

Announcements

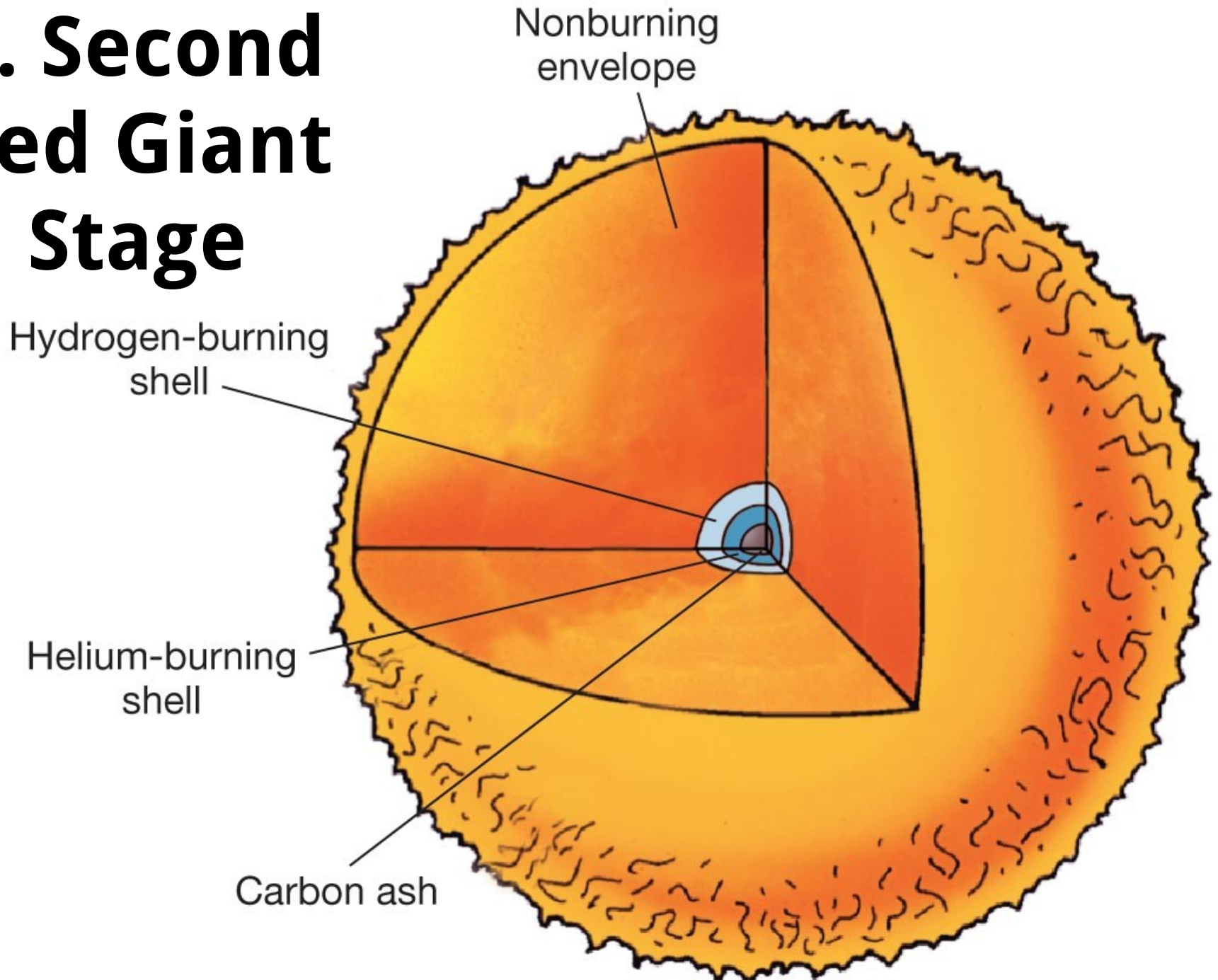
- Quiz 7 due on Monday – Chapters 10 and 11
- Problem Set 7 for practice
- Today and Monday: Chapter 12
- Next week: Chapter 13, neutron stars and black holes
- Next midterm will be Wednesday after spring break – more info next week

Astronomy 103

The Lives and Deaths of Stars
and the Origin of the Elements

Please read chapter 12

V. Second Red Giant Stage



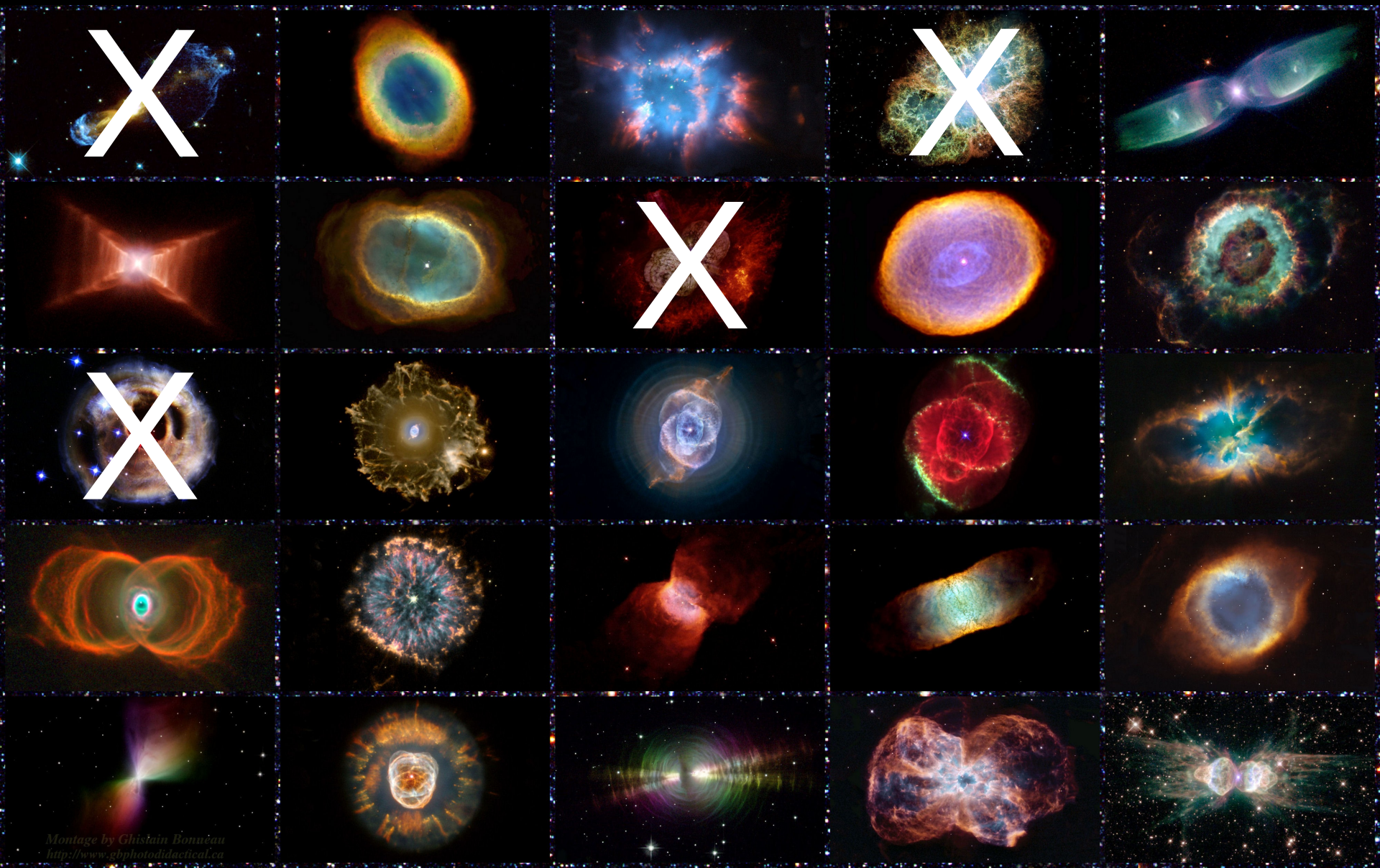
What happens next?

Now we have 3 sources of energy

- Contraction of the core
- Ferocious fusion of helium to carbon in a shell around the core
- Rapid fusion of hydrogen to helium in a second shell

With more energy from these reactions than in its first red giant stage, the star becomes even larger than it did the first time.

Eventually, driven by the increasing temperature of the core and the weak gravitational attraction at the very extended surface, its outer layers are blown entirely off the star, creating a **planetary nebula**.



Montage by Ghislain Bonneau
<http://www.gbphotodidactical.ca>

VI. The Death of Stars like the Sun: Ejection of planetary nebula and white dwarf formation (book stages 12-13)

With the hydrogen shell gone, the hydrogen and helium burning shells runs out of fuel and the carbon core slowly cools off. If gravity would have its way, the carbon core would heat up and ignite, but before it does **degeneracy pressure** takes over.

Degeneracy pressure

If you try to cram too many electrons into a small enough space, the electron's quantum mechanics prevent you from squeezing them any more tightly together – this is called **degeneracy pressure**.

Degeneracy pressure in metals gives them their resistance to compression



White dwarfs, planetary nebulae

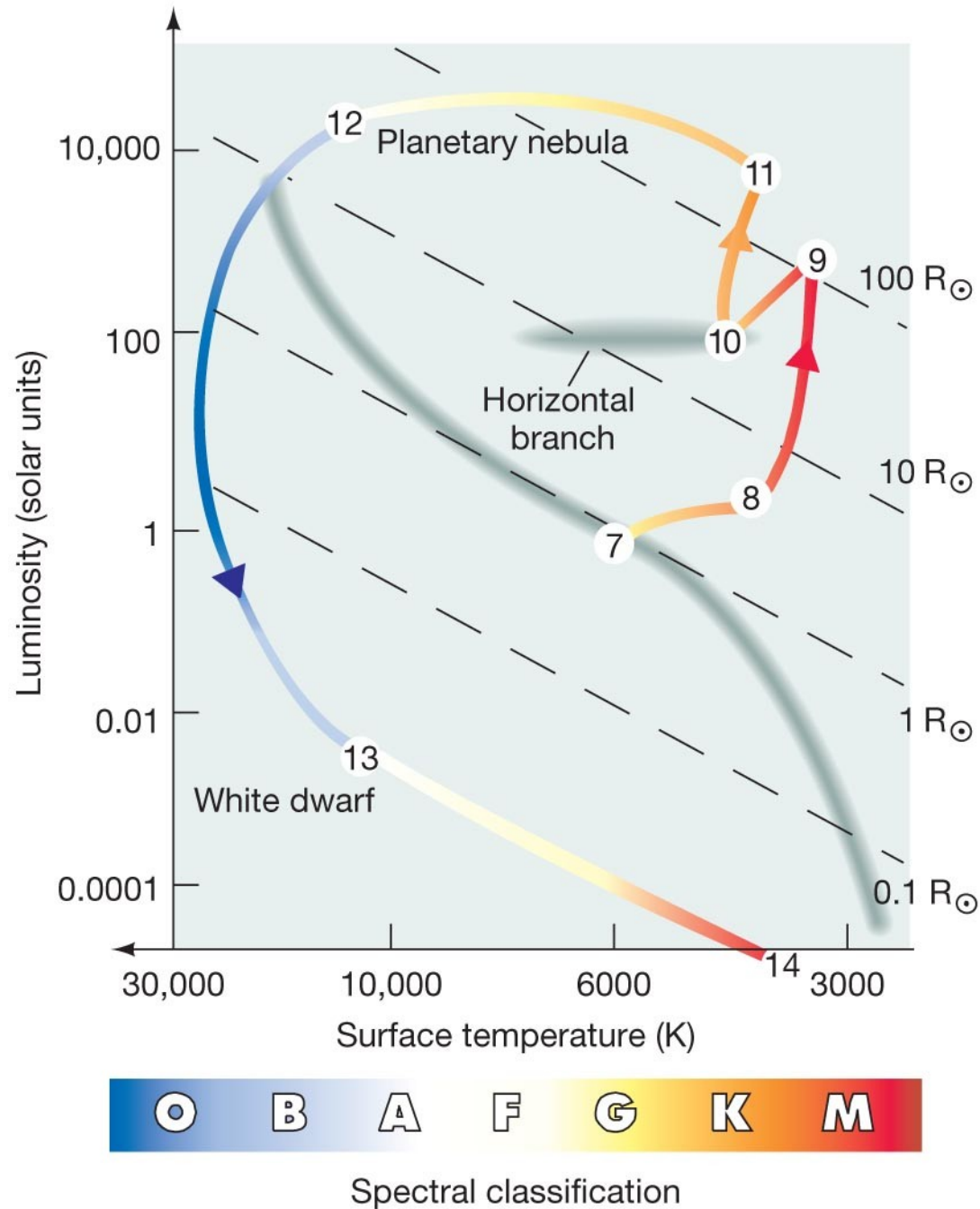
- To support a star's core against gravity, the degeneracy pressure is much larger than it would be for any metal on earth. These stars that are supported by degeneracy pressure are called **white dwarfs**.
- The Sun itself will end as a white dwarf, compressed to about the size of the Earth. A typical white dwarf radius is then about the radius of the Earth. Its density is about **5 tons per teaspoon**.
- A star **smaller than 4 solar masses** ends its life by ejecting a planetary nebula and settling down to become a white dwarf.
- **Planetary nebulae are thus found around white dwarfs.**

