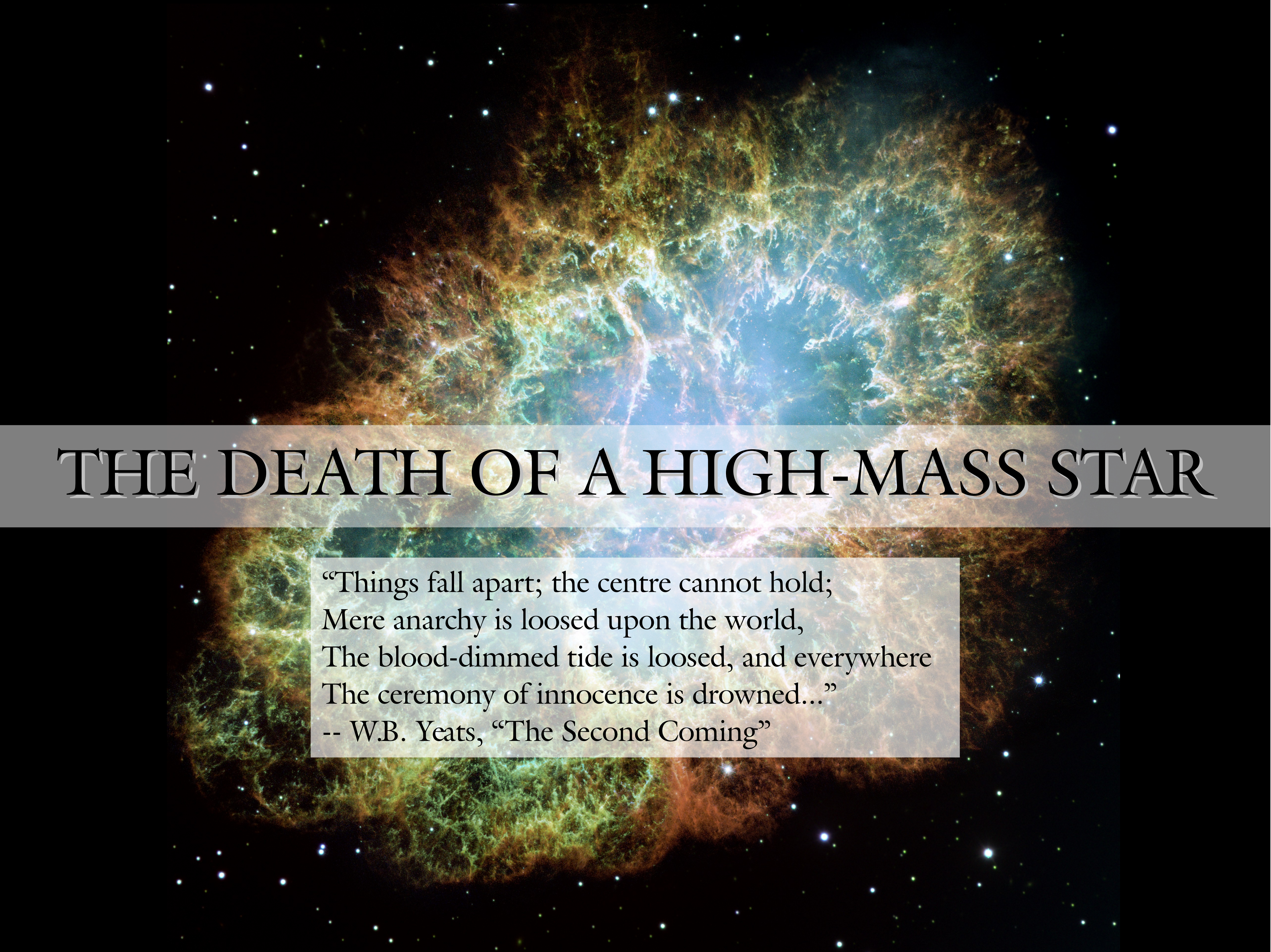
- Binary star systems are quite common in the cosmos
  - Mizar in the "Big Dipper" (the constellation Ursa Major, the "Great Bear") is actually composed of two close "companion" stars orbiting each other.
- A White Dwarf may develop as a companion to a second star, one still on the Main Sequence.
  - If this is the case, there can still be some excitement ahead for a White Dwarf: outbursts of energy called "Novae"



Artists conception of a companion Main Sequence star feeding atmospheric matter onto a White Dwarf. The matter heats to ignition, causing brief increases in luminosity called “Novae”.



Artist's conception of Novae in the Z Camelopardalis System.



THE DEATH OF A HIGH-MASS STAR

"Things fall apart; the centre cannot hold;
Mere anarchy is loosed upon the world,
The blood-dimmed tide is loosed, and everywhere
The ceremony of innocence is drowned..."
-- W.B. Yeats, "The Second Coming"

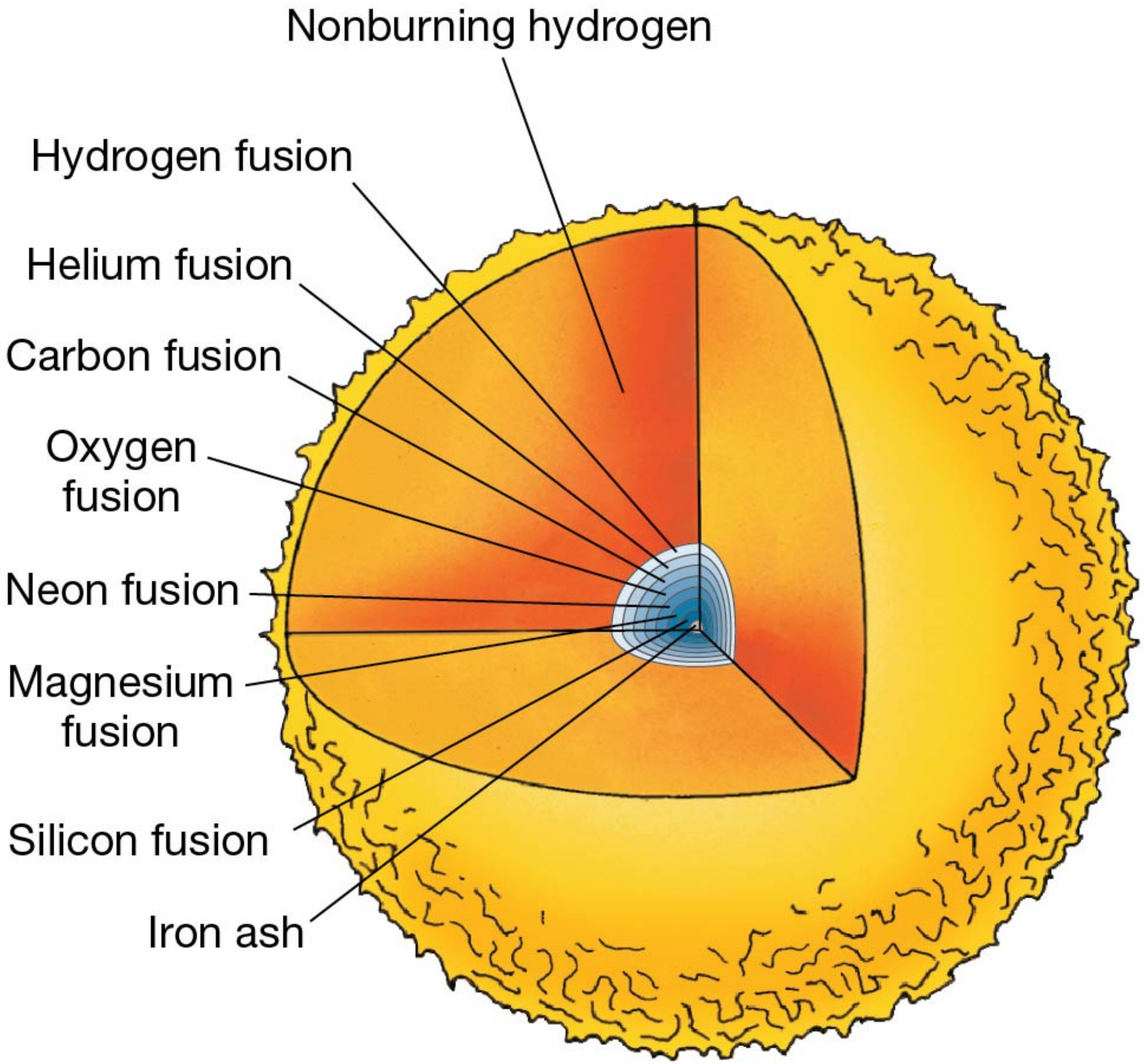
Formation of Heavy Elements

- Sun-mass stars can produce Helium and Carbon in their cores
- At 4-times solar mass, we see that Helium, Carbon, and Oxygen can form.
- At 10-times solar mass, the star is so heavy that when the core contracts after Carbon-burning begins that even the Oxygen ash core can be ignited into fusion
  - Oxygen burning, which occurs at around 1 billion Kelvin, can produce many elements: Silicon, Sulfur, Phosphorus, and Magnesium.
- The heavier the star, the faster it proceeds through burning up its nuclear fuel. For instance, the oxygen in the core of such a heavy star burns away in 5 years or less.

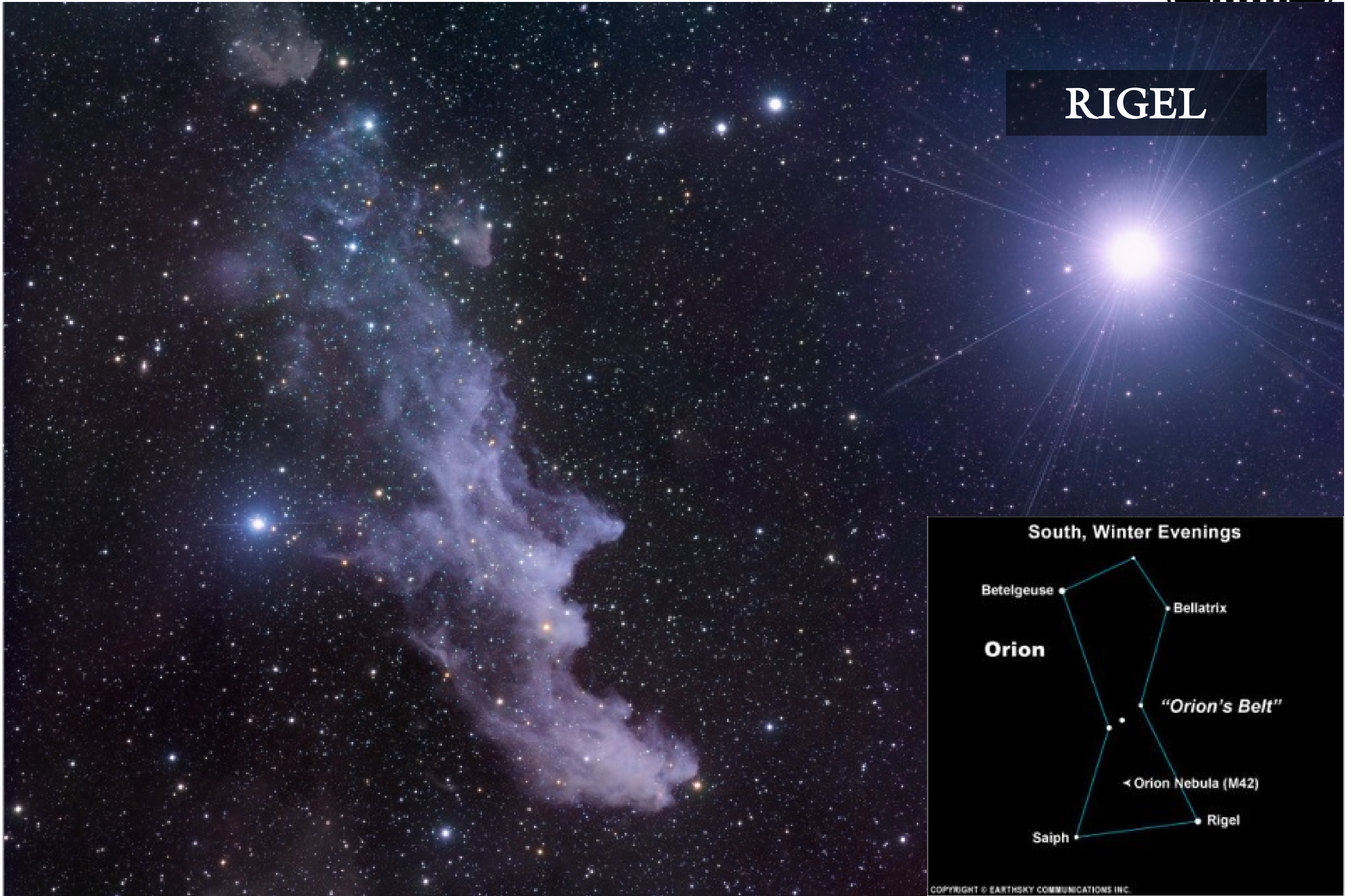
Red Supergiant

For Main Sequence stars with masses 8-times the Sun (or greater), corresponding to O- and B-class stars,they burn so hot and so fast that their lives are much shorter than the lower-mass BAFGKM-class stars.

When they swell at the end of their lives, their cores are already burning at 100 million Kelvin, and they swell to become **Red Supergiants**.



Supergiant Stars



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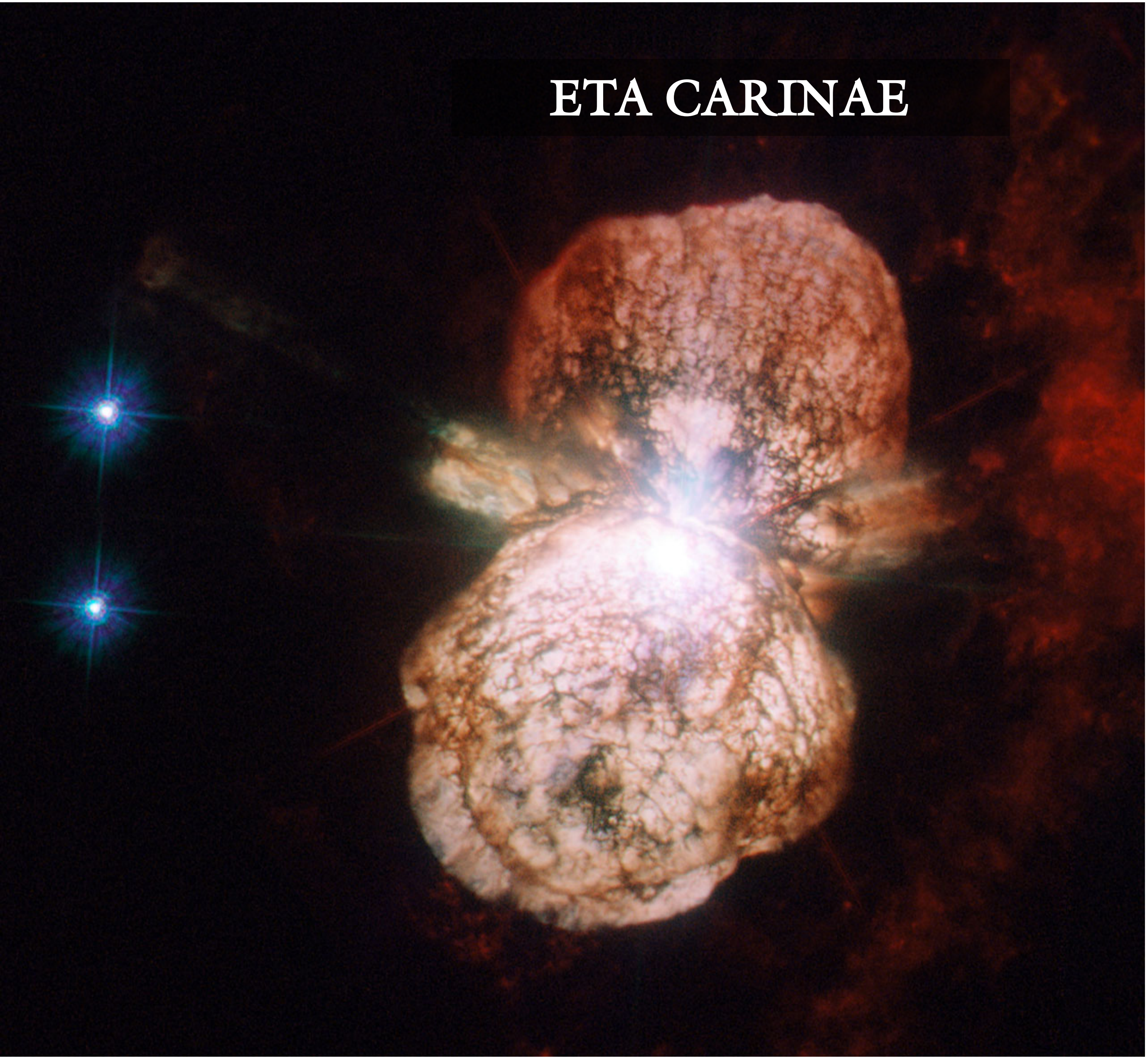
Supergiant Stars



The blue supergiant at the heart of this nebula is ejecting stellar atmosphere material in a violent solar wind. It’s estimated that this star has ejected 3 solar masses of material during this current outburst, and previous ones over the past 100 years.

The next stage for a high-mass star

- In rough terms, a 20-solar-mass star (blue supergiant)
  - Burns hydrogen for 10 million years
  - Burns helium for 1 million years
  - Burns carbon for 1000 years
  - Burns oxygen for 1 year
  - Burns silicon for 1 week
  - Silicon fuses into iron… that iron core grows for less than one day.
- Iron is a nuclear "fire-extinguisher" - in the great scheme of nuclear physics, iron is a very stable nucleus – trying to fuse it yields insufficient energy to sustain fusion. When you hit iron, you've hit the end of the nuclear road.

The End of the Road

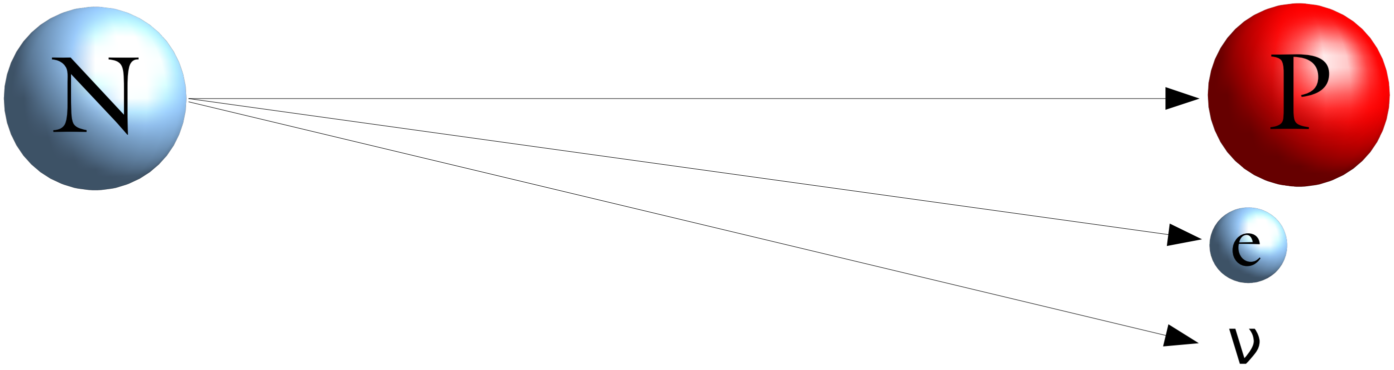
- The iron core not only ceases all nuclear burning, but the immense mass of this core and the lack of nuclear radiation pressure causes the star to contract RAPIDLY.
- The contraction under gravitational force heats the core up to 10 billion Kelvin, so hot that the heat of the core gives off gamma rays that split nuclei down to protons and neutrons. This is known as **photodisintegration** – light so energetic it destroys nuclei.
- This is bad.

Core Collapse

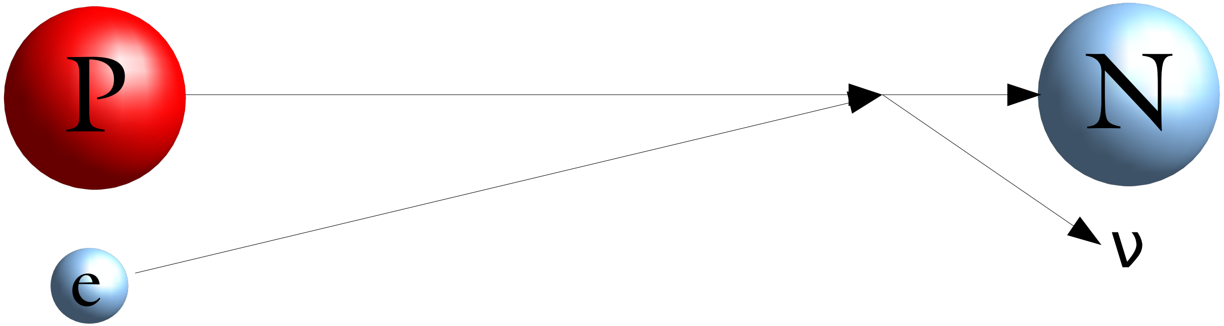
- In a low-mass star, as the core goes through its final collapse, electrons push back with a kind of “quantum pressure” that prevents further collapse.
- The gravity of a very high-mass star (12 × the Sun or greater) is SO GREAT that even our poor electrons cannot hold up the core.
- We have a very hot core filled with densely packed protons, neutrons, and electrons. Electrons and protons are brought into such close contact that nuclear reactions occur that convert protons into neutrons, emitting neutrinos in the process.

Nuclear Interactions

A free neutron, unbound from an atomic nucleus, decays in about 20 minutes to protons, electrons, and neutrinos. For example:



If an electron is forced too close to a proton, we can reverse some of the above reactions and get a neutron, at the expense of a neutrino.



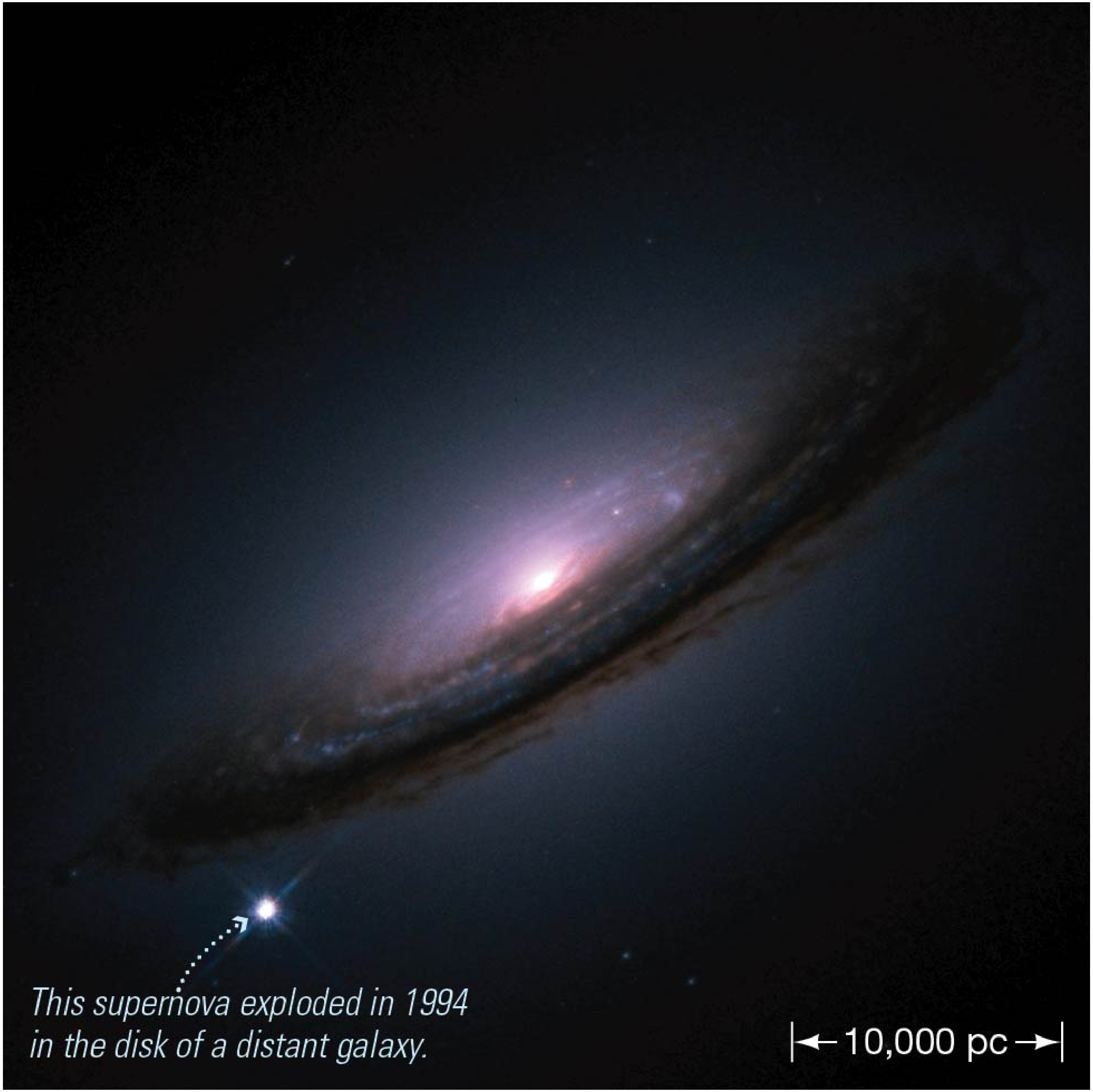
Core Collapse (cont.)

- Electrons combine with protons to make neutrons and neutrinos in the core
- The neutrinos escape the core in a huge blast wave, heating the core material and surrounding envelope as they escape the star
  - Yes, a single neutrino can pass through a light-year of lead before having even 1 interaction, but there are so many neutrinos emitted during core collapse that even if only a tiny fraction of them suffer interactions with stellar material, this causes a huge amount of heating due to their overwhelming numbers.

A computer simulation using the best physics knowledge and data from stars and supernova, this movie shows just about half-a-second of time in the collapsing core of a heavy star. This simulation took months of supercomputer time to produce.

Supernova

- The collapse of the core, for reasons still not completely understood from fundamental physics, causes a “rebound” - a shockwave that blows the rest of the star away from the core in a tremendous release of energy.
- This release of energy is known as a “Supernova”. Whereas a “nova” is a temporary flare up on the surface of a White Dwarf, a “Supernova” is the total annihilation of a star outside its core. A Supernova is millions of times brighter than a Nova.



(a)

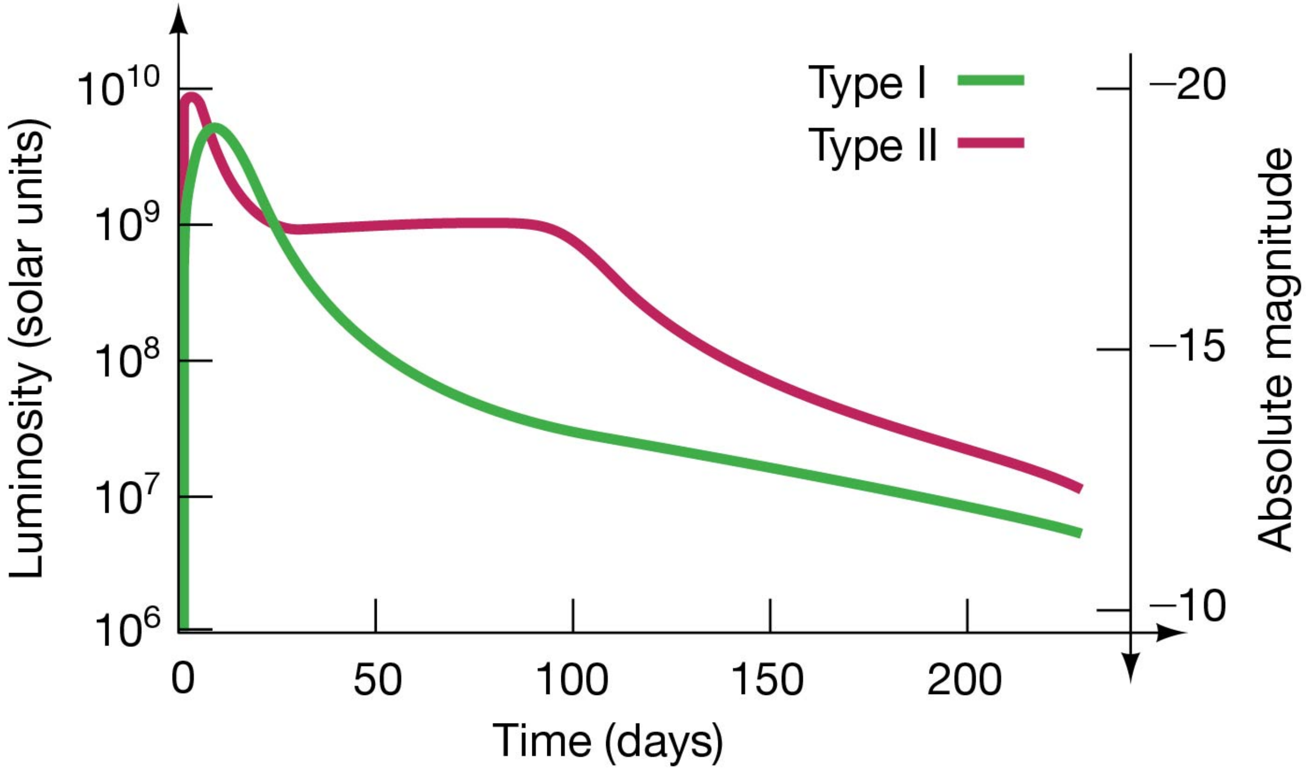
Supernovae shine brightly for long periods of time (weeks or months) and outshine their host galaxy.

Stars, Mass, and Fate

- The high-mass/low-mass distinction has been made at the number of "8 solar masses"
  - To be precise, this refers to the mass of the star when it enters the carbon-burning phase of its life.
  - If its mass is in excess of 8 solar masses, carbon burning will lead to oxygen burning, etc. and eventually to core collapse and the supernova death.

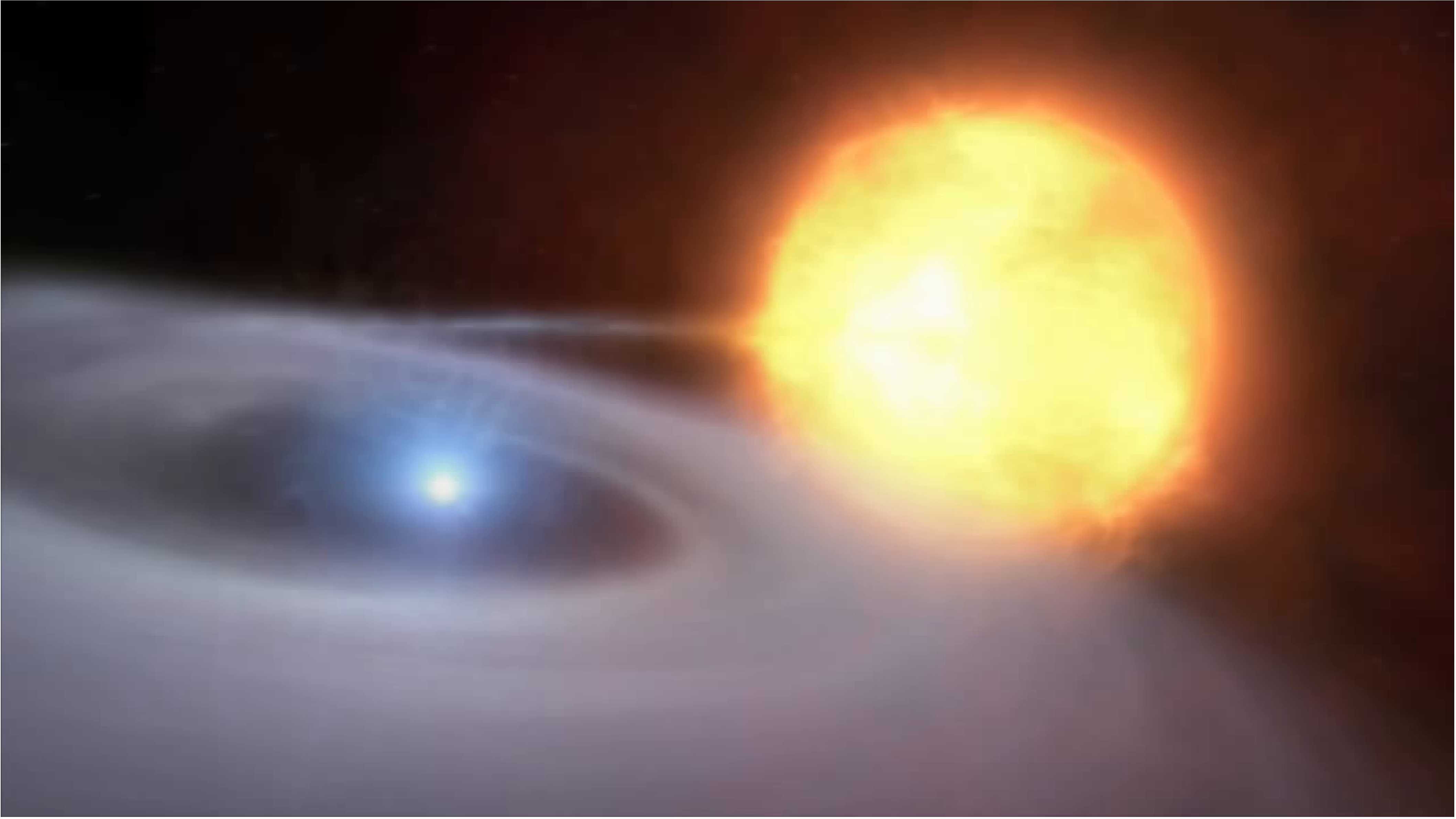
Supernovae (cont.)

- There are two major classes of Supernova, distinguished by the way that their brightness (luminosity) changes with time.



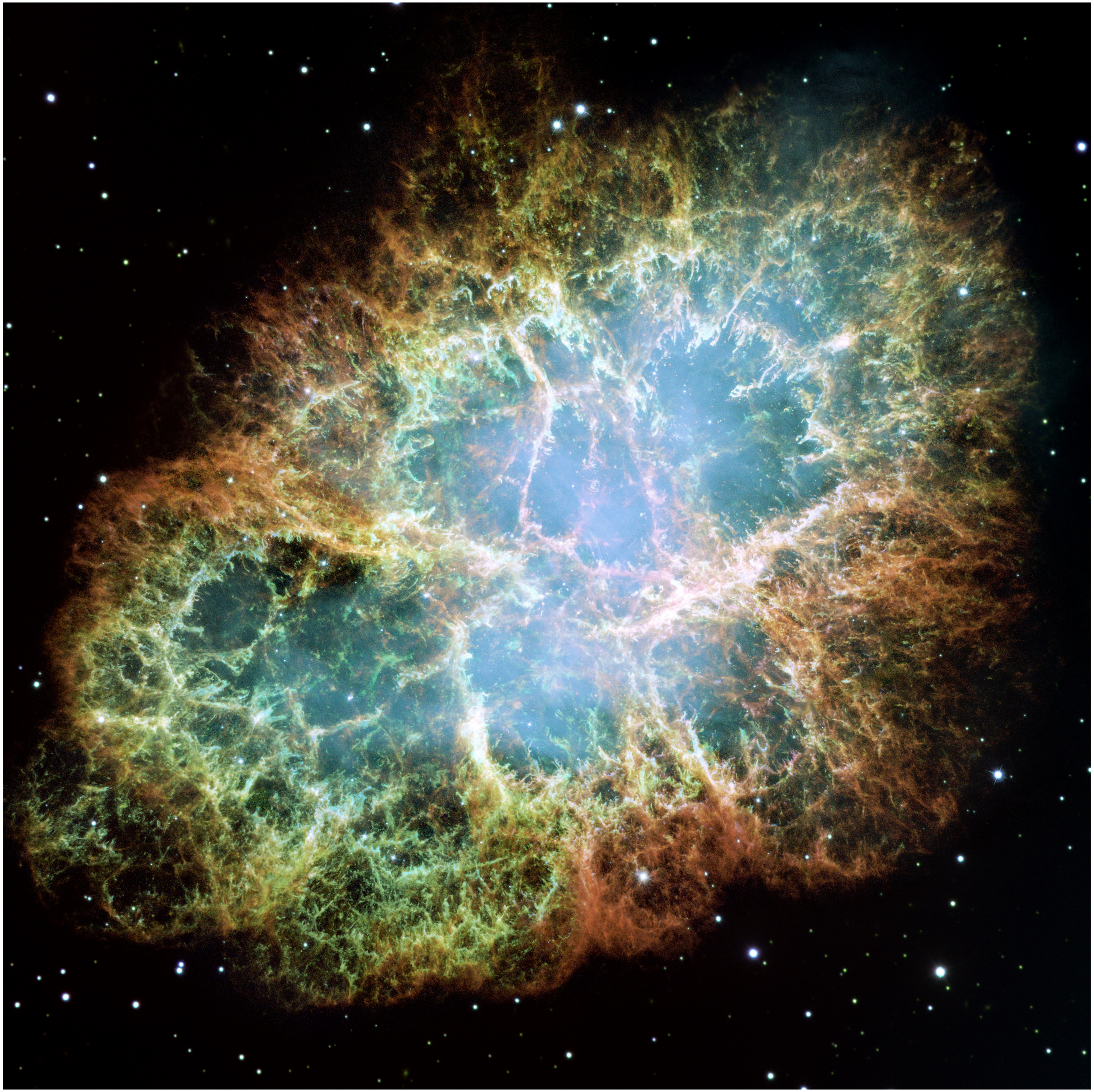
Supernova Types

- Type I – very little hydrogen in their spectra
  - This is now understood to be due to a White Dwarf feeding on the atmosphere of a companion Red Giant. Instead of resulting in a nova – a temporary flare – the mass of the White Dwarf increases until its core becomes heavy enough to overcome electron pressure and it collapses. This happens when the mass of the White Dwarf exceeds 1.4 solar masses, a number referred to as the Chandrasekhar Limit.
- Type II – hydrogen-rich
  - These are the core-collapse supernova we've been looking at so far in this lecture – a star imploding all on its own.



A visualization of a “Type-Ia Supernova” - a White Dwarf is feeding on atmospheric gases from a companion, a Red Giant. As material feeds onto the star, the mass of the White Dwarf increases beyond the critical threshold for core collapse to continue. These are highly regular events, and make excellent “standard candles” for measuring distances in the Universe.

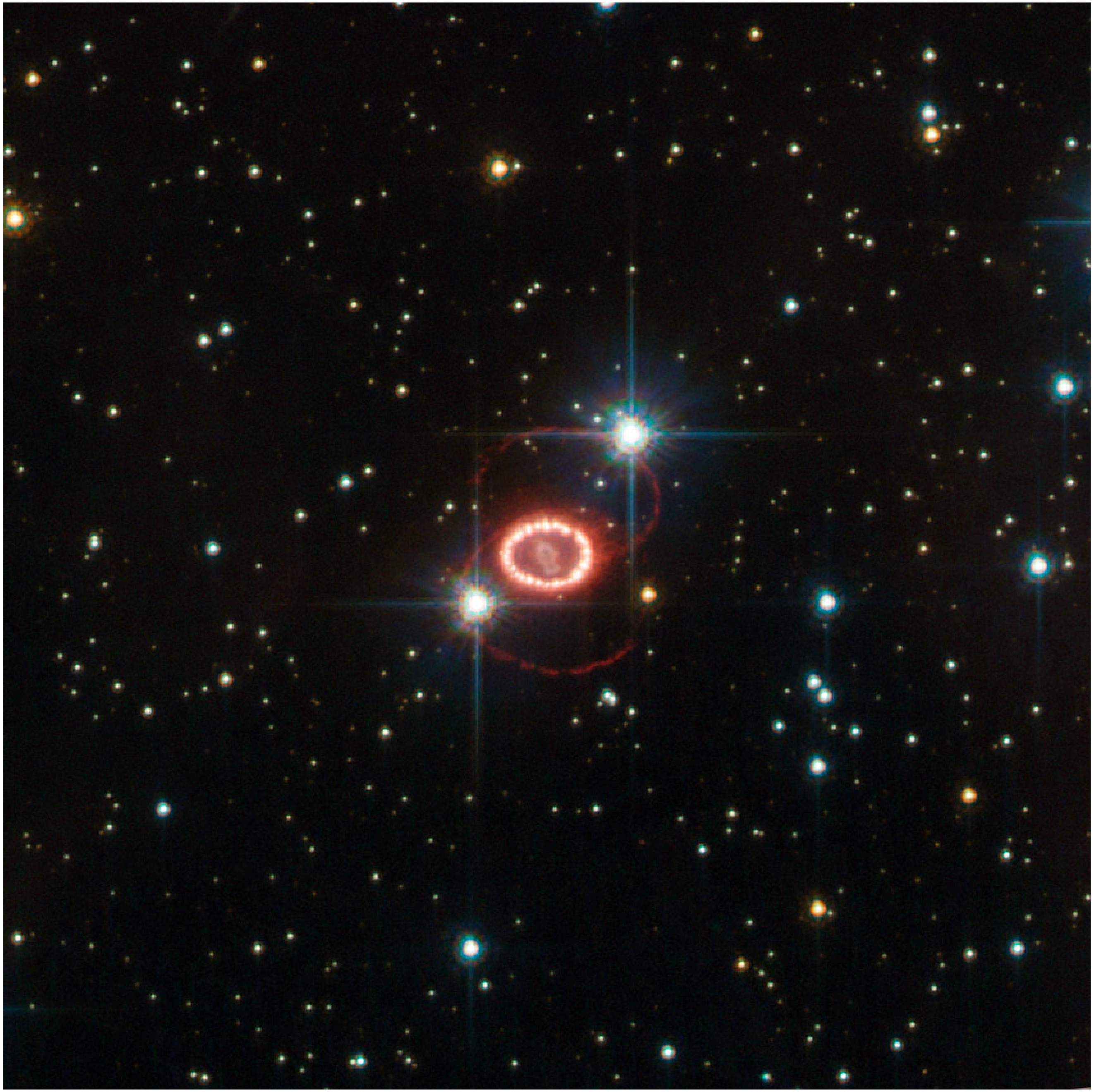
Supernova Remnants



The Crab Nebula

Located about 6500 light-years away, this is the remnant of a supernova explosion that occurred in about 1054AD. There were no telescopes back then; the supernova was visible in the sky to the naked eye, and recorded by Chinese and Japanese astronomers.

Supernova Remnants



SN 1987A

A Type-I Supernova in 1987 in the Large Magellenic Clouds, about 168,000 light-years away. This supernova has been imaged in many kinds of light and provided a wealth of information about stellar explosions. We'll talk more about this image in the next lecture.

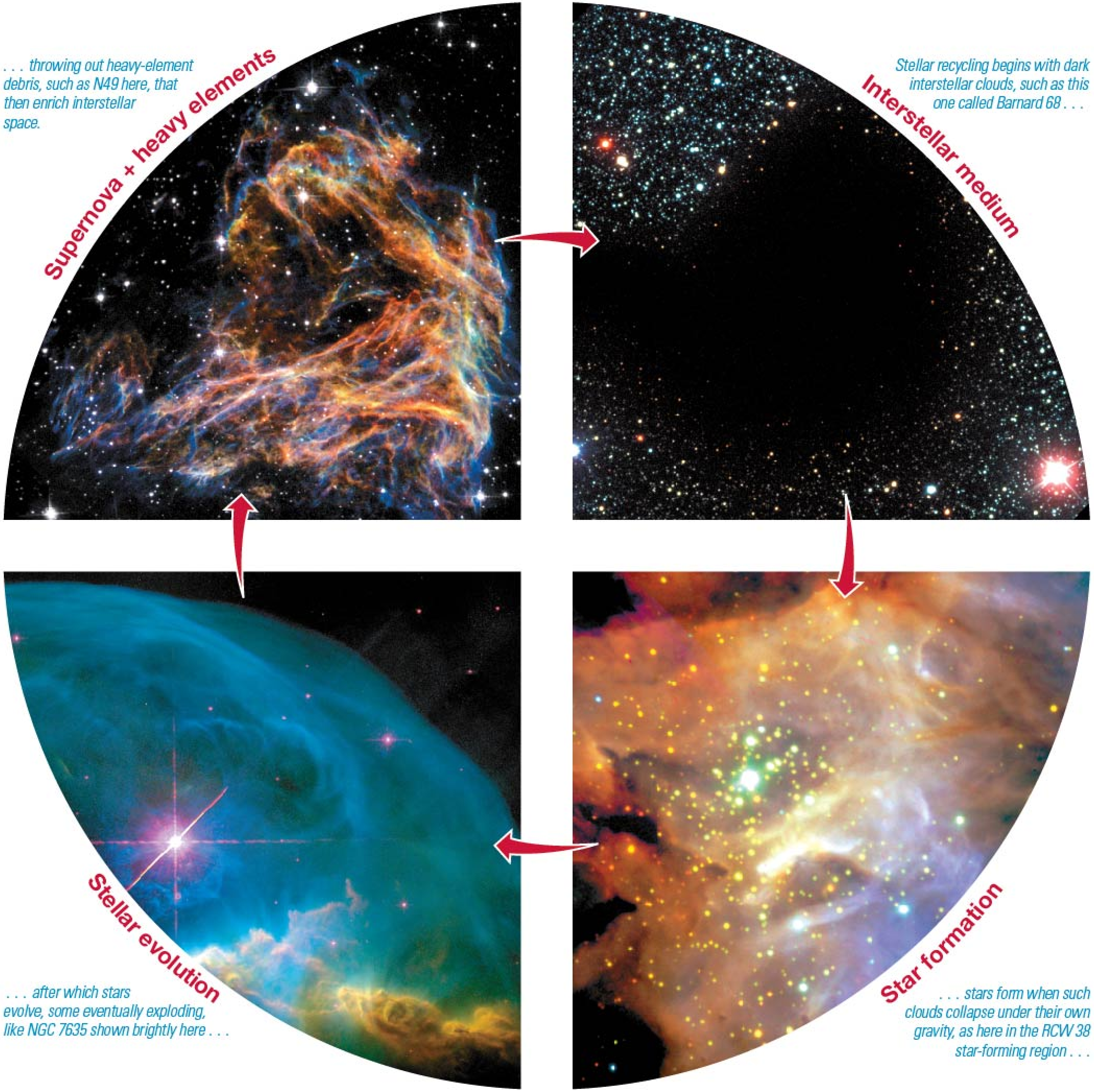
Testing Hypotheses: SN1987A

A model of Kamiokande II

Neutrino detectors on Earth, including Kamiokande II (Japan), IMB (US), and Baksan (Russia), all reported seeing neutrinos from the direction of SN 1987A 3 HOURS before the light arrived. This confirmed that core-collapse supernova yield a huge blast of neutrinos. Why does it arrive before the light? Neutrinos escape the core when the collapse occurs; light, on the other hand, is trapped in the dense core until it can make it to the surface and escape.

The Origin of the Heavy Elements

- Evidence tells us that the Universe's Hydrogen and Helium were forged at the birth of the Universe in the Big Bang (we'll return to this later)
- However, the Big Bang fails to explain the origin of heavy elements: carbon, oxygen, calcium, silicon, magnesium, iron, etc.
- Supernovas, however, readily explain the origin of heavy elements – heavy elements are naturally forged in the fusion processes of heavy stars, and these explosions scatter the heavy elements into the interstellar medium to later forge planets, stars, and other bodies.



Stellar recycling begins with dark interstellar clouds, such as this one called Barnard 68 . . .

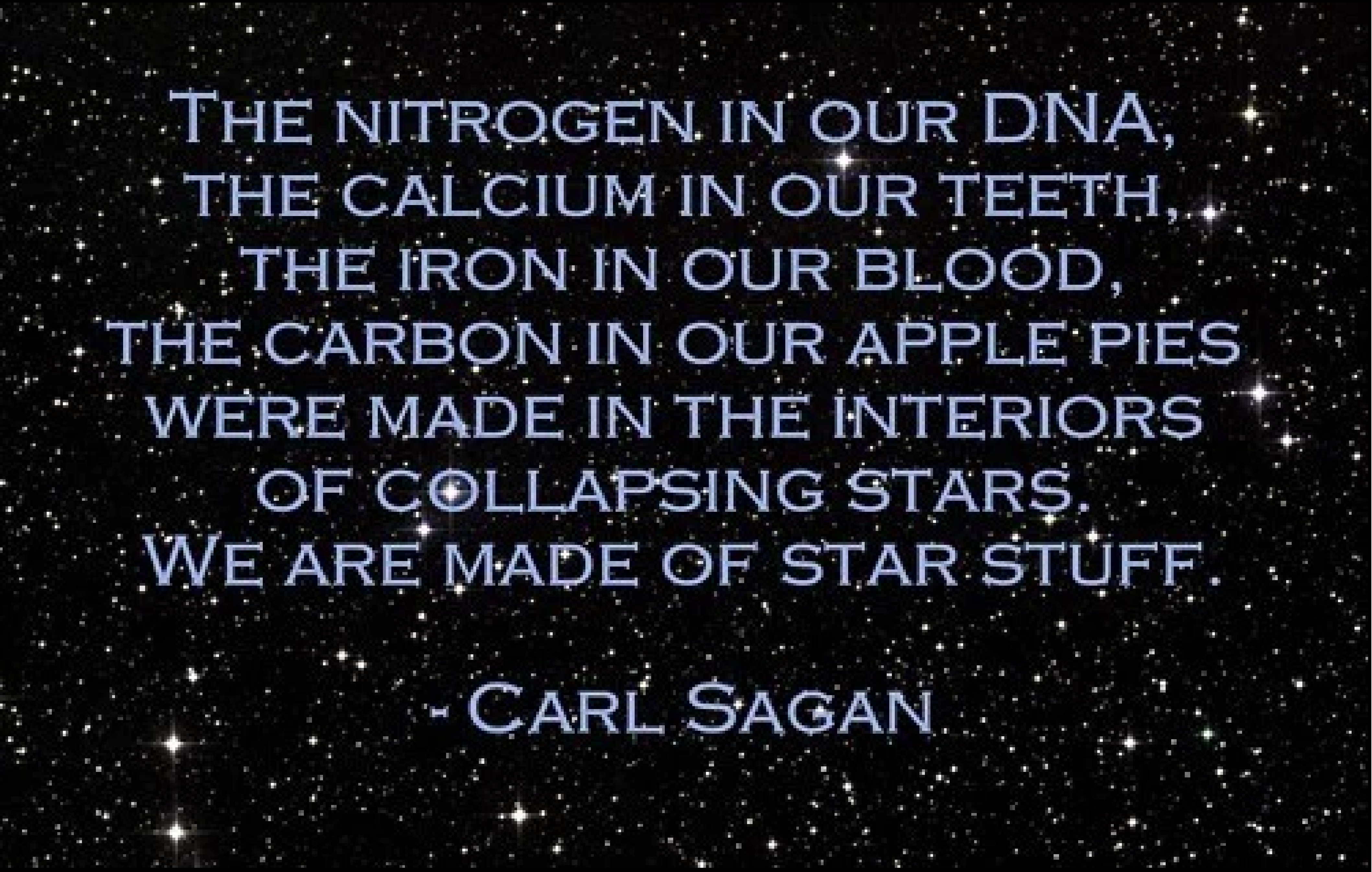
. . . stars form when such clouds collapse under their own gravity, as here in the RCW 38 star-forming region . . .

. . . after which stars evolve, some eventually exploding, like NGC 7635 shown brightly here . . .

. . . throwing out heavy-element debris, such as N49 here, that then enrich interstellar space.

Lessons

- All stars on the Main Sequence will build up a core of “Helium Ash”, which then begins their journey off the Main Sequence.
- As the star core contracts and expands, new stages of fusion are initiated; Helium fusion is the last core fusion of low-mass, Sun-like stars. They eventually expand to become Red Giants, then cool and contract to become White Dwarves.
- For high-mass stars – those that have a mass of 8 or more solar masses after helium burning has run its course, further stages of fusion will proceed. This eventually can lead to iron production in the core, which extinguishes the nuclear fire. The star can collapse, unable to fight gravity, and a supernova results.
- Supernovas seed the interstellar medium again.



The nitrogen in our DNA,
the calcium in our teeth,
the iron in our blood,
the carbon in our apple pies
were made in the interiors
of collapsing stars.
We are made of star stuff.

- Carl Sagan