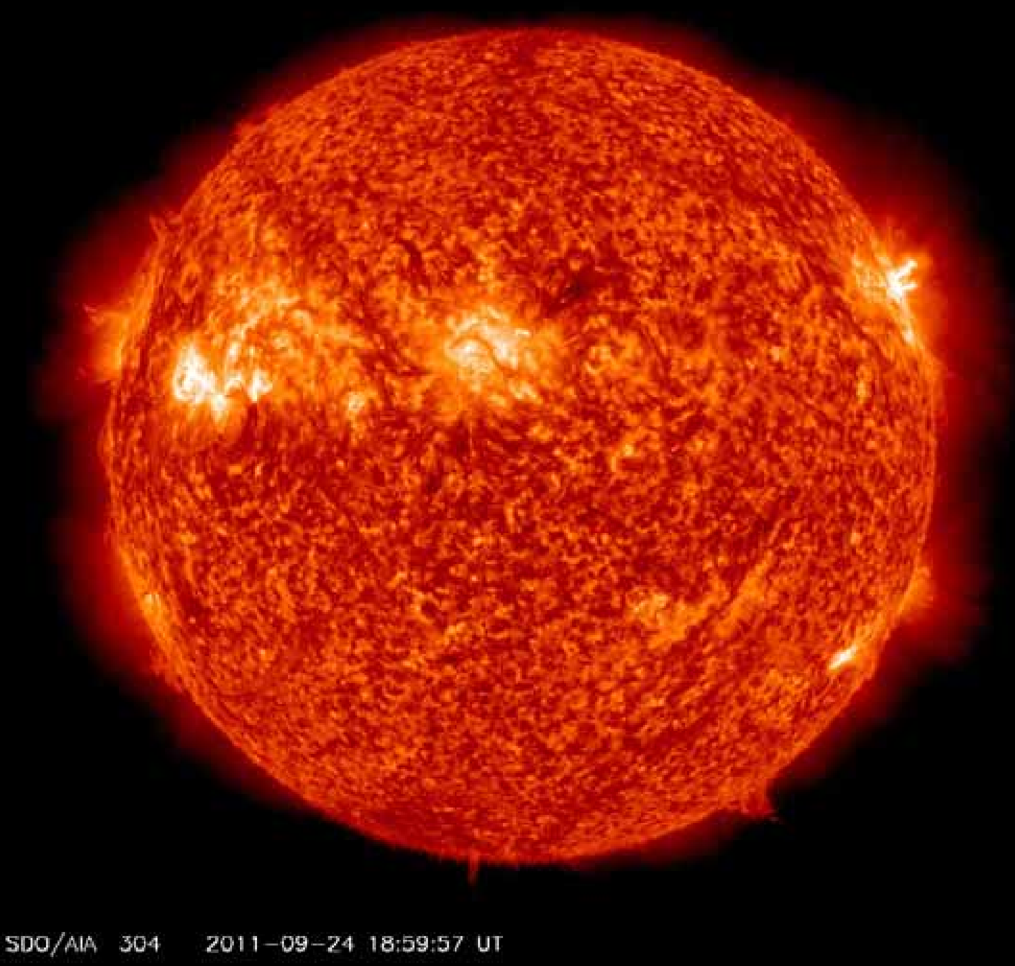

STELLAR EVOLUTION
Joseph L Seymour

INTRODUCTION

Stars, like our own Sun, just as human beings, have a finite existence.



INTRODUCTION

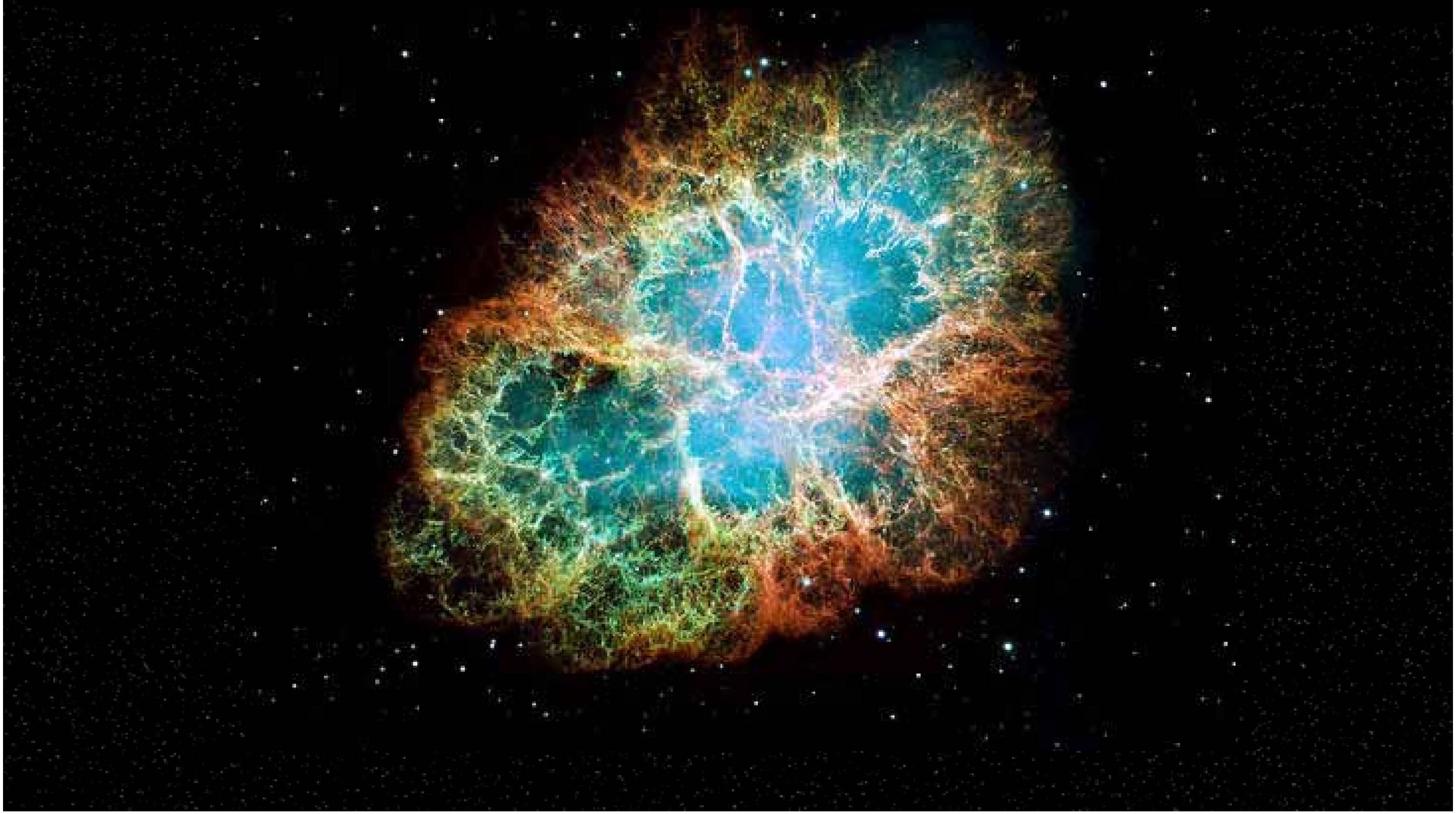
They go through a fetal stage

INTRODUCTION

They are born and live out lifetimes of varying lengths

INTRODUCTION

And they die

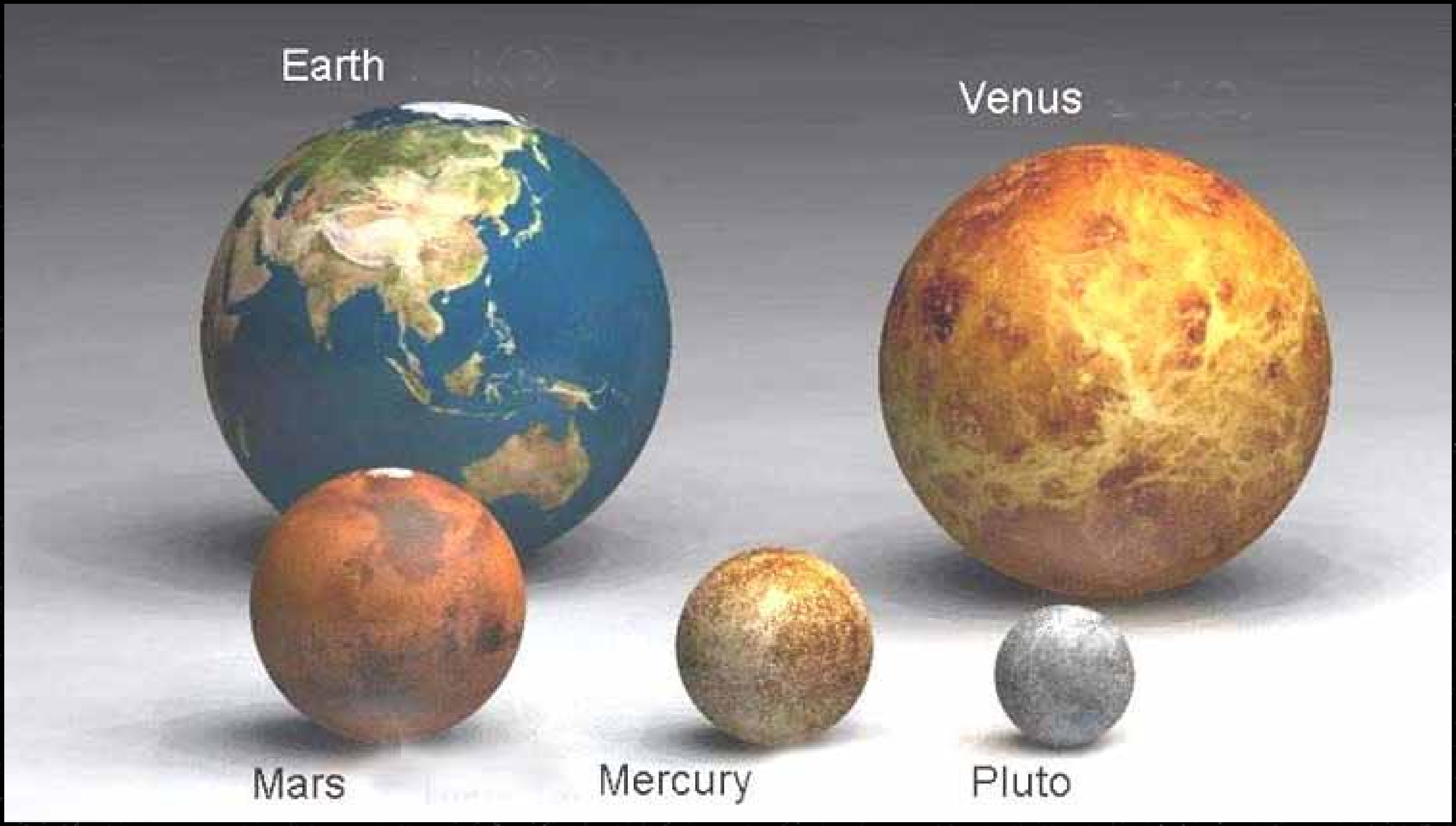


INTRODUCTION

- How long a star lives is determined by how massive it is.
- Some stars are small – like our Sun
- And some stars are huge!

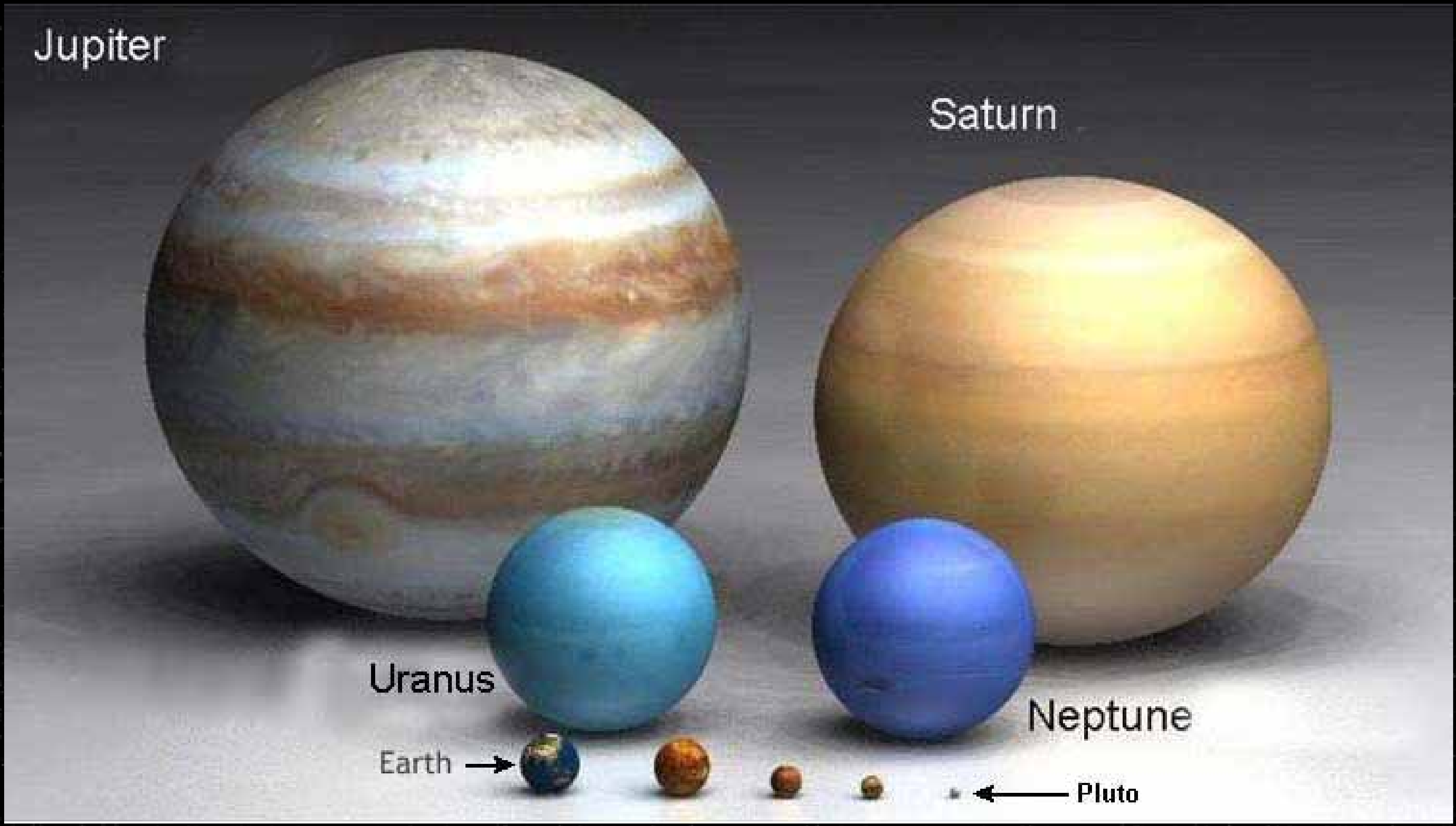
INTRODUCTION

SIZE MATTERS!

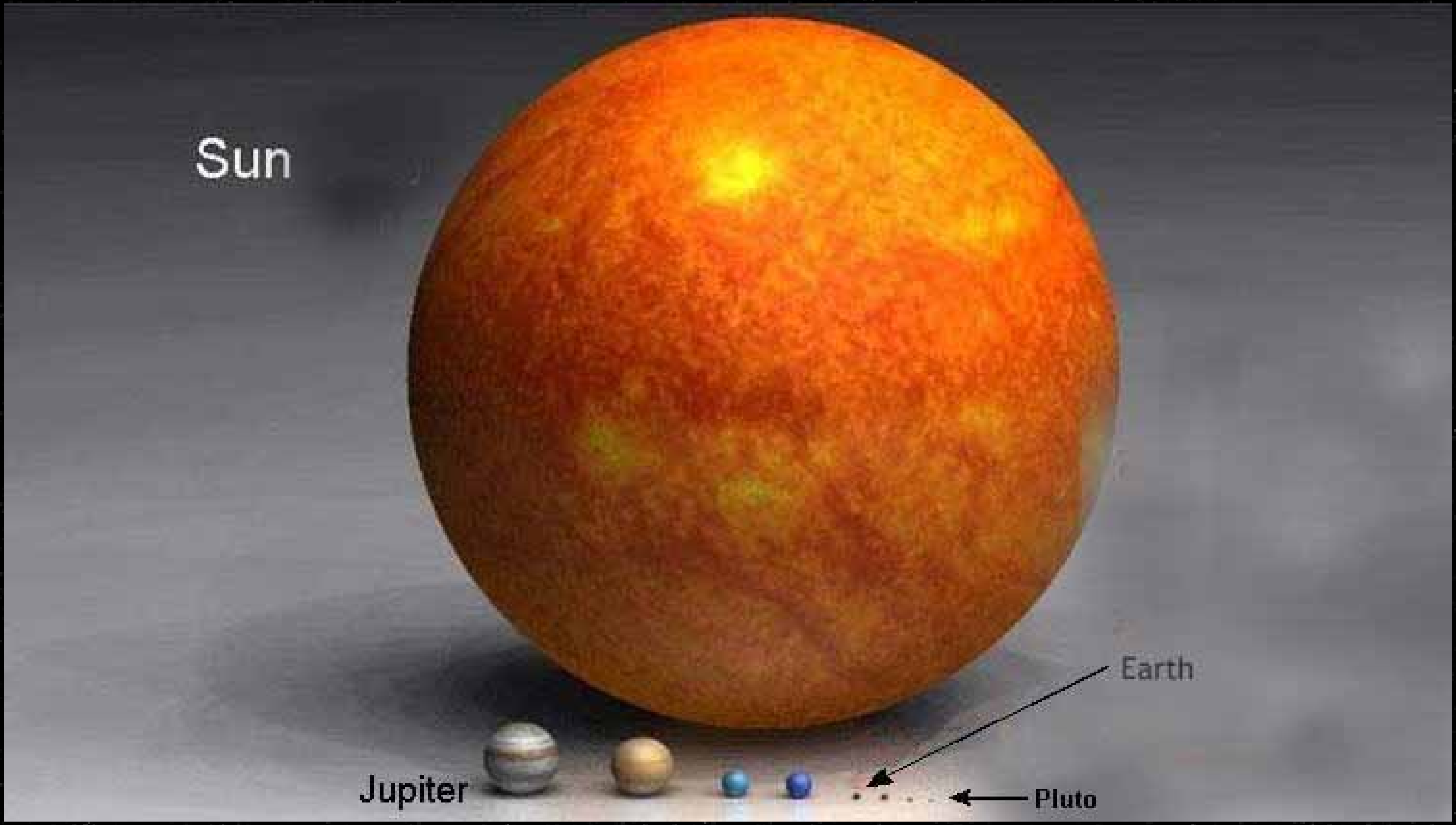


INTRODUCTION

SIZE MATTERS!

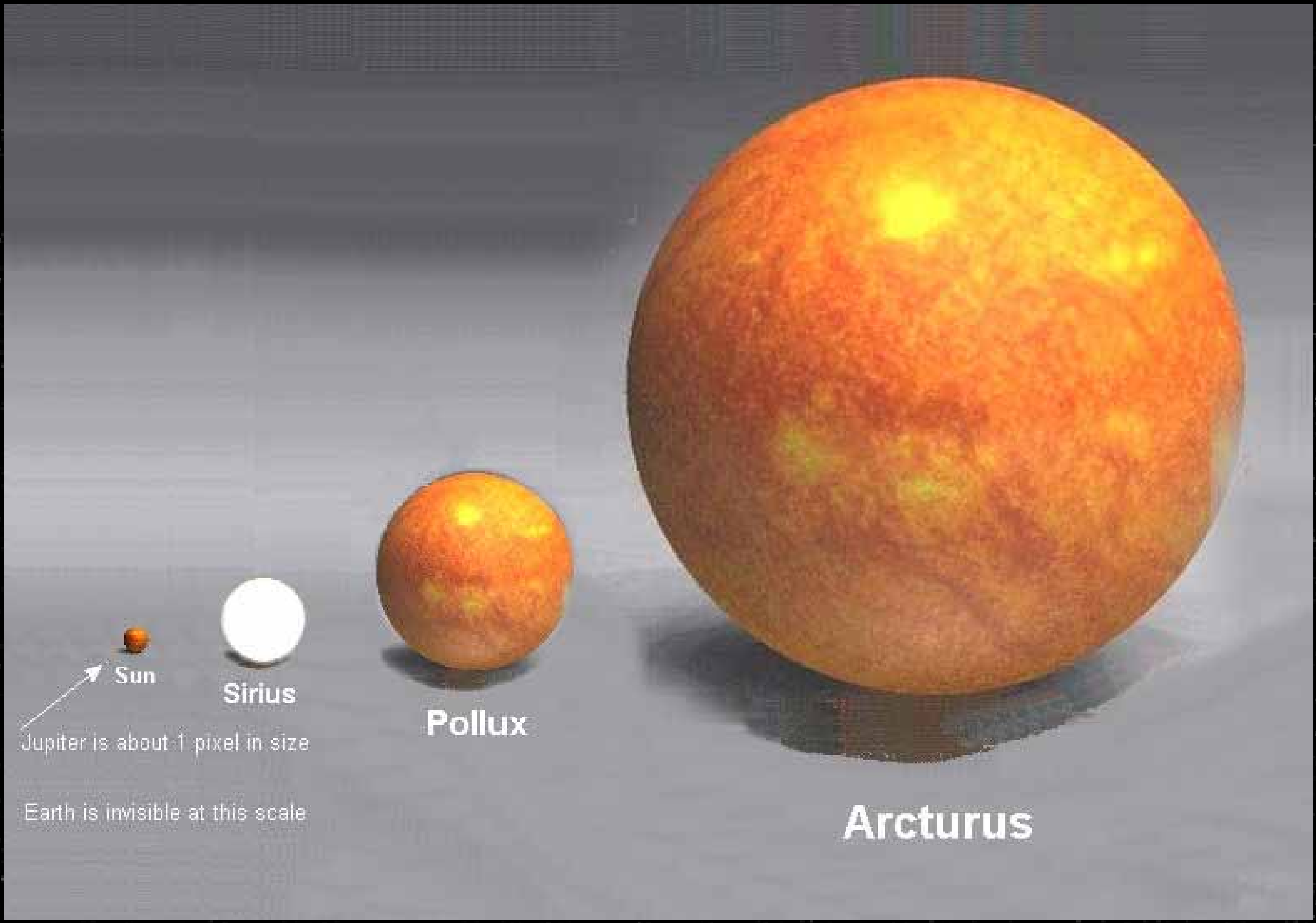


INTRODUCTION
SIZE MATTERS!



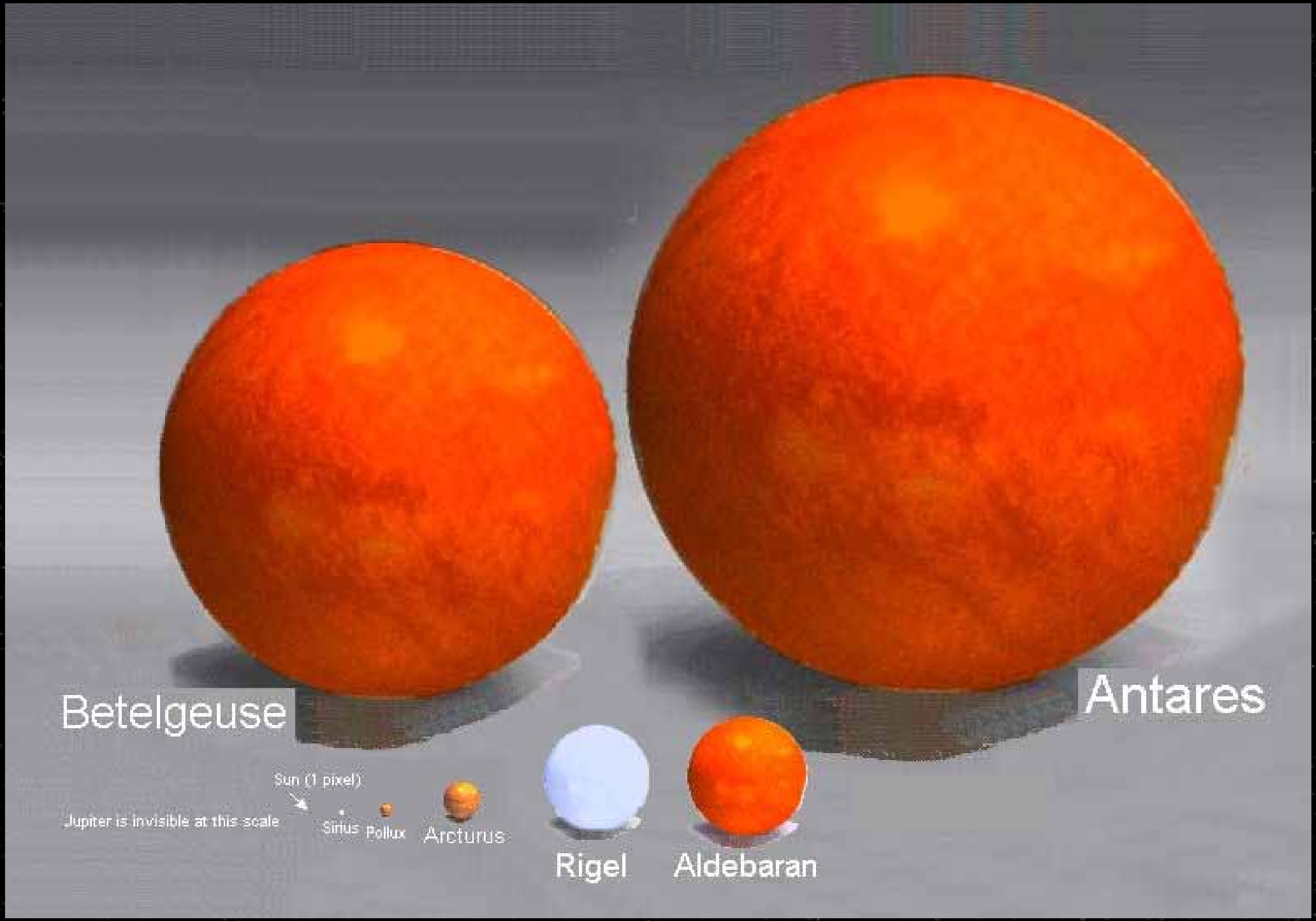
INTRODUCTION

SIZE MATTERS!



INTRODUCTION

SIZE MATTERS!



INTRODUCTION

- How long a star lives depends on its mass.
- How a star dies depends on its mass.

INTRODUCTION

We can relate stellar mass to approximate stellar lifetime by –
(with masses in solar masses and lifetimes in solar lifetimes)

$$\text{Stellar Lifetime} \propto \frac{1}{(\text{Stellar Mass})^3}$$

TABLE 17.5 Key Properties of Some Well-Known Main-Sequence Stars

Star	Spectral Type	Mass, *M* (Solar Masses)	Central Temperature (10^6 K)	Luminosity, *L* (Solar Luminosities)	Estimated Lifetime (*M/L*) (10^6 years)
Spica B*	B2V	6.8	25	800	90
Vega	A0V	2.6	21	50	500
Sirius A	A1V	2.1	20	22	1000
Alpha Centauri	G2V	1.1	17	1.6	7000
Sun	G2V	1.0	15	1.0	10,000
Proxima Centauri	M5V	0.1	0.6	0.00006	16,000,000

* *The "star" Spica is, in fact, a binary system comprising a B1III giant primary (Spica A) and a B2V main-sequence secondary (Spica B).*

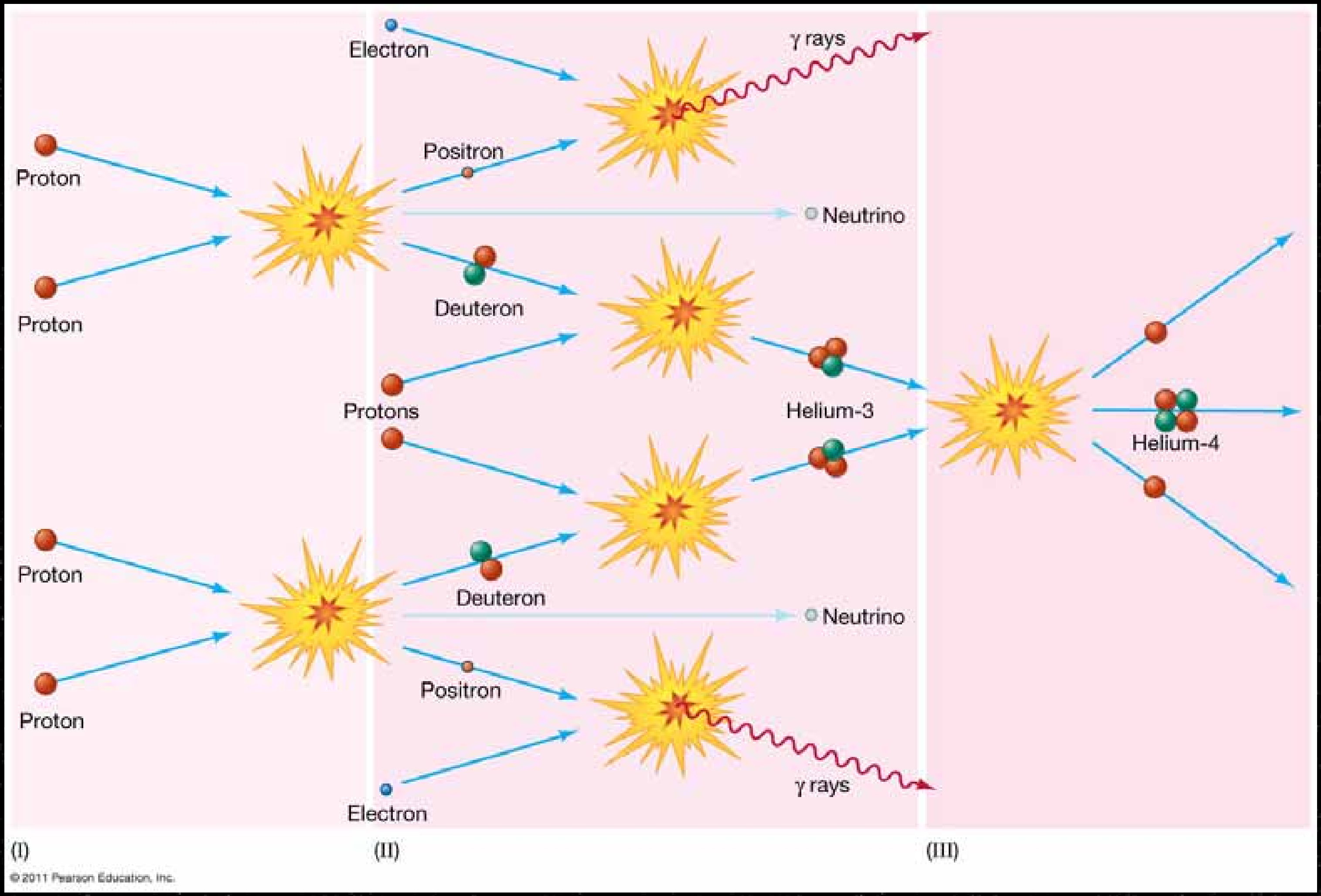
ENERGY PRODUCTION

- Einstein

$$E = mc^2$$

ENERGY PRODUCTION

Nuclear Fusion



ENERGY PRODUCTION

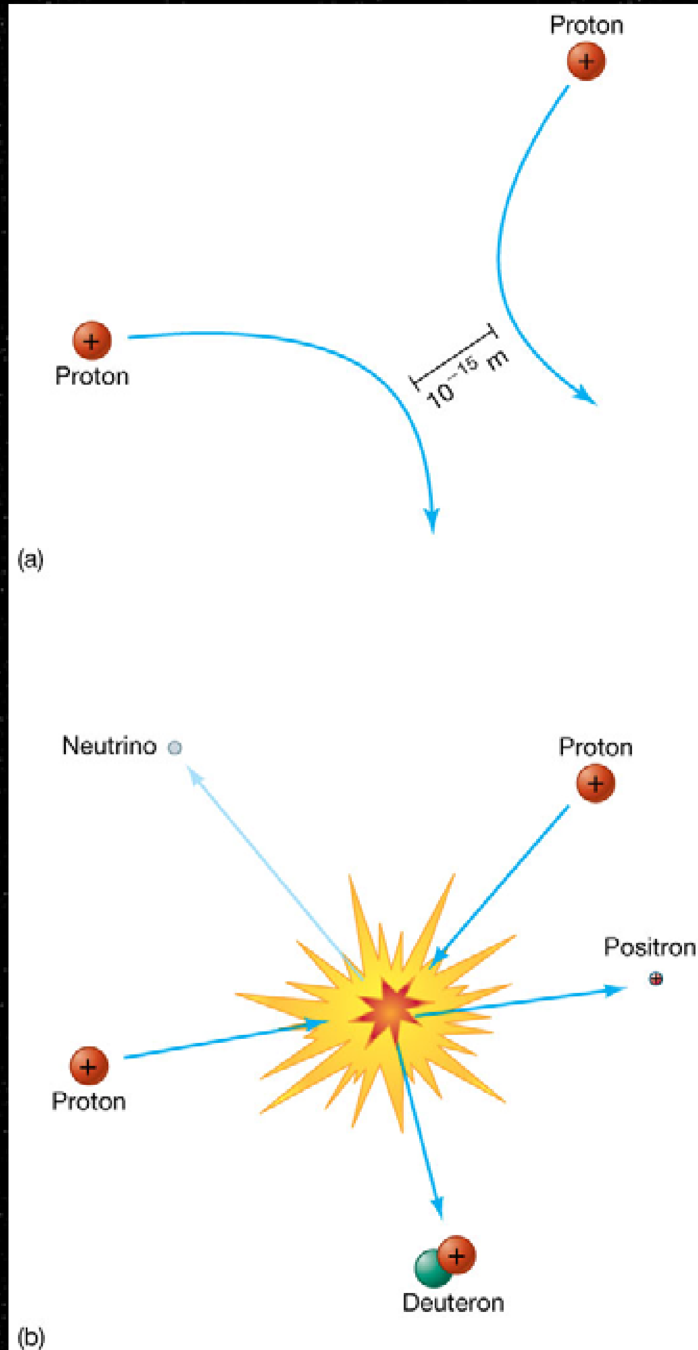
- Fusion take place in the core of stars.
- Requirements for fusion
  - High Temperature (~10,000,000 K)
  - High Pressure

ENERGY PRODUCTION

- The Sun generates energy equivalent to detonating 10 billion (10,000,000,000) 1 kiloton nuclear bombs every second!

- The Sun consumes hydrogen at a rate of about

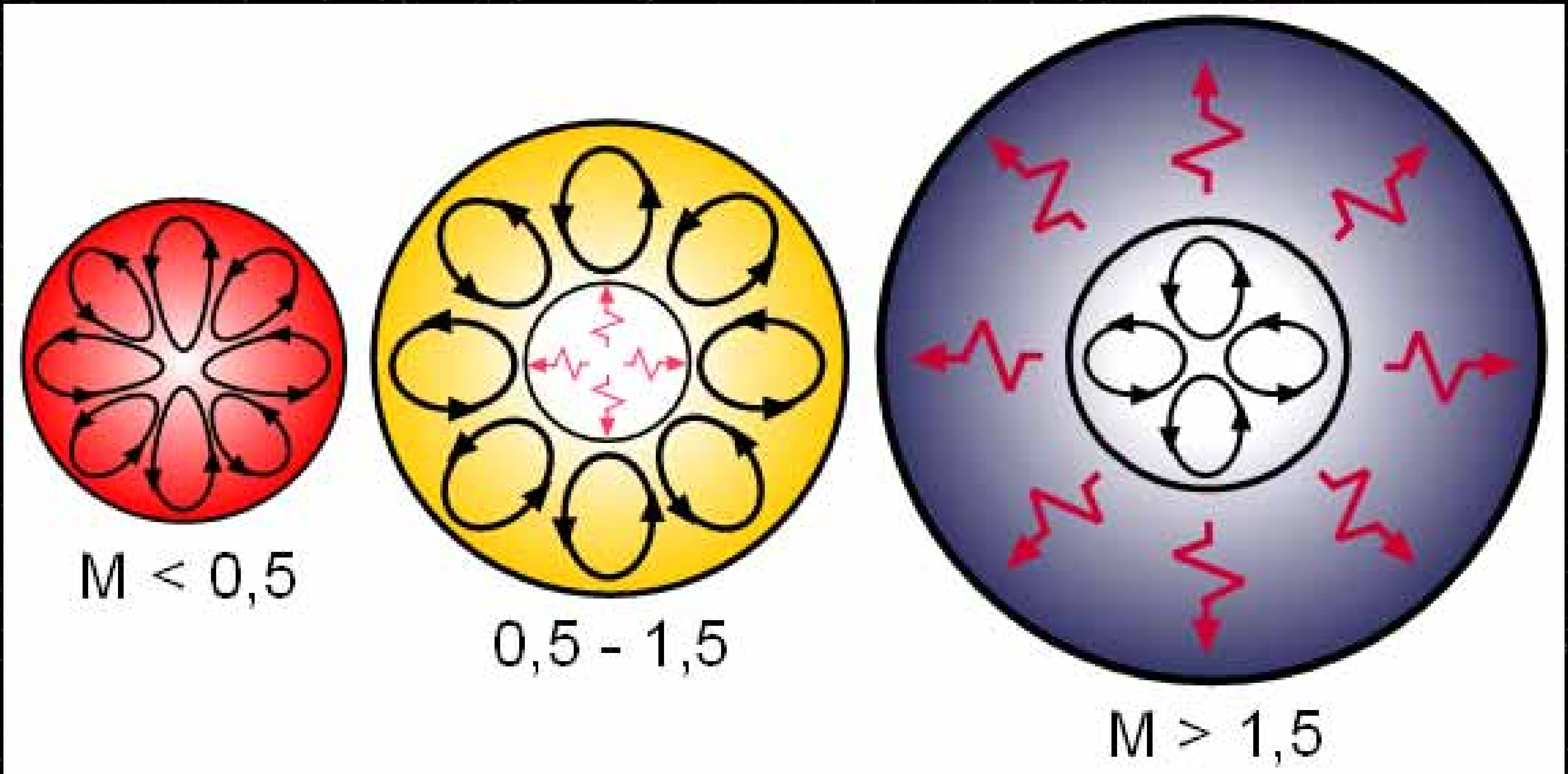
$$6.20 \times 10^{11} \text{ kilograms/second}$$


Proton
Proton
10^{-15} m
(a)
Neutrino
Proton
Positron
Proton
Deuteron
(b)

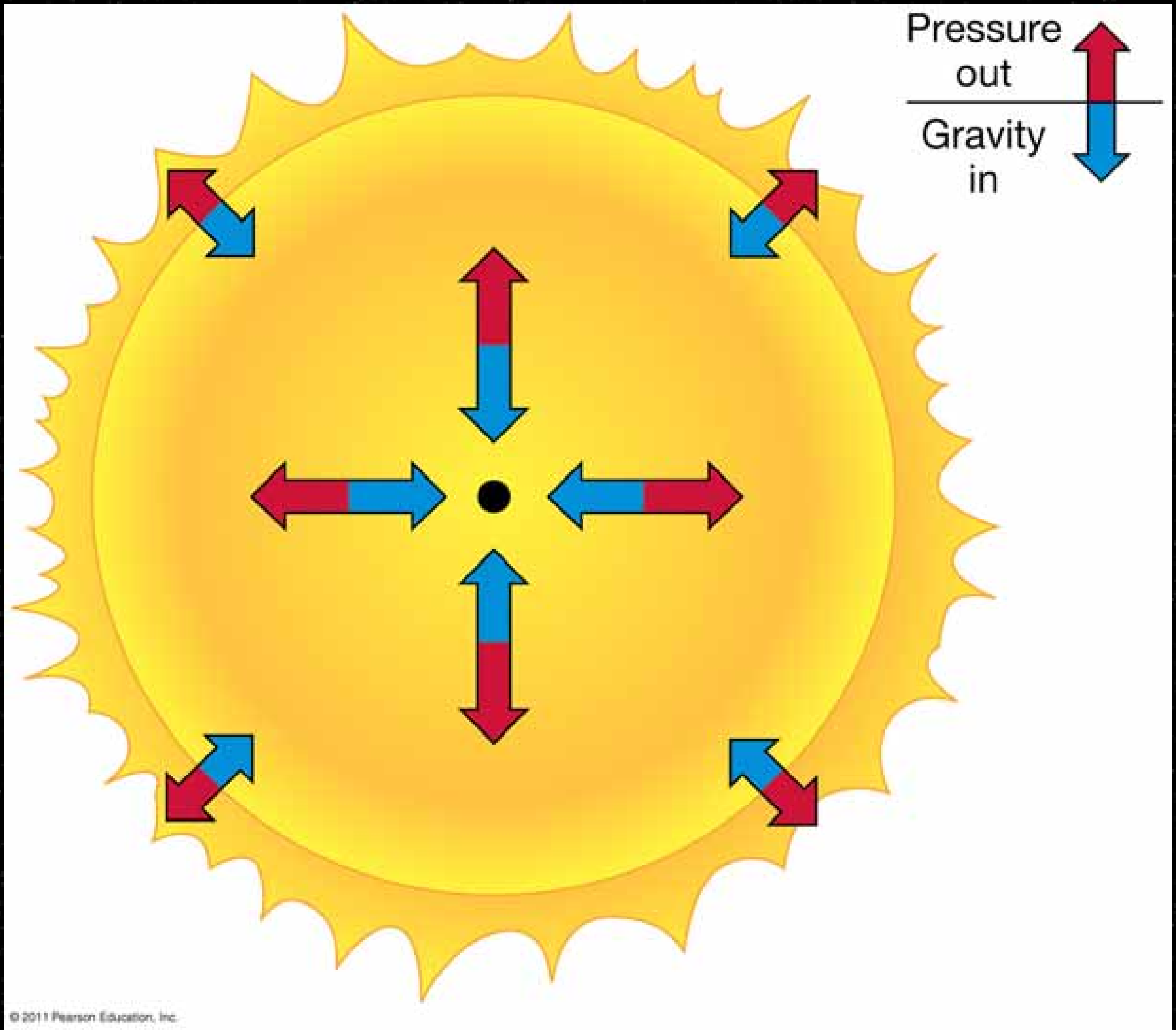
ENERGY TRANSPORT

- Conduction
- Convection
- Radia*t*ion

ENERGY TRANSPORT



HYDROSTATIC EQILIBRIUM



MASS vs.. STELLAR LIFETIME

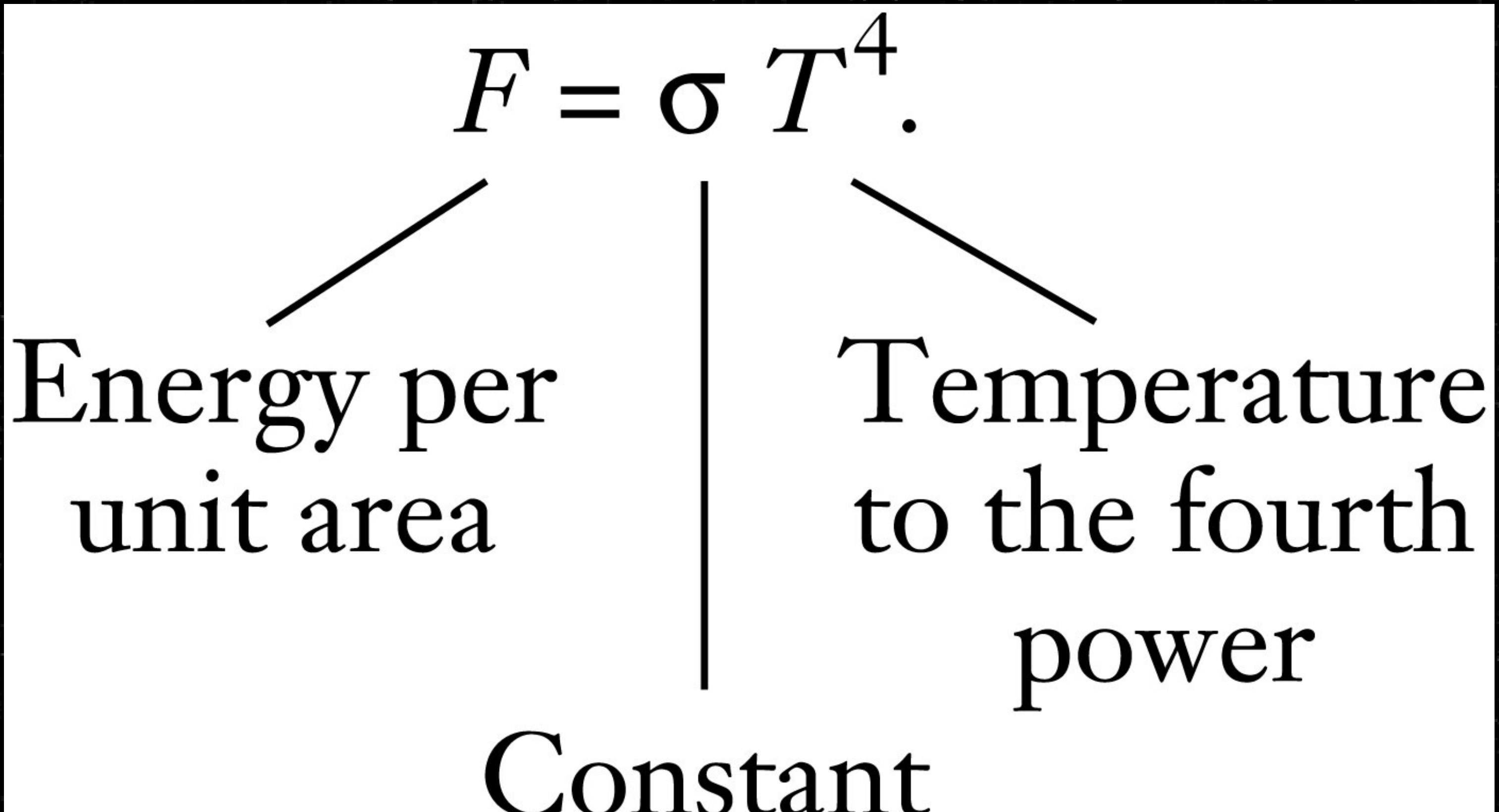
- We have already stated that

$$\text{Stellar Lifetime} \propto \frac{1}{(\text{Stellar Mass})^3}$$

- This may seem counter intuitive because the more mass you have the longer is should last. Right?....NO!

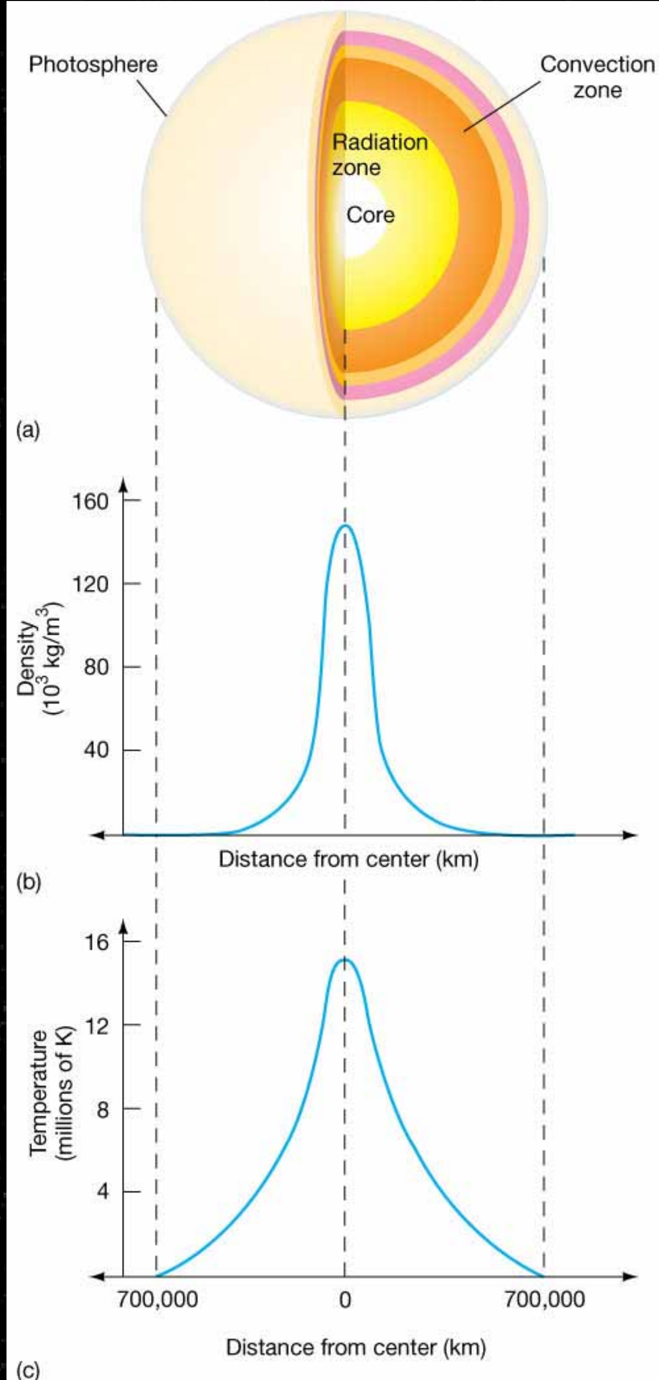
MASS vs.. STELLAR LIFETIME

Relationship between Temperature and Energy Production



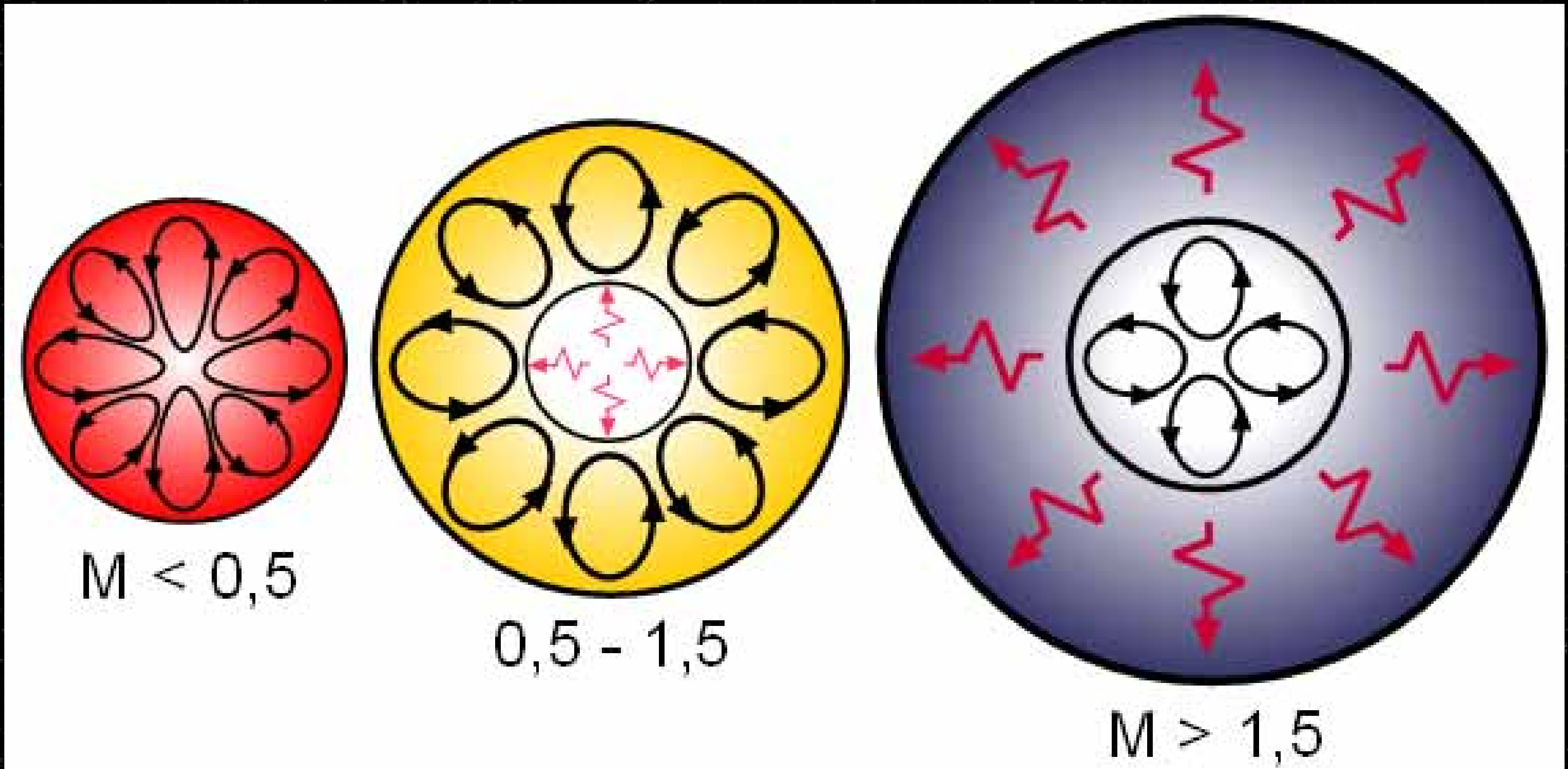
MASS vs. STELLAR LIFETIME

- The greater the star’s mass the greater the gravitational energy.
- The greater the gravitational energy the higher the temperature.
- The greater the mass the denser the core.



Photosphere
Convection zone
Radiation zone
Core
(a)
160
120
80
40
Density (10^3 kg/m^3)
Distance from center (km)
(b)
16
12
8
4
Temperature (millions of K)
700,000
0
700,000
Distance from center (km)
(c)

ENERGY TRANSPORT



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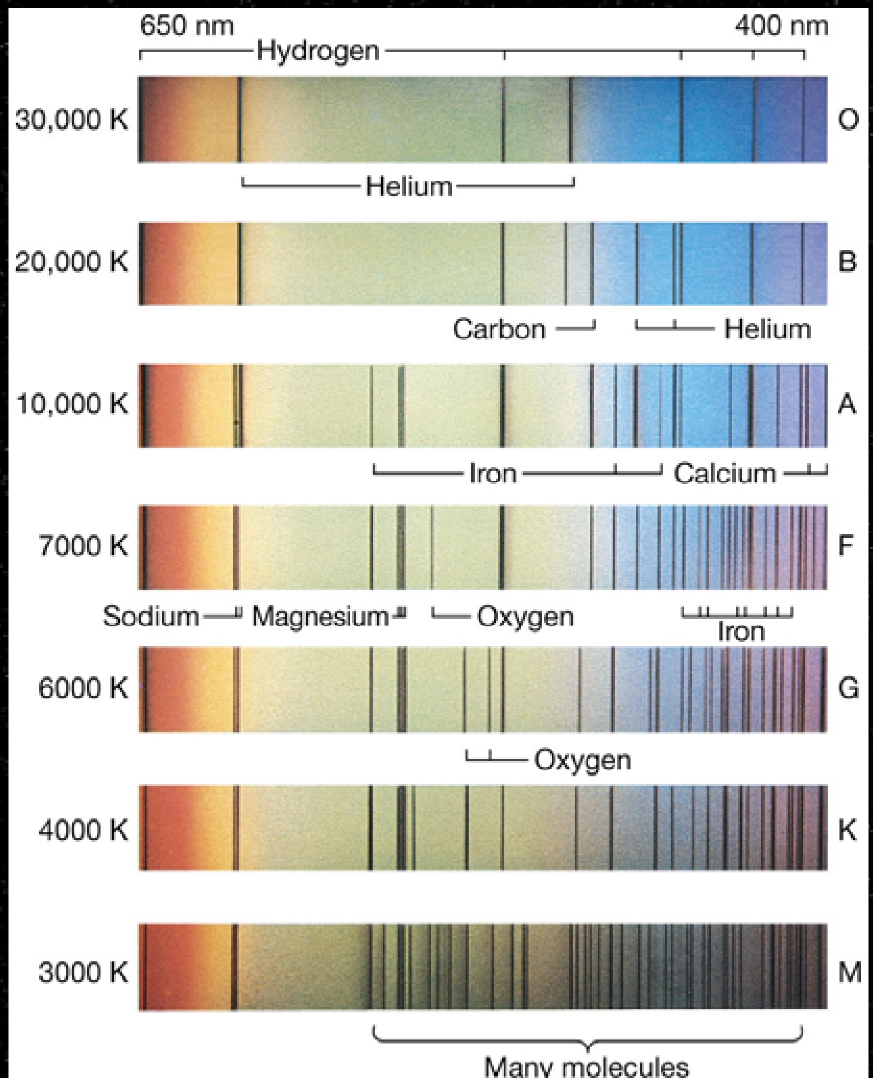
Stellar Spectra and Classification



Stellar Spectra and Classification

Annie Jump Cannon (1863-1941)

"A life spent in the routine of science need not destroy the attractive human element of a woman's nature."

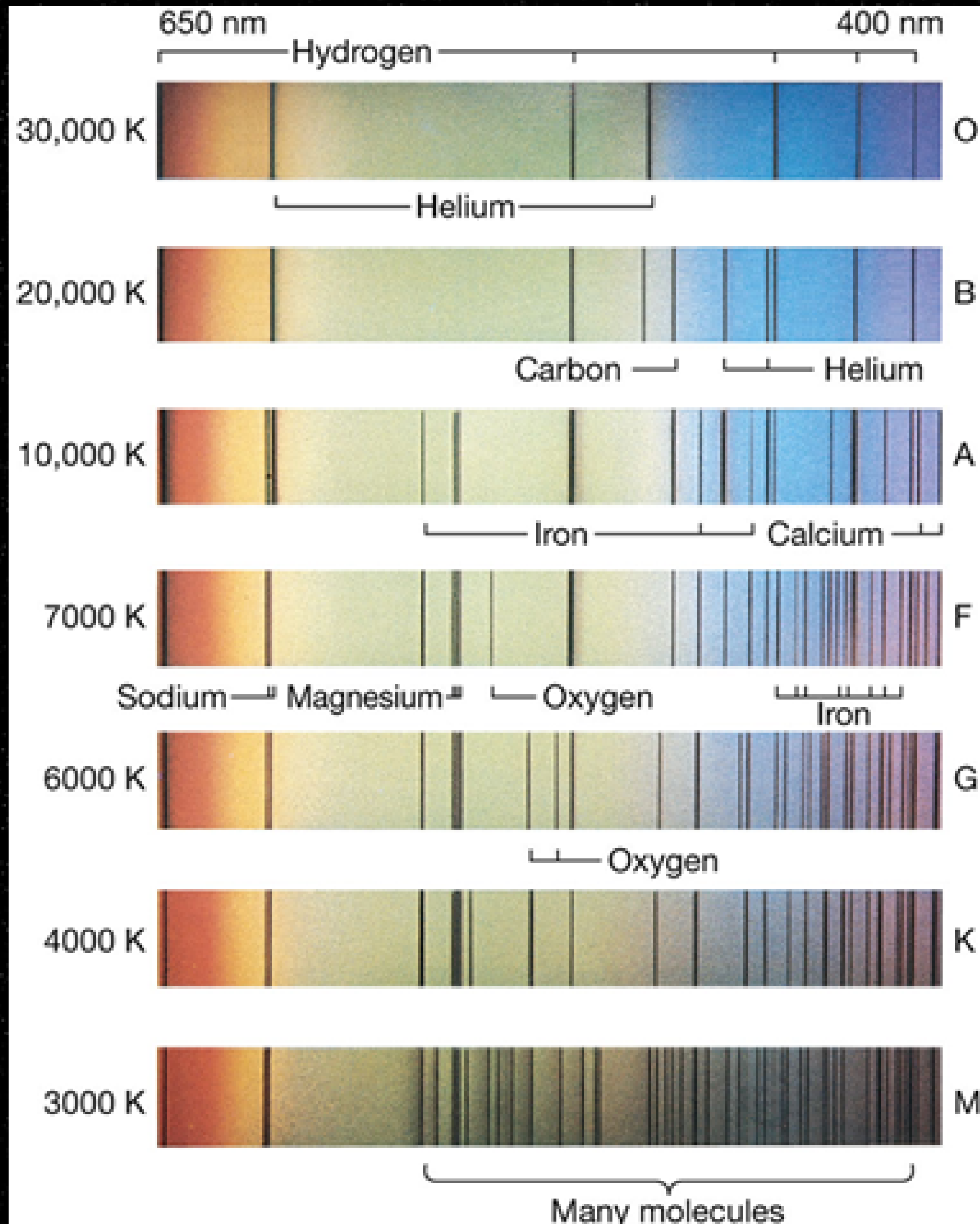
Annie Jump Cannon is most famous for inventing the Harvard Classification Scheme of stars according to their temperatures.

Stellar Spectra and Classification

- In the 1890s, Cannon became a member of a group of women hired by the director of the Harvard College Observatory, Edward Pickering, to reduce data and carry out astronomical calculations.
- Several members of this group, collectively known as the "**Harvard Computers**", became famous astronomers of their day and their pioneering work is considered fundamental in the modern field of stellar astrophysics.
- Pickering's long-term project consisted of obtaining photographic plates of stellar spectra of as many stars as possible, and to index and classify them accordingly. A star's spectrum is obtained by decomposing the star's light into colors after it passes through a prism.

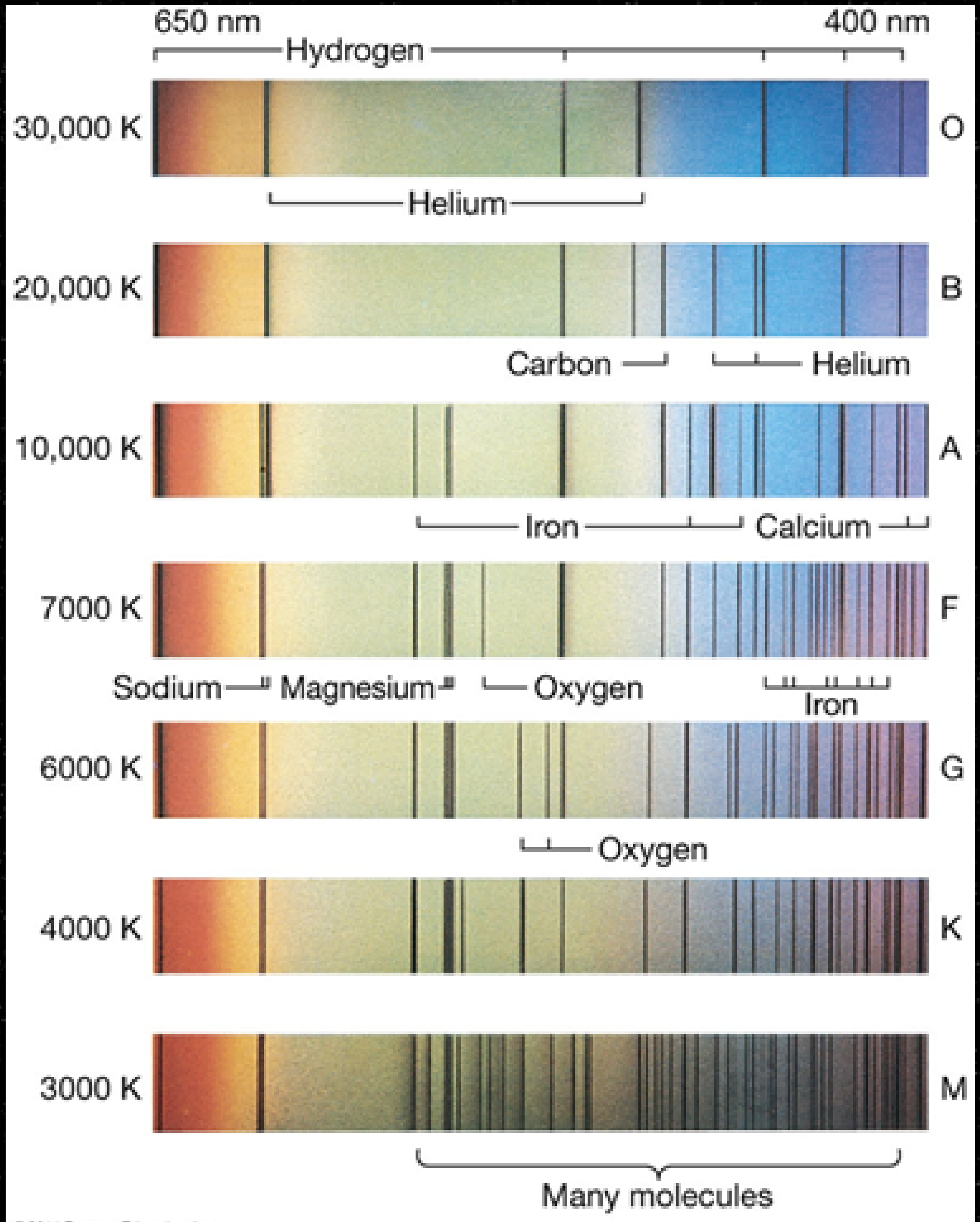
Stellar Spectra and Classification

- Most stellar spectra show a number of dark lines, called absorption lines, which can be used to determine the chemical composition of the star as well as its temperature.
- Each element is responsible for a unique set of absorption lines in the spectrum, thought of as that element's fingerprint, which can be measured very accurately in a laboratory. Then, if a particular element's set of lines is observed in a stellar spectrum, that element must be present in that star.
- The spectral absorption line pattern also depends on the temperature of the star-in general, the strength of the hydrogen lines as well as the number of other lines present are indicative of a star's temperature.


650 nm
400 nm
Hydrogen
30,000 K
O
Helium
20,000 K
B
Carbon
Helium
10,000 K
A
Iron
Calcium
7000 K
F
Sodium
Magnesium
Oxygen
Iron
6000 K
G
Oxygen
4000 K
K
3000 K
M
Many molecules

Stellar Spectra and Classification

- Cannon cataloged nearly 400,000 stars into the categories O, B, A, F, G, K, and M (P and Q were used for planetary nebulae and objects with peculiar spectra, but these are no longer included among the stellar classes), continuing and vastly improving the work of her colleagues Williamina Fleming and Antonia Maury.
- Cannon also published catalogs of variable stars, including
  300 that she discovered. Her career spanned more than forty years during which she received numerous recognitions-several of which had never been given to a woman before.
- At Harvard, she was named Curator of Astronomical Photographs, but it was only in 1938, two years before her retirement, that she obtained a regular Harvard appointment as the William C. Bond Astronomer.



650 nm
400 nm
Hydrogen
30,000 K
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20,000 K
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Carbon
Helium
10,000 K
A
Iron
Calcium
7000 K
F
Sodium
Magnesium
Oxygen
Iron
6000 K
G
Oxygen
4000 K
K
3000 K
M
Many molecules

OBAFGKM

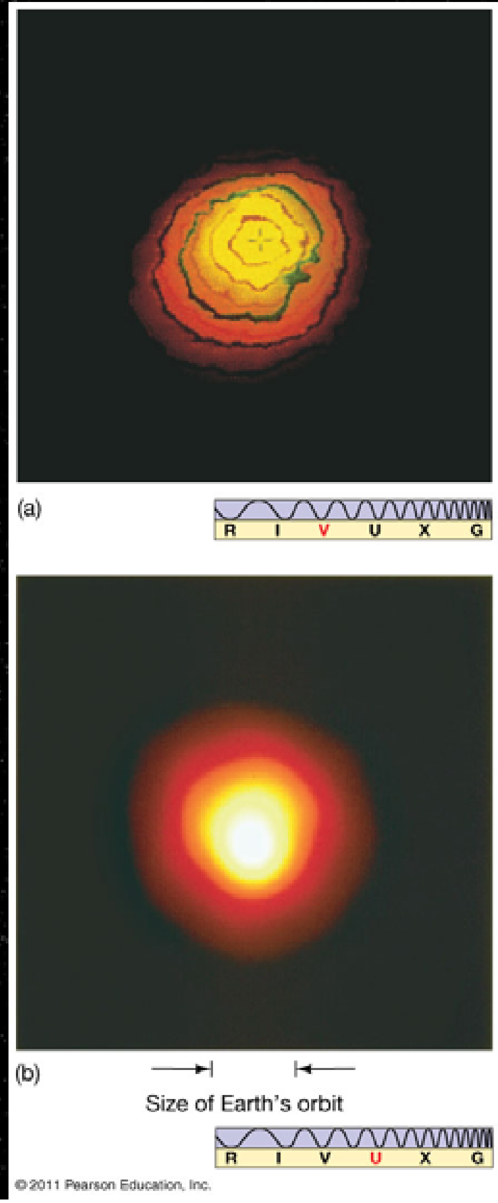
Astronomers have devised a classification scheme which describes the absorption lines of a spectrum. They have seven categories (OBAFGKM) each of which is subdivided into 10 subclasses. Thus, the spectral sequence includes B8, B9, A0, A1, etc. A traditional mnemonic for the sequence is **O**h, **B**e, **A F**ine **G**irl/Guy, **K**iss **M**e!

Class	Surface temperature[8] (kelvin)	Conventional color	Apparent color[9][10][11]	Mass[8] (solar masses)	Radius[8] (solar radii)	Luminosity[8] (bolometric)	Hydrogen lines	Fraction of all main-sequence stars[12]
O	≥ 33,000 K	blue	blue	≥ 16 $M_\odot$	≥ 6.6 $R_\odot$	≥ 30,000 $L_\odot$	Weak	~0.00003%
B	10,000–33,000 K	white to blue white	blue white	2.1–16 $M_\odot$	1.8–6.6 $R_\odot$	25–30,000 $L_\odot$	Medium	0.13%
A	7,500–10,000 K	white	white to blue white	1.4–2.1 $M_\odot$	1.4–1.8 $R_\odot$	5–25 $L_\odot$	Strong	0.6%
F	6,000–7,500 K	yellowish white	white	1.04–1.4 $M_\odot$	1.15–1.4 $R_\odot$	1.5–5 $L_\odot$	Medium	3%
G	5,200–6,000 K	yellow	yellowish white	0.8–1.04 $M_\odot$	0.96–1.15 $R_\odot$	0.6–1.5 $L_\odot$	Weak	7.6%
K	3,700–5,200 K	orange	yellow orange	0.45–0.8 $M_\odot$	0.7–0.96 $R_\odot$	0.08–0.6 $L_\odot$	Very weak	12.1%
M	≤ 3,700 K	red	orange red	≤ 0.45 $M_\odot$	≤ 0.7 $R_\odot$	≤ 0.08 $L_\odot$	Very weak	76.45%

Hertzsprung – Russell (HR) Diagram

Stellar Sizes

A few very large, very close stars can be imaged directly using speckle interferometry. This is Betelgeuse.



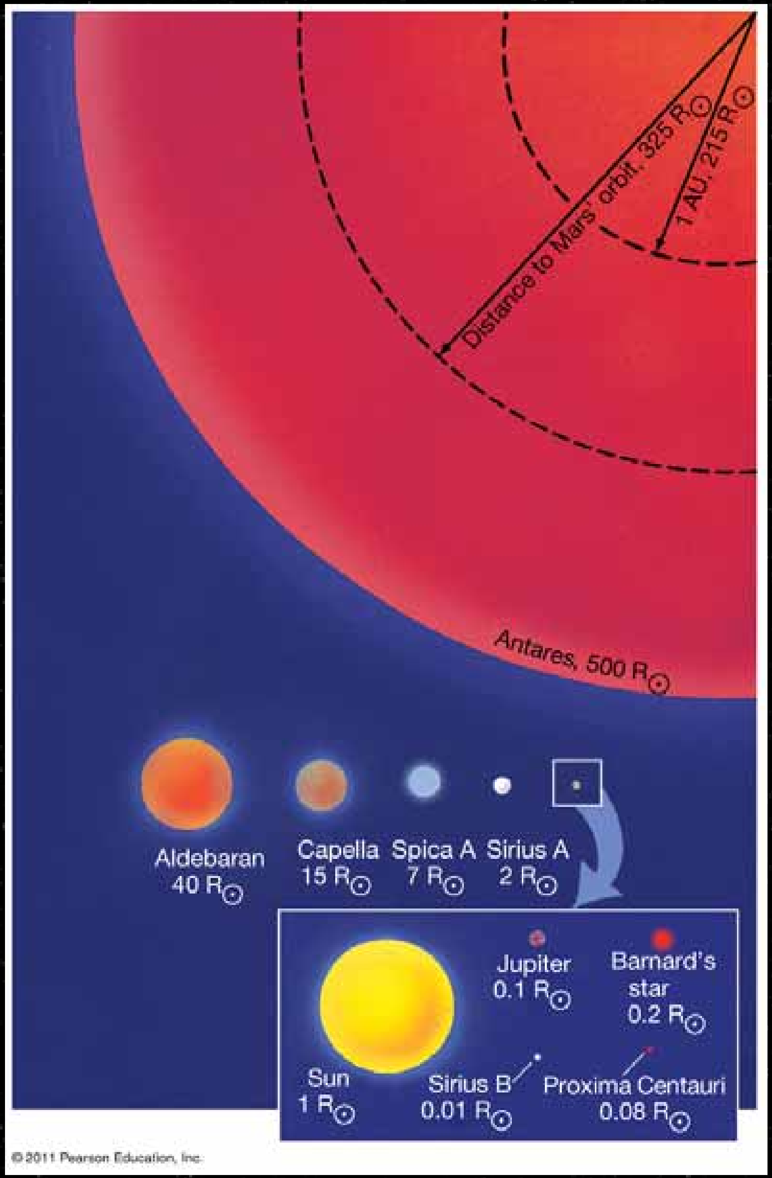
Stellar Sizes

For the vast majority of stars that cannot be imaged directly, size must be calculated knowing the luminosity and temperature

- Giant stars have radii between 10 and 100 times the Sun's
- Dwarf stars have radii equal to, or less than, the Sun's
- Supergiant stars have radii more than 100 times the Sun's

Stellar Sizes

Stellar radii vary widely



Estimating Stellar Radii

Combining the Stefan-Boltzman law for the power per unit area emitted by a blackbody as a function of temperature with the formula for the area of a sphere gives the total luminosity

$$L = 4\pi\sigma R^2 T^4$$

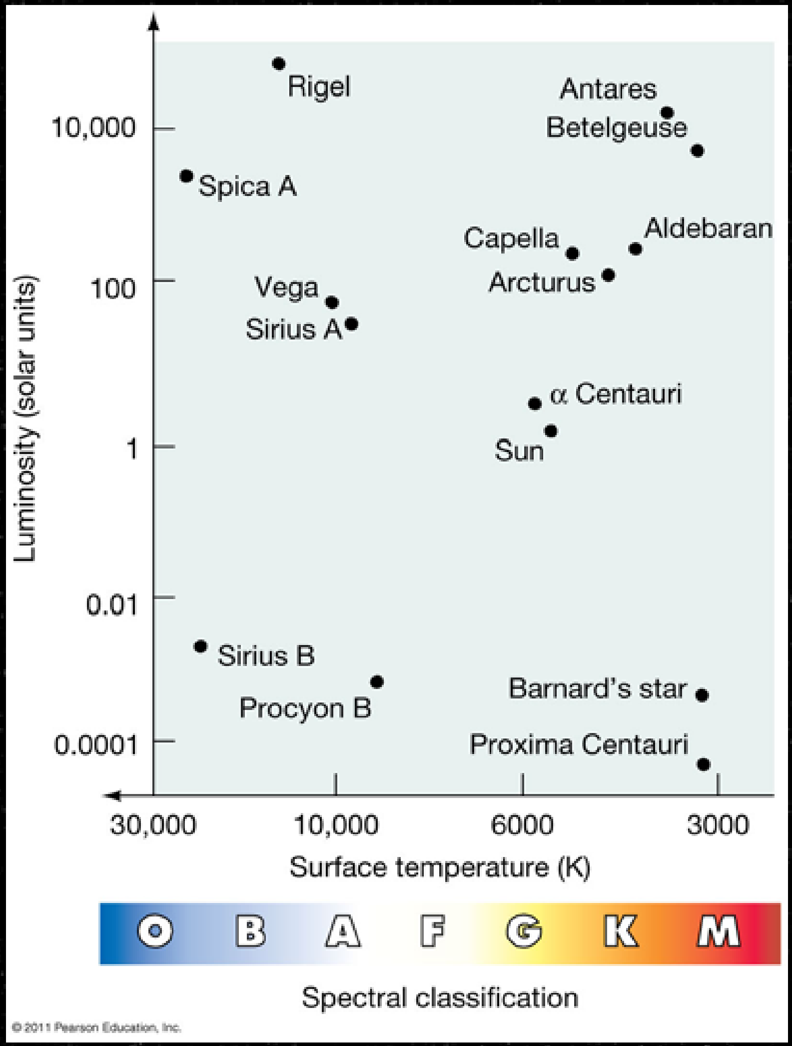
If we measure luminosity, radius, and temperature in solar units, we can write

$$L = R^2 T^4$$

The Hertzsprung–Russell Diagram

The H–R diagram plots stellar luminosity against surface temperature.

This is an H–R diagram of a few prominent stars.



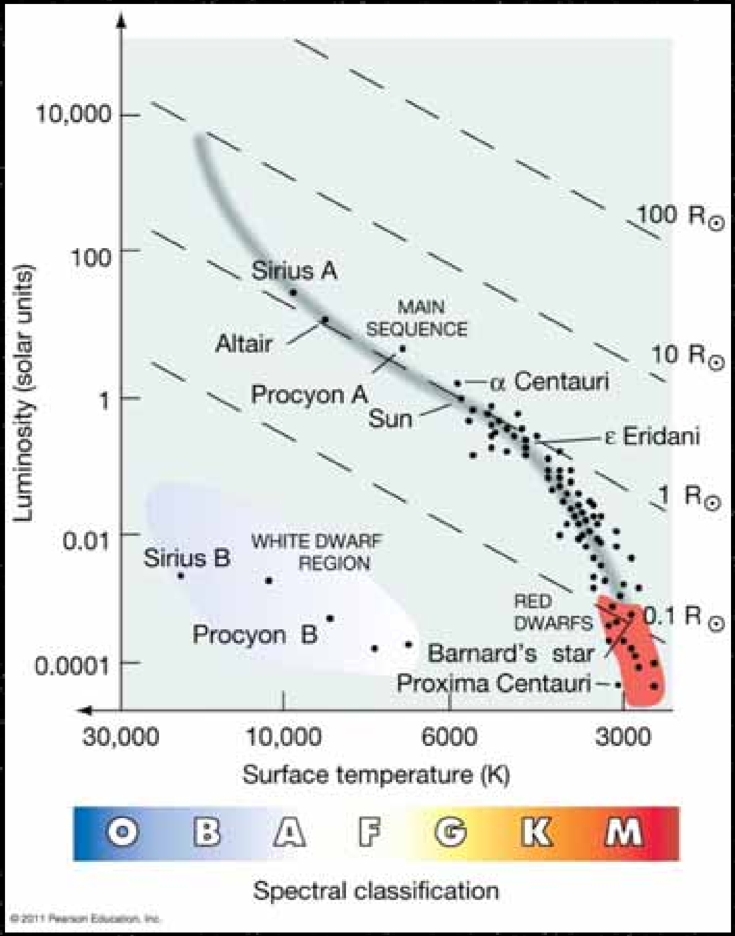
The Hertzsprung–Russell Diagram

Once many stars are plotted on an H–R diagram, a pattern begins to form.

These are the 80 closest stars to us; note the dashed lines of constant radius.

The darkened curve is called the main sequence, as this is where most stars are.

Also indicated is the white dwarf region; these stars are hot but not very luminous, as they are quite small.

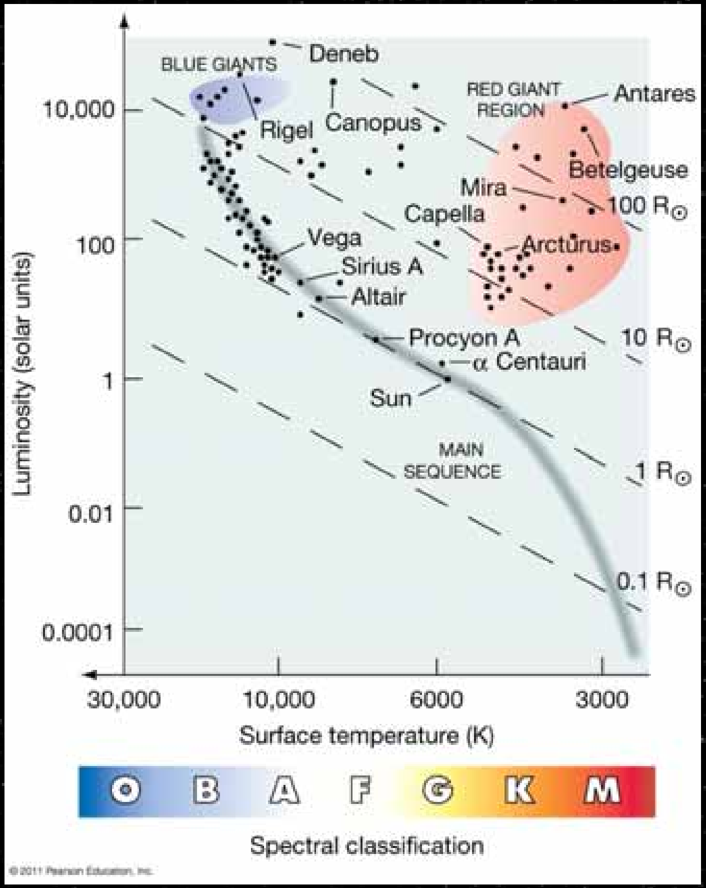


The Hertzsprung–Russell Diagram

An H–R diagram of the 100 brightest stars looks quite different.

These stars are all more luminous than the Sun. Two new categories appear here—the red giants and the blue giants.

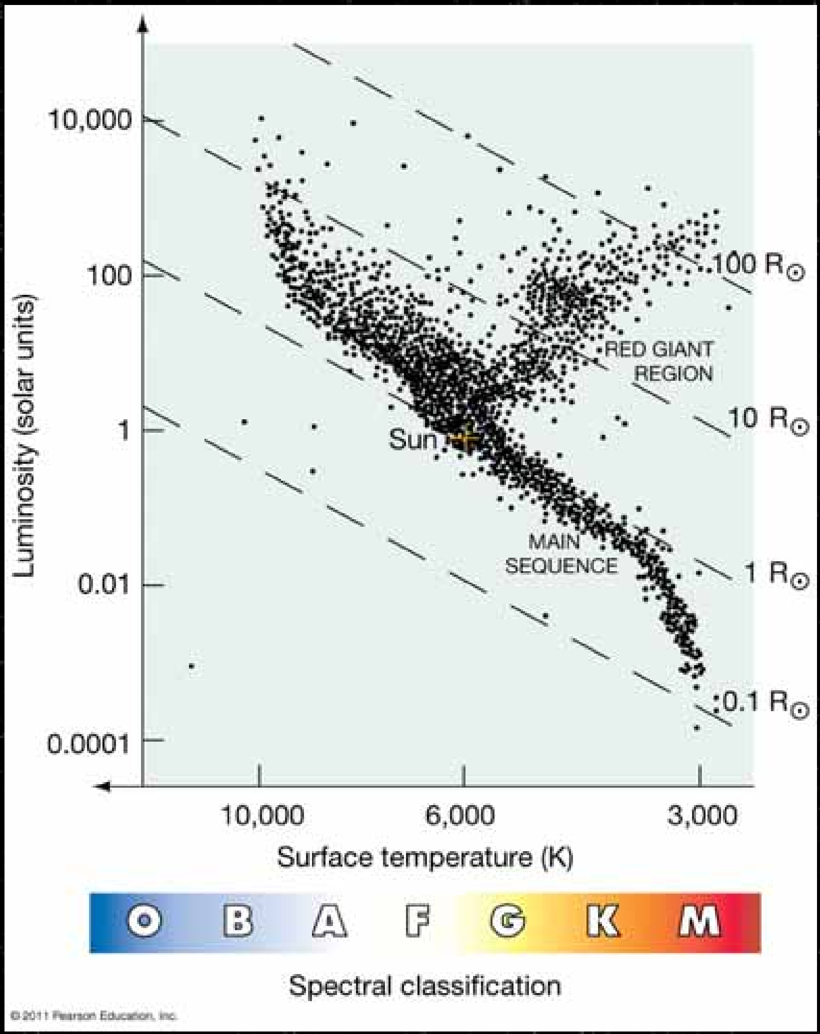
Clearly, the brightest stars in the sky appear bright because of their enormous luminosities, not their proximity.



The Hertzsprung–Russell Diagram

This is an H–R plot of about 20,000 stars. The main sequence is clear, as is the red giant region.

About 90% of stars lie on the main sequence; 9% are red giants and 1% are white dwarfs.



The Birth of Stars

The Birth of Stars

Start with a cold Dark Nebula

19.1 Star-Forming Regions

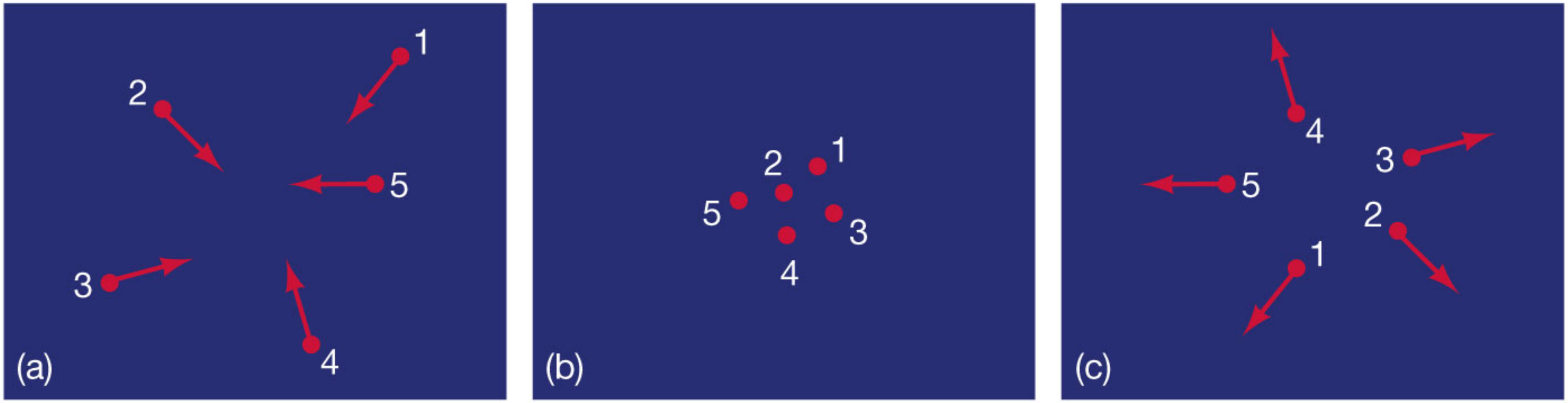
Star formation is ongoing. Star-forming regions are seen in our galaxy as well as others.

Star-Forming Regions

Star formation happens when part of a dust cloud begins to contract under its own gravitational force; as it collapses, the center becomes hotter and hotter until nuclear fusion begins in the core.

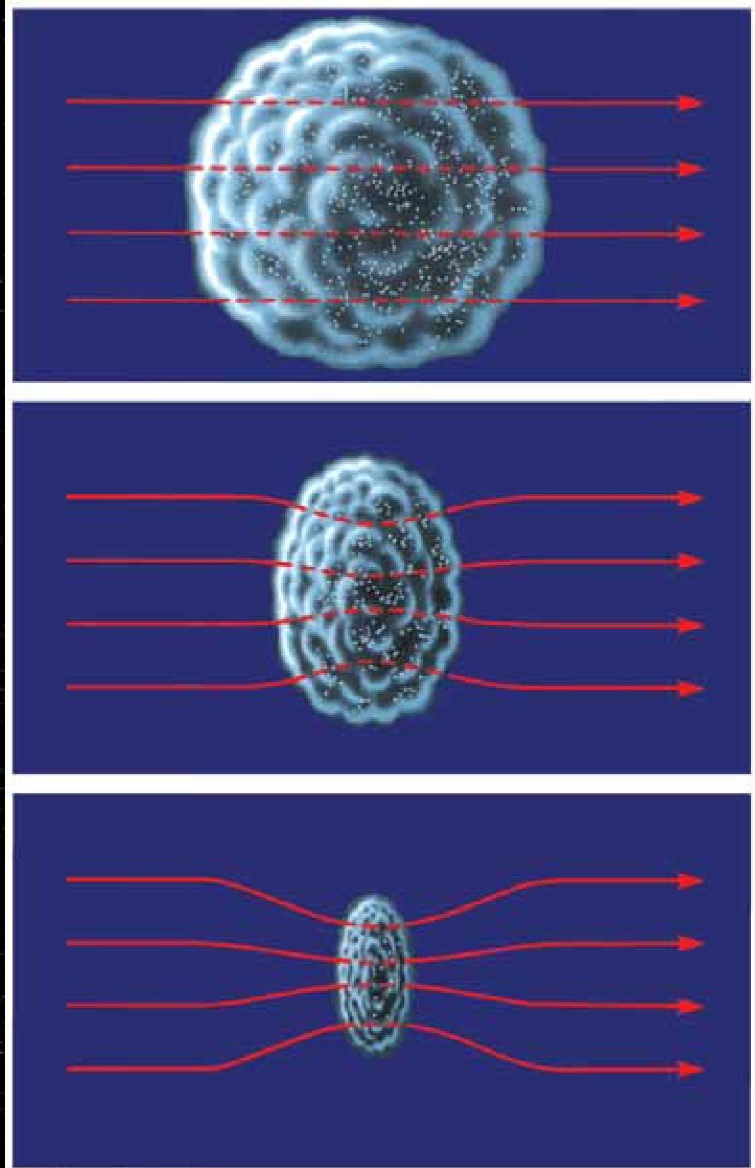
Star-Forming Regions

When looking at just a few atoms, the gravitational force is nowhere near strong enough to overcome the random thermal motion



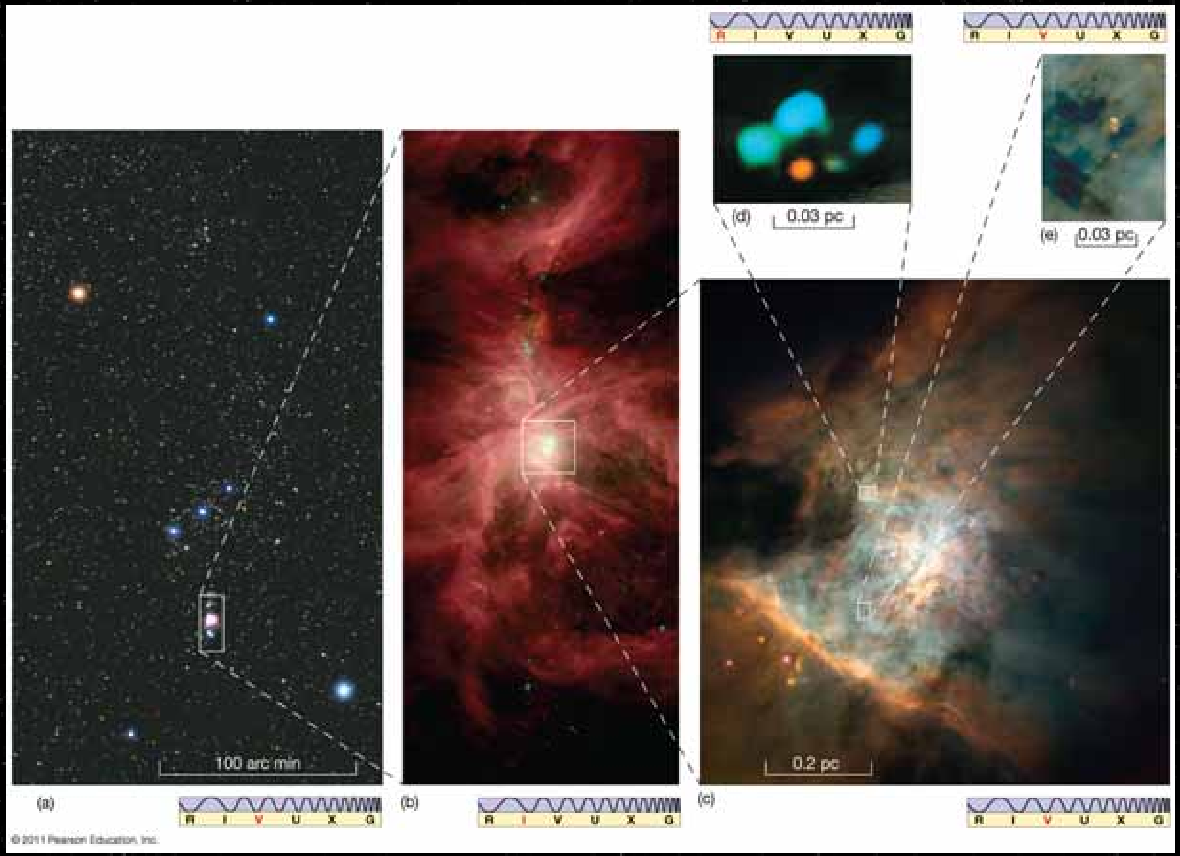
Competition in Star Formation

Rotation can also interfere with gravitational collapse, as can magnetism. Clouds may very well contract in a distorted way.



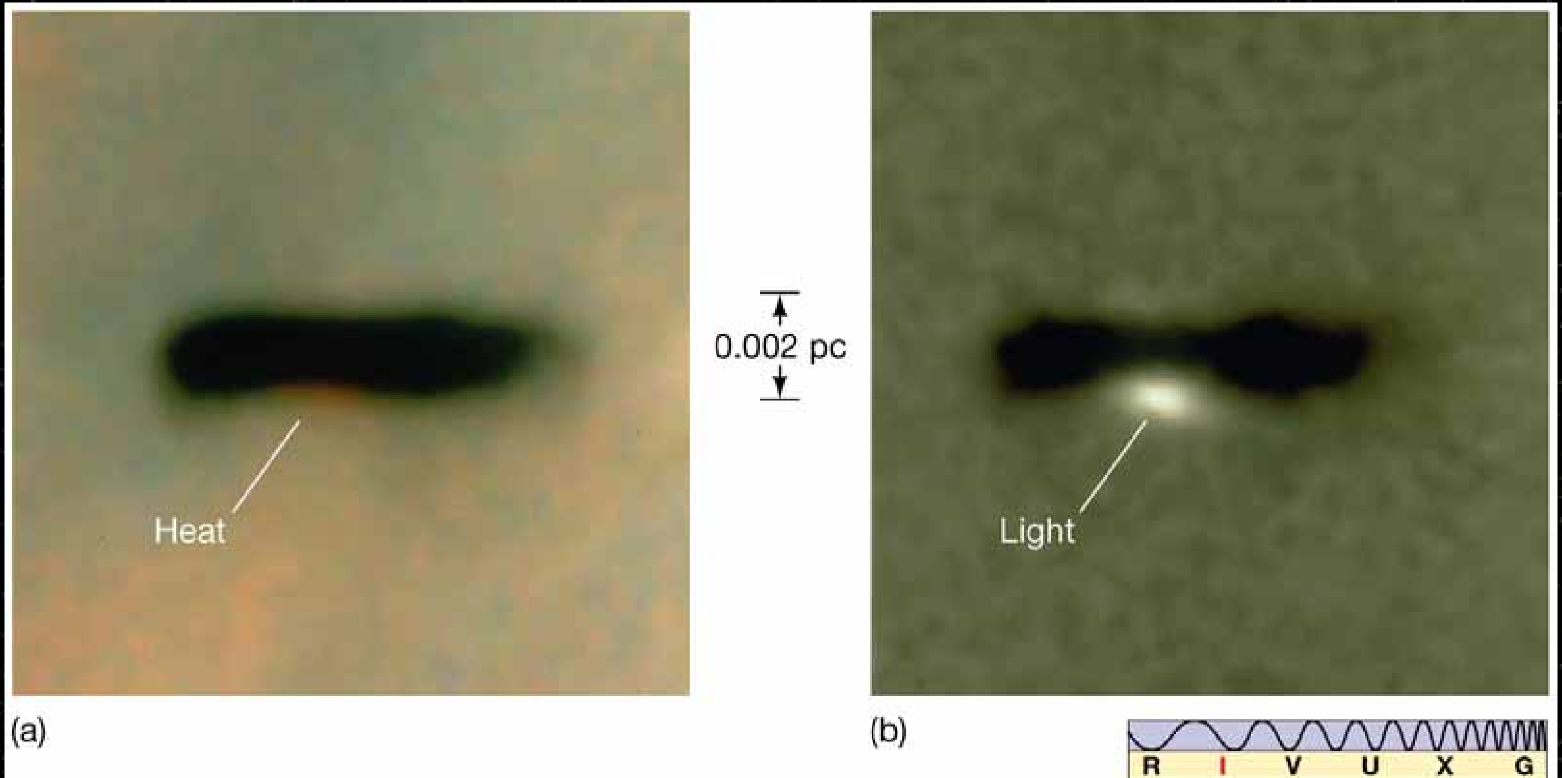
Observations of Cloud Fragments and Protostars

The Orion Nebula has many contracting cloud fragments, protostars, and newborn stars

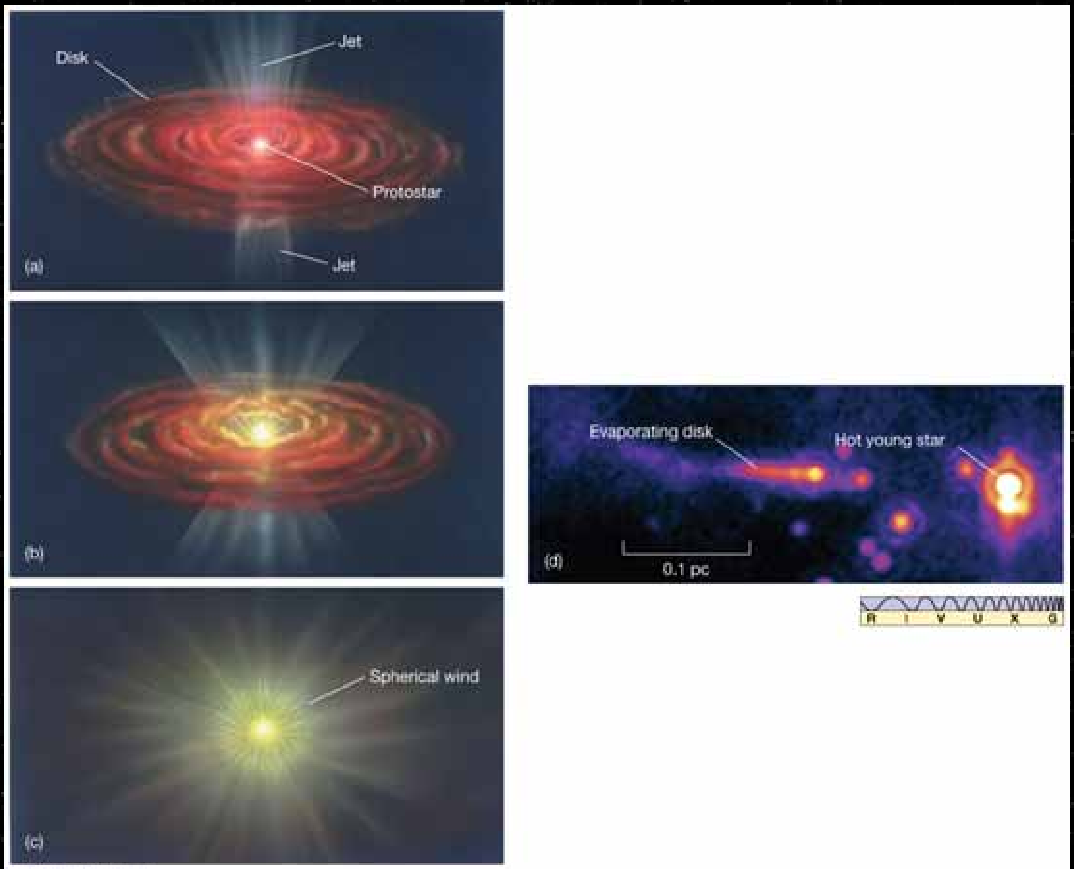


Observations of Cloud Fragments and Protostars

These are two protostars in the Orion Nebula, at around stage 5 in their development



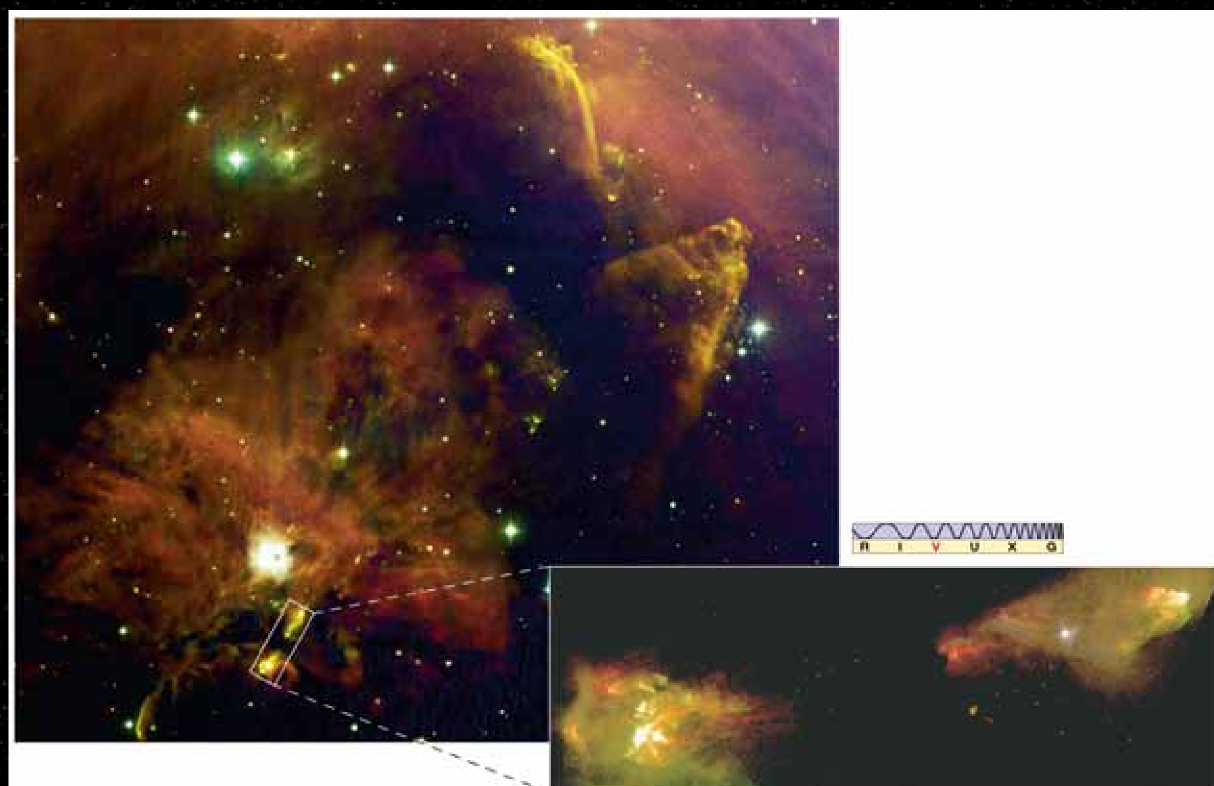
Observations of Cloud Fragments and Protostars



Protostars are believed to have very strong winds, which clear out an area around the star roughly the size of the solar system

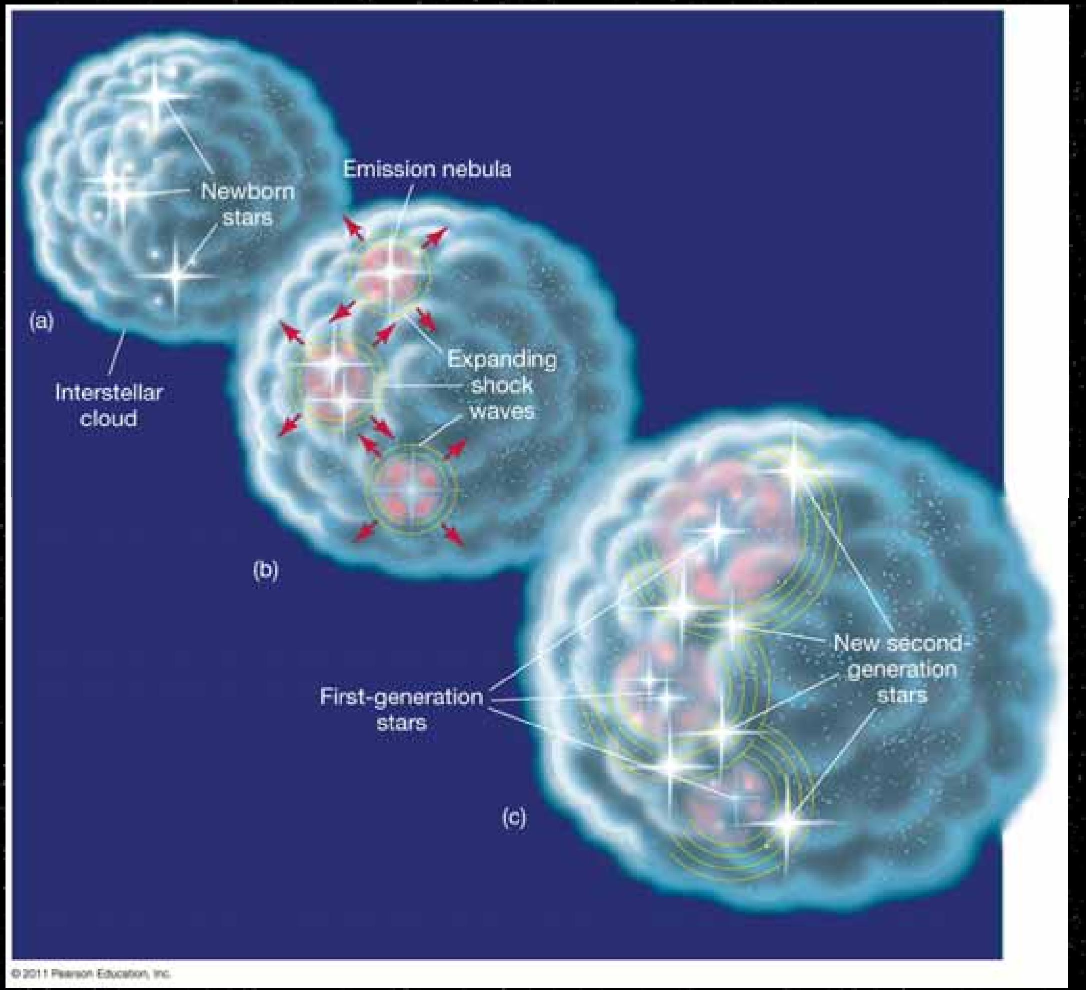
Observations of Cloud Fragments and Protostars

These two jets are matter being expelled from around an unseen protostar, still obscured by dust



Shock Waves and Star Formation

Shock waves from nearby star formation can be the trigger needed to start the collapse process in an interstellar cloud



Shock Waves and Star Formation

Other triggers:

- Death of a nearby Sun-like star
- Supernova
- Density waves in galactic spiral arms
- Galaxy collisions

The Formation of Stars Like the Sun

Stars go through a number of stages in the process of forming from an interstellar cloud

TABLE 19.1 Prestellar Evolution of a Solar-Type Star

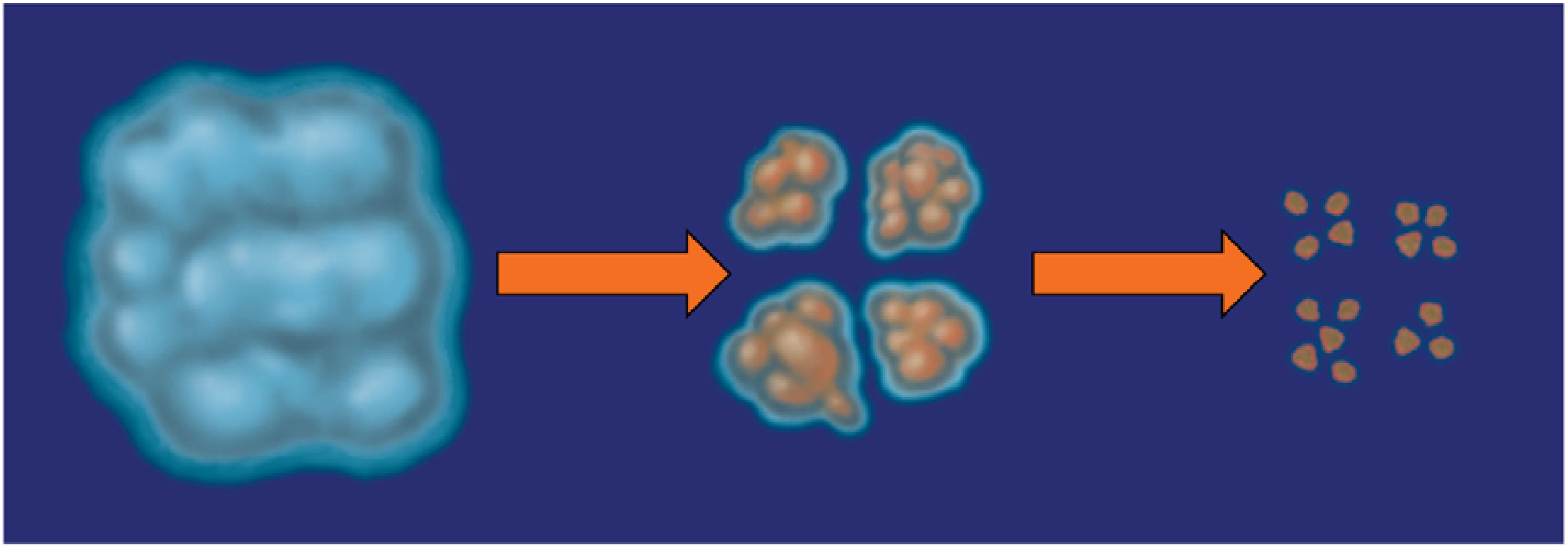
Stage	Approximate Time to Next Stage (yr)	Central Temperature (K)	Surface Temperature (K)	Central Density (particles/m^3)	Diameter* (km)	Object
1	2×10^6	10	10	10^9	10^{14}	Interstellar cloud
2	3×10^4	100	10	10^{12}	10^{12}	Cloud fragment Cloud fragment/protostar
3	10^5	10,000	100	10^{18}	10^{10}	
4	10^6	1,000,000	3000	10^{24}	10^8	Protostar
5	10^7	5,000,000	4000	10^{28}	10^7	Protostar
6	3×10^7	10,000,000	4500	10^{31}	2×10^6	Star
7	10^{10}	15,000,000	6000	10^{32}	1.5×10^6	Main-sequence star

* *Round numbers; for comparison, recall that the diameter of the Sun is 1.4×10^6 km, whereas that of the solar system is roughly 1.5×10^{10} km.*

The Formation of Stars Like the Sun

Stage 1:

Interstellar cloud starts to contract, probably triggered by shock or pressure wave from nearby star. As it contracts, the cloud fragments into smaller pieces.



The Formation of Stars Like the Sun

Stage 2:

Individual cloud fragments begin to collapse. Once the density is high enough, there is no further fragmentation.

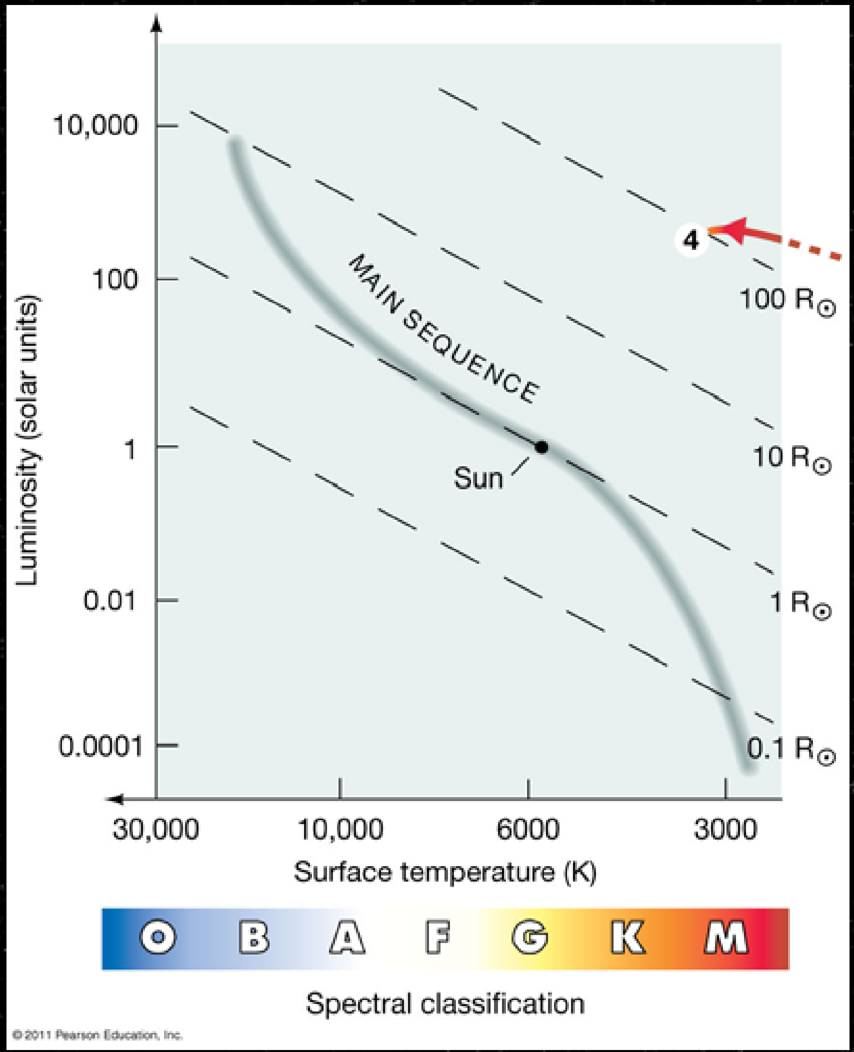
Stage 3:

The interior of the fragment has begun heating and is about 10,000 K.

The Formation of Stars Like the Sun

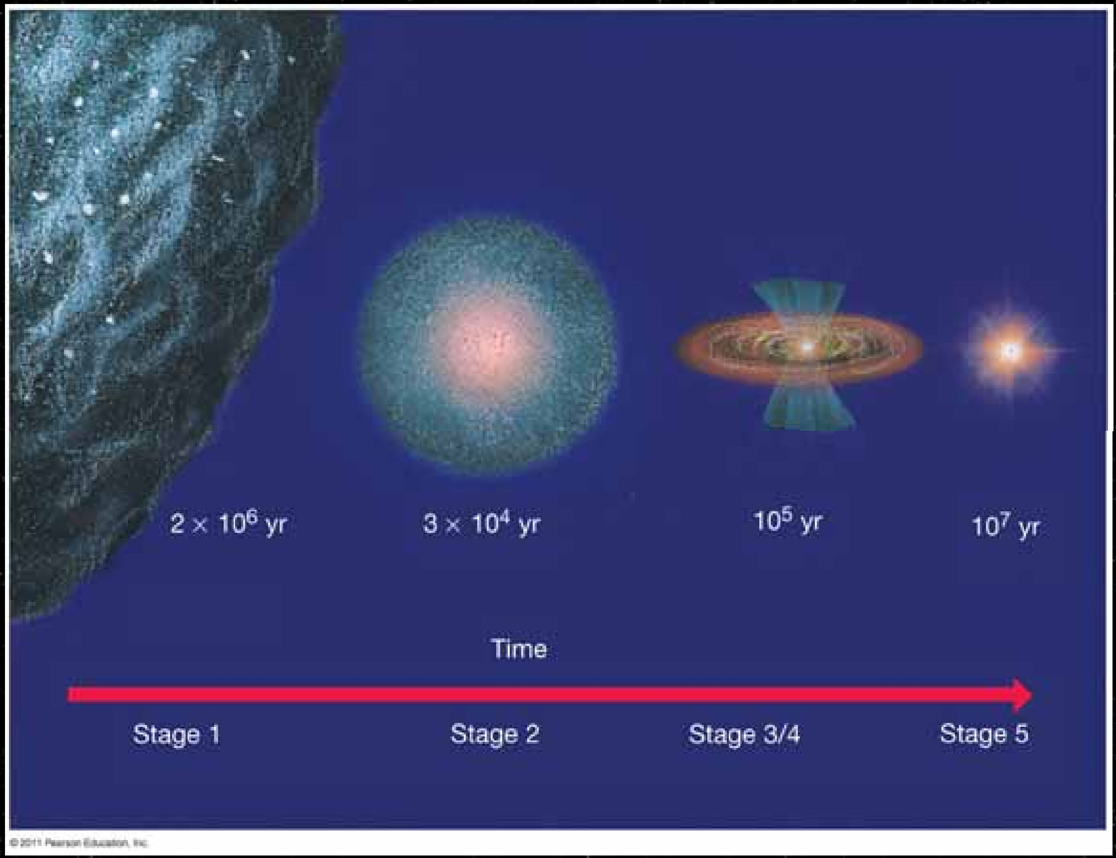
Stage 4:

The core of the cloud is now a protostar and makes its first appearance on the H–R diagram.



The Formation of Stars Like the Sun

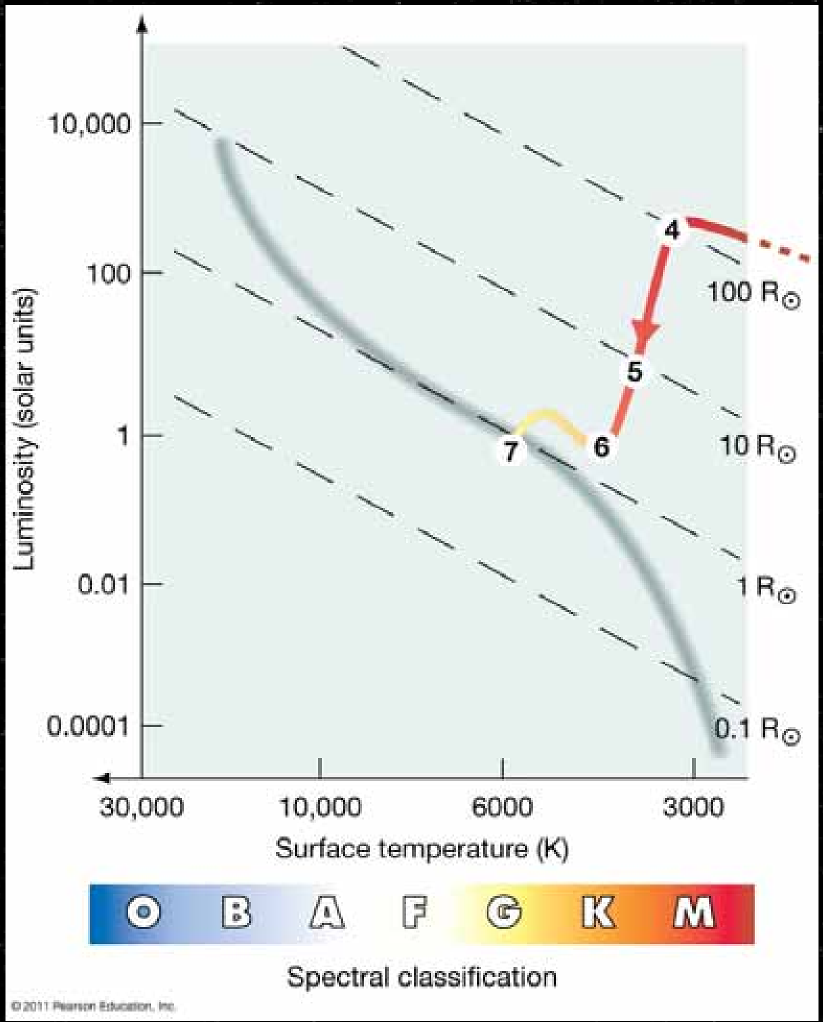
Planetary formation has begun, but the protostar is still not in equilibrium—all heating comes from the gravitational collapse.



The Formation of Stars Like the Sun

The last stages can be followed on the H–R diagram:

The protostar's luminosity decreases even as its temperature rises because it is becoming more compact.



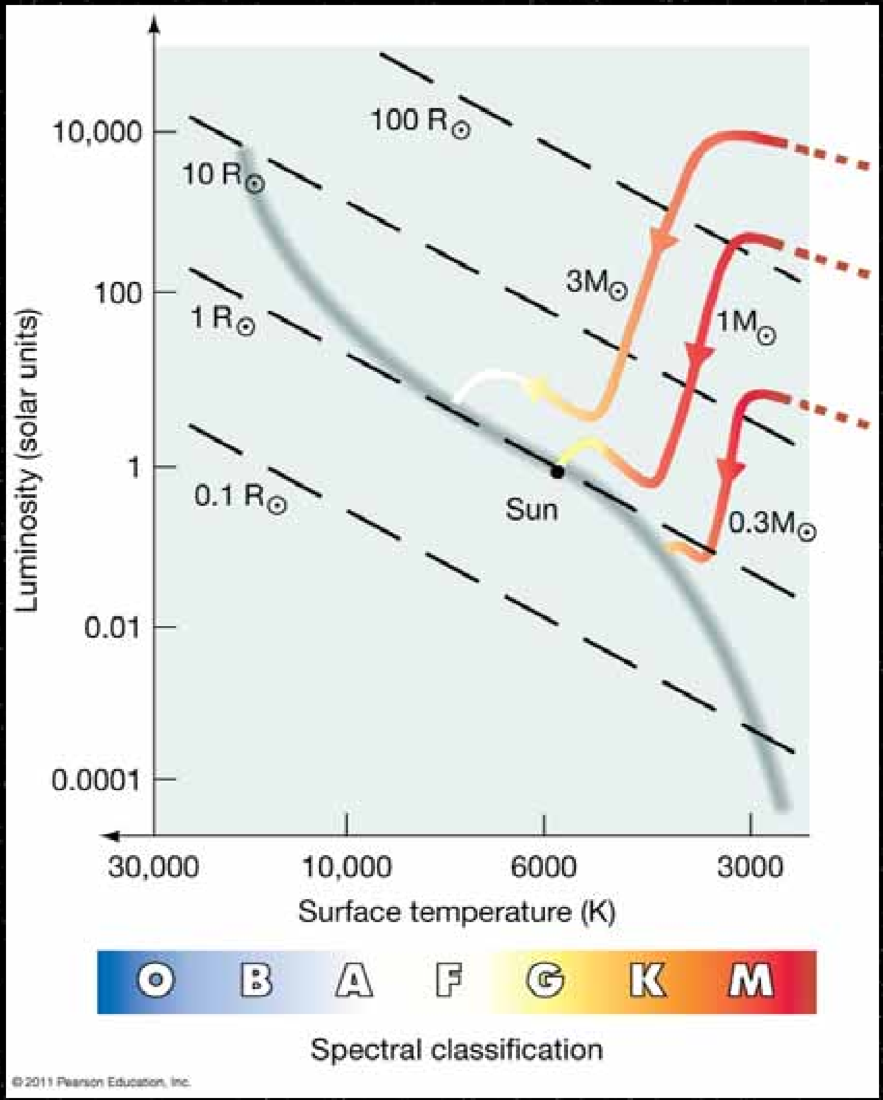
The Formation of Stars Like the Sun

At stage 6, the core reaches 10 million K, and nuclear fusion begins. The protostar has become a star.

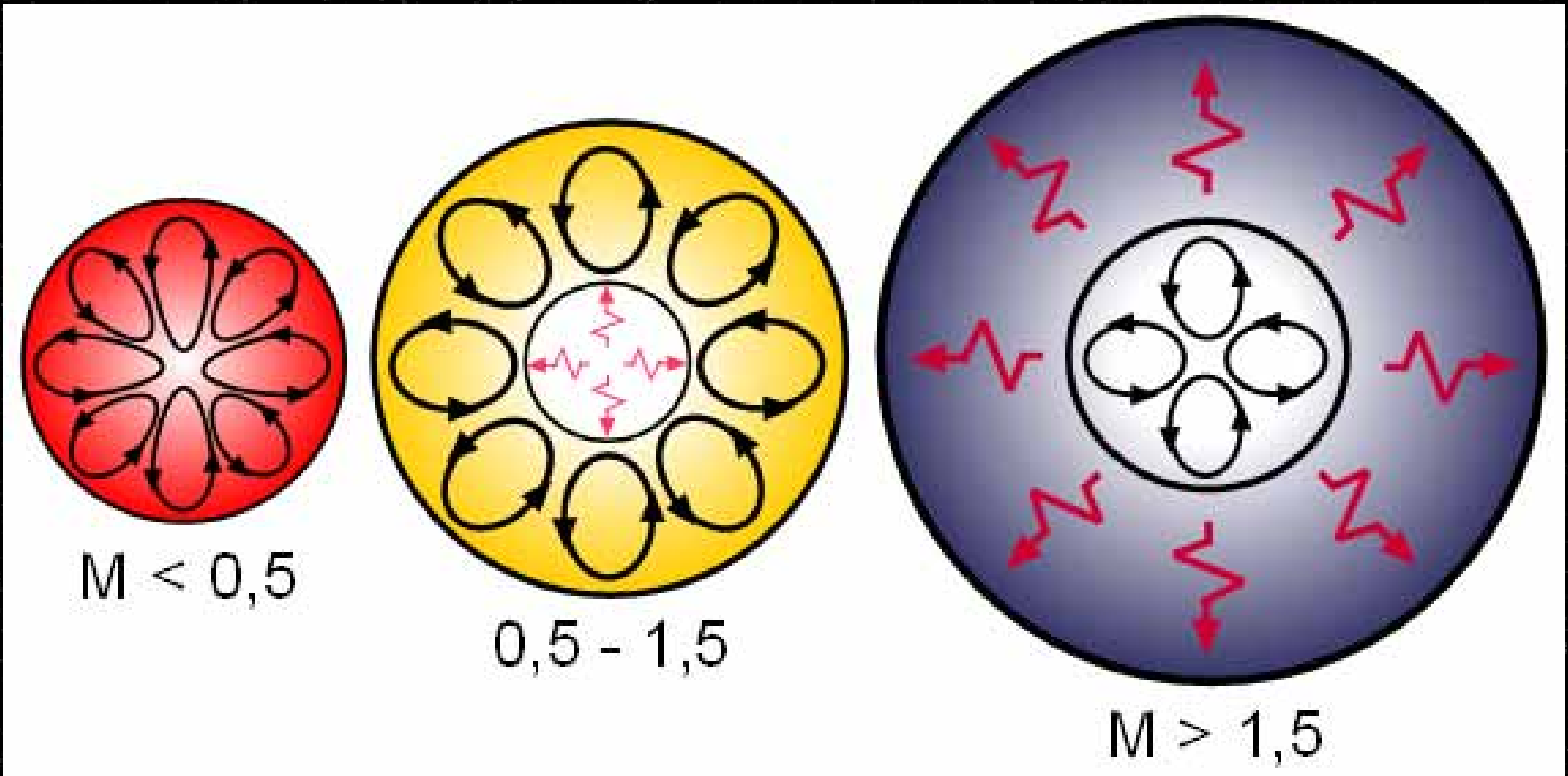
The star continues to contract and increase in temperature until it is in hydrostatic equilibrium. This is stage 7: The star has reached the main sequence and will remain there as long as it has hydrogen to fuse.

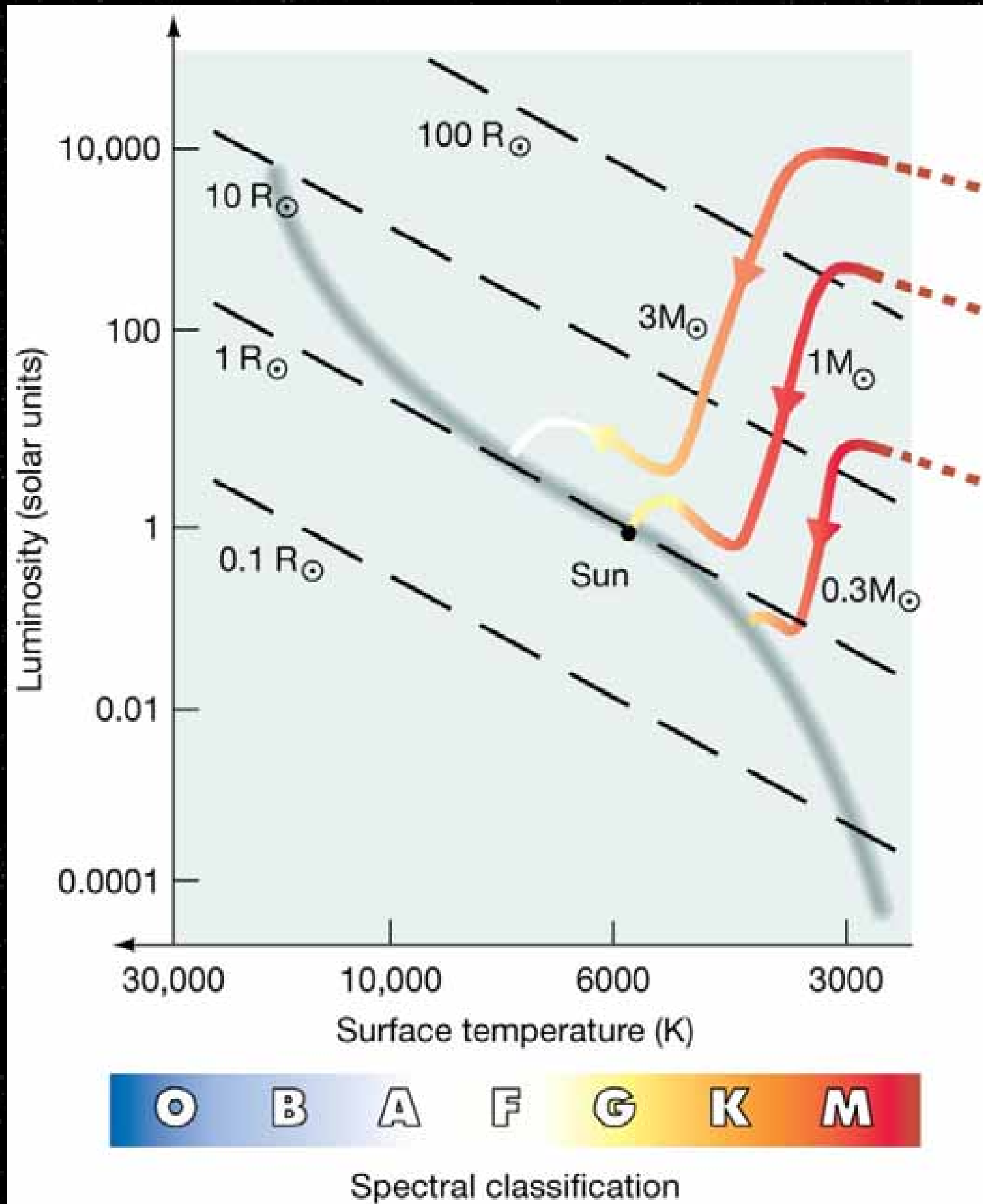
Stars of Other Masses

This H–R diagram shows the evolution of stars somewhat more and somewhat less massive than the Sun. The shape of the paths is similar, but they wind up in different places on the main sequence.



ENERGY TRANSPORT





10,000
100
1
0.01
0.0001
Luminosity (solar units)
100 R☉
10 R☉
1 R☉
0.1 R☉
3M☉
1M☉
0.3M☉
Sun
30,000
10,000
6000
3000
Surface temperature (K)
O
B
A
F
G
K
M
Spectral classification

Stars of Other Masses

The main sequence is a band, rather than a line, because stars of the same mass can have different compositions.

Most important: Stars do not move along the main sequence! Once they reach it, they are in equilibrium and do not move until their fuel begins to run out.

Stars of Other Masses

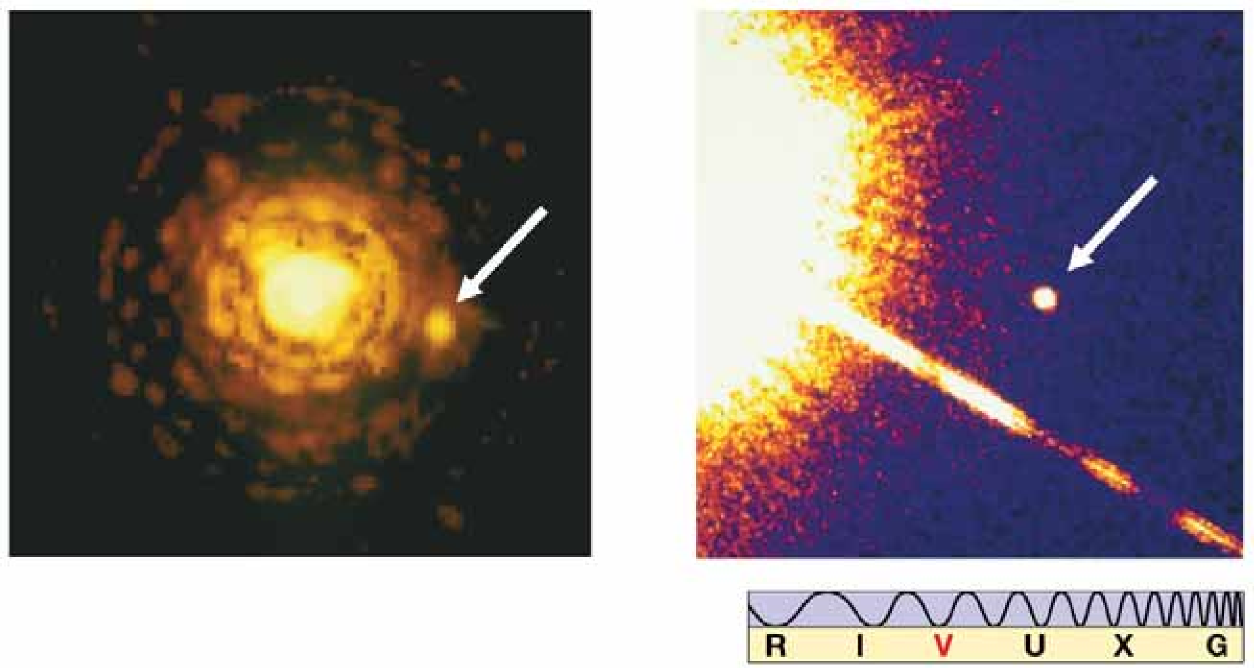
Some fragments are too small for fusion ever to begin. They gradually cool off and become dark "clinkers."

A protostar must have 0.08 the mass of the Sun (which is 80 times the mass of Jupiter) in order to become dense and hot enough that fusion can begin.

If the mass of the "failed star" is about 12 Jupiter masses or more, it is luminous when first formed, and is called a brown dwarf.

Observations of Brown Dwarfs

Brown dwarfs are difficult to observe directly, as they are very dim. These images are of two binary-star systems, each believed to contain a brown dwarf. The difference in luminosity between the star and the brown dwarf is apparent.



Leaving the Main Sequence

We cannot observe a single star going through its whole life cycle; even short-lived stars live too long for that.

Observation of stars in star clusters gives us a look at stars in all stages of evolution; this allows us to construct a complete picture.

Leaving the Main Sequence

During its stay on the Main Sequence, any fluctuations in a star's condition are quickly restored; the star is in equilibrium

Leaving the Main Sequence

Eventually, as hydrogen in the core is consumed, the star begins to leave the Main Sequence

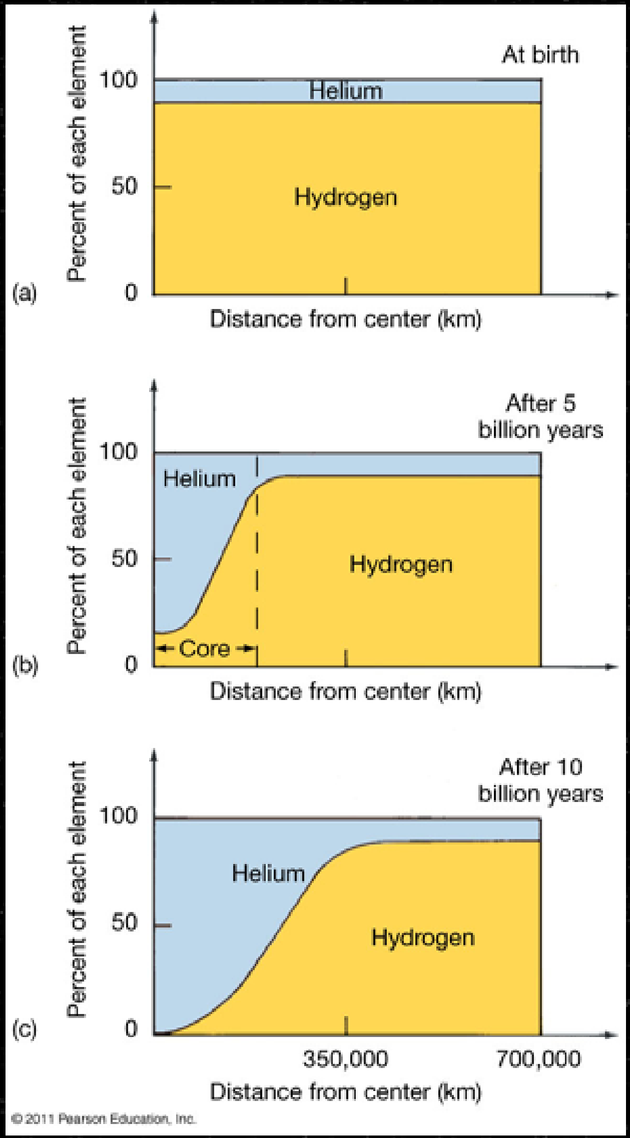
Its evolution from then on depends very much on the mass of the star:

Low-mass stars go quietly

High-mass stars go out with a bang!

Evolution of a Sun-like Star

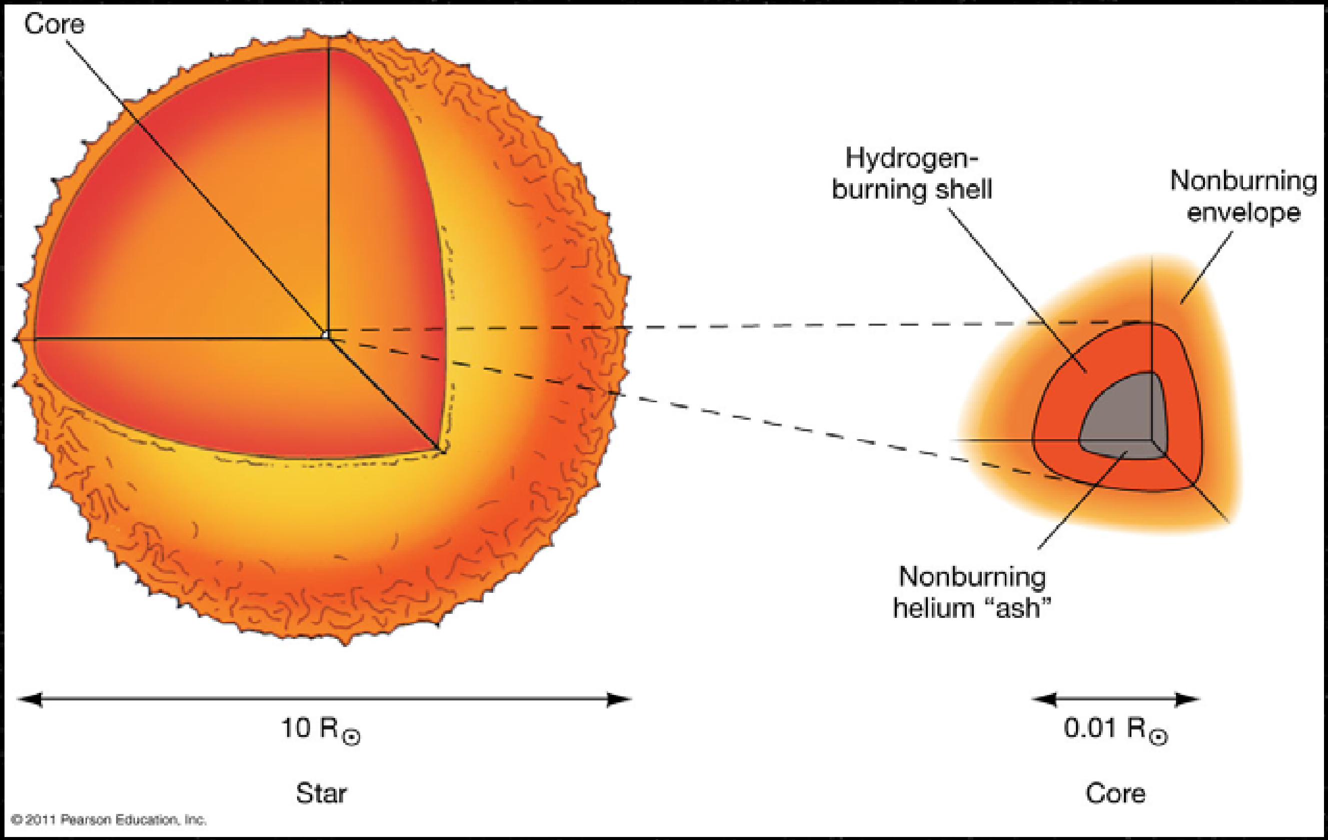
Even while on the Main Sequence, the composition of a star's core is changing



Evolution of a Sun-Like Star

As the fuel in the core is used up, the core contracts; when it is used up the core begins to collapse.

Hydrogen begins to fuse outside the core:



Evolution of a Sun-Like Star

Stages of a star leaving the Main Sequence:

TABLE 20.1 Evolution of a Sun-like Star

Stage	Approximate Time to Next Stage (Yr)	Central Temperature (10^6 K)	Surface Temperature (K)	Central Density (kg/m^3)	Radius (km)	Radius (solar radii)	Object
7	10^{10}	15	6000	10^5	7×10^5	1	Main-sequence star
8	10^8	50	4000	10^7	2×10^6	3	Subgiant branch
9	10^5	100	4000	10^8	7×10^7	100	Helium flash
10	5×10^7	200	5000	10^7	7×10^6	10	Horizontal branch
11	10^4	250	4000	10^8	4×10^8	500	Asymptotic-giant branch
12	10^5	300	100,000	10^{10}	10^4	0.01	Carbon core
		—	3000	10^{-17}	7×10^8	1000	Planetary nebula*
13	—	100	50,000	10^{10}	10^4	0.01	White dwarf
14	—	Close to 0	Close to 0	10^{10}	10^4	0.01	Black dwarf

* *Values refer to the envelope.*

Evolution of a Sun-Like Star

Stage 9: The Red-Giant Branch

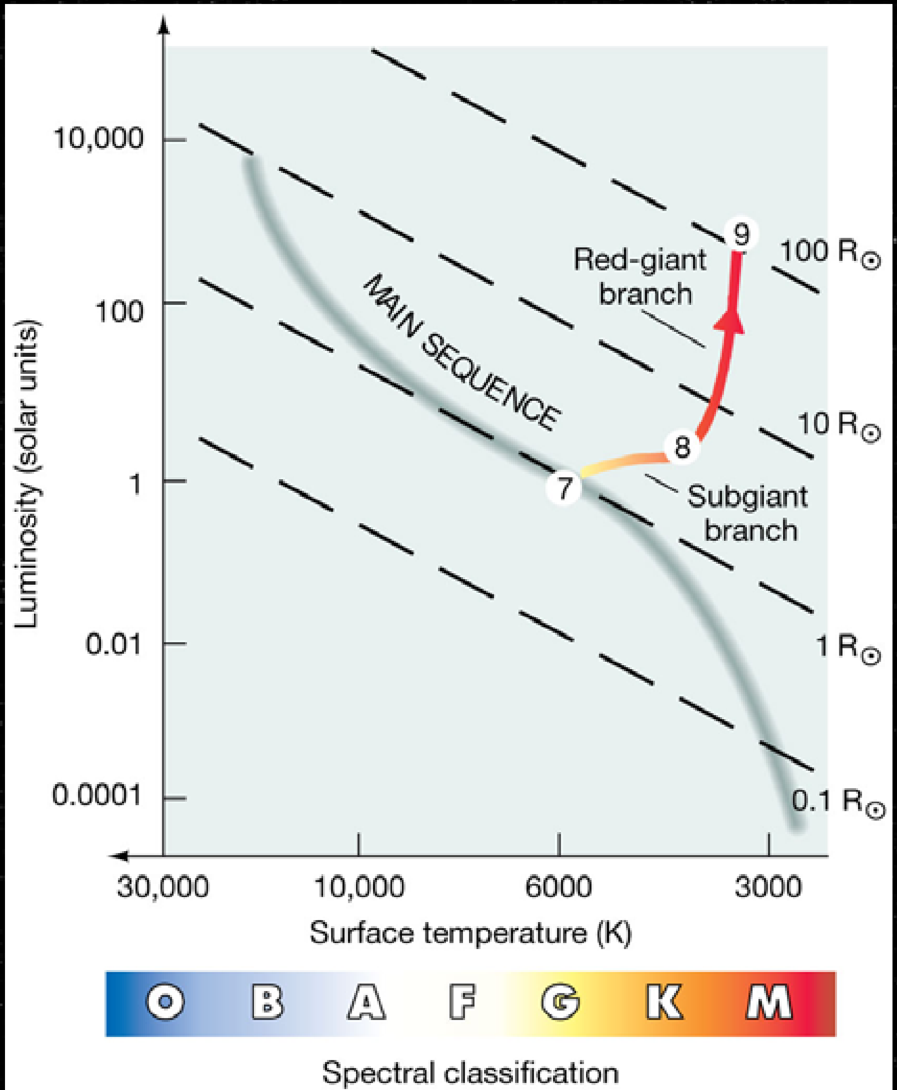
As the core continues to shrink, the outer layers of the star expand and cool.

It is now a red giant, extending out as far as the orbit of Mercury.

Despite its cooler temperature, its luminosity increases enormously due to its large size.

Evolution of a Sun-like Star

The red giant stage on the H-R diagram:



Evolution of a Sun-Like Star

Stage 10: Helium fusion

Once the core temperature has risen to 100,000,000 K, the helium in the core starts to fuse, through a three-alpha process:

$$^{4}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{8}\mathrm{Be} + \text{energy}$$

$$^{8}\mathrm{Be} + {}^{4}\mathrm{He} \rightarrow {}^{12}\mathrm{C} + \text{energy}$$

The ^{8}Be nucleus is highly unstable and will decay in about 10^{-12} s unless an alpha particle fuses with it first. This is why high temperatures and densities are necessary.

Evolution of a Sun-Like Star

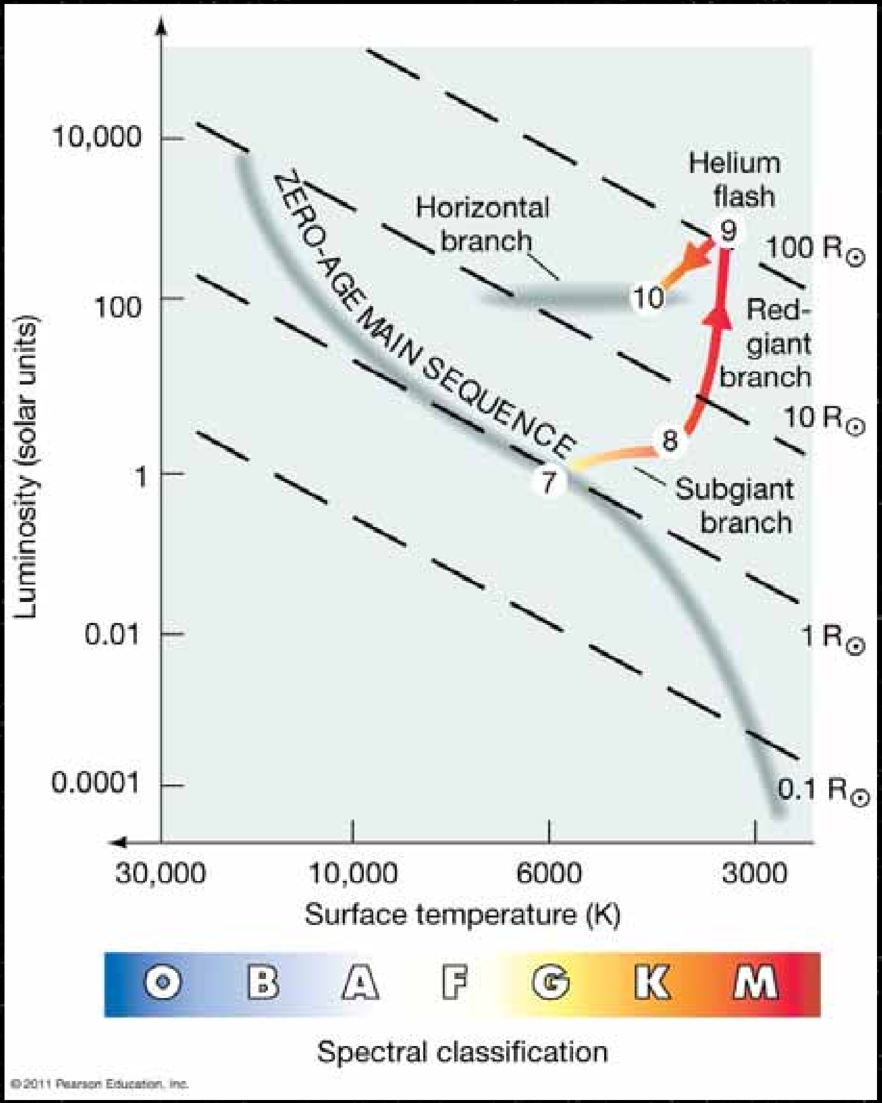
The helium flash:

The pressure within the helium core is almost totally due to "electron degeneracy"—two electrons cannot be in the same quantum state, so the core cannot contract beyond a certain point.

This pressure is almost independent of temperature—when the helium starts fusing, the pressure cannot adjust.

Evolution of a Sun-Like Star

Helium begins to fuse extremely rapidly; within hours the enormous energy output is over, and the star once again reaches equilibrium

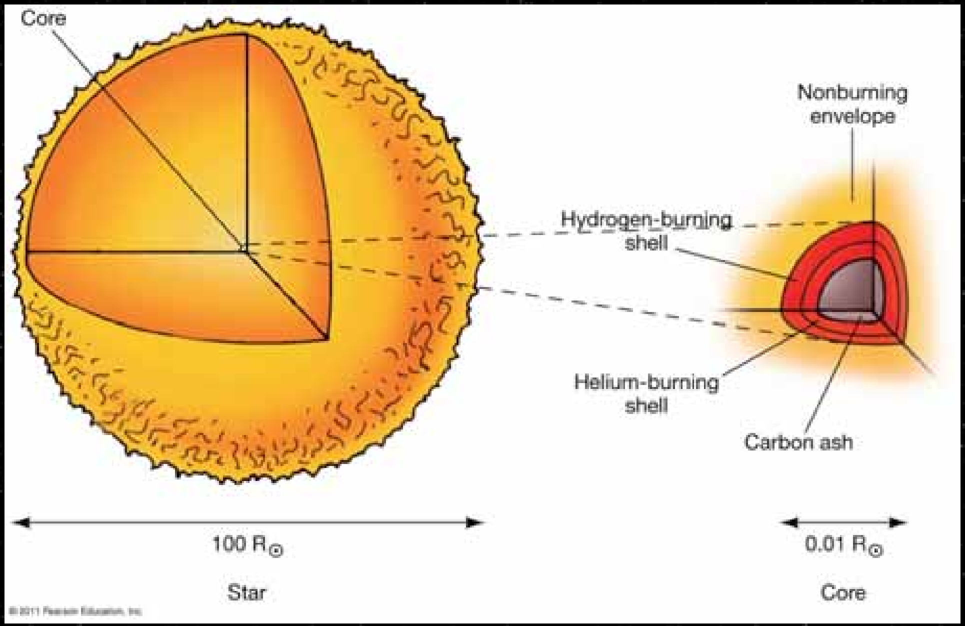


Evolution of a Sun-Like Star

Stage 11: Back to the giant branch

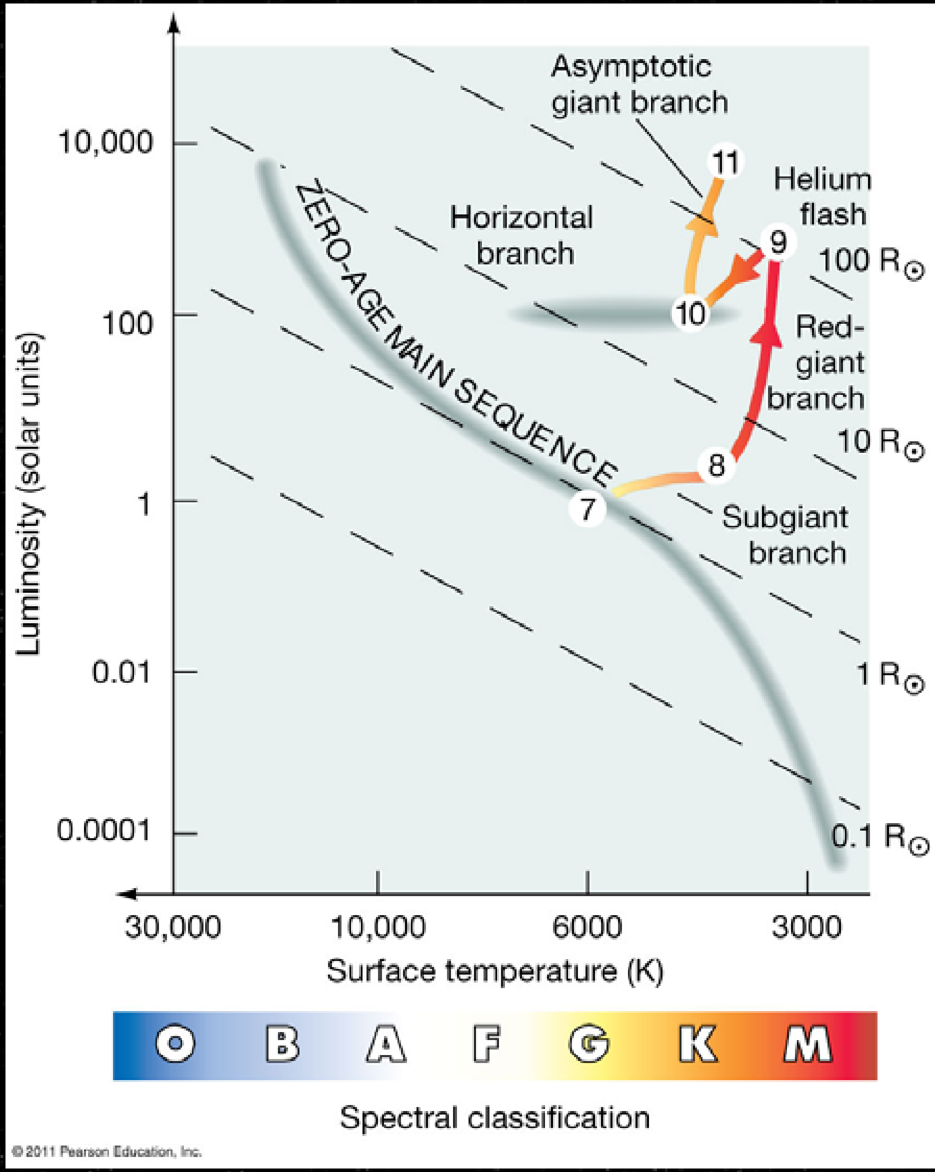
As the helium in the core fuses to carbon, the core becomes hotter and hotter, and the helium burns faster and faster.

The star is now similar to its condition just as it left the Main Sequence, except now there are two shells:



20.2 Evolution of a Sun-Like Star

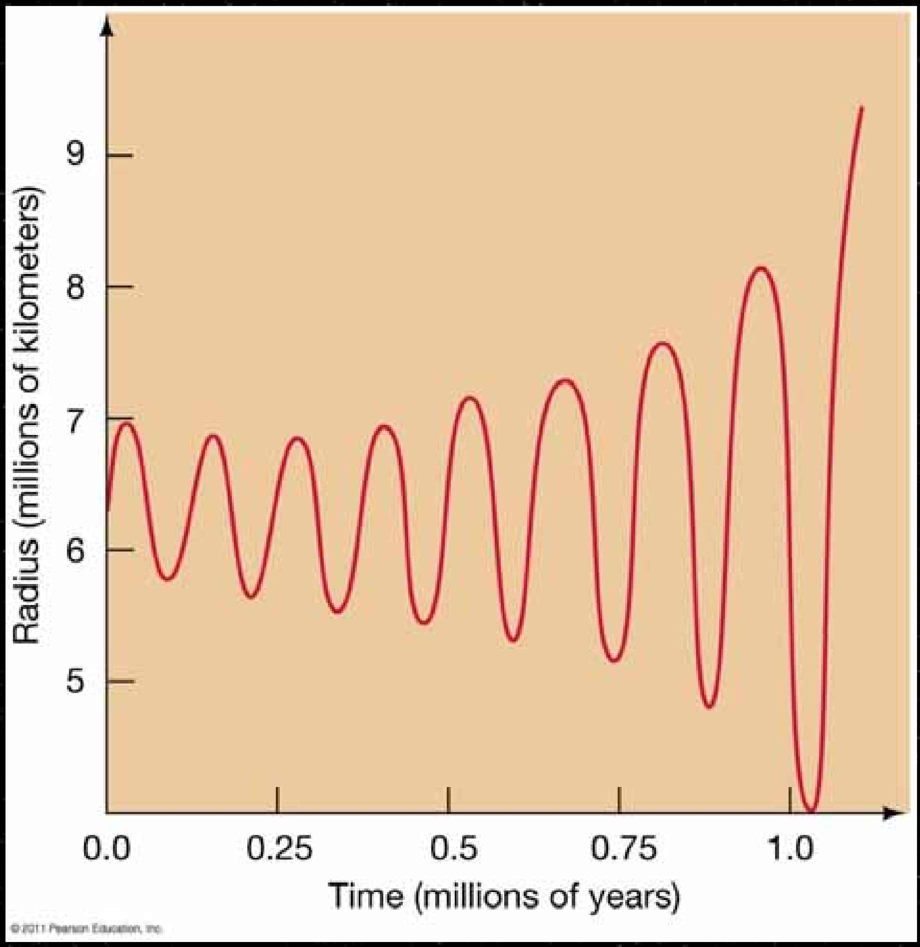
The star has become a red giant for the second time



The Death of a Low-Mass Star

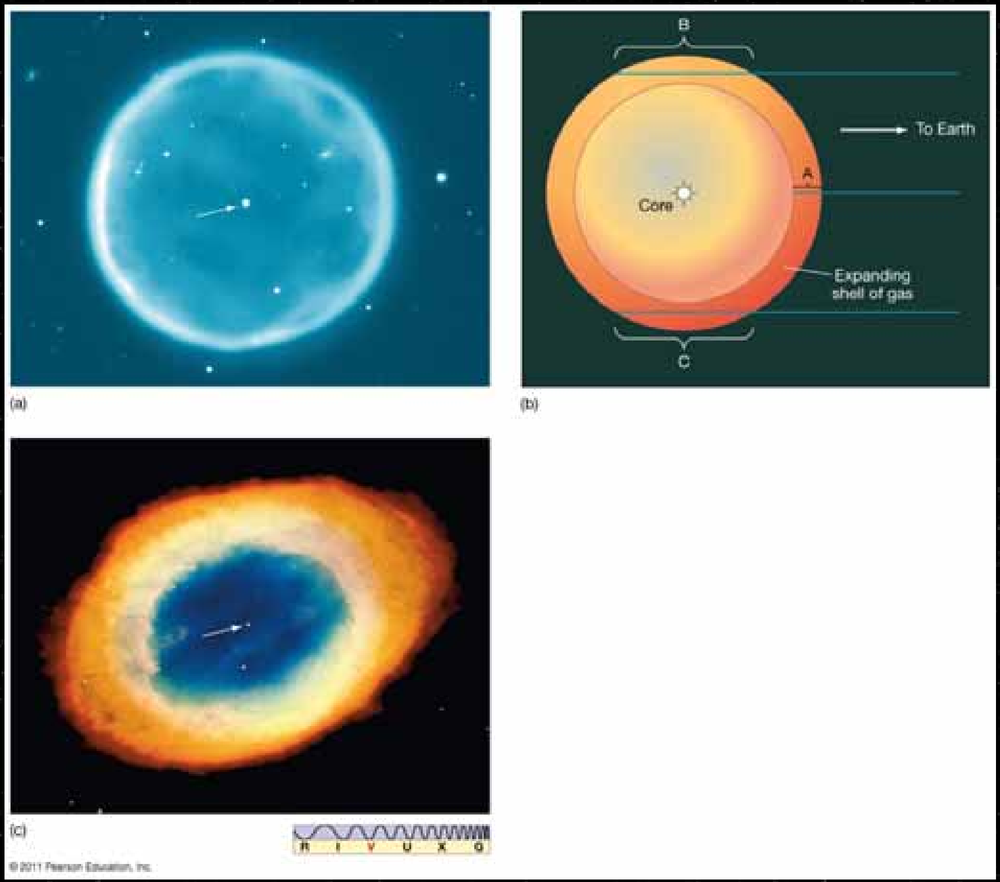
There is no more outward fusion pressure being generated in the core, which continues to contract.

The outer layers become unstable and are eventually ejected.



The Death of a Low-Mass Star

The ejected envelope expands into interstellar space, forming a planetary nebula.



The Death of a Low-Mass Star

The star now has two parts:

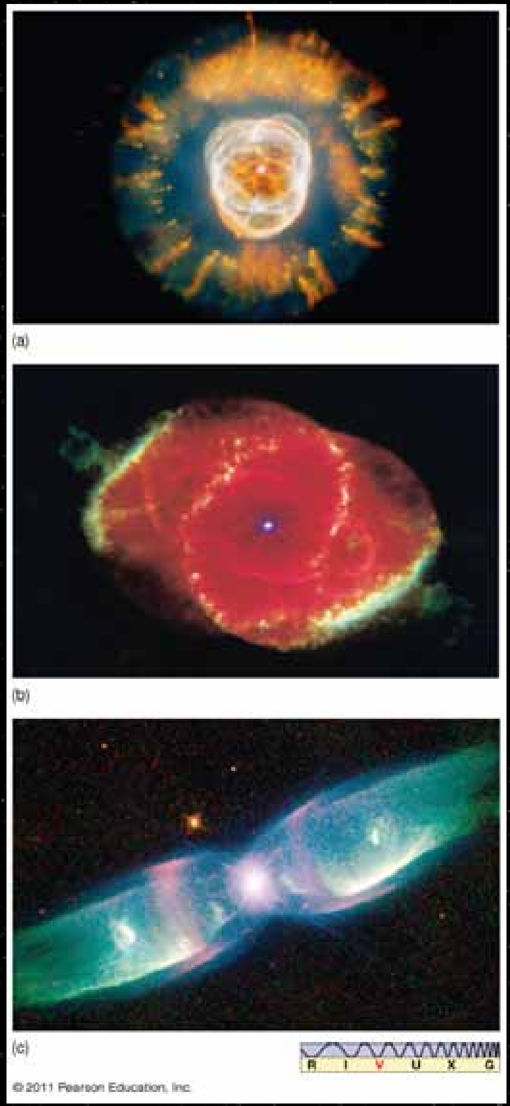
- A small, extremely dense carbon core
- An envelope about the size of our solar system.

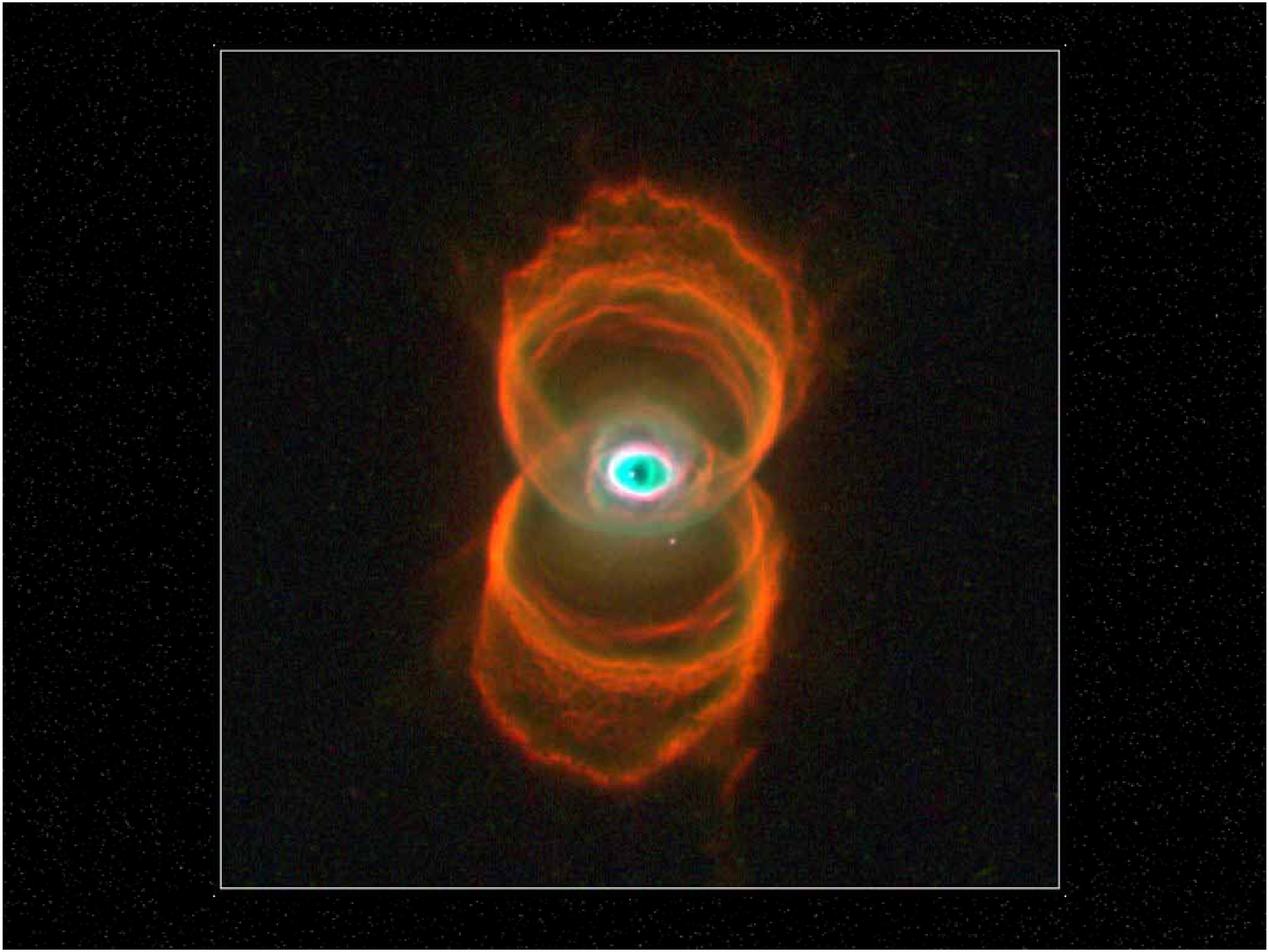
The envelope is called a planetary nebula, even though it has nothing to do with planets—early astronomers viewing the fuzzy envelope thought it resembled a planetary system.

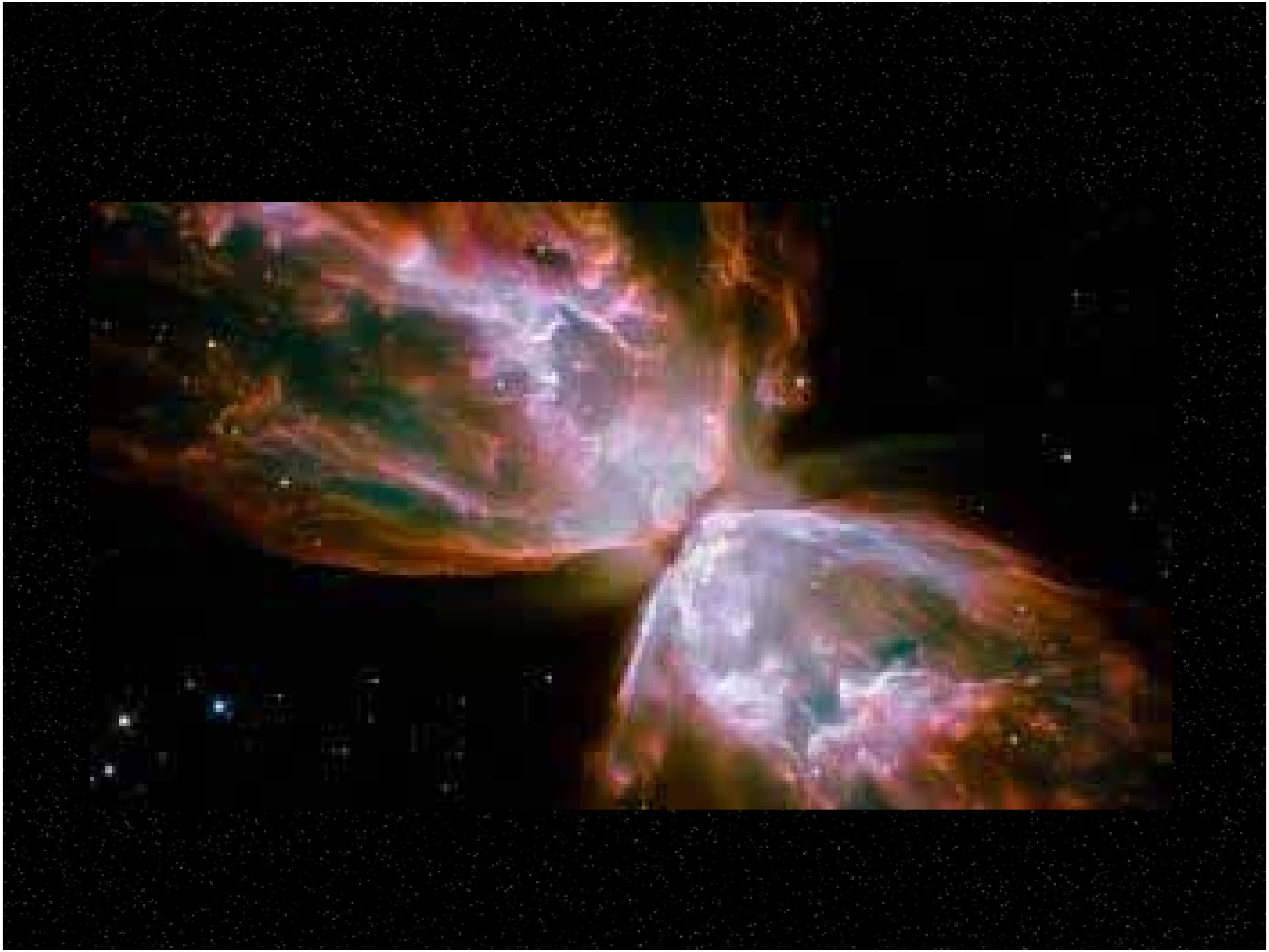
The Death of a Low-Mass Star

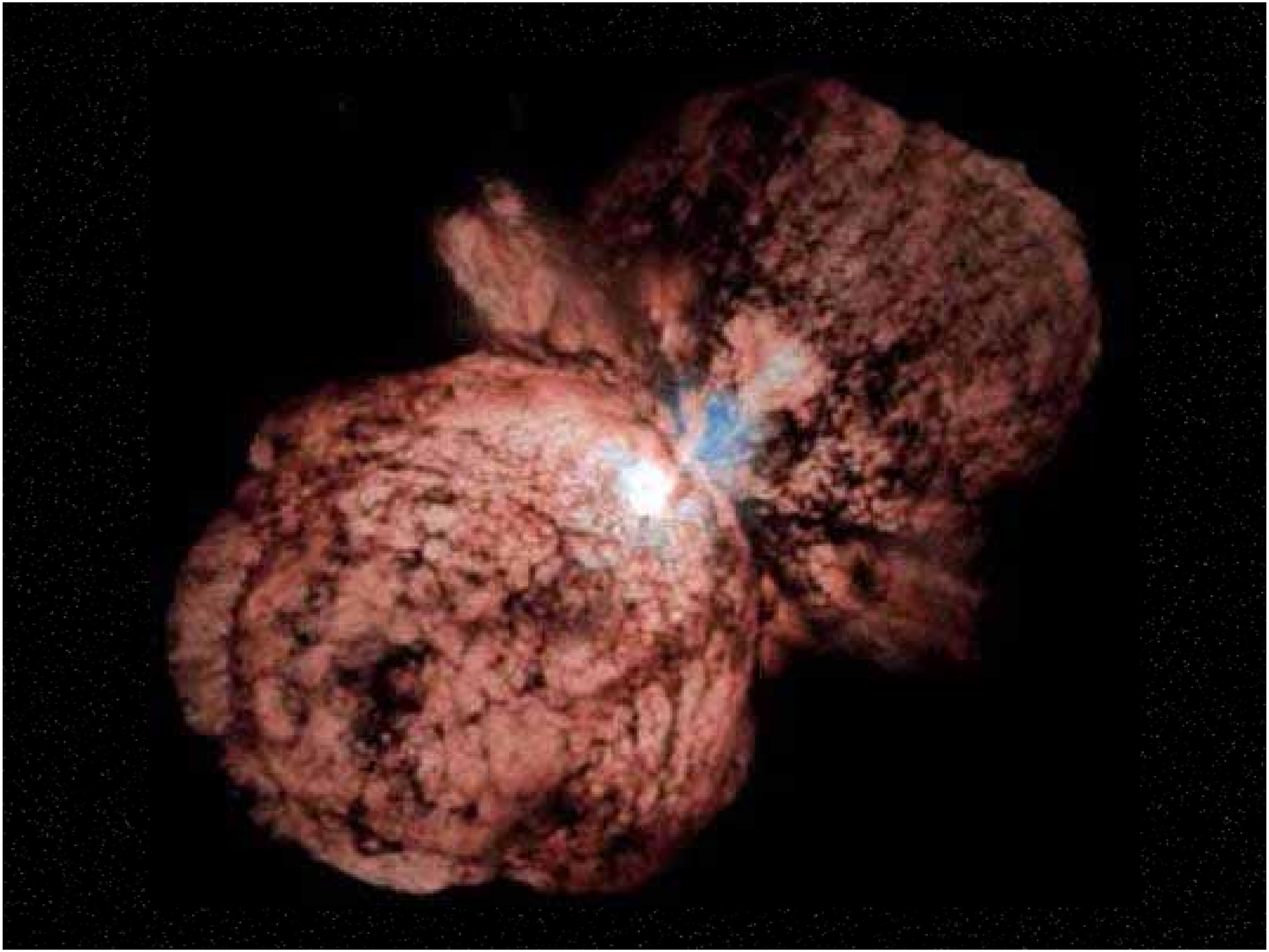
Planetary nebulae can have many shapes:

As the dead core of the star cools, the nebula continues to expand and dissipates into the surroundings.







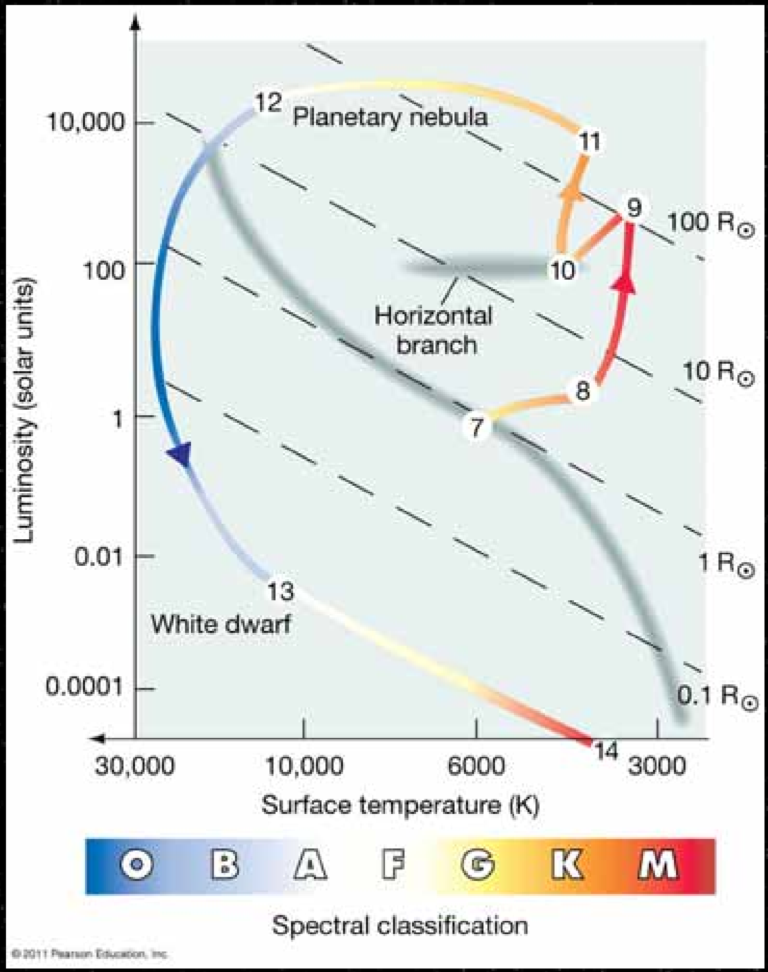


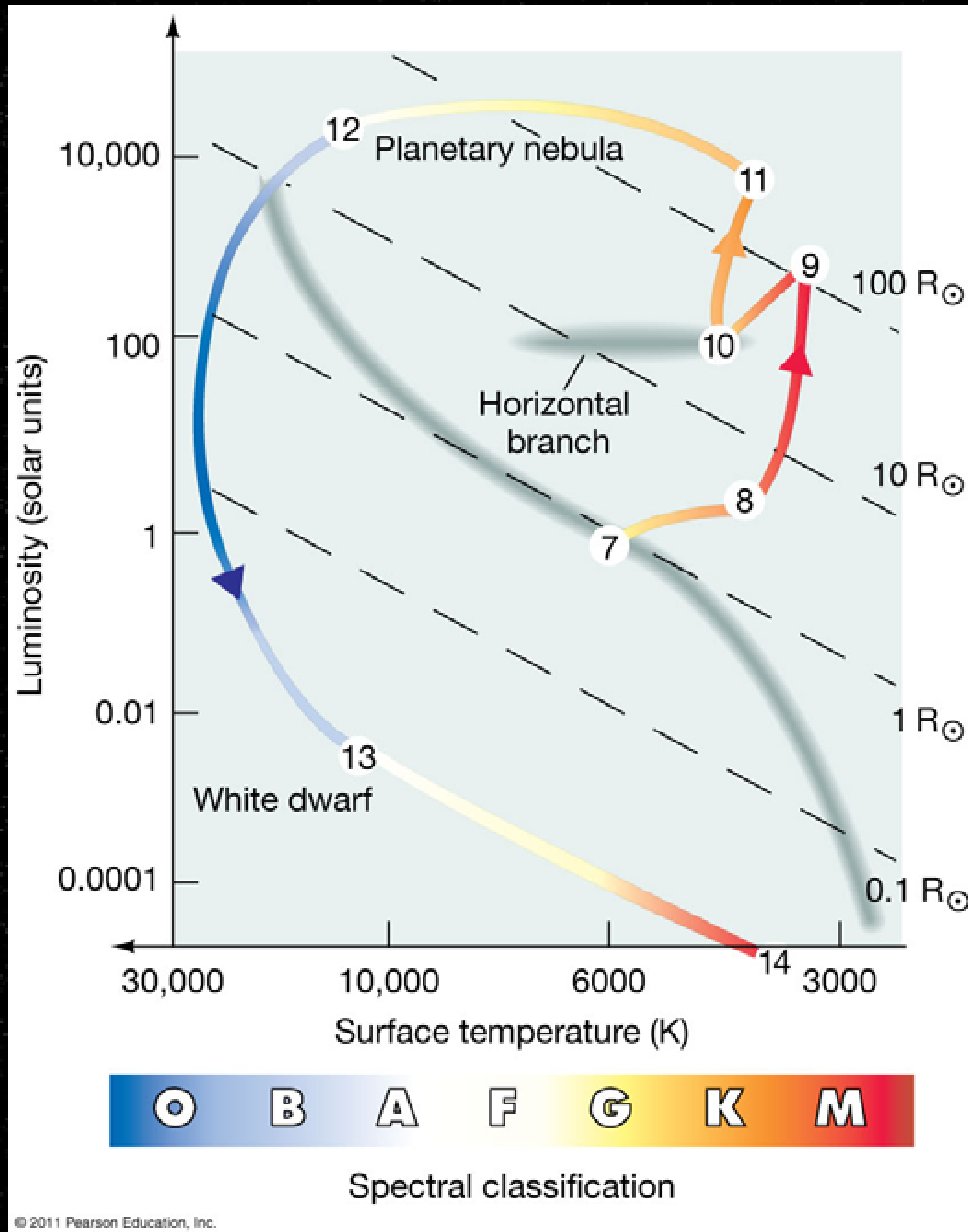
The Death of a Low-Mass Star

Stages 13 and 14: White and black dwarfs

Once the nebula has gone, the remaining core is extremely dense and extremely hot, but quite small.

It is luminous only due to its high temperature.





Luminosity (solar units)
10,000
100
1
0.01
0.0001
12
Planetary nebula
11
9
100 R⊙
10
Horizontal branch
10 R⊙
8
7
1 R⊙
13
White dwarf
0.1 R⊙
14
30,000
10,000
6000
3000
Surface temperature (K)
O
B
A
F
G
K
M
Spectral classification
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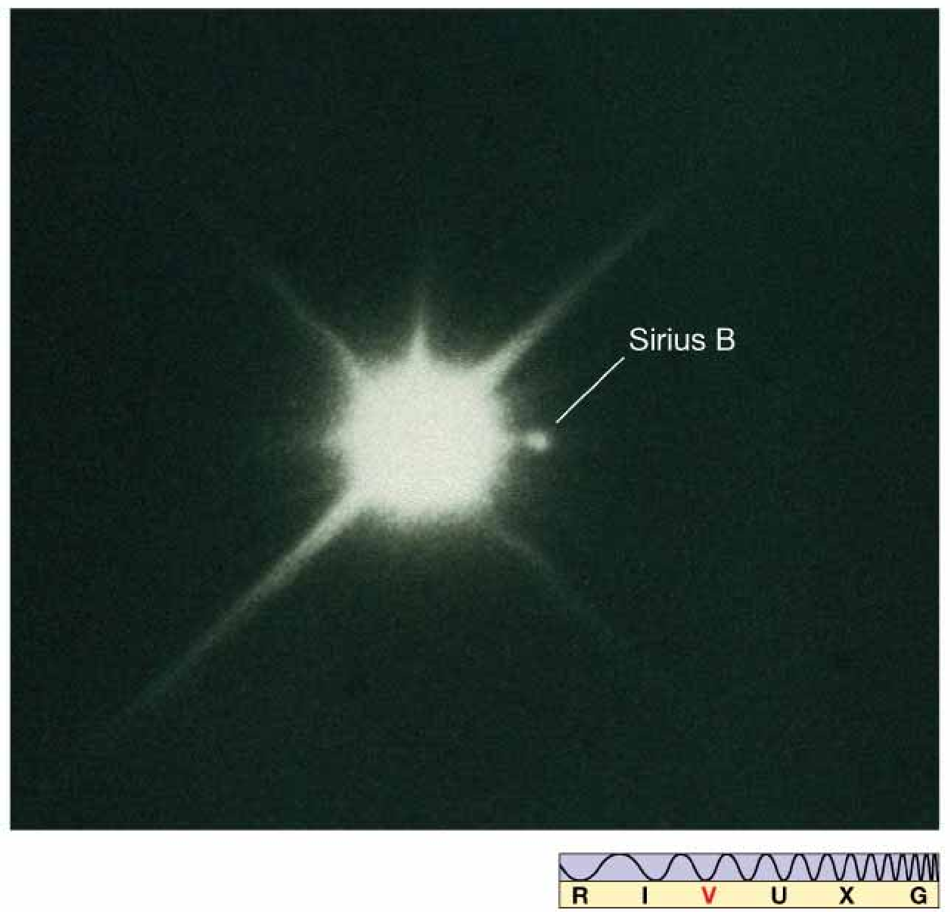
The Death of a Low-Mass Star

As the white dwarf cools, its size does not change significantly; it simply gets dimmer and dimmer, and finally ceases to glow.

The Death of a Low-Mass Star

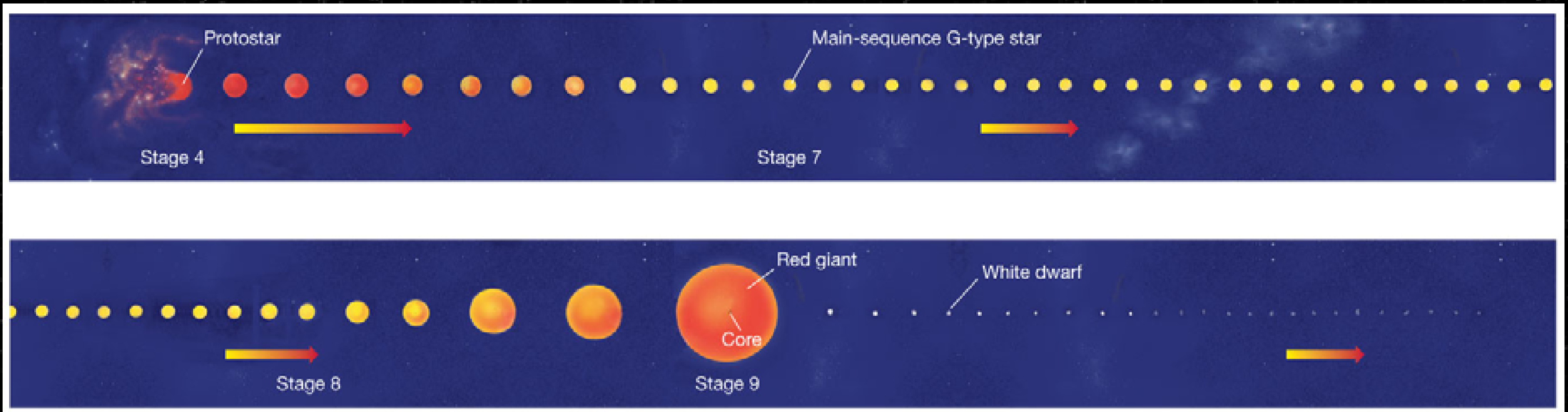
The small star Sirius B is a white-dwarf companion of the much larger and brighter Sirius A:



The Death of a Low-Mass Star

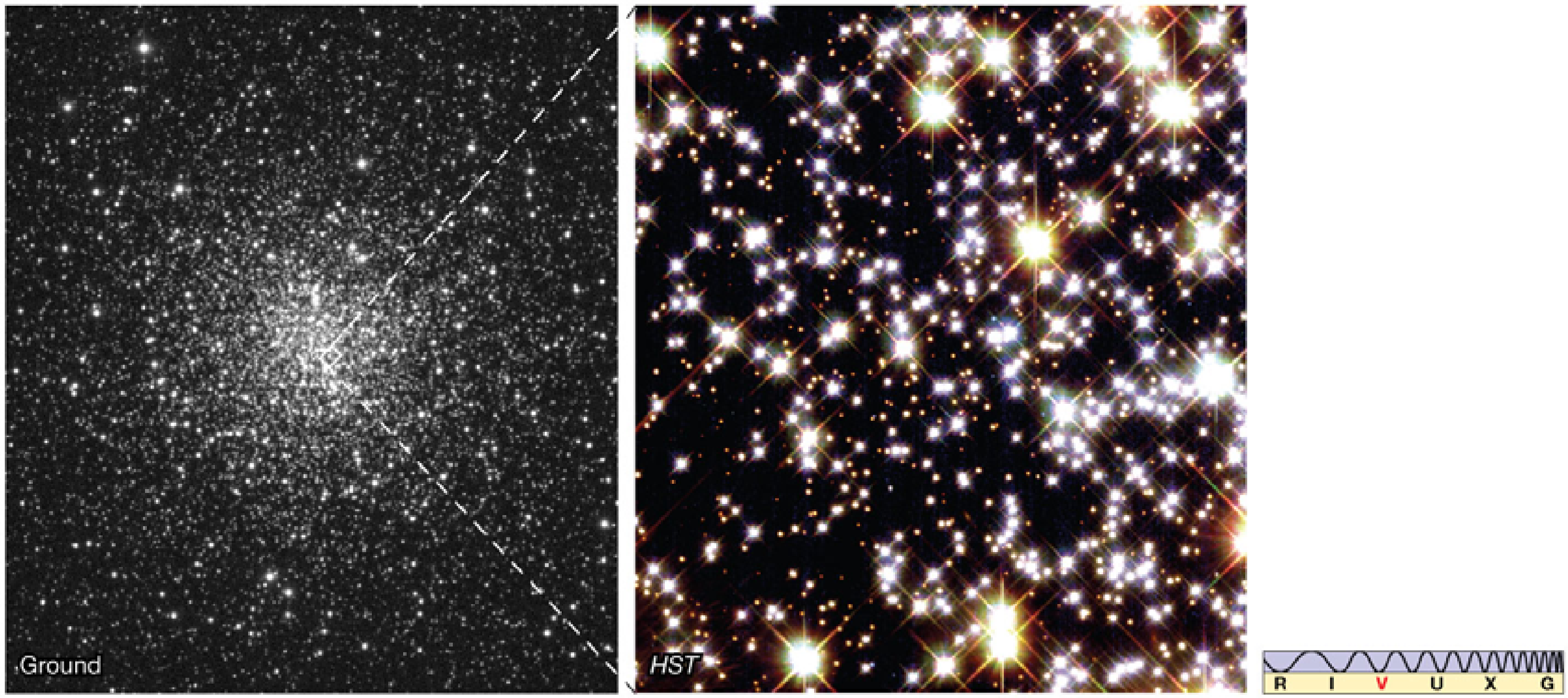
This graphic shows the entire evolution of a Sun-like star.

Such stars never become hot enough for fusion past carbon to take place.



The Death of a Low-Mass Star

The Hubble Space Telescope has detected white dwarf stars in globular clusters:



(a) (b)

Evolution of Stars More Massive than the Sun

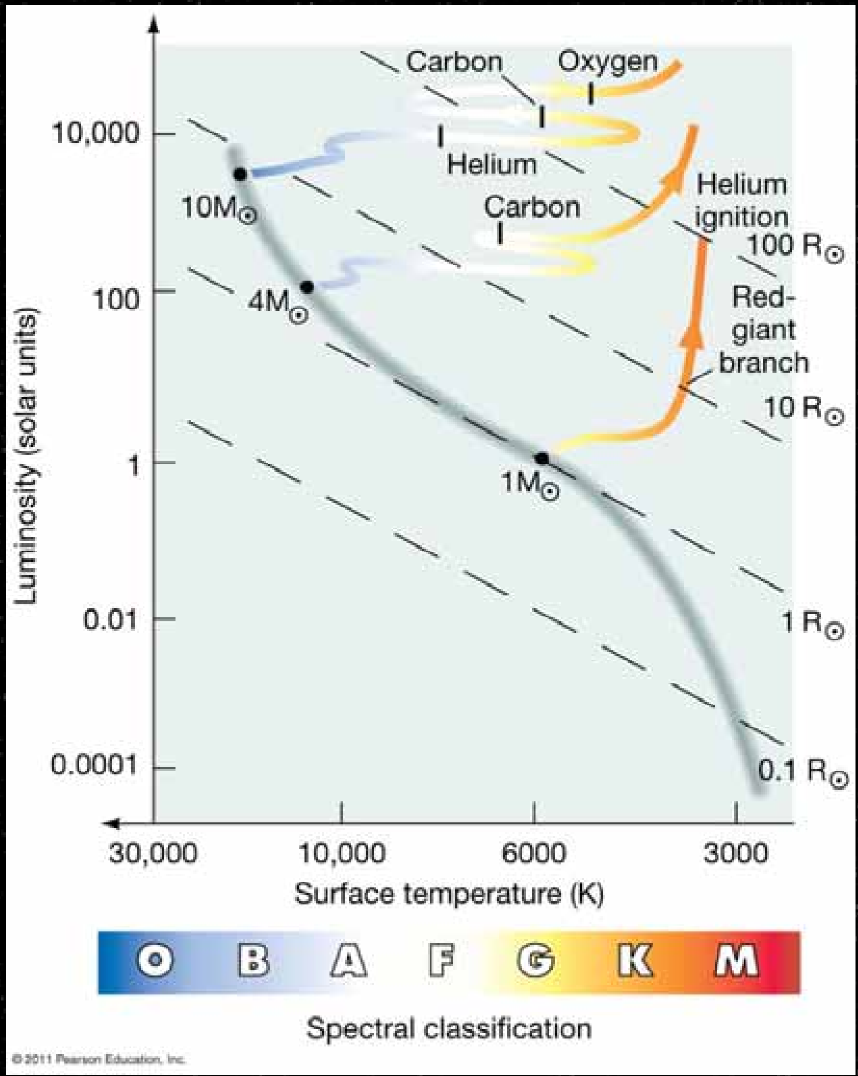
A star of more than 8 solar masses can fuse elements far beyond carbon in its core, leading to a very different fate.

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

Eventually the star dies in a violent explosion called a supernova.

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

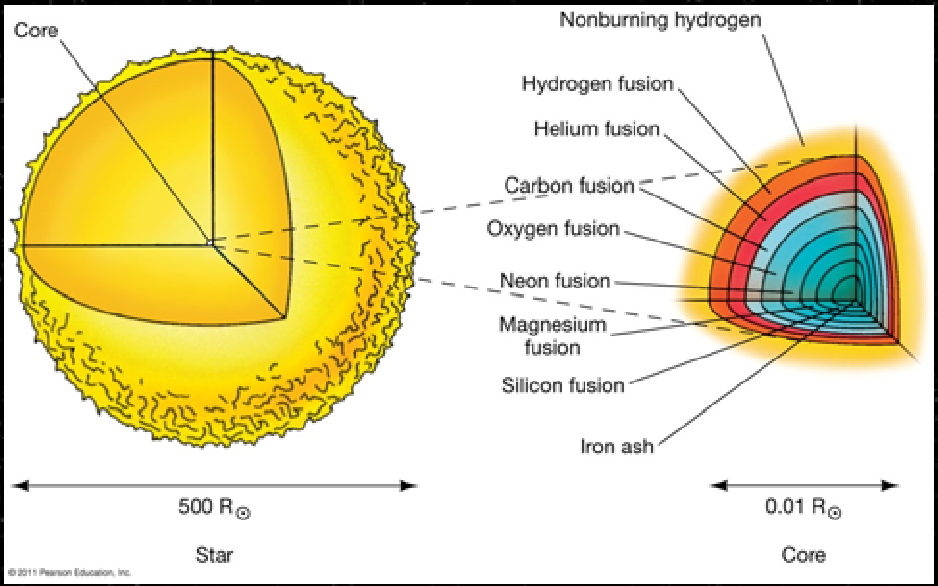
Stars with masses more than 2.5 solar masses do not experience a helium flash—helium burning starts gradually.

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

The End of a High-Mass Star

A high-mass star can continue to fuse elements in its core right up to iron (after which the fusion reaction is energetically unfavored).

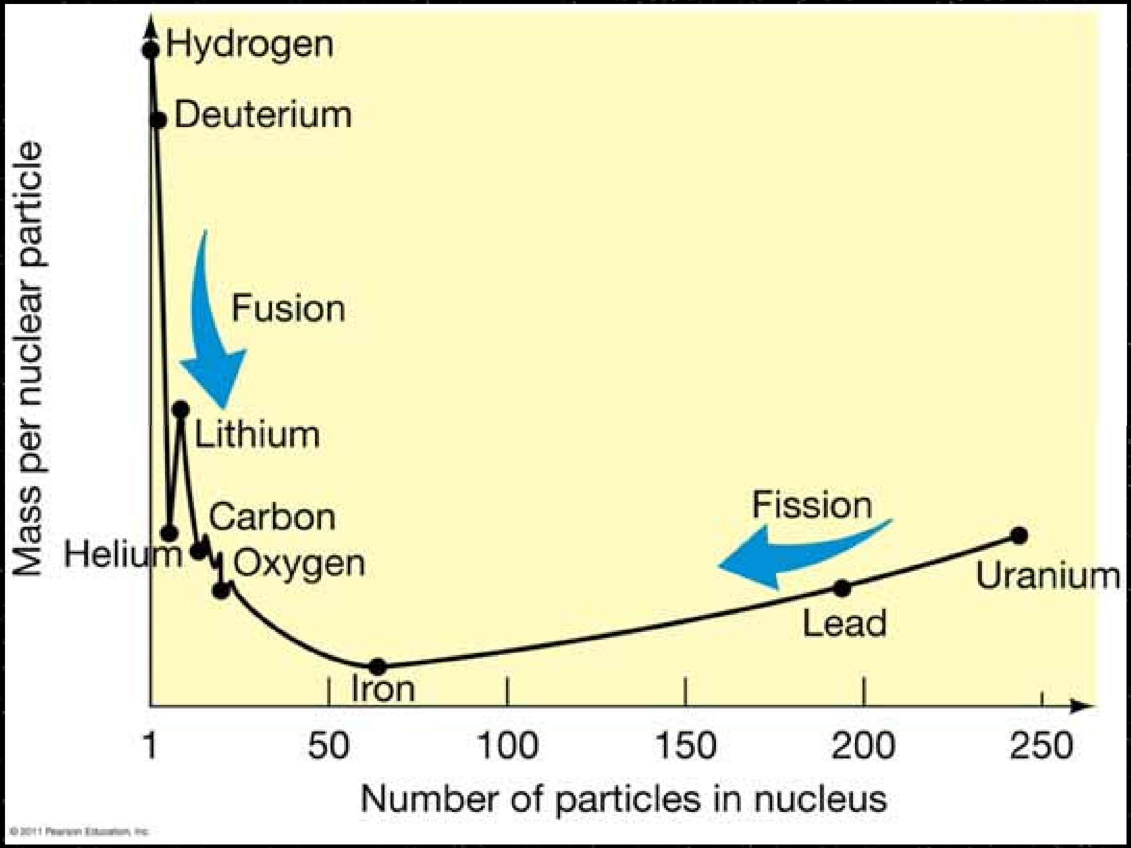
As heavier elements are fused, the reactions go faster and the stage is over more quickly. A 20-solar-mass star will burn carbon for about 10,000 years, but its iron core lasts less than a day.



The End of a High-Mass Star

This graph shows the relative stability of nuclei. On the left, nuclei gain energy through fusion; on the right they gain it through fission:

Iron is the crossing point; when the core has fused to iron, no more fusion can take place



Evolution of Stars More Massive than the Sun

In summary:

TABLE 20.3 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 (Chapter 21)

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

Mass Loss from Giant Stars

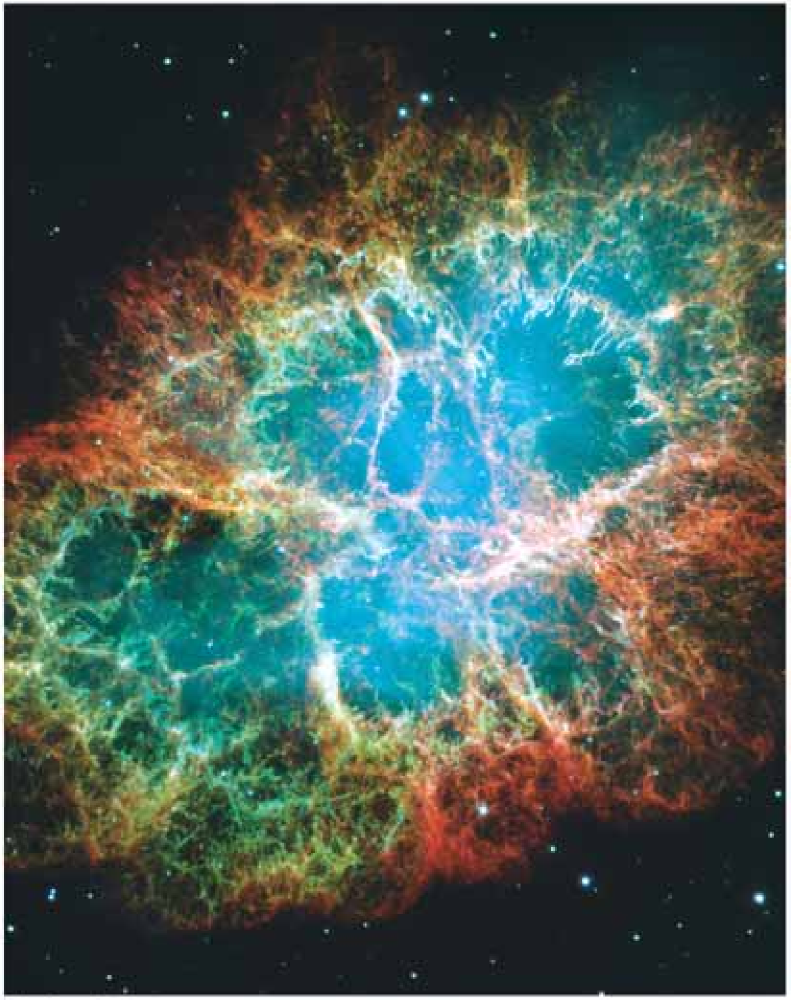
All stars lose mass via some form of stellar wind. The most massive stars have the strongest winds; O- and B-type stars can lose a tenth of their total mass this way in only a million years.

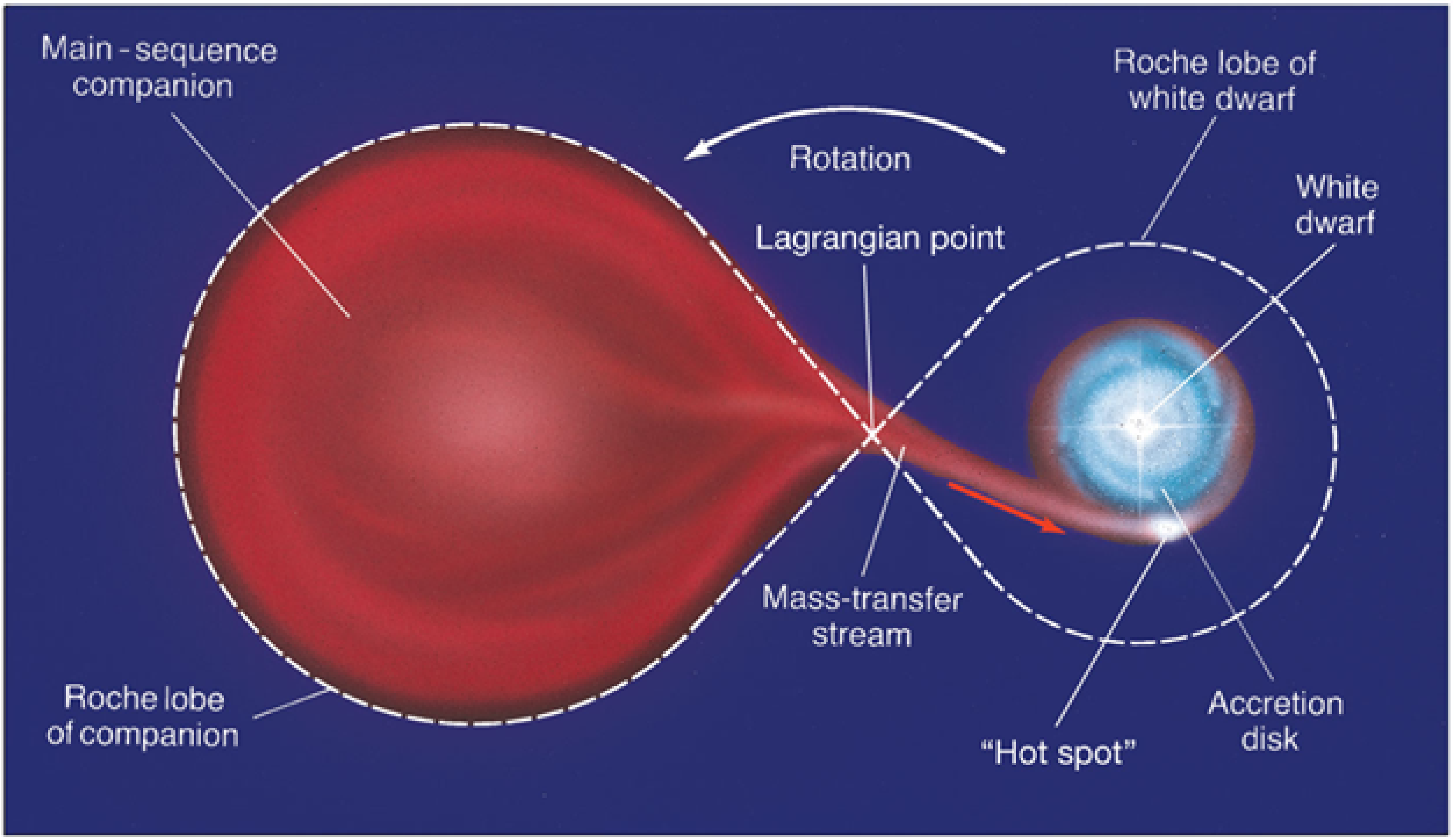
These stellar winds hollow out cavities in the interstellar medium surrounding giant stars.

Mass Loss from Giant Stars

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

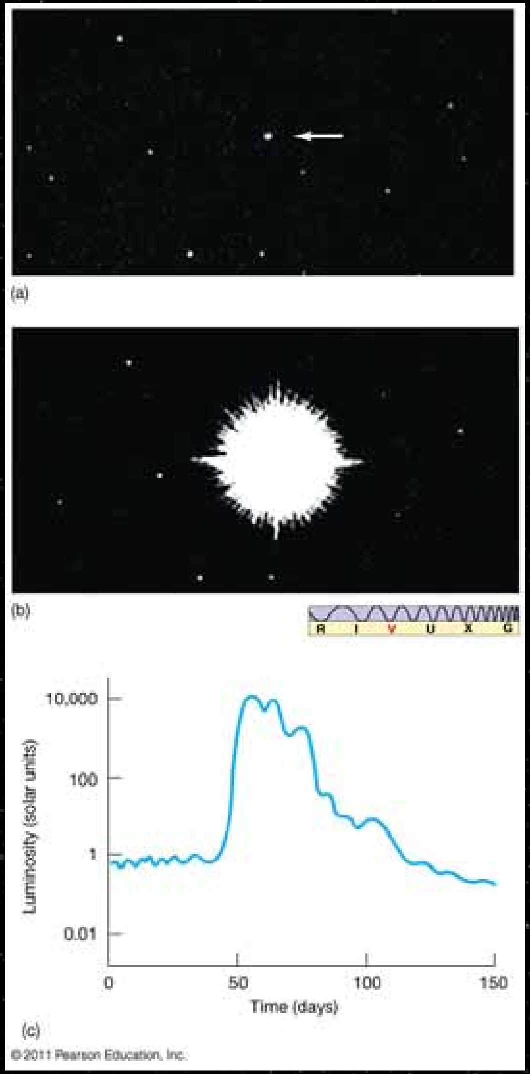
Stellar Explosions

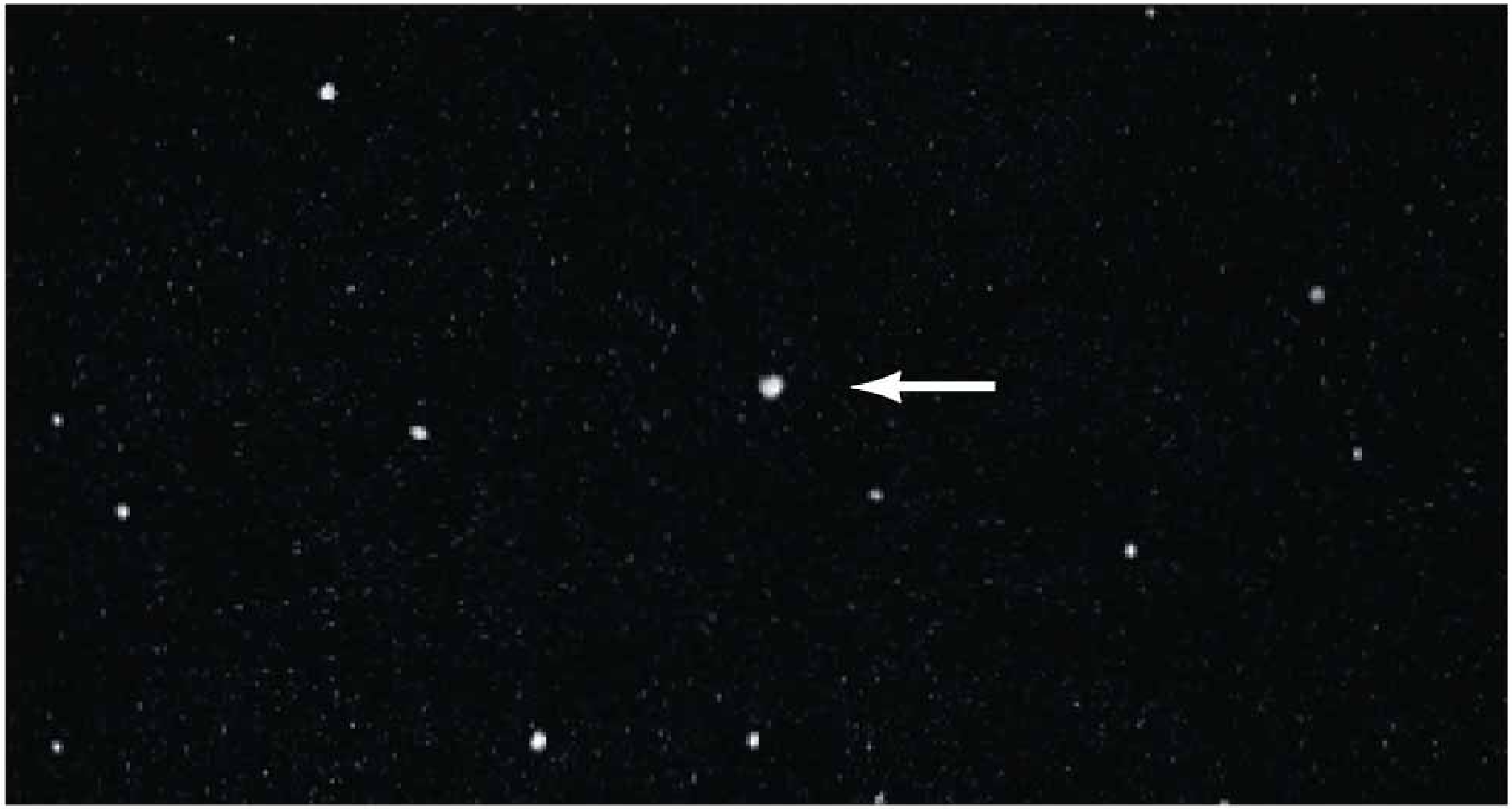



Main - sequence companion
Roche lobe of white dwarf
Rotation
White dwarf
Lagrangian point
Mass-transfer stream
Roche lobe of companion
"Hot spot"
Accretion disk

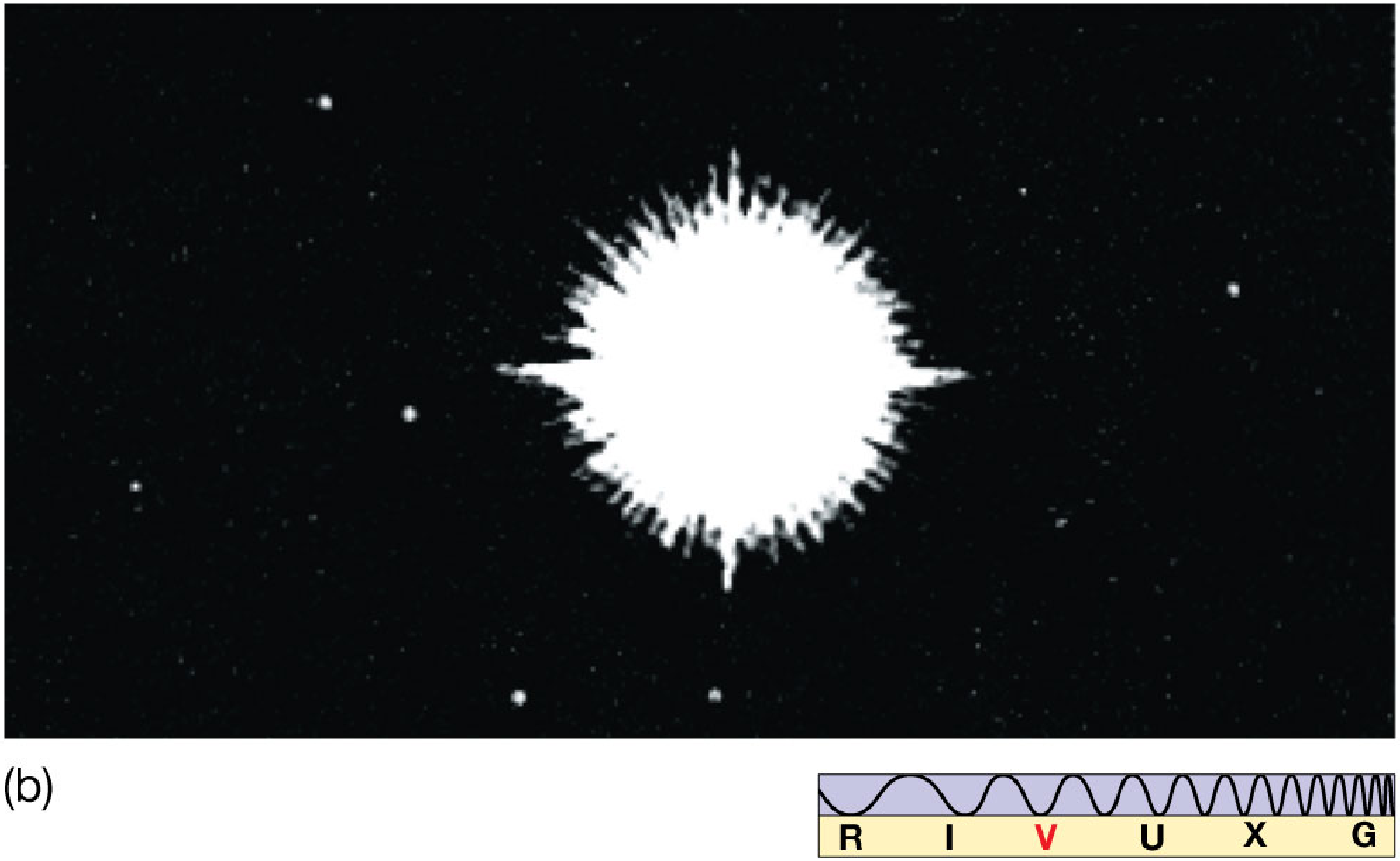
Life after Death for White Dwarfs

A nova is a star that flares up very suddenly and then returns slowly to its former luminosity:

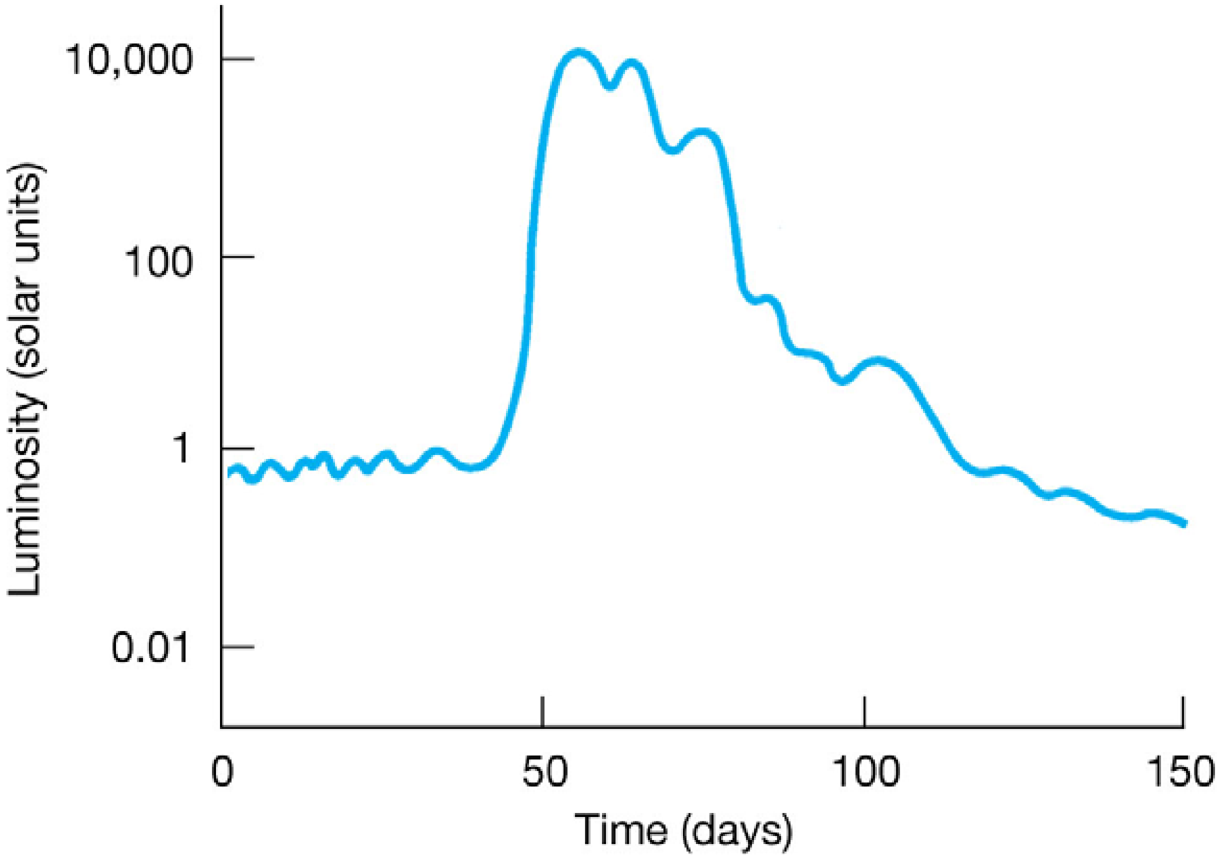




(a)



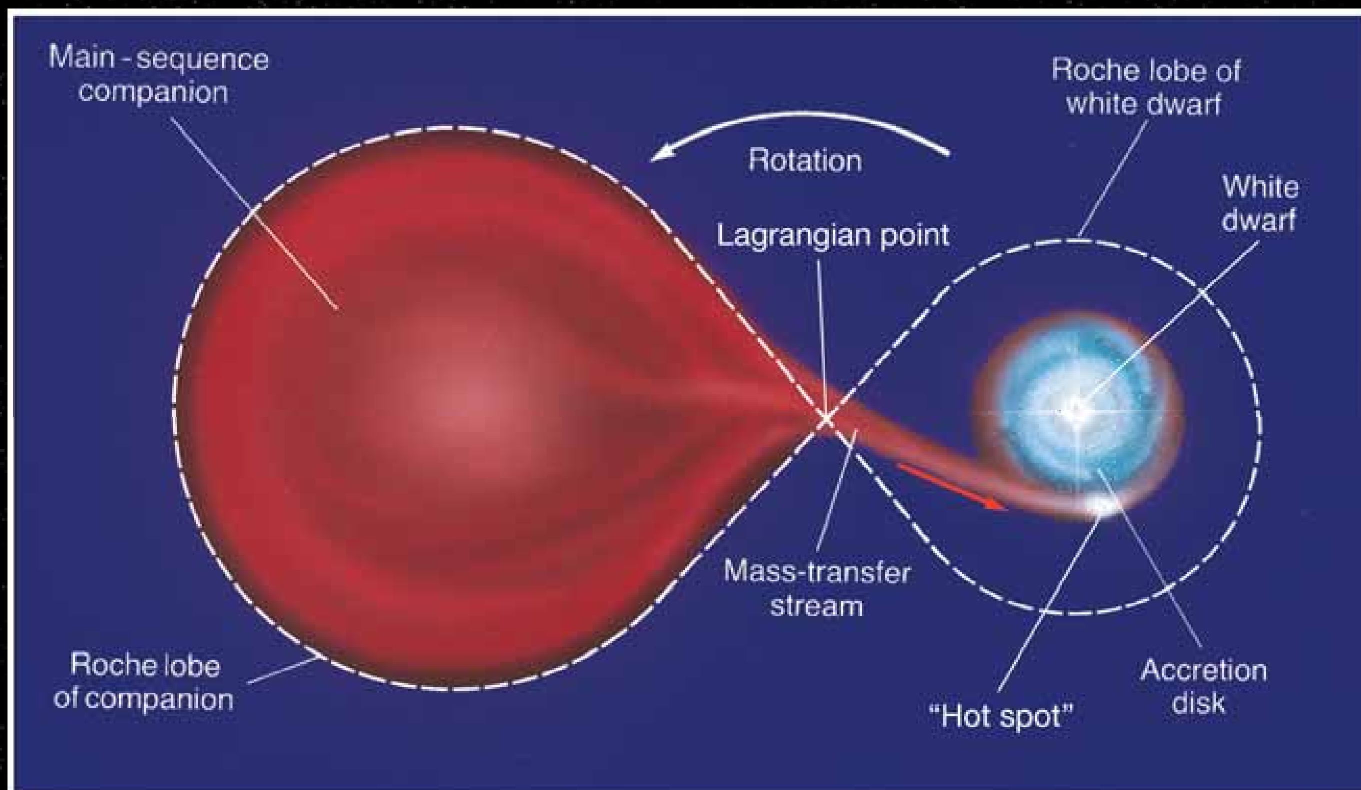
(b)



(c)

Life after Death for White Dwarfs

A white dwarf that is part of a semidetached binary system can undergo repeated novas.

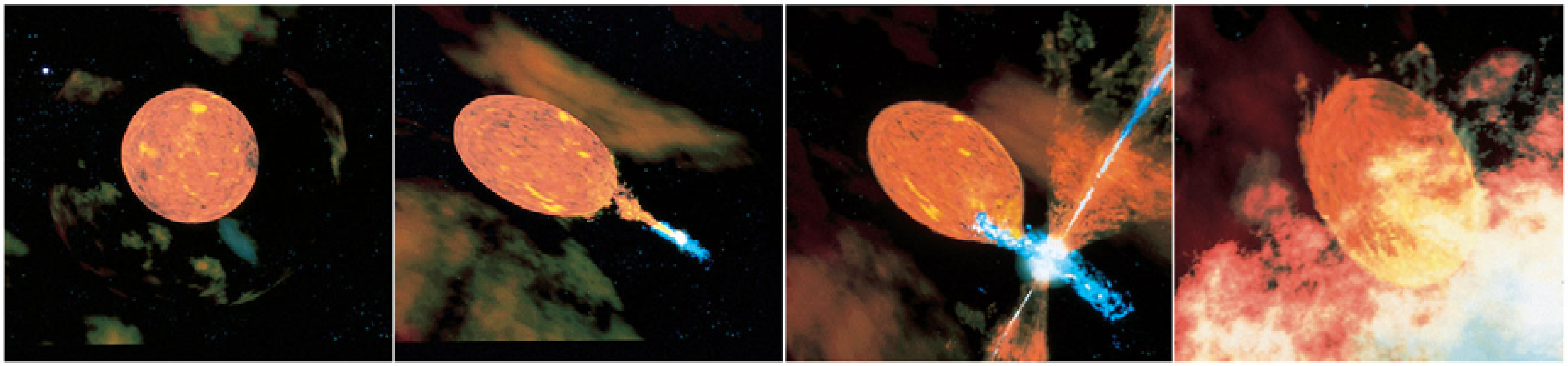


Life after Death for White Dwarfs

Material falls onto the white dwarf from its main-sequence companion.

When enough material has accreted, fusion can reignite very suddenly, burning off the new material.

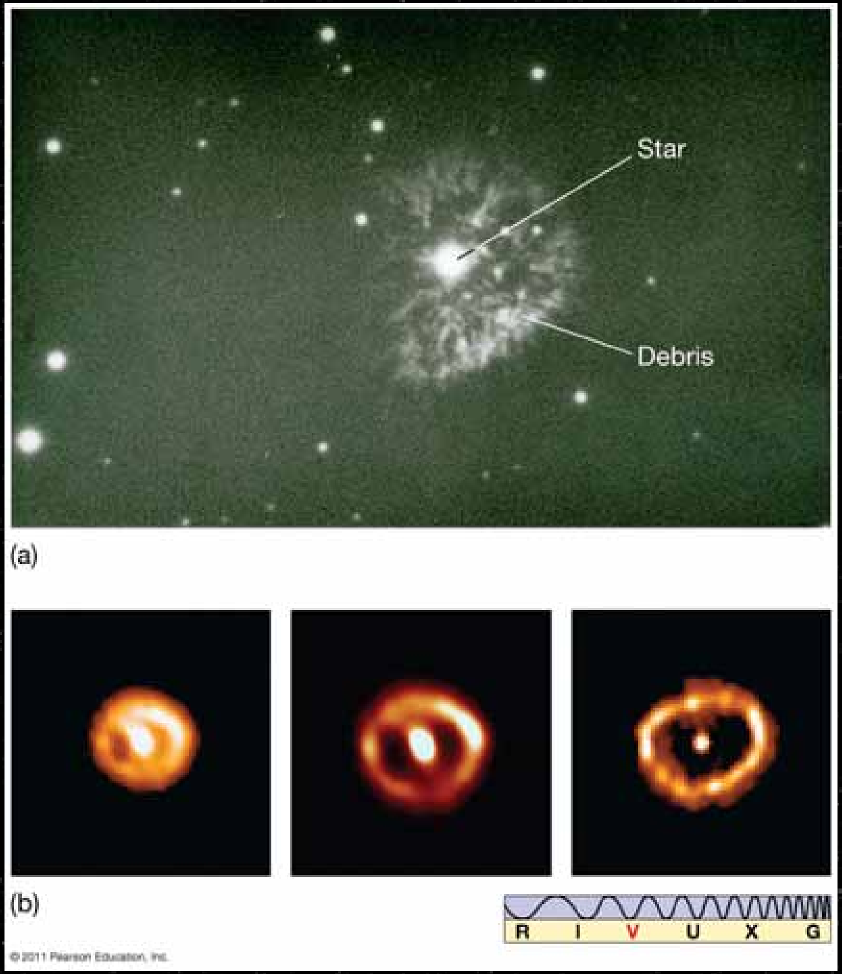
Material keeps being transferred to the white dwarf, and the process repeats, as illustrated here:



(a) (b) (c) (d)

Life after Death for White Dwarfs

This series of images shows ejected material expanding away from a star after a nova explosion:



Learning Astronomy from History

Sirius is the brightest star in the northern sky and has been recorded throughout history. But there is a mystery!

All sightings recorded between about 100 BCE and 200 CE describe it as being red—it is now blue-white. Why?

Could there have been an intervening dust cloud? (Then where is it?)

Could its companion have been a red giant? (It became a white dwarf very quickly, then!)

The End of a High-Mass Star

The inward pressure is enormous, due to the high mass of the star.

There is nothing stopping the star from collapsing further; it does so very rapidly, in a giant implosion.

As it continues to become more and more dense, the protons and electrons react with one another to become neutrons:

$$p + e \rightarrow n + \text{neutrino}$$

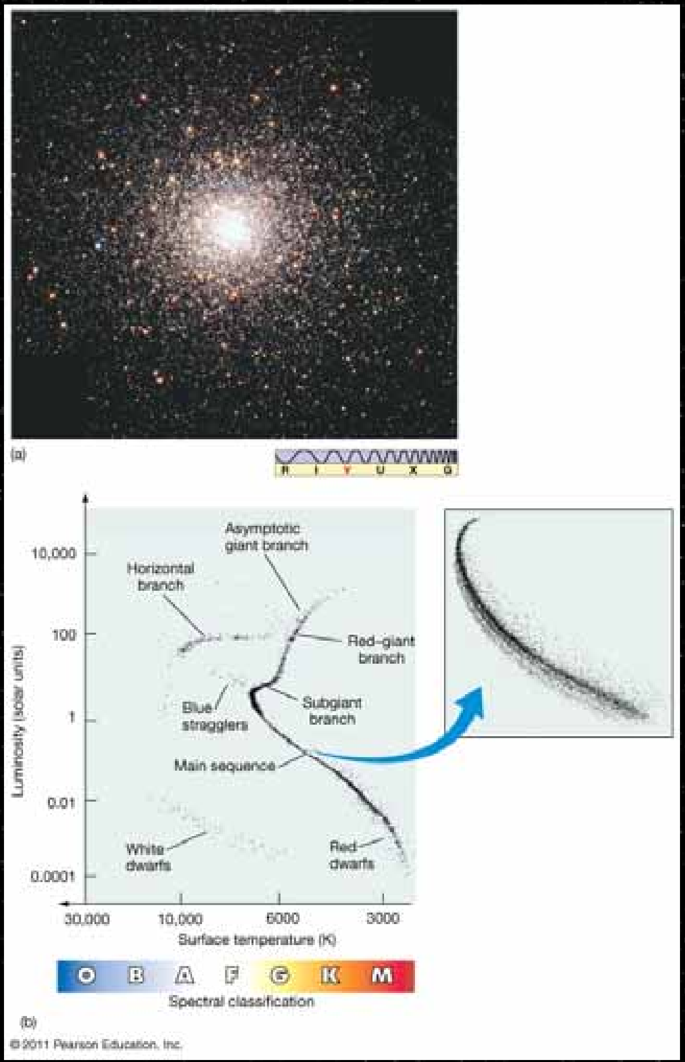
The End of a High-Mass Star

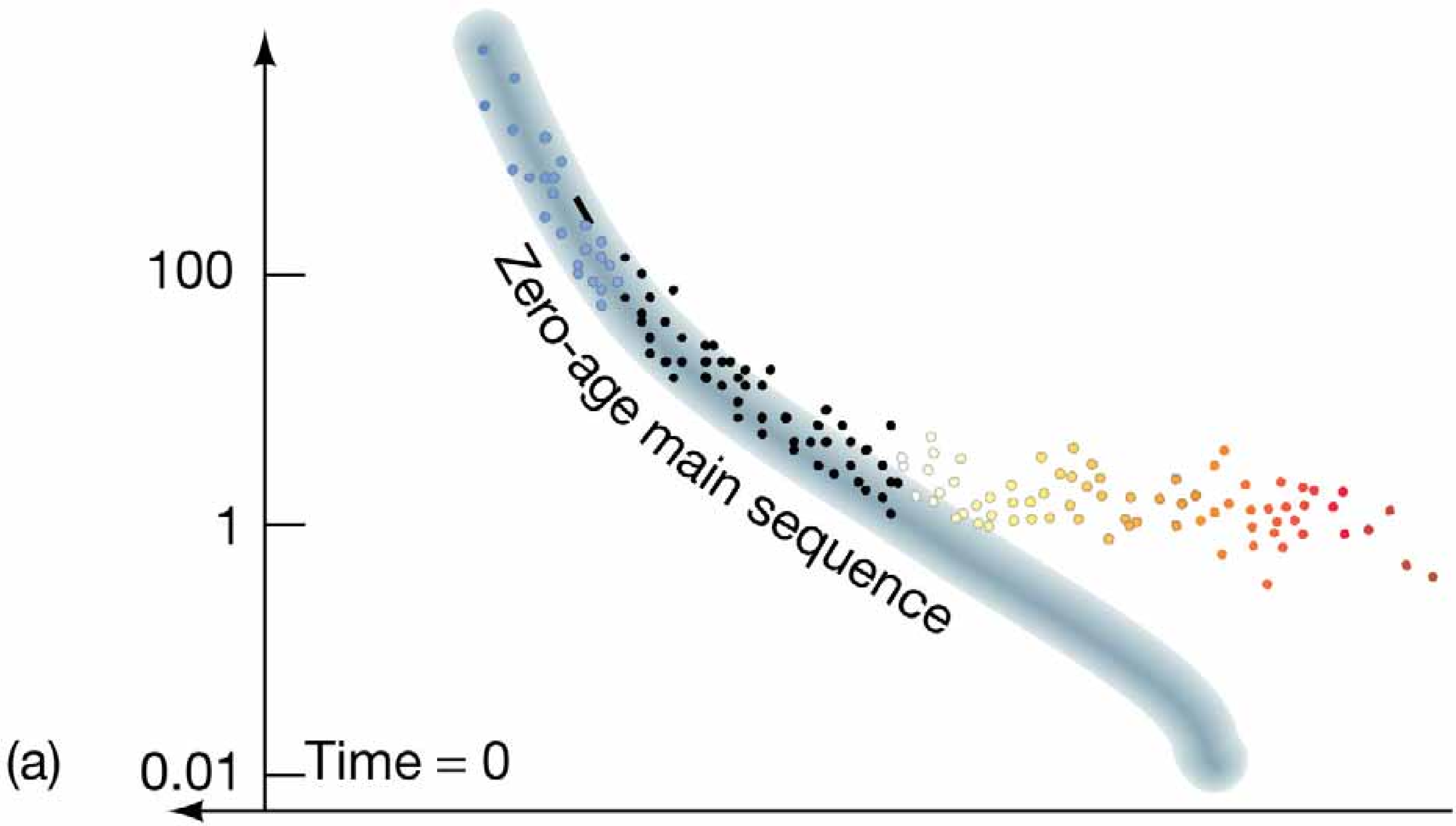
The neutrinos escape; the neutrons are compressed together until the whole star has the density of an atomic nucleus, about 10^{15} kg/m^3.

The collapse is still going on; it compresses the neutrons further until they recoil in an enormous explosion as a supernova.

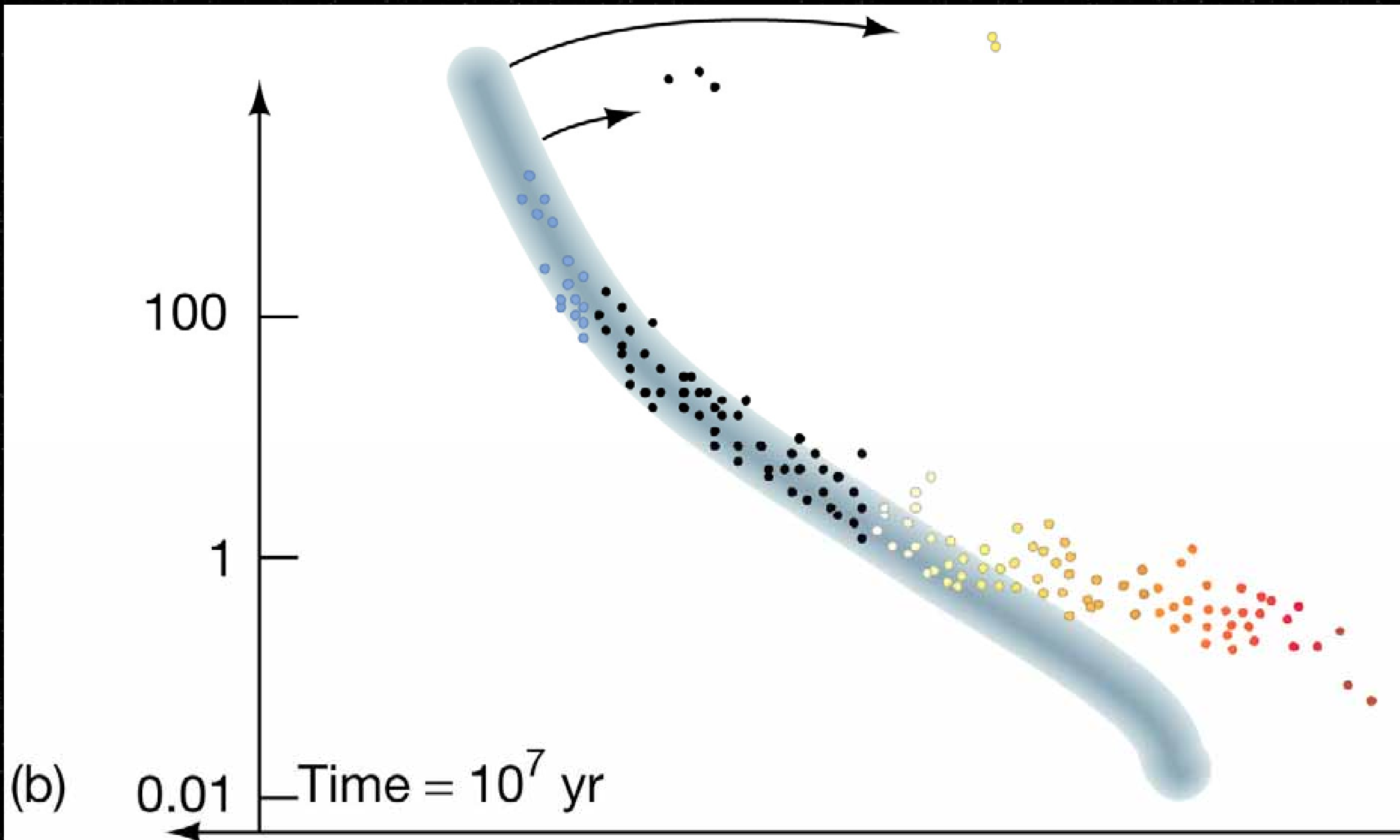
The Death of a Low-Mass Star

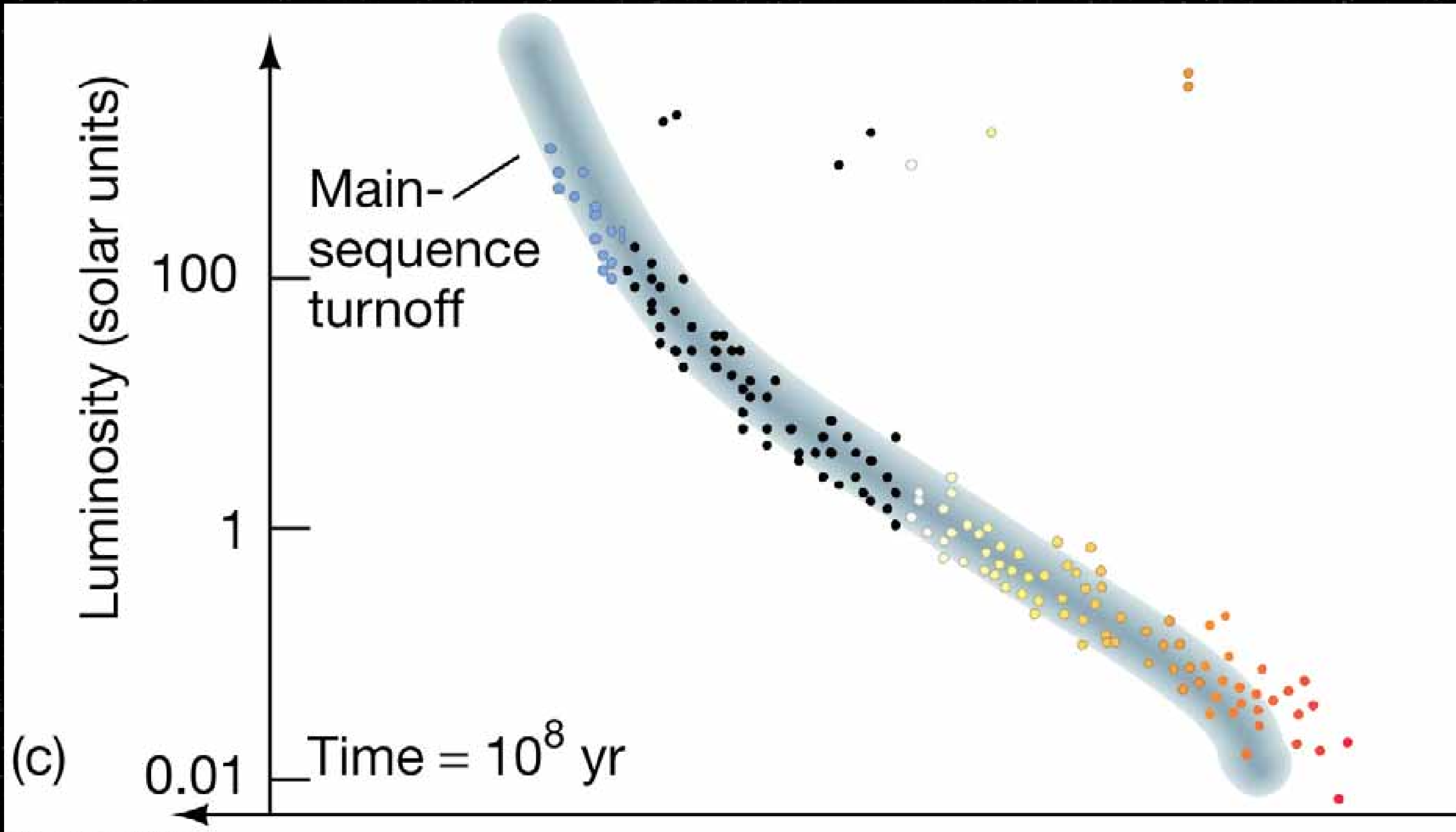
This outline of stellar formation and extinction can be compared to observations of star clusters. Here a globular cluster:

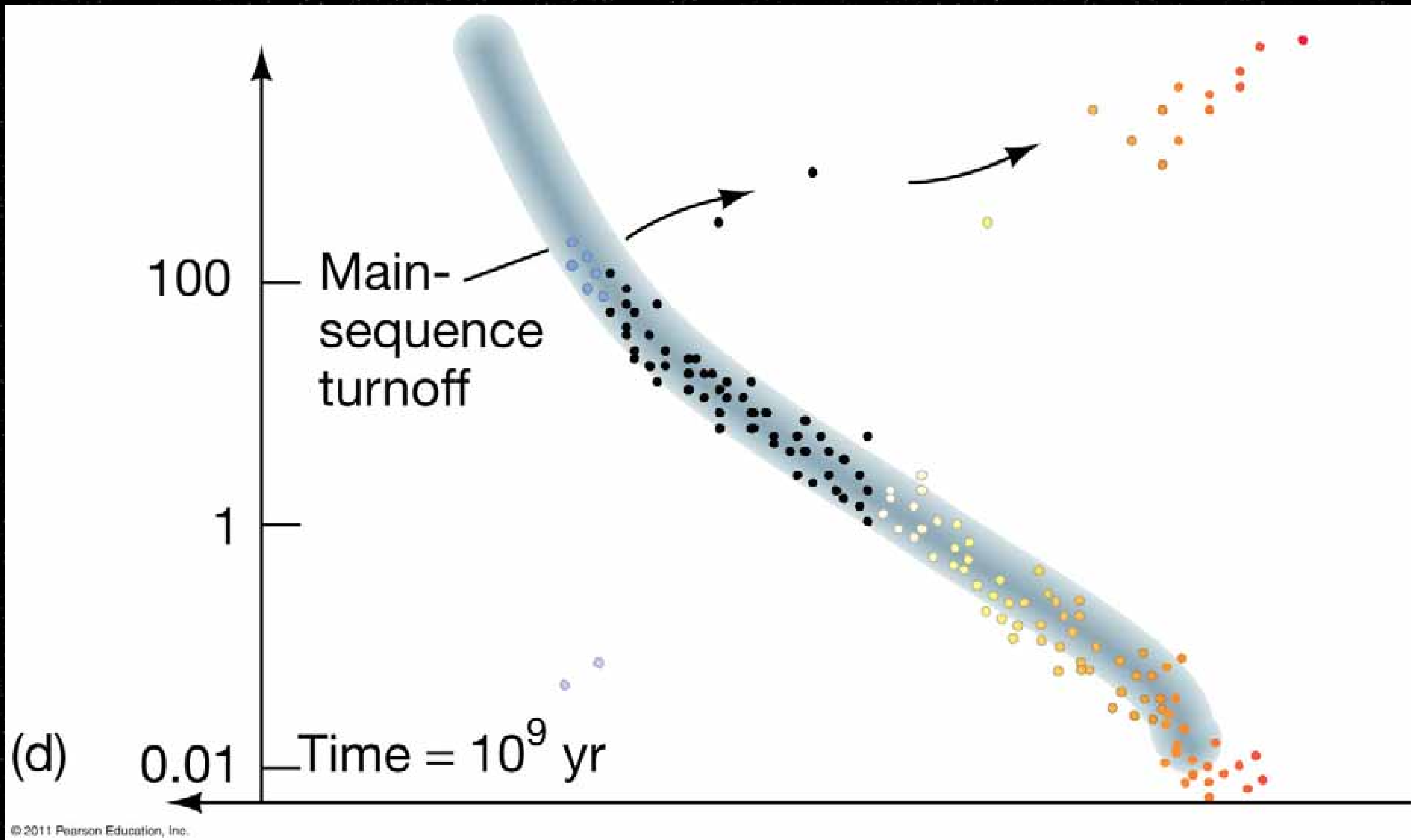


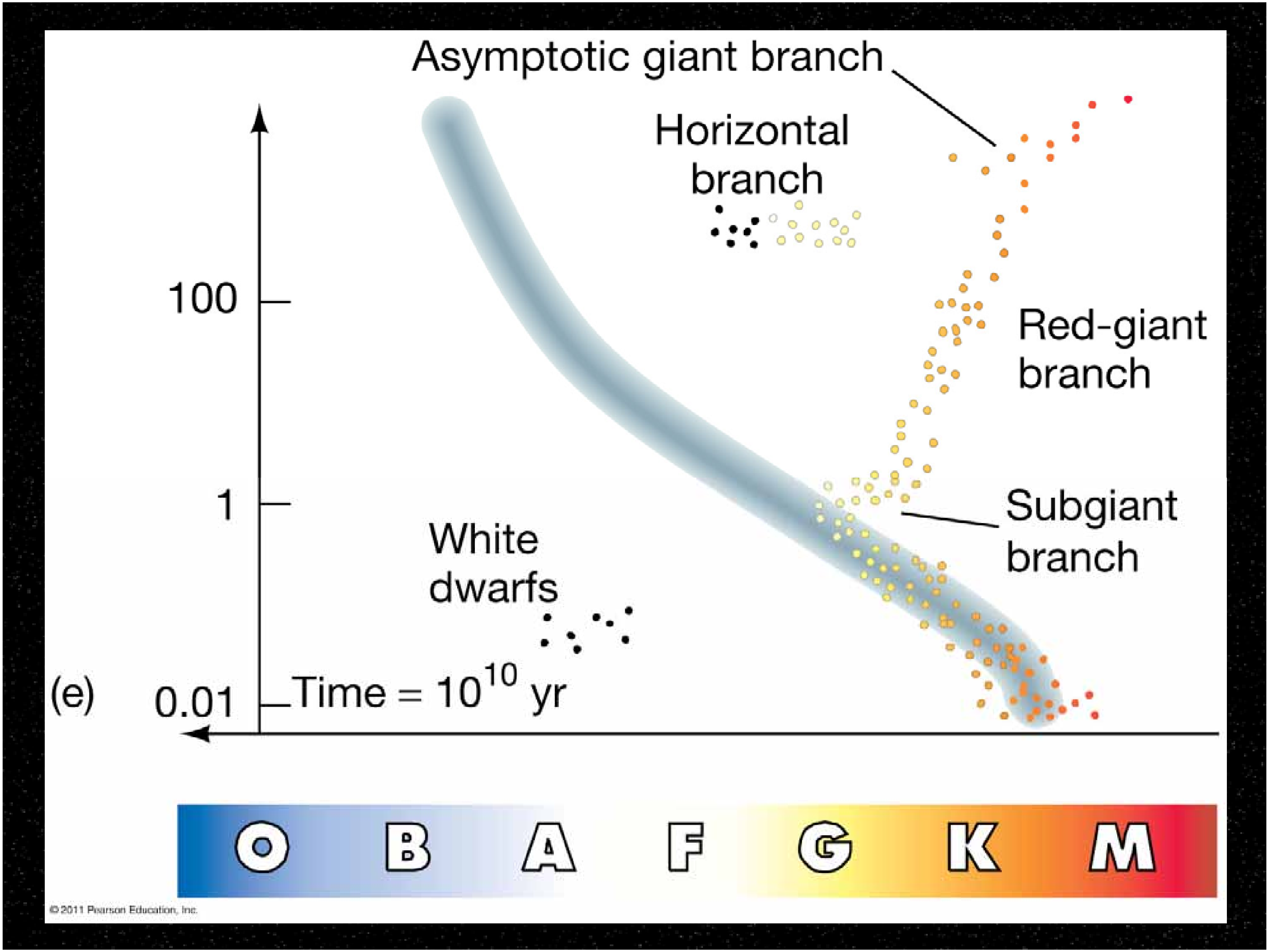


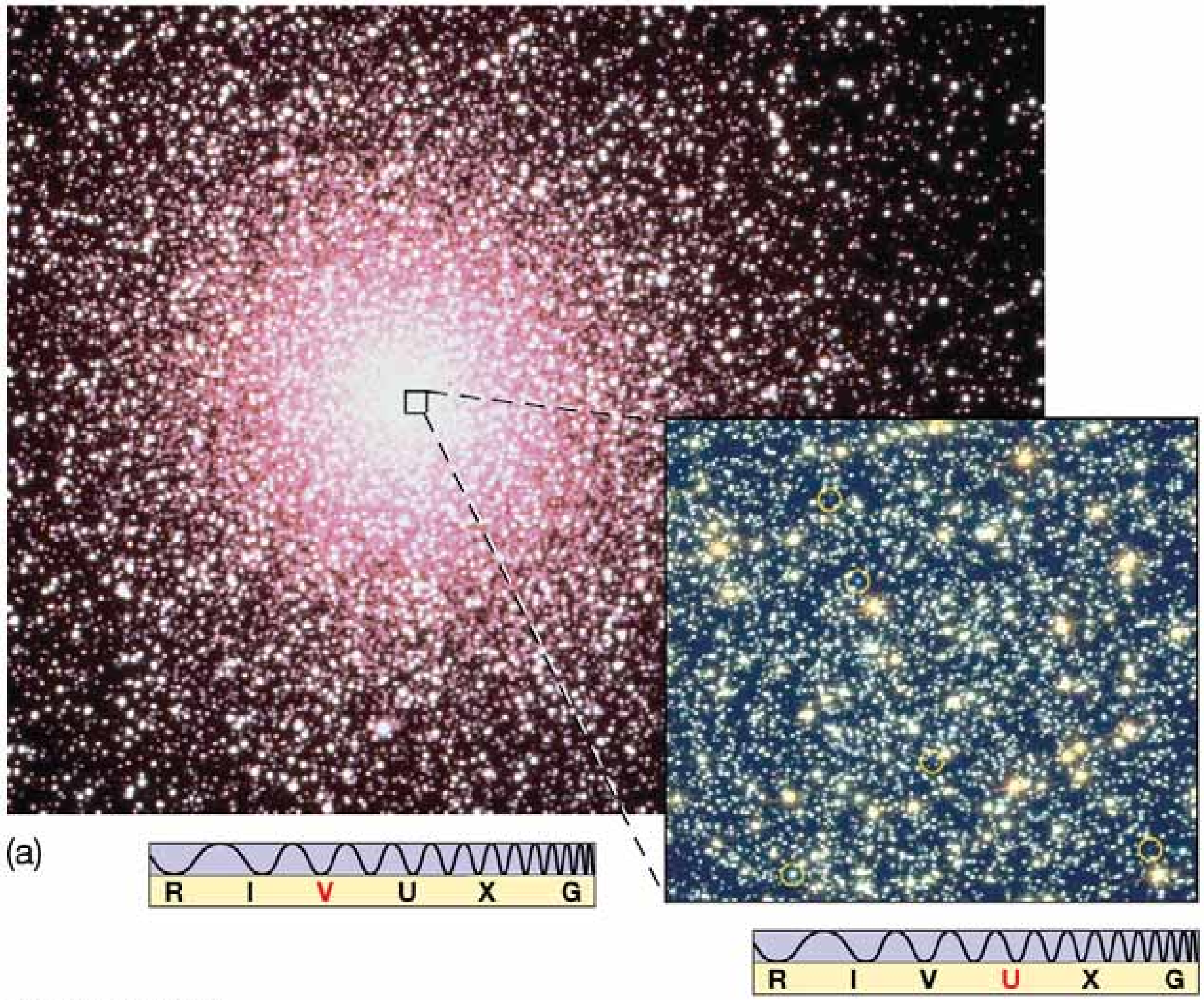
100
1
0.01
(a)
Time = 0
Zero-age main sequence

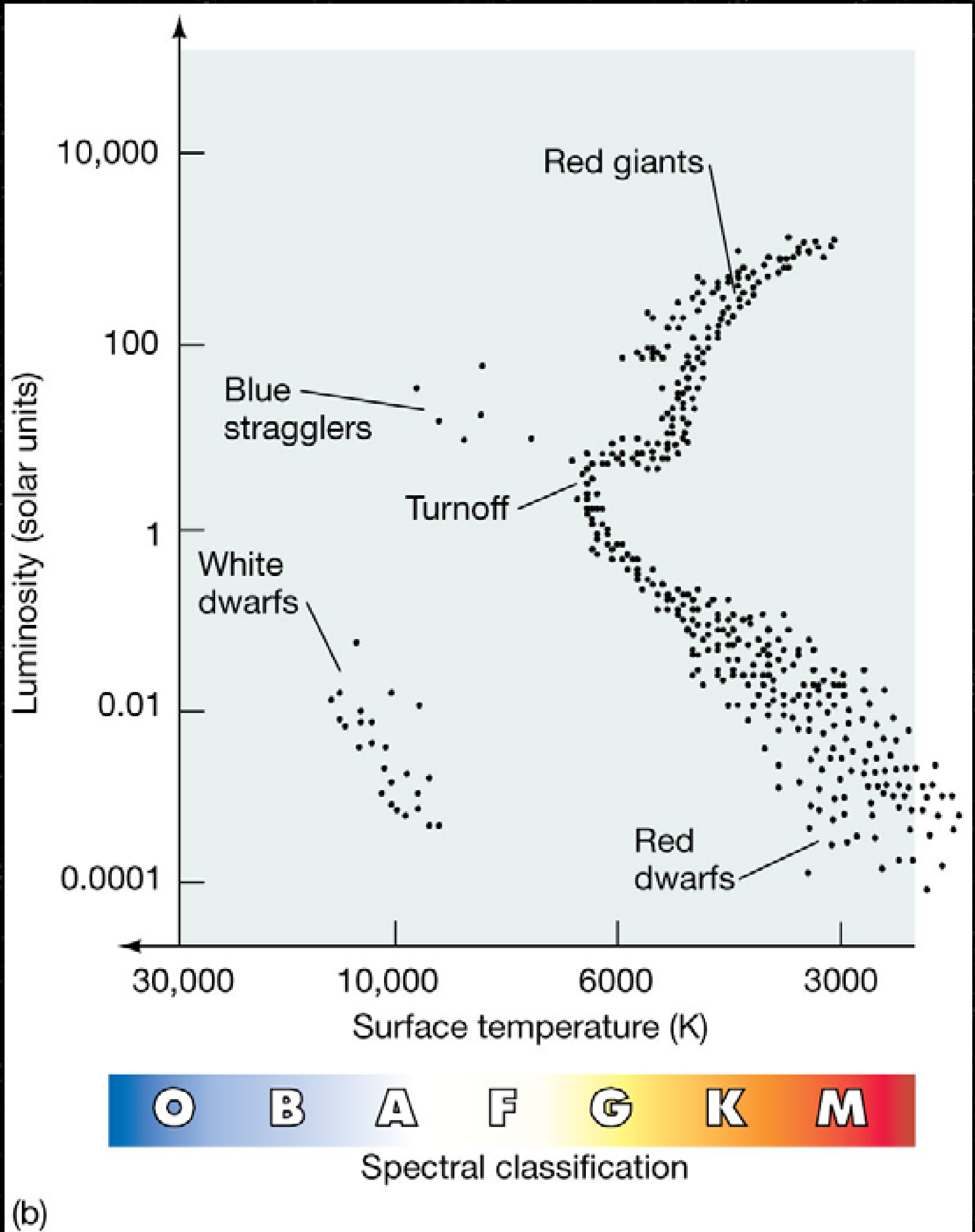

100
1
0.01
(b)
Time = 10^7 yr


Luminosity (solar units)
100
1
0.01
Main-sequence turnoff
(c)
Time = 10^8 yr


100
1
0.01
Main-
sequence
turnoff
(d)
Time = 10^9 yr


Asymptotic giant branch
Horizontal branch
100
Red-giant branch
1
Subgiant branch
White dwarfs
(e)
0.01
Time = 10^10 yr
O
B
A
F
G
K
M


(a)
R I V U X G
R I V U X G



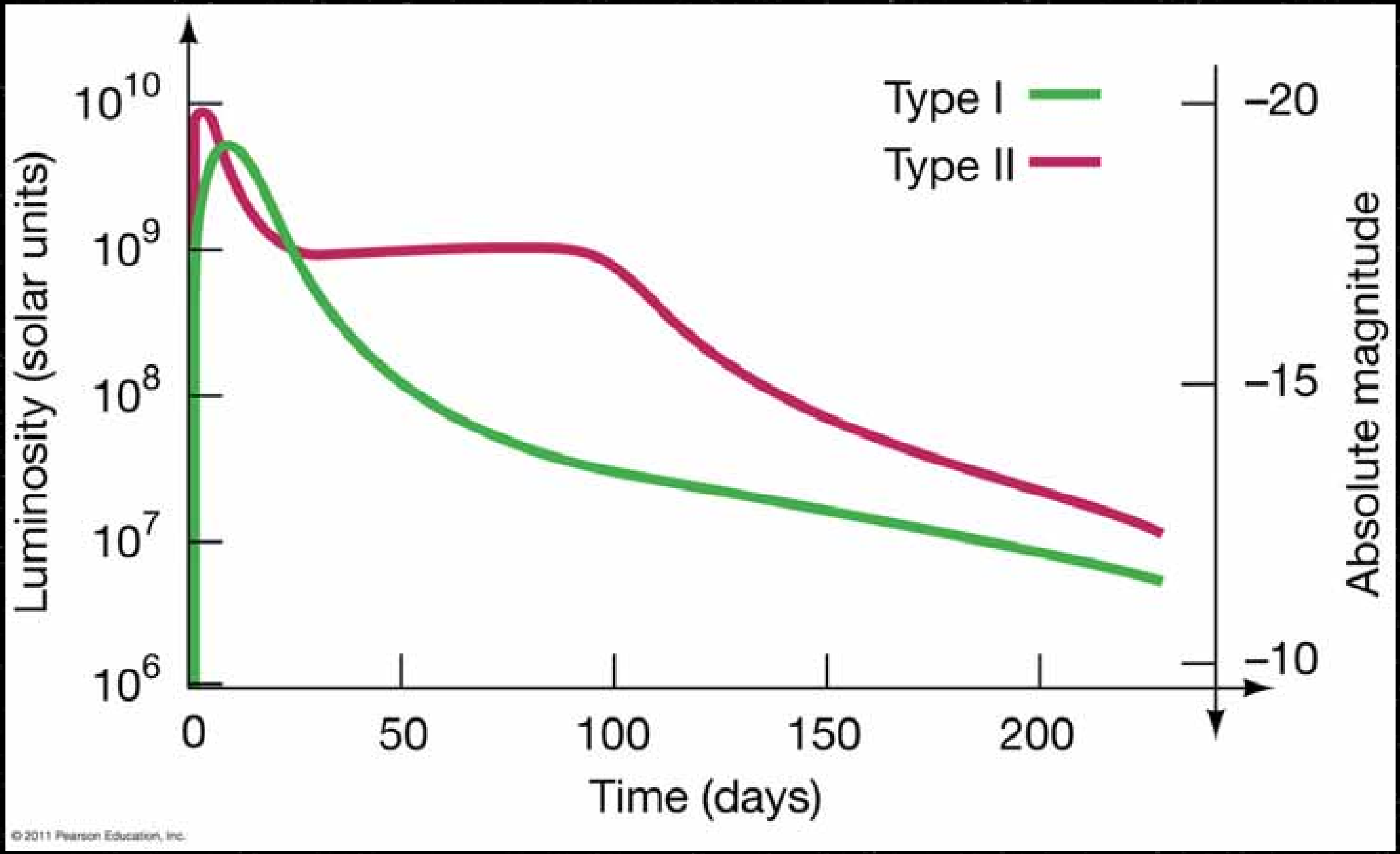
10,000
100
1
0.01
0.0001
Luminosity (solar units)
Red giants
Blue
stragglers
Turnoff
White
dwarfs
Red
dwarfs
30,000
10,000
6000
3000
Surface temperature (K)
O
B
A
F
G
K
M
Spectral classification
(b)

The Death of a Low-Mass Star

The "blue stragglers" in the previous H-R diagram are not exceptions to our model; they are stars that have formed much more recently, probably from the merger of smaller stars.

Supernovae

A supernova is incredibly luminous—as can be seen from these curves—and more than a million times as bright as a nova:



Supernovae

A supernova is a one-time event—once it happens, there is little or nothing left of the progenitor star.

There are two different types of supernovae, both equally common:

- Type I, which is a carbon-detonation supernova, and
- Type II, which is the death of a high-mass star just described

Supernovae