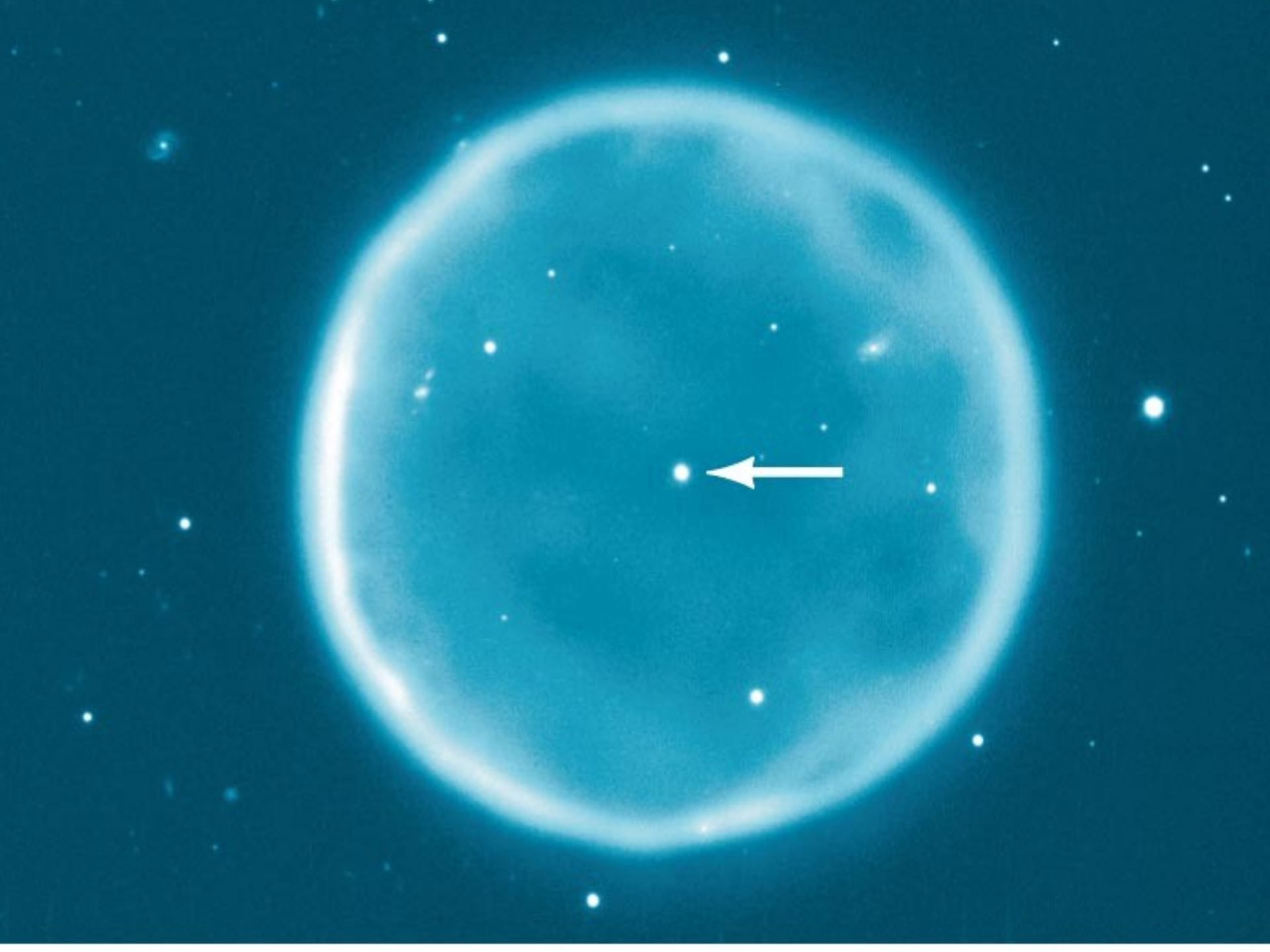
White dwarfs

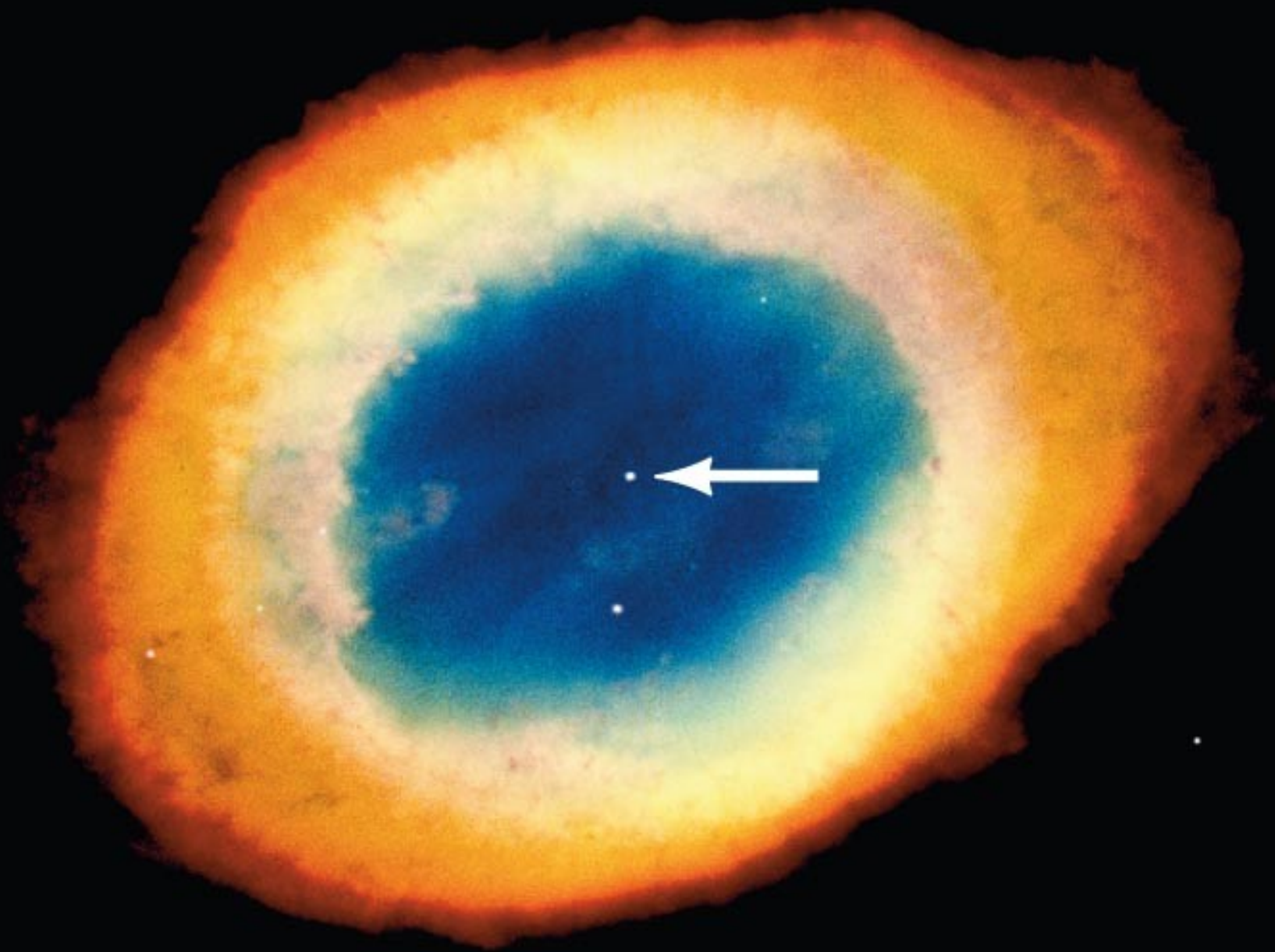
The star burns so brightly that it sheds a planetary nebula—gas that travels away from the star (12).

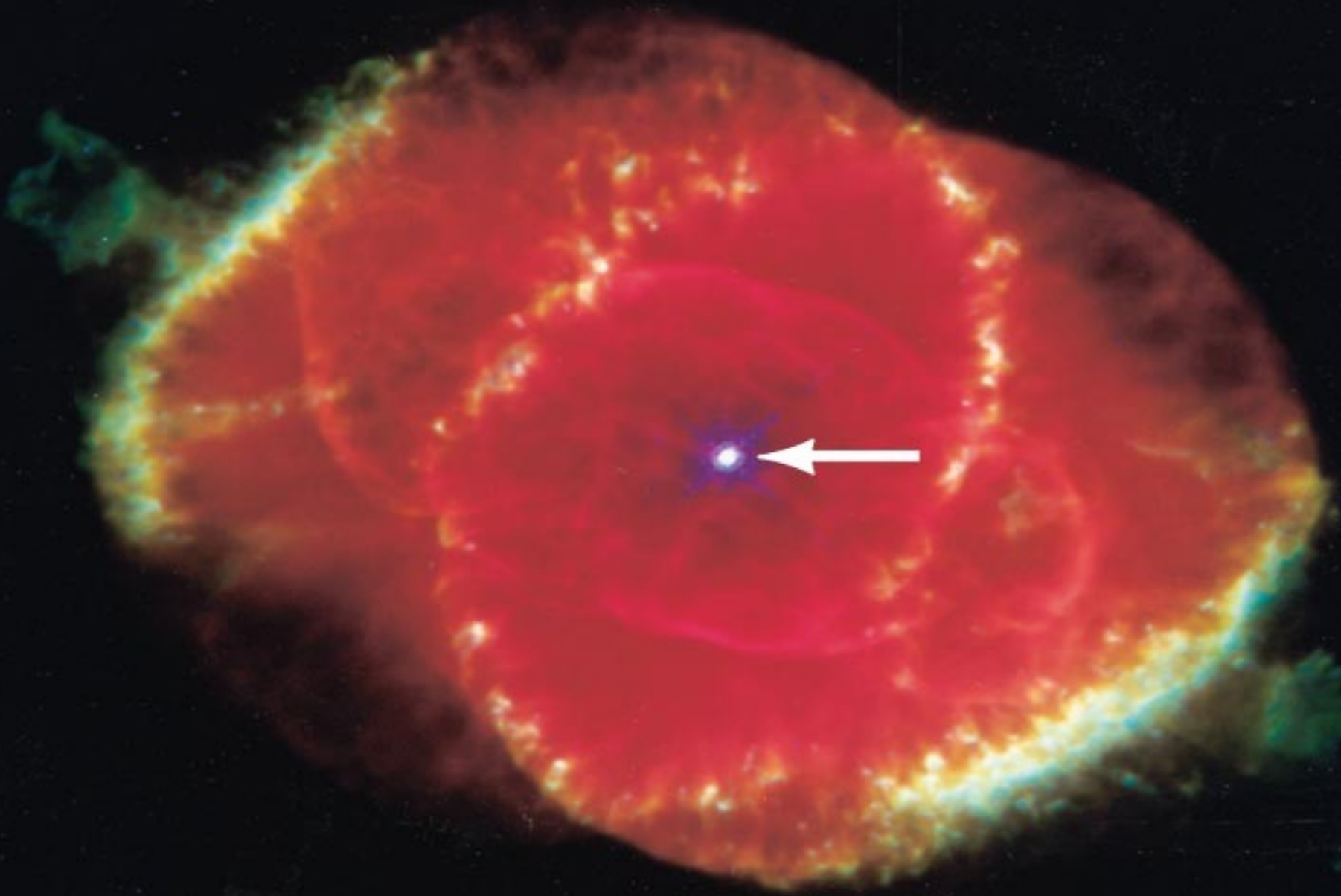
Once the star runs completely out of nuclear fuel what remains of the star contracts and forms a white dwarf (13).

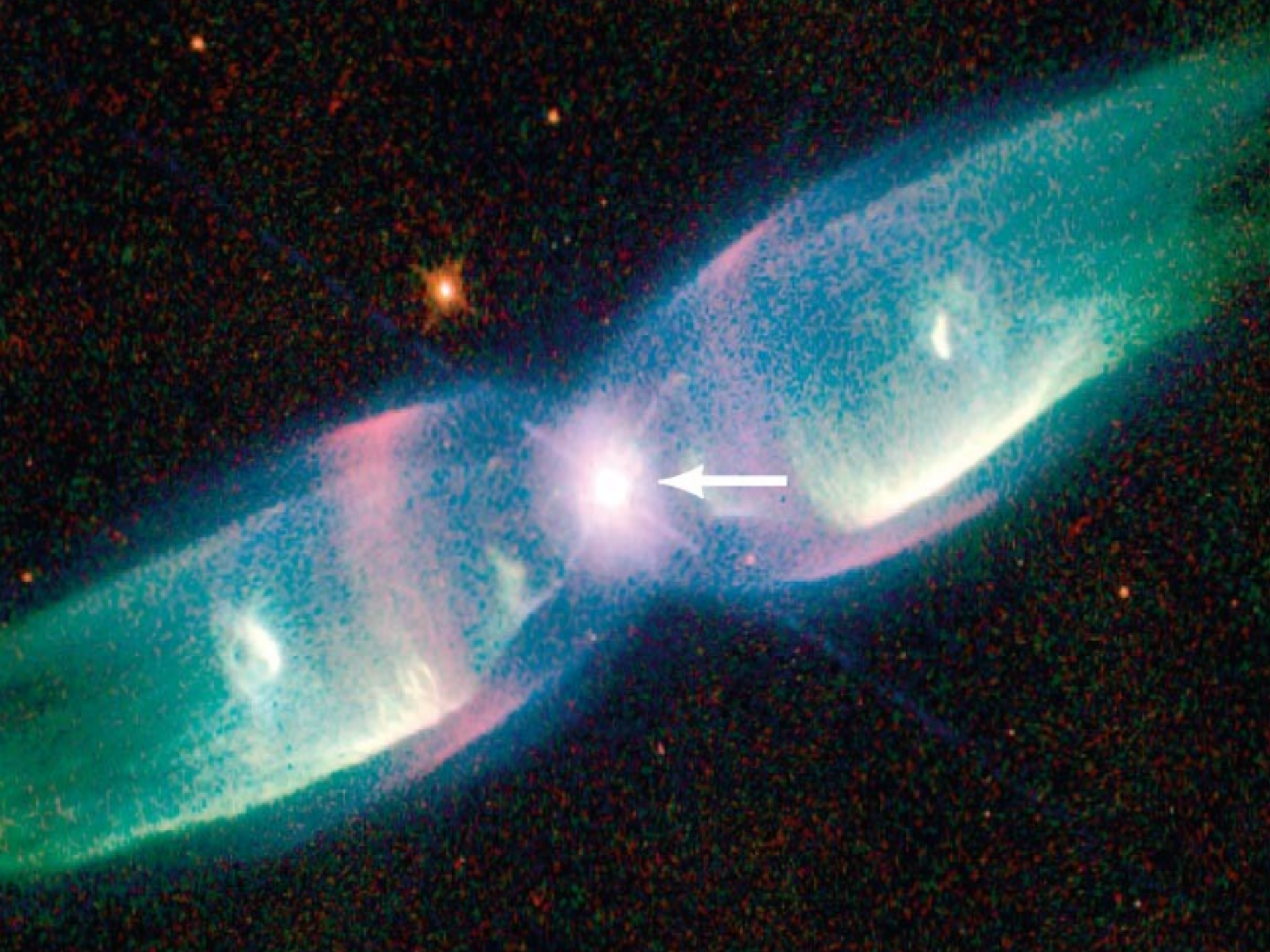
The star cools eventually becoming a black dwarf, too small and faint to see (14).











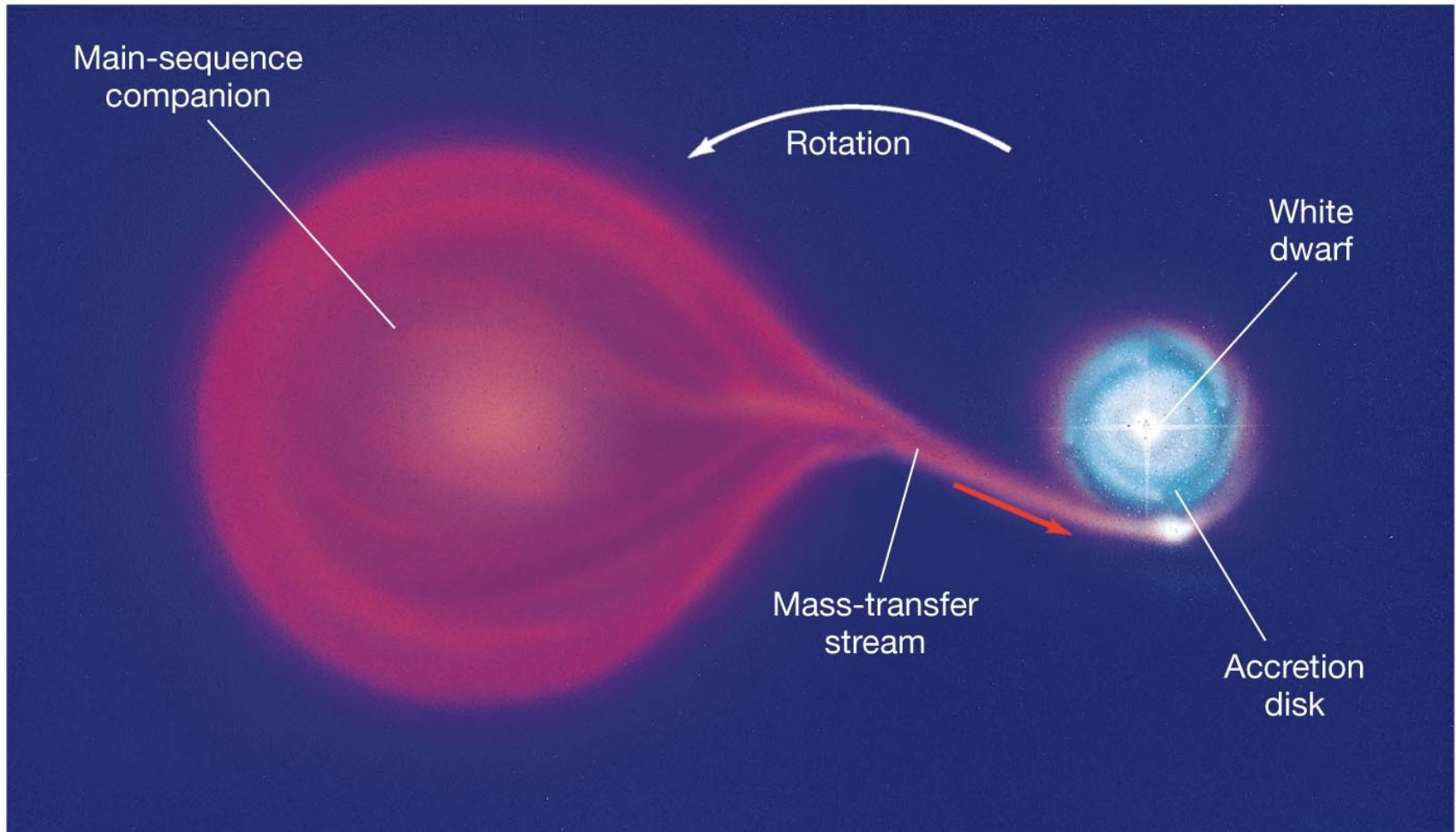
Novae: H-bombs at the surface of white dwarfs

Some white dwarfs are in binary systems with another star.

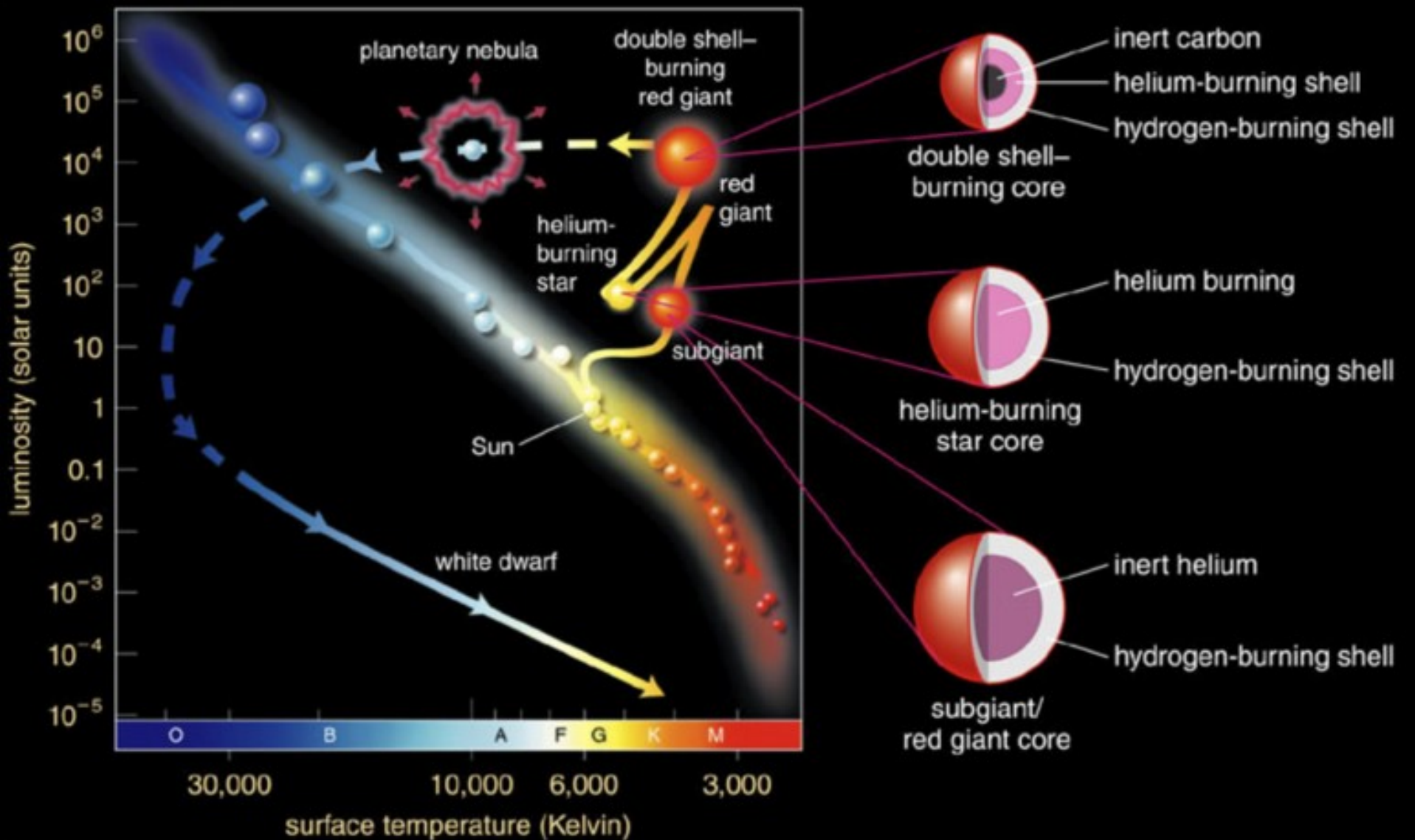
In a close binary, or when the other star becomes a red giant and is sufficiently large, hydrogen from the surface of the other star falls onto the white dwarf.

Once enough hydrogen builds up on a white dwarf, it will suddenly fuse to helium. This is a **nova**, the sudden fusion of hydrogen to helium on the surface of a dwarf.

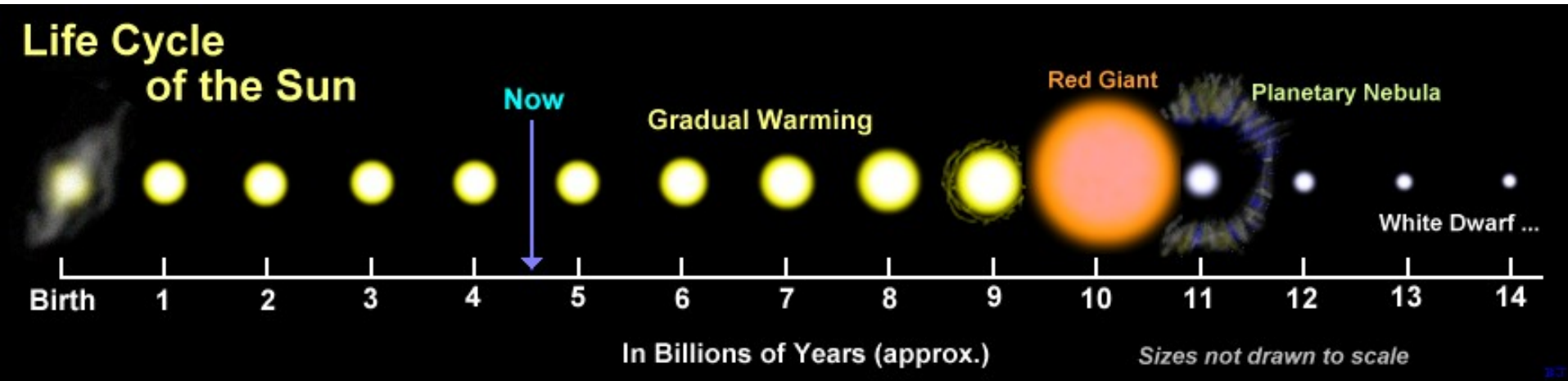
Nova, the sudden fusion of hydrogen to helium at the surface of a dwarf due to built up matter on a white dwarf



Evolution of the Sun

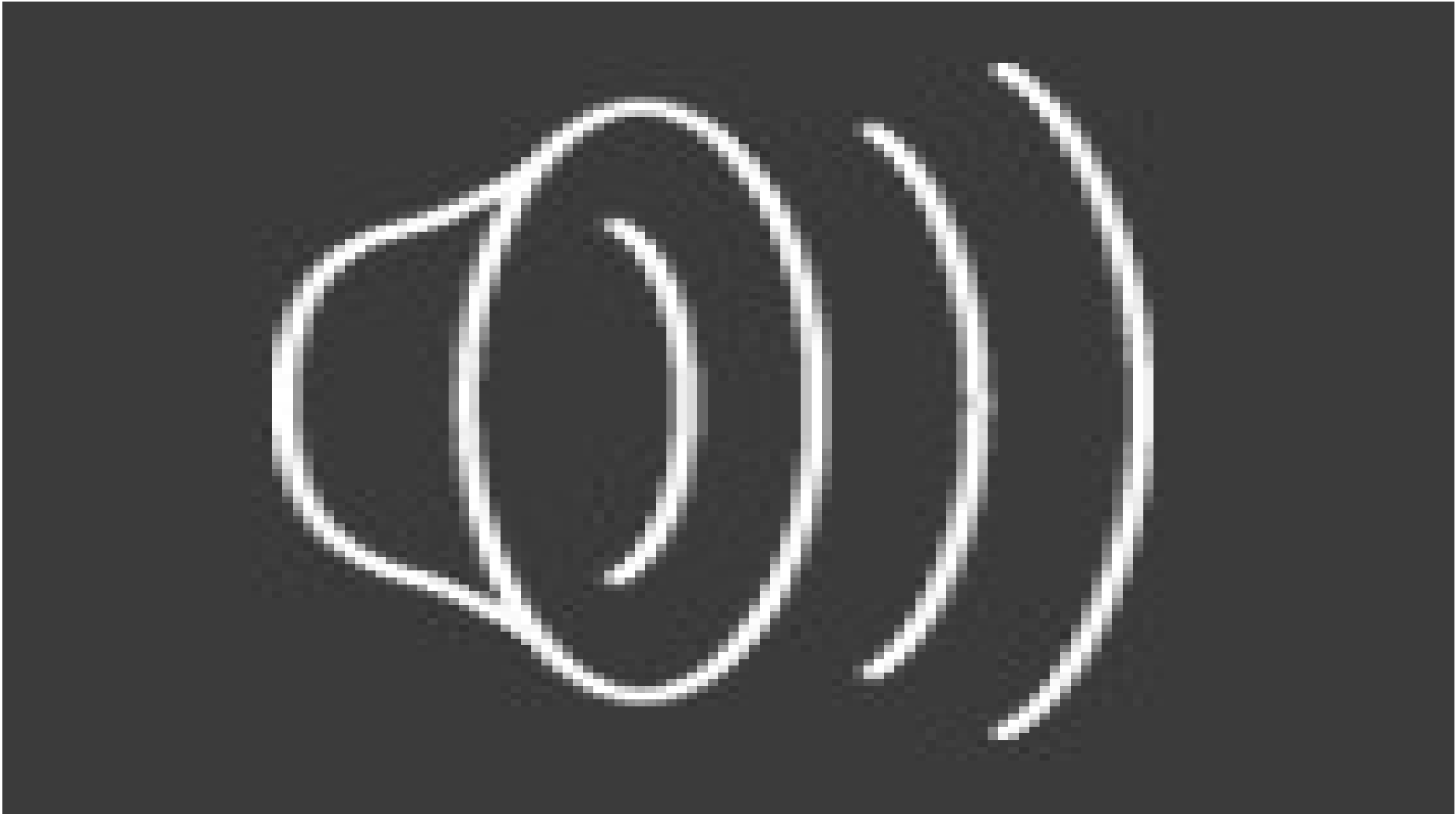


Evolution of the Sun



A star like the Sun spends most of its life on the main sequence, and then a shorter and shorter amount of time in each phase until it cools as a white dwarf.

Outflows during Red Giant Phase



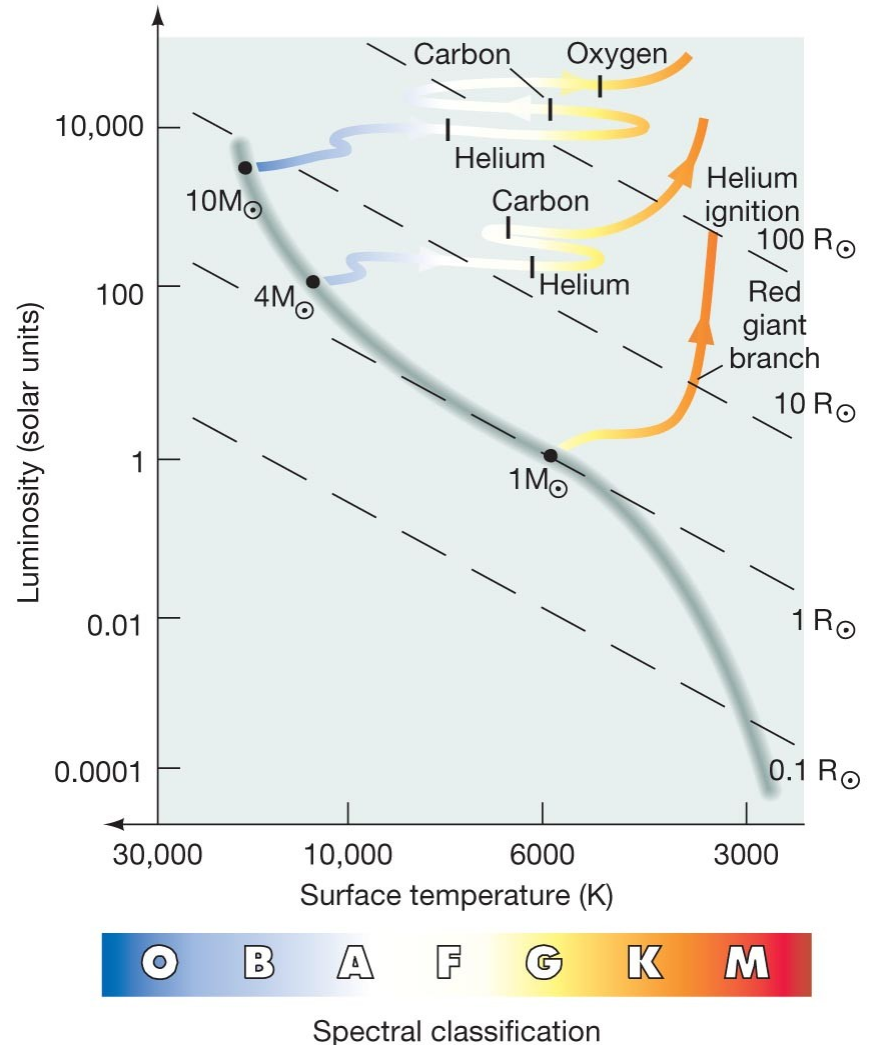
Late evolution of stars more massive than the Sun and the formation of the elements

More massive stars will build heavier elements up from carbon:

- $M < 0.08 M_{\odot}$ No fusion at all
- $0.08 M_{\odot} \dots 0.4 M_{\odot}$ $H \rightarrow He$ only
- $0.4 M_{\odot} \dots 4 M_{\odot}$ $H \rightarrow He, He \rightarrow C$
- $4 M_{\odot} \dots 8 M_{\odot}$ $C \rightarrow Ne, Na, Mg, O$
- $> 8 M_{\odot}$ $Ne, O \rightarrow$ higher mass
elements up to Fe

Evolution of Stars More Massive than the Sun

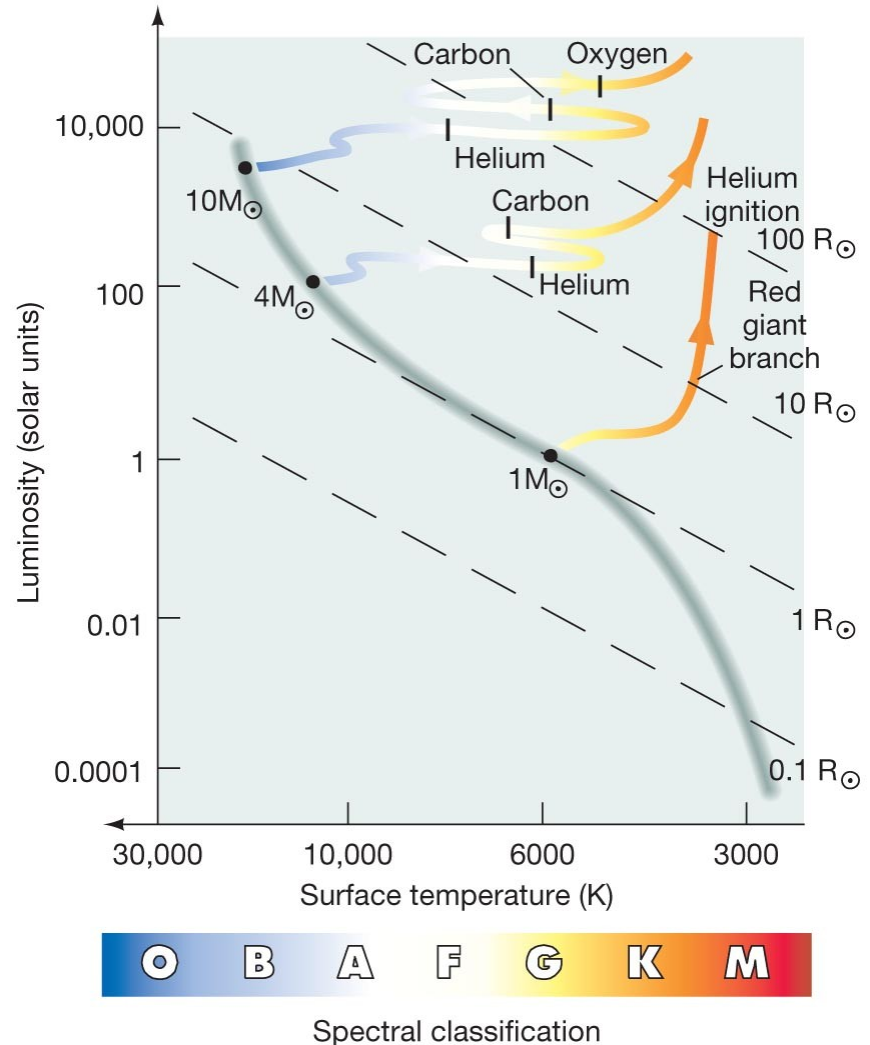
It can be seen from this H-R diagram that stars more massive than the Sun follow very different paths when leaving the main sequence.



Evolution of Stars More Massive than the Sun

High-mass stars, like all stars, leave the main sequence when there is no more hydrogen fuel in their cores.

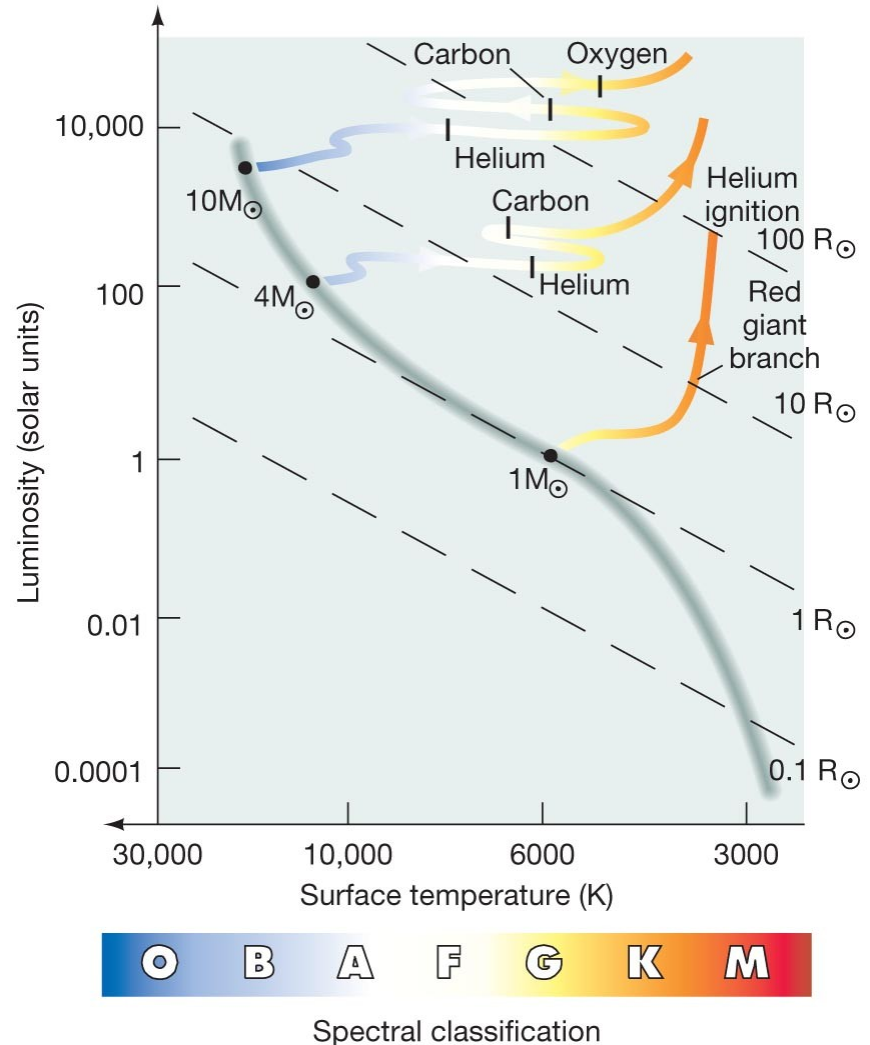
The first few events are similar to those in lower-mass stars – first a hydrogen shell, then a core burning helium to carbon, surrounded by helium- and hydrogen-burning shells.



Evolution of Stars More Massive than the Sun

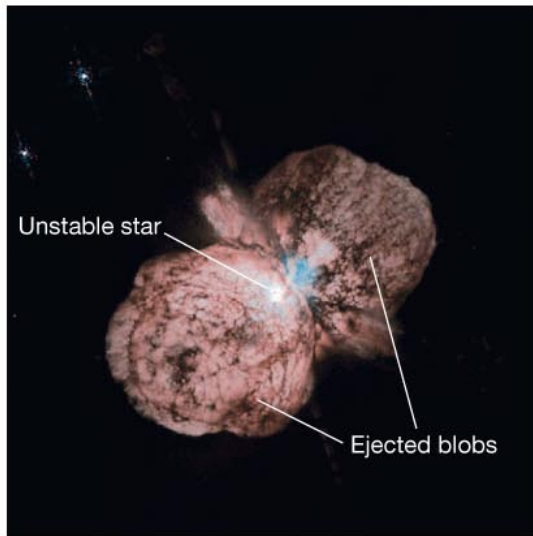
Stars with masses more than 2.5 solar masses do not experience a helium flash – helium burning starts gradually.

A 4-solar-mass star makes no sharp moves on the H-R diagram – it moves smoothly back and forth.



Evolution of Stars More Massive than the Sun

The sequence below, of actual Hubble images, shows first a very massive star, then a very unstable red giant star as it emits a burst of light, illuminating the dust around it.



(a)



(b)



η (Eta) Carinae
HST WFPC2

F658N [N II]
F656N H α
F631N [O I]
F502N [O III]
F336W U

0.5 light-year
0.15 parsec 14"



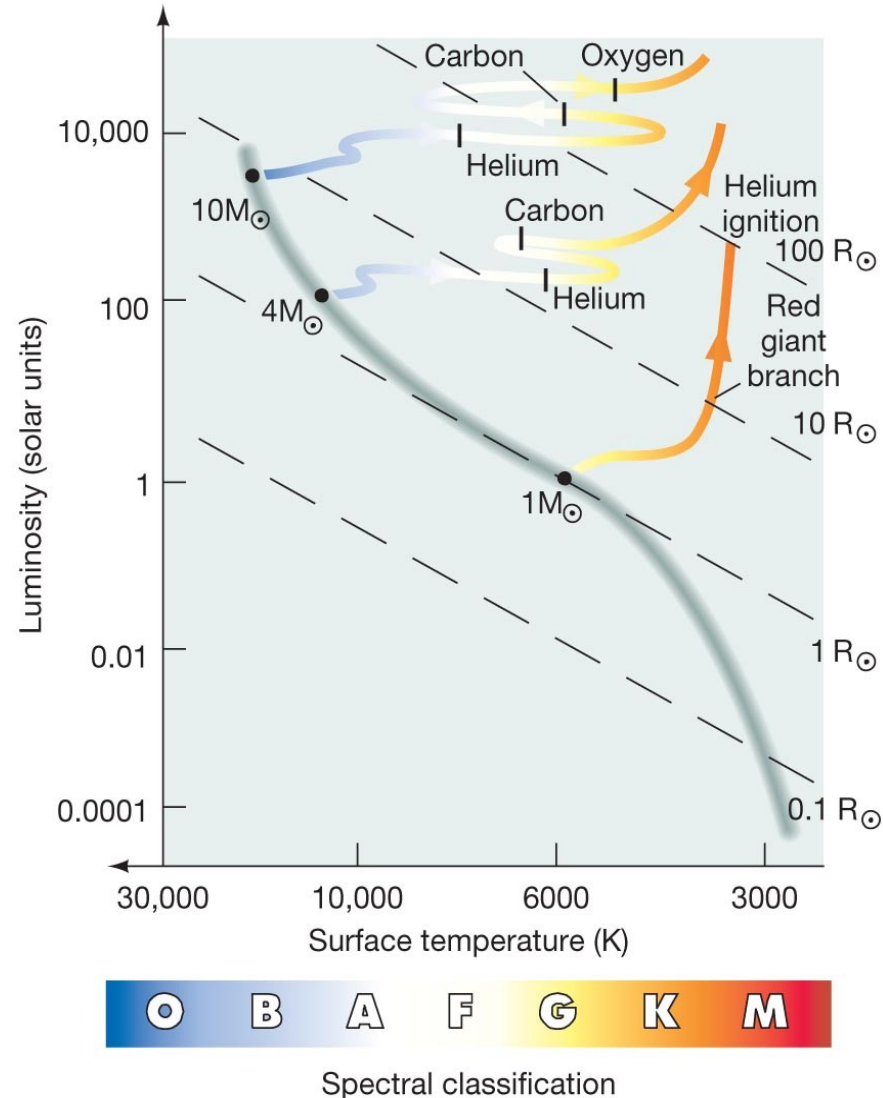
Very massive stars become unstable towards the end of their lives. They develop strong winds and can blow a tenth or more of their total mass into space.

This is one of the most famous examples, the massive star Eta Carinae. The nebula surrounding the star is gas that has been blown off – Eta Carinae has probably lost 2-3 times the mass of the Sun.

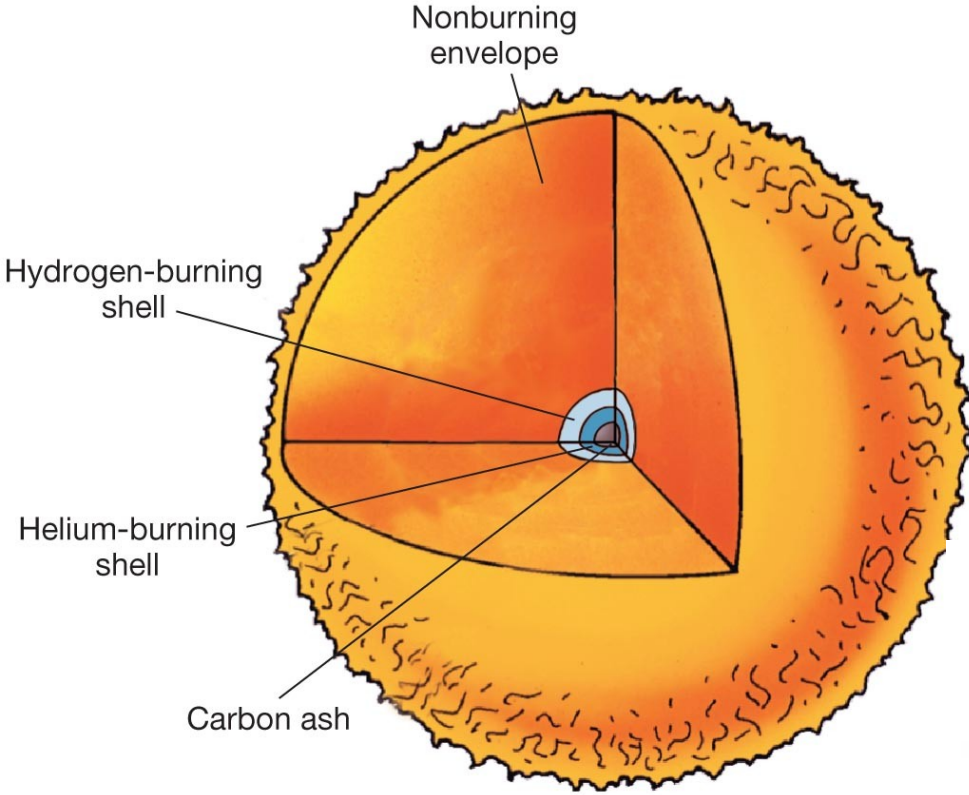
Evolution of Stars More Massive than the Sun

A star of more than 8 solar masses can fuse elements far beyond carbon in its core, leading to a very different fate.

Its path across the H-R diagram is essentially a straight line – it stays at just about the same luminosity as it cools off.

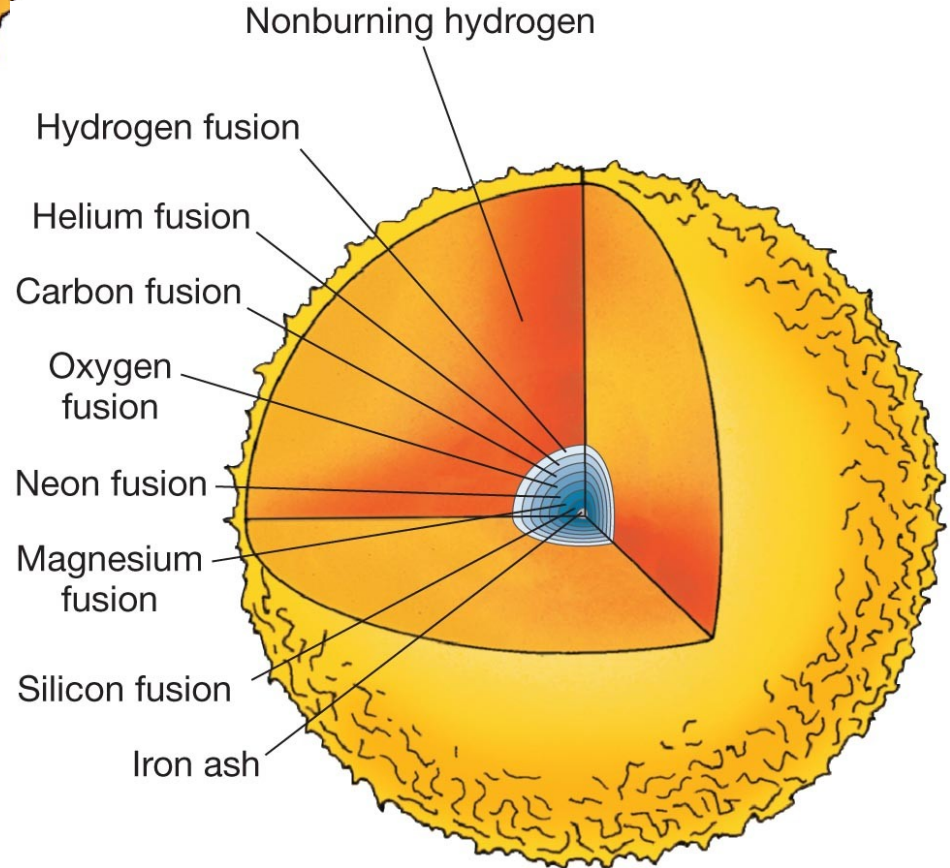


Stars with lower masses only produce Carbon



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Stars with higher masses produce Iron



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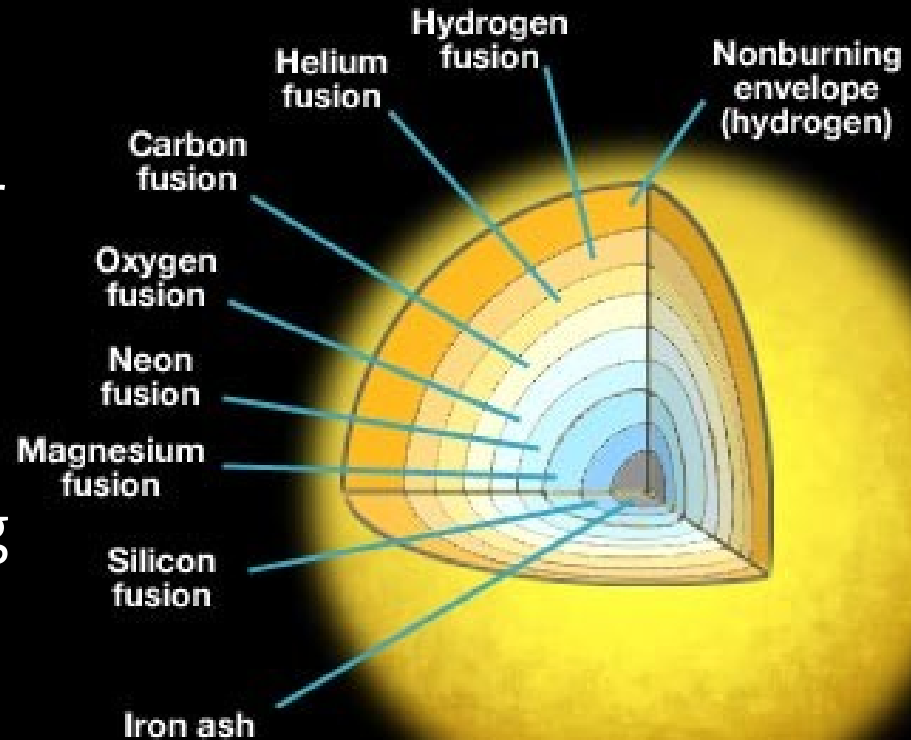
Evolution of the most massive stars

The most massive stars are hot enough to fuse heavier and heavier elements in their cores

Fusion of the heaviest element occurs in the center, surrounded by shells burning each of the lighter elements

Star has an “onion” structure

This happens until the core of the star has been fused into iron



Not to scale! The core containing the layers of fusion is only a small part of the star.

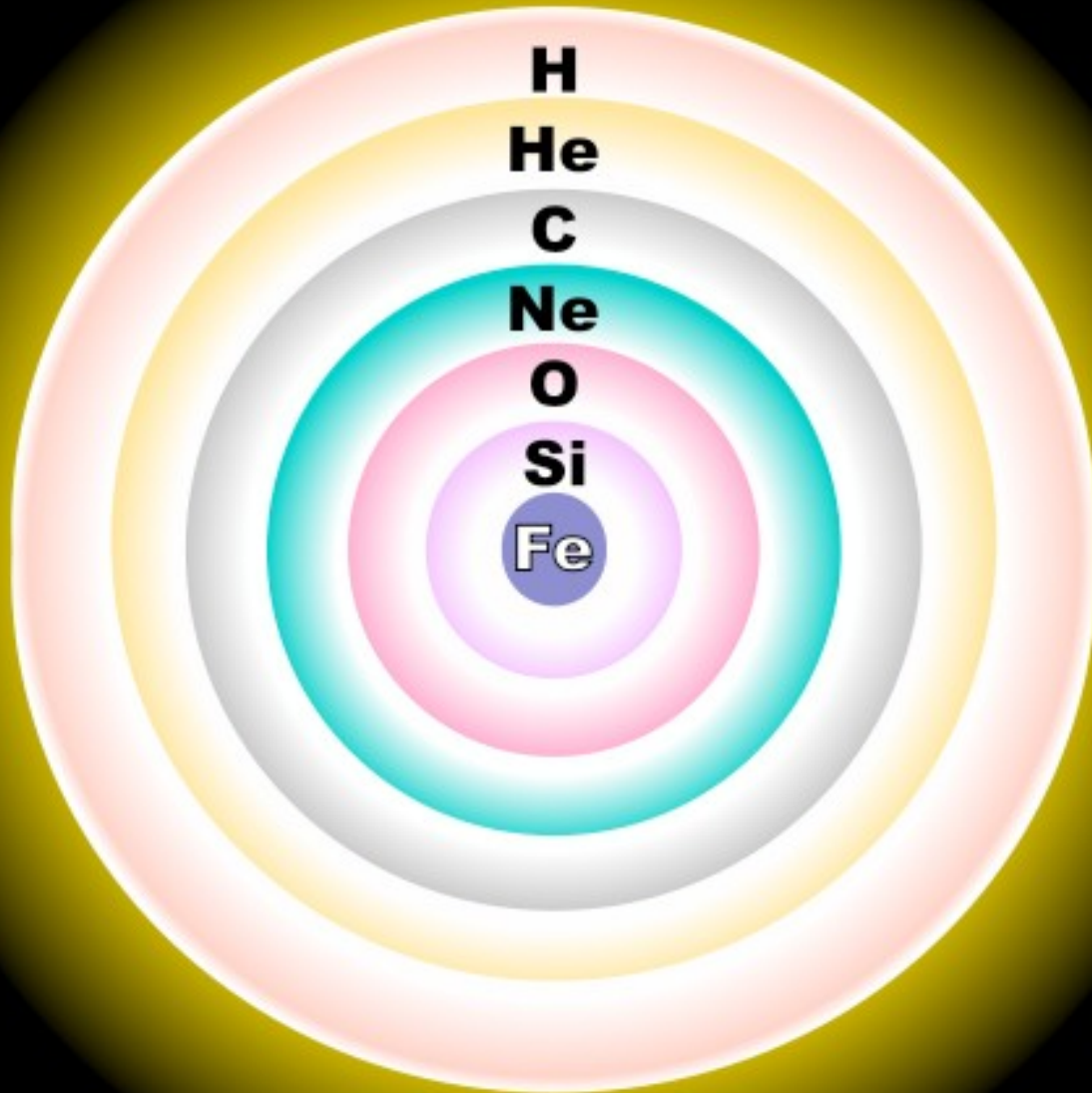
Stellar Nucleosynthesis

Iron is the most stable element – it has the most tightly bound nucleus.

The heavy elements up to iron are built in the cores of stars.

You are made of stardust

All the atoms in you that are heavier than helium first formed in a star, and nearly all atoms between helium and iron were forged in the core of a massive star. The story of a star's life is also the story of the how the elements were built.



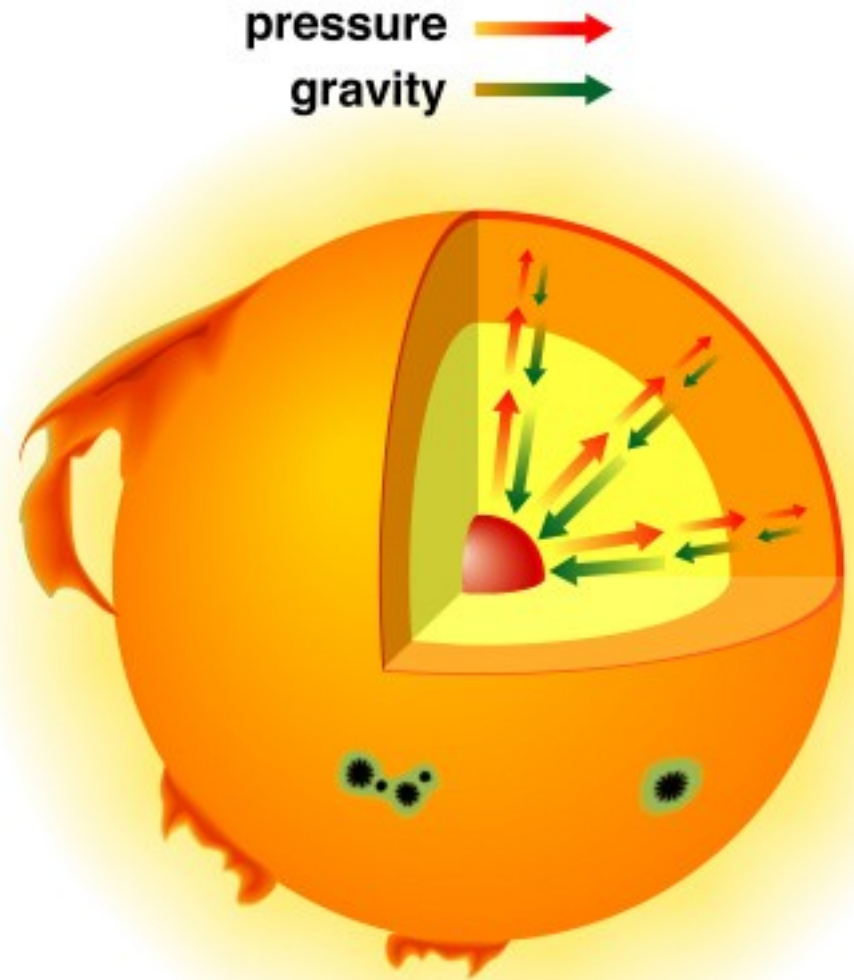
“The nitrogen in our DNA,
the calcium in our teeth,
the iron in our blood, the
carbon in our apple pies
were made in the
interiors of collapsing
stars. We are made of
starstuff.”

— Carl Sagan, *Cosmos*

Evolution of the most massive stars

Recall that stars are in **hydrostatic equilibrium**: nuclear fusion at the center produces enough **pressure** to balance the force of **gravity** and keep the star from collapsing

Our very massive star now has a core made out of iron... and this is a very big problem!



Evolution of the most massive stars

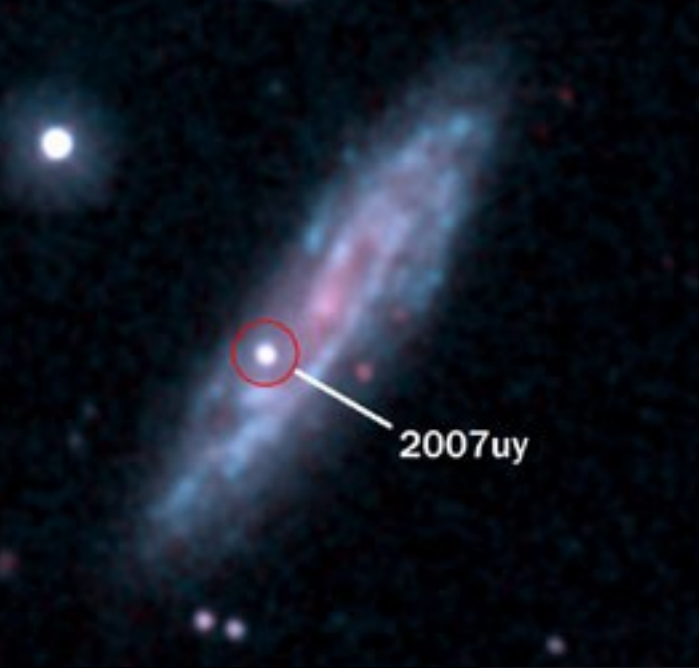
- Iron is the most stable element – it has the most tightly bound nucleus
- For elements lighter than iron, fusing them into heavier elements produces energy
- This doesn't work for iron: fusing iron atoms together into heavier atoms does not create energy



Evolution of the most massive stars

- So our massive star suddenly no longer has fusion at its core, and it can't create the pressure needed to support itself against gravity
- This results in a sudden, catastrophic collapse of the star: a **core-collapse or Type-II supernova**

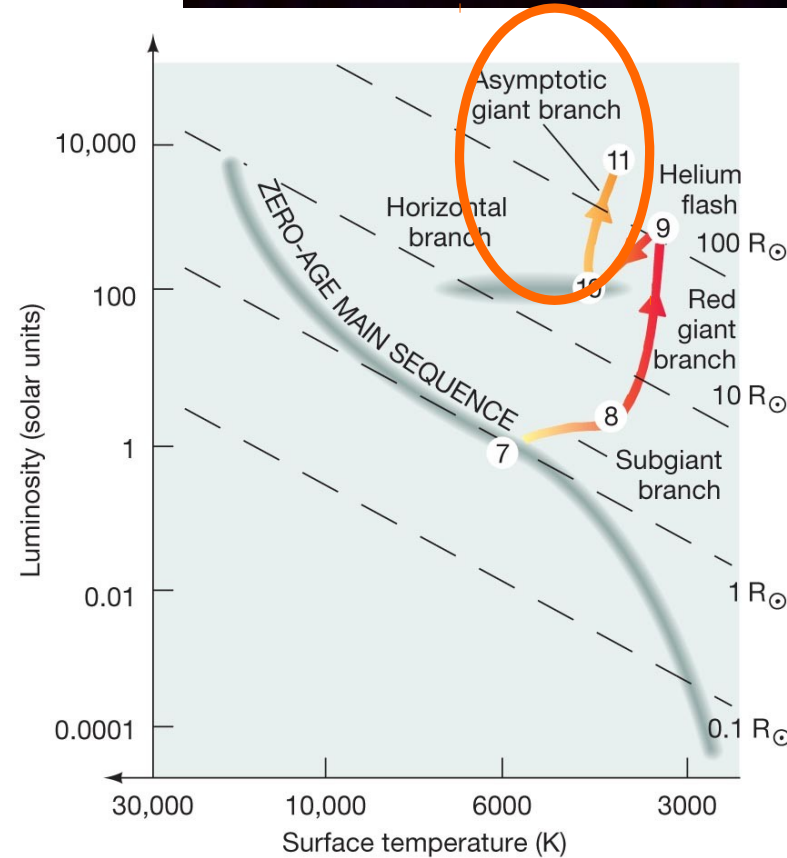
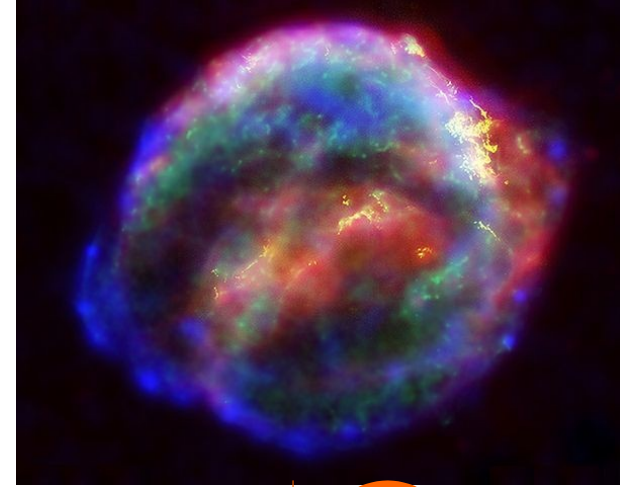




Supernovae can be brighter than all of the other stars in the galaxy combined!

Where do elements heavier than iron come from?

- **Supernova nucleosynthesis:** heavy elements can be created during supernovae via a process involving rapid capture of neutrons by heavy nuclei like iron
- There is also a **slow neutron capture process** which occurs in late stages of stellar evolution, mostly in Asymptotic Giant Branch (AGB) stars
- These two processes account for most of the elements heavier than iron



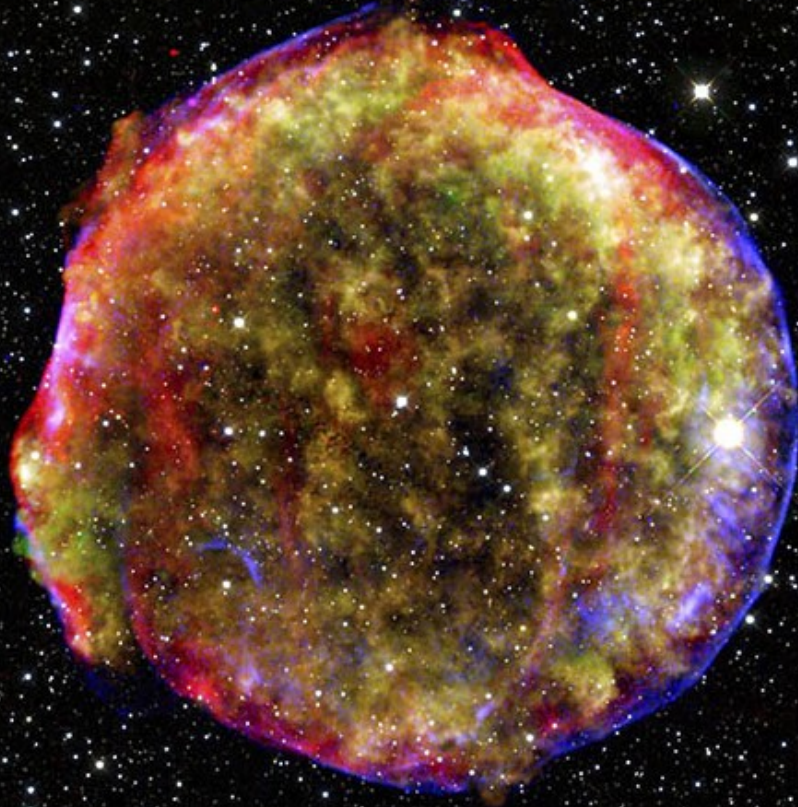
Supernovae and the death of stars much more massive than the Sun



Supernova 1987A in the LMC



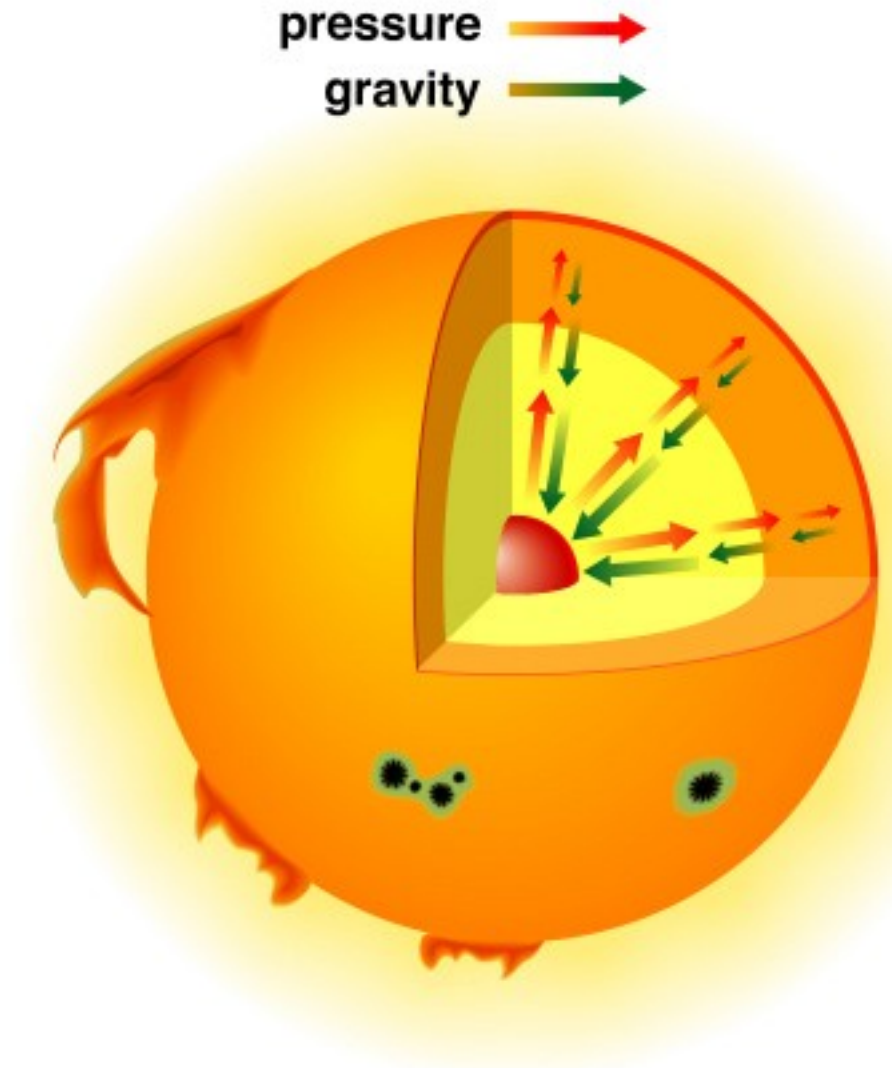
Supernovae are the explosions of dead stars: the dead core of a massive star or the dead matter in a white dwarf.



There is an important relation between the universe's speed limit (the speed of light) and the upper limit on the mass of these dead remnants of stars.

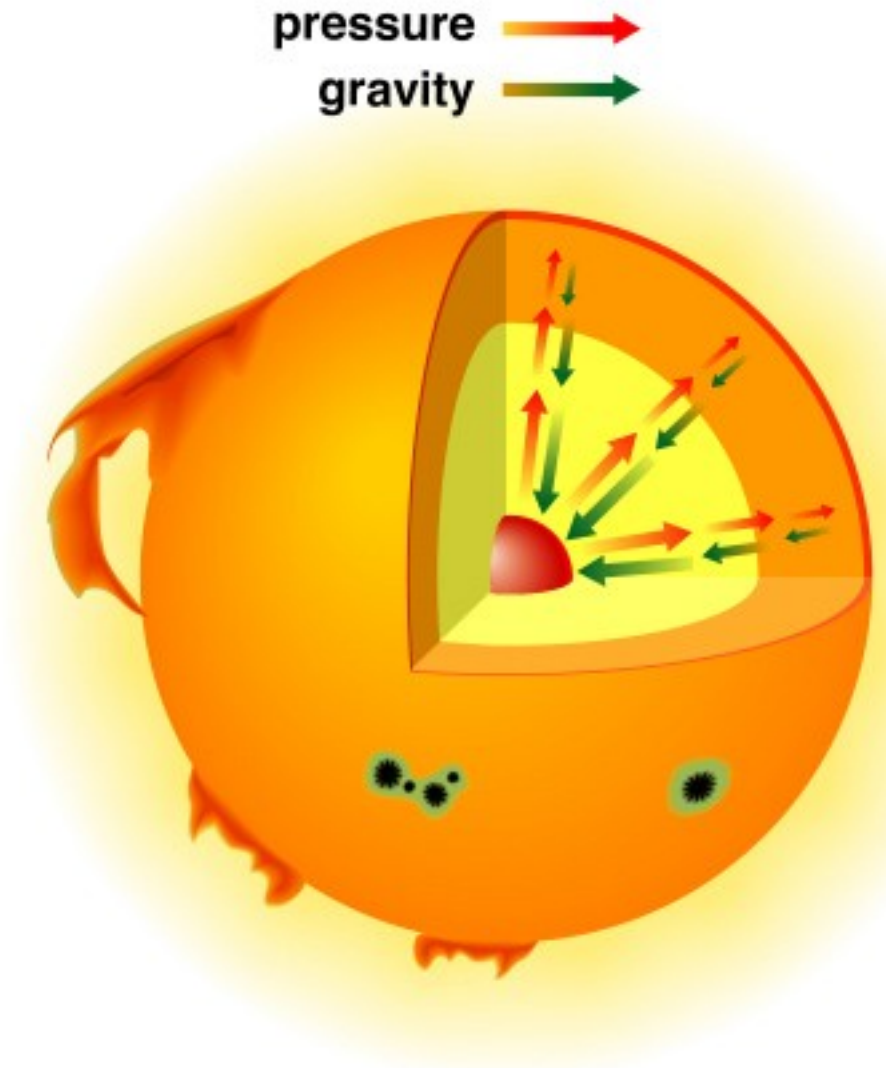
Chandrasekhar's upper mass limit

Any star is held apart by pressure and pulled together by gravity. Pressure is due to the motion of the particles that comprise a star; the faster the particles move, the greater the pressure.



Chandrasekhar's upper mass limit

But there is an upper limit on pressure, because there is an upper limit on the speed of the particles: nothing can go faster than light. If we add mass to a white dwarf, it gets denser, and the gravity that pulls it together grows stronger.



Chandrasekhar's upper mass limit

The pressure also increases as we add mass, but there is no limit on the force of gravity pulling the star together. And there is a limit to the pressure.

So as we add mass to a white dwarf, the gravity pulling it together will always beat the pressure pushing it apart, and the mass at which gravity wins — for which the electrons would have to go faster than light to keep the star apart — is **1.4 solar masses**.

Chandrasekhar's upper mass limit

This means that no white dwarf can have a mass greater than 1.4 solar masses!

Its electrons would have to travel faster than light to supply the pressure needed to keep it from collapsing.

Chandrasekhar's upper mass limit

This limit was discovered in 1930 by a 20 year-old student, **Subrahmanyan Chandrasekhar**, who was on a ship traveling from India to England, where he was going to do graduate work with Eddington (who we met when discussing hydrogen fusion in the Sun).

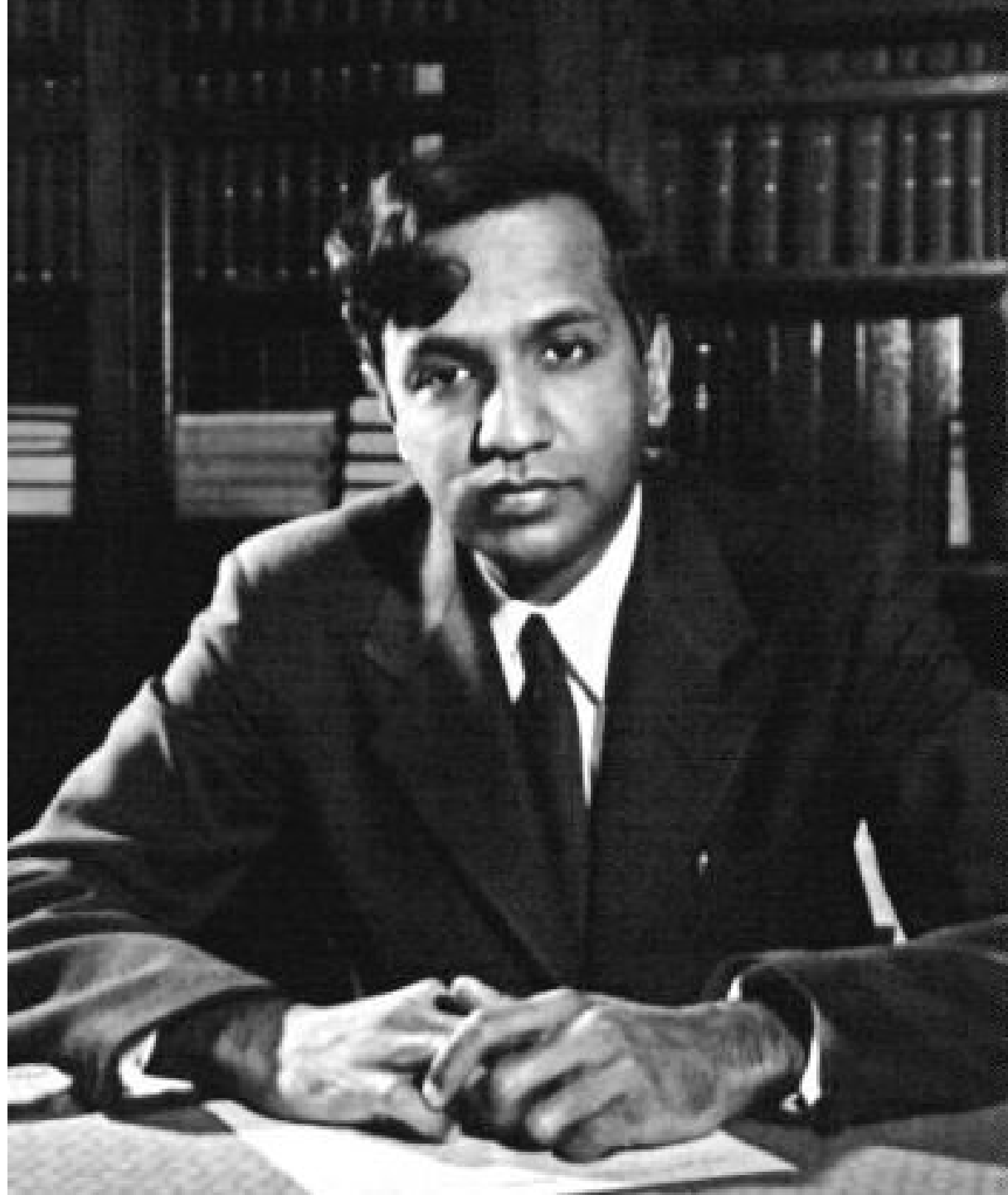
The argument explained the last great mystery of ancient astronomy, the sudden appearance and fading of new bright stars, called "guest stars" by the Chinese, new stars by the Europeans.

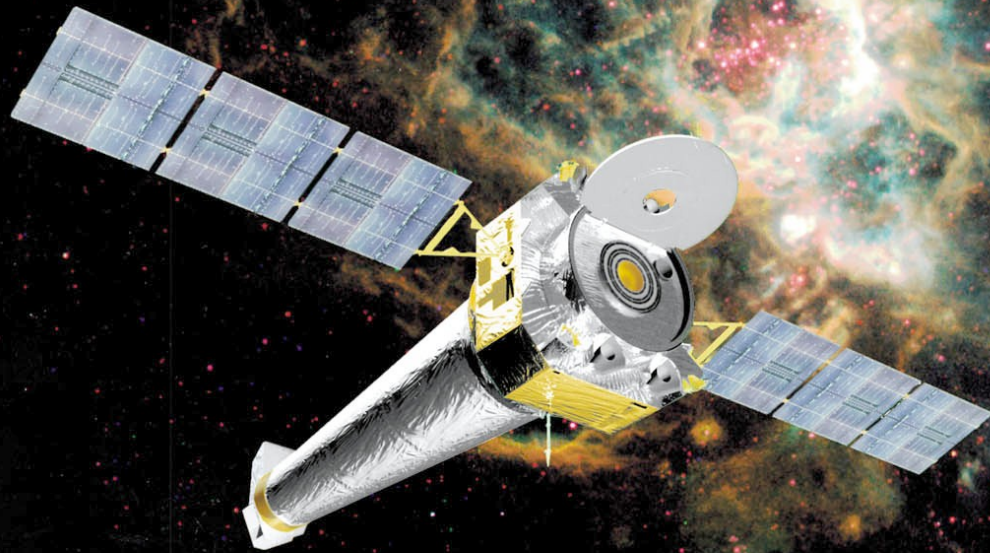
Chandrasekhar's upper mass limit

Because Eddington (the leading astrophysicist of his day) did not accept the argument — he thought that some new physics would arise to protect white dwarfs from collapse — it took decades before Chandrasekhar's work was understood and accepted by astronomers.

Fifty years after his discovery, in 1983, the Nobel committee finally gave Chandra the prize.

Chandrasekhar at about the time he found that the upper limit on the mass of white dwarfs was set by the upper limit c on the speed at which electrons can travel.





The Chandra X-ray Observatory, shown here in a composite image with a supernova remnant, is named for Chandrasekhar.



Matter is supported against gravity by its pressure, and the pressure of a collection of particles depends on the particles' speed. There is an upper limit on the speed at which a particle can travel — and hence an upper limit on the pressure that matter can exert. But there is no upper limit on the gravitational force.



When the mass of a dense object is too large, gravity overwhelms pressure and the object **collapses**.

If a white dwarf accretes too much mass from a companion, or if it merges with another white dwarf, its mass will exceed the Chandrasekhar limit. What happens then?

Type I Supernovae

If a white dwarf accretes too much mass from a companion, or if it merges with another white dwarf, its mass will exceed the Chandrasekhar limit. What happens then?

Type I Supernovae

If a white dwarf accretes too much mass from a companion, or if it merges with another white dwarf, its mass will exceed the Chandrasekhar limit. What happens then?

Nearly all the electrons in the star are pulled onto the protons in the helium and carbon nuclei, turning the protons into neutrons and turning the star into a giant atomic nucleus, called a neutron star.

Remember that an atom is mostly empty space — In a scale model the nucleus was a marble in the center of Miller Park, with the electrons at the dome and nothing inside.

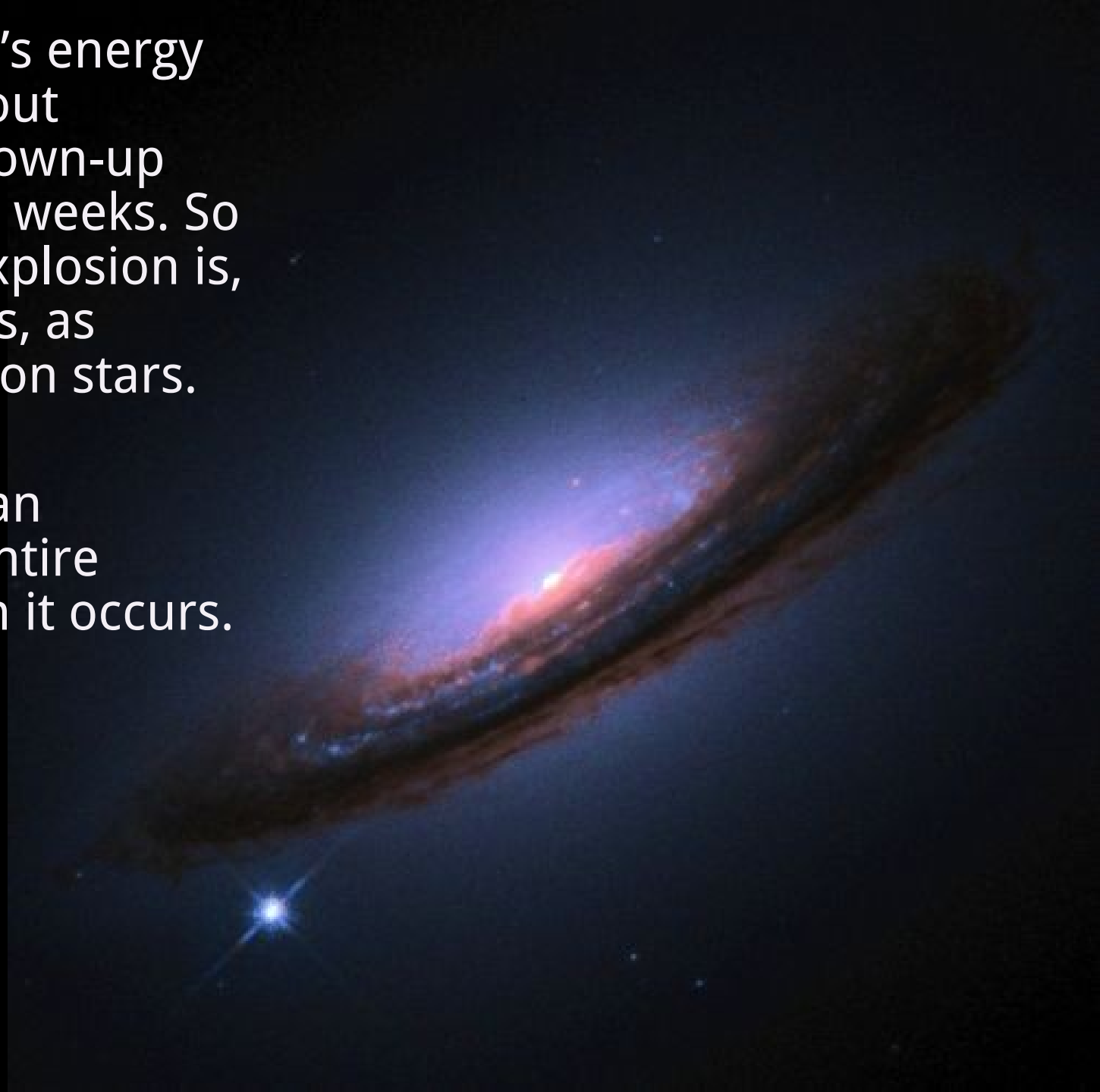
Type I Supernovae

When a white dwarf collapses, the electrons are pushed down onto the nuclei — Miller Park collapses to the size of a marble. When each of its atoms collapses, the star collapses from the size of the Earth to the size of Milwaukee, about 20 km (13 mi) in diameter.

More energy is released in a few seconds by the collapse than by the slow contraction of a red giant's core that helps power the giant for 100 million years.

The supernova's energy works its way out through the blown-up star over a few weeks. So a supernova explosion is, for a few weeks, as bright as a billion stars.

A supernova can outshine the entire galaxy in which it occurs.



A **Type I supernova** is the violent gravitational collapse of a white dwarf pushed over its upper mass limit.



The Deaths of Massive Stars

- No dead iron core of a star can have a mass greater than 1.4 solar masses
- A Type II supernova is the explosion caused by the violent gravitational collapse of the core of a massive star at the end of its evolution (when enough iron has been added to it to exceed the 1.4 solar mass limit)
- Most of the star is blown away, and the expanding cloud it becomes is called a supernova remnant
- The most massive main-sequence stars end their lives in supernovae

The Deaths of Massive Stars

- Elements that are formed in low mass stars stay inside the stars. Elements heavier than helium are distributed throughout the galaxy by the supernova explosions that blow apart the most massive stars.
- Nearly everything in you except hydrogen was once in a massive star that blew itself apart in a supernova.
- Supernovae are the way elements heavier than helium get out of the stars where they form and are distributed through the universe.

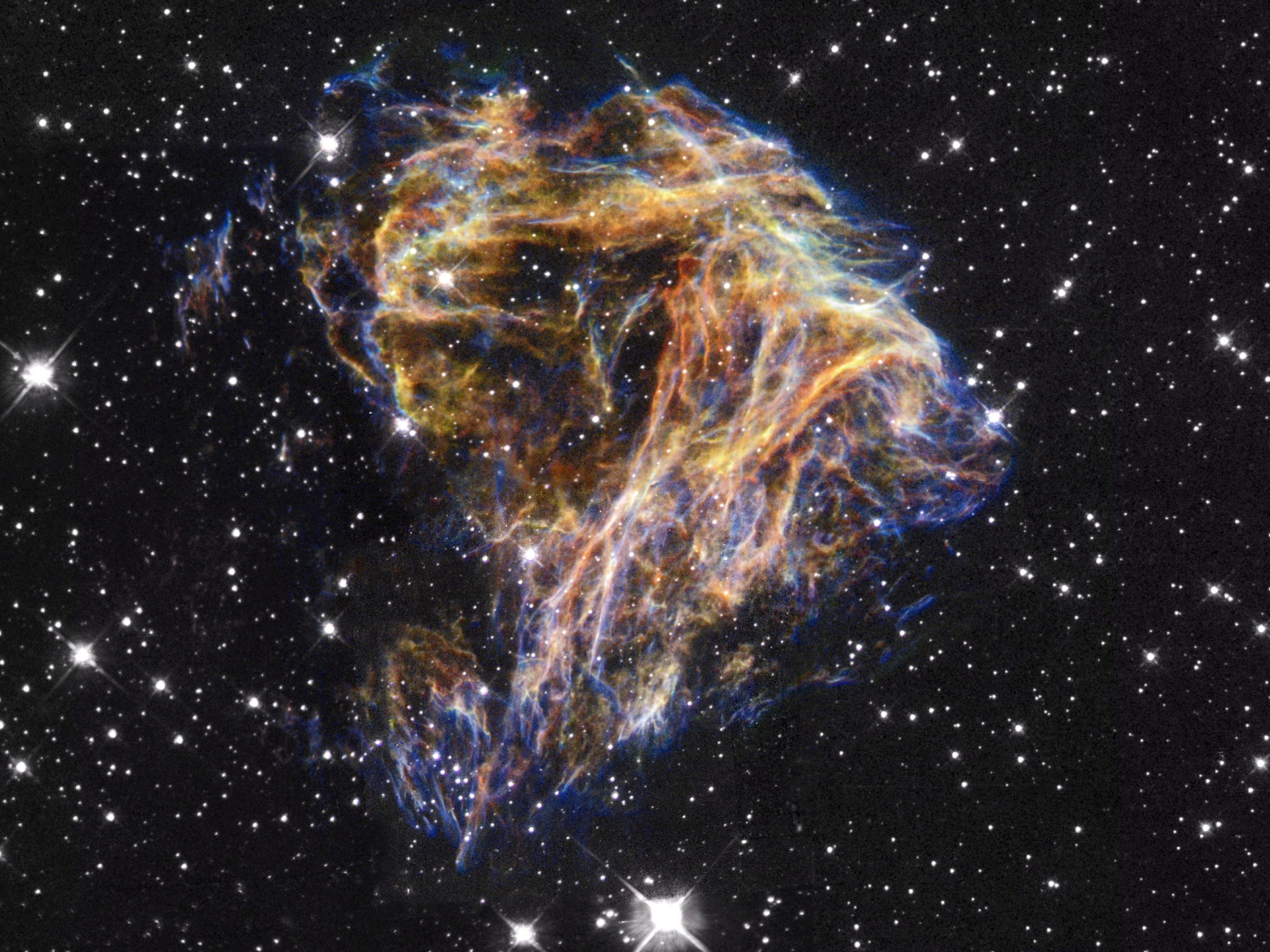
Summary: Two types of supernovae

- **Type I:**

The collapse of an accreting white dwarf when its mass reaches 1.4 solar masses.

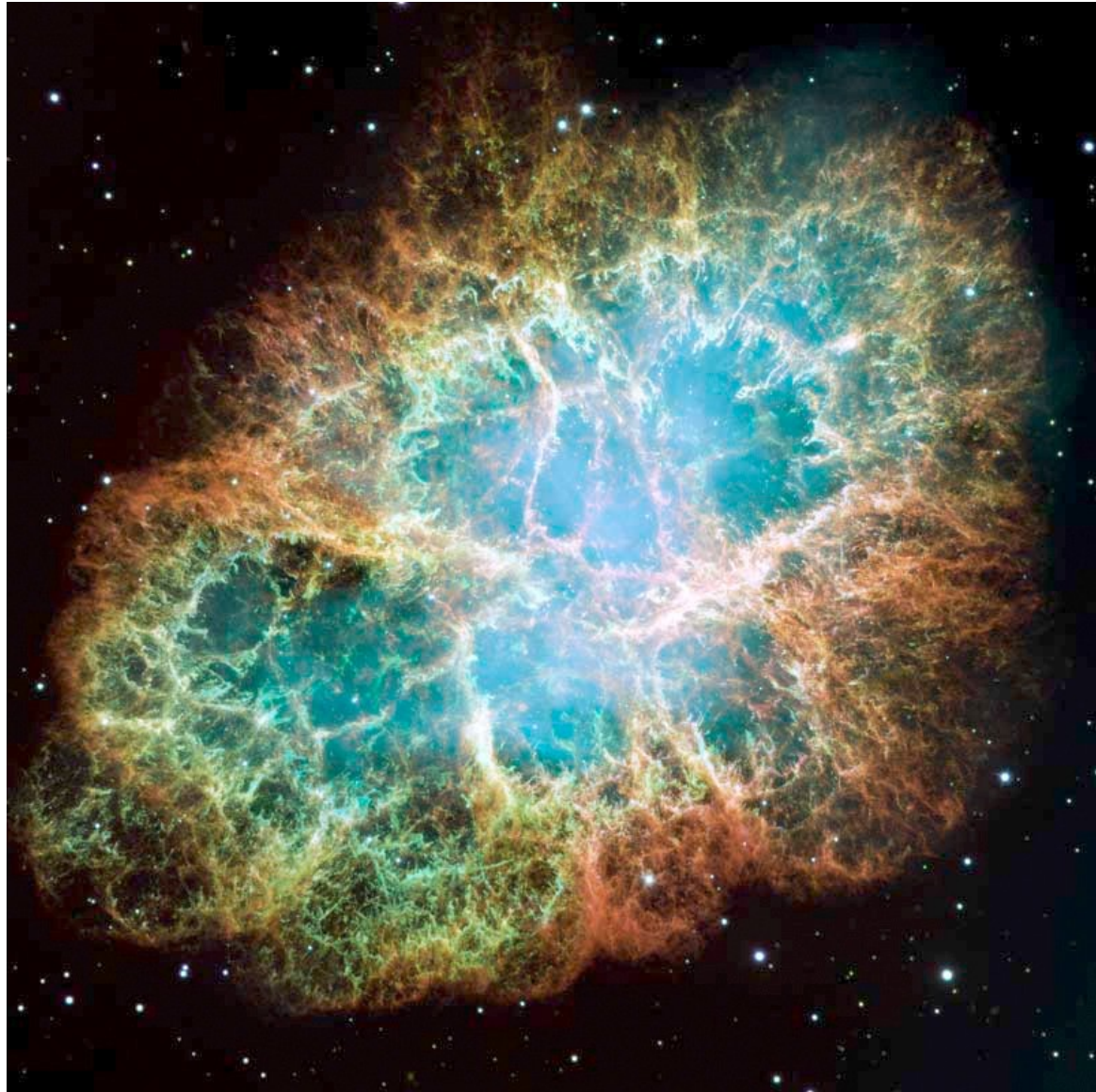
- **Type II:**

The collapse of the iron core of a massive star when its mass reaches 1.4 solar masses. The energy of matter falling during the gravitational collapse (and then rebounding) is the energy that explodes the rest of the star.



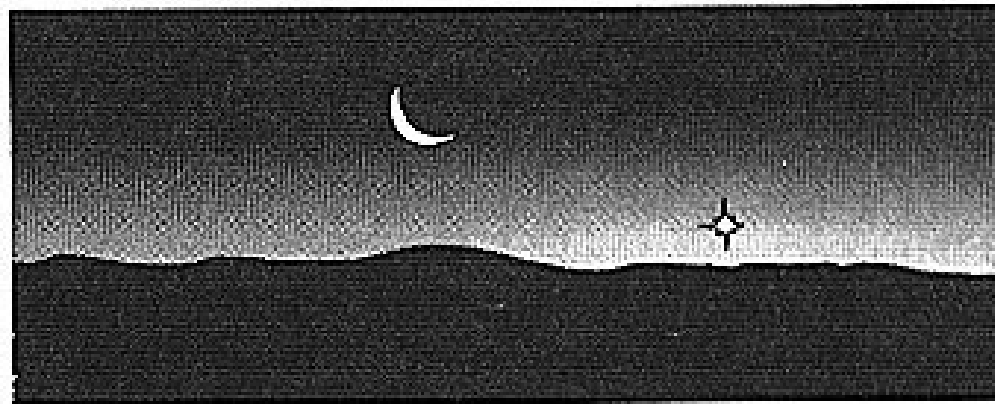
Supernovae remnant: Crab nebula

- One of the most famous supernova remnants is the Crab Nebula
- Supernova was in 1054: recorded by Chinese astronomers

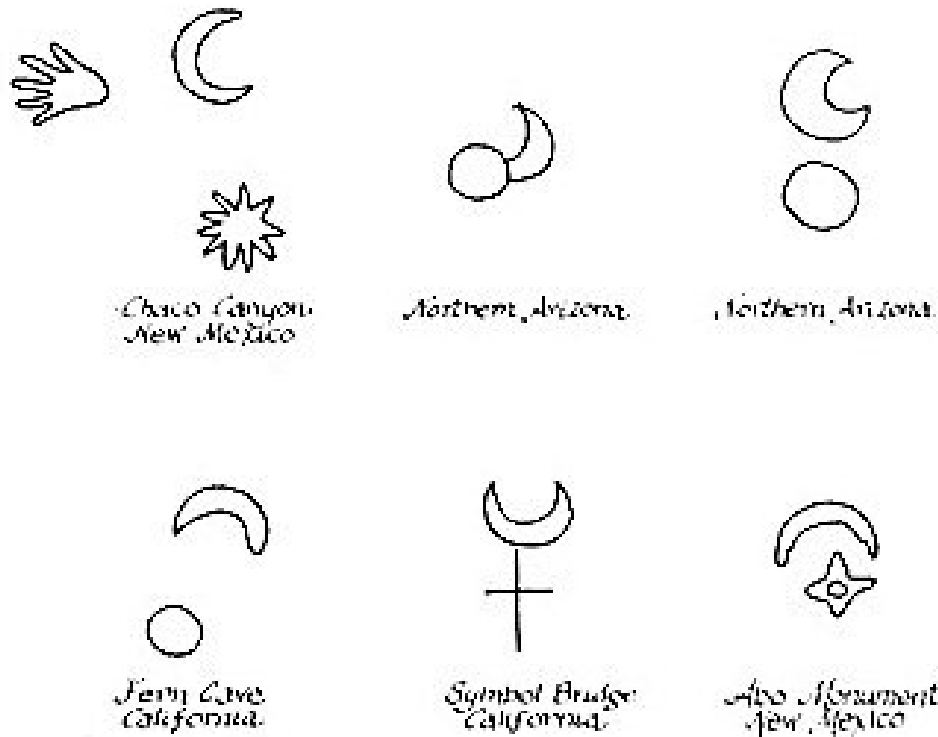


Crab Supernova was in 1054 -- probably also observed by the Anasazi in North America





The crescent moon was visible in western North America near the Crab supernova in the predawn eastern sky on July 5, A.D. 1054.



Several examples of crescents in rock art from the American Southwest are associated with what may be representations of the A.D. 1054 supernova.

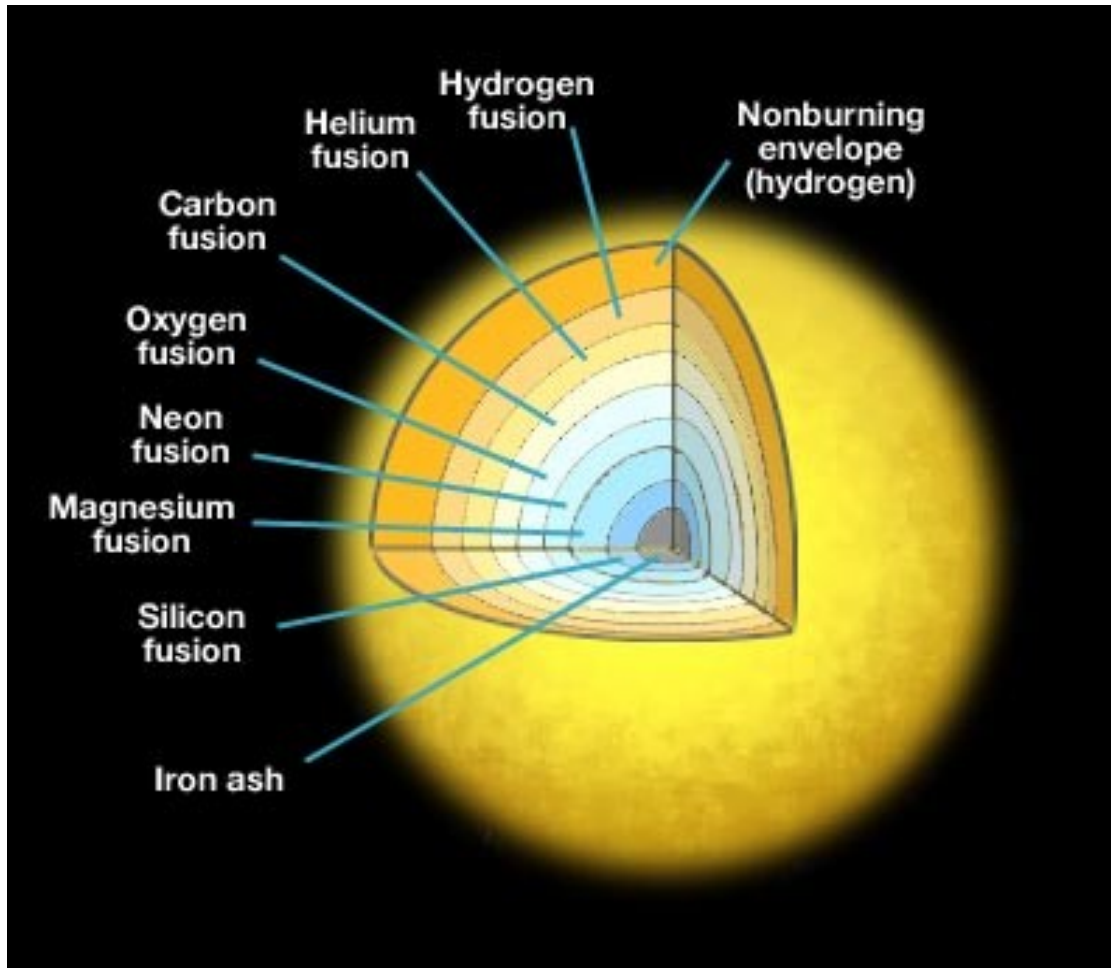
Evolution of Stars More Massive than the Sun

TABLE 12.3 End Points of Evolution for Stars of Different Masses

Initial Mass (Solar Masses)	Final State
Less than 0.08	(Hydrogen) brown dwarf
0.08–0.25	Helium white dwarf
0.25–8	Carbon–oxygen white dwarf
8–12 (approx.)*	Neon–oxygen white dwarf
Greater than 12*	Supernova

*Precise numbers depend on the (poorly known) amount of mass lost while the star is on, and after it leaves, the main sequence.

Which of these is the most likely mass of the star shown in this diagram?



A

0.4 Msun

B

1 Msun

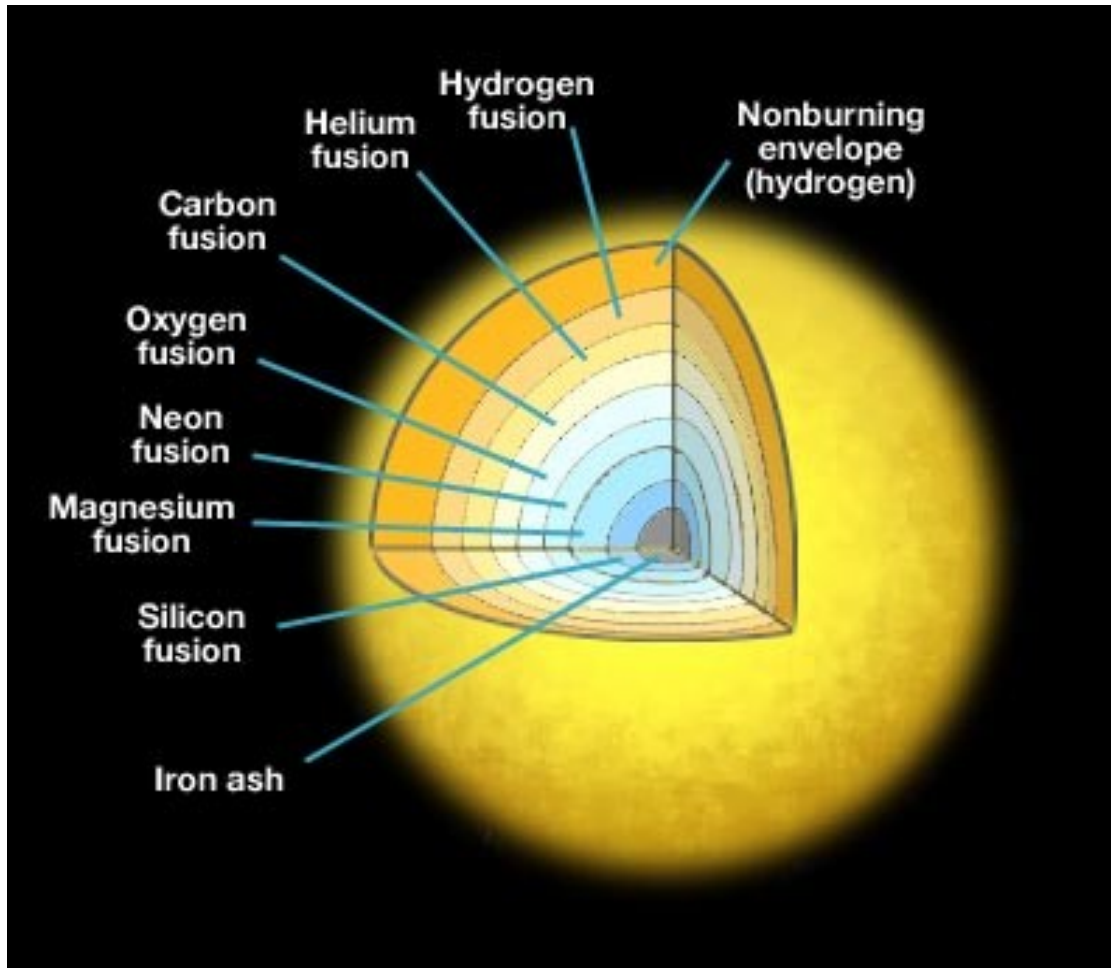
C

4 Msun

D

10 Msun

Which of these is the most likely mass of the star shown in this diagram?



A

0.4 Msun

B

1 Msun

C

4 Msun

D

10 Msun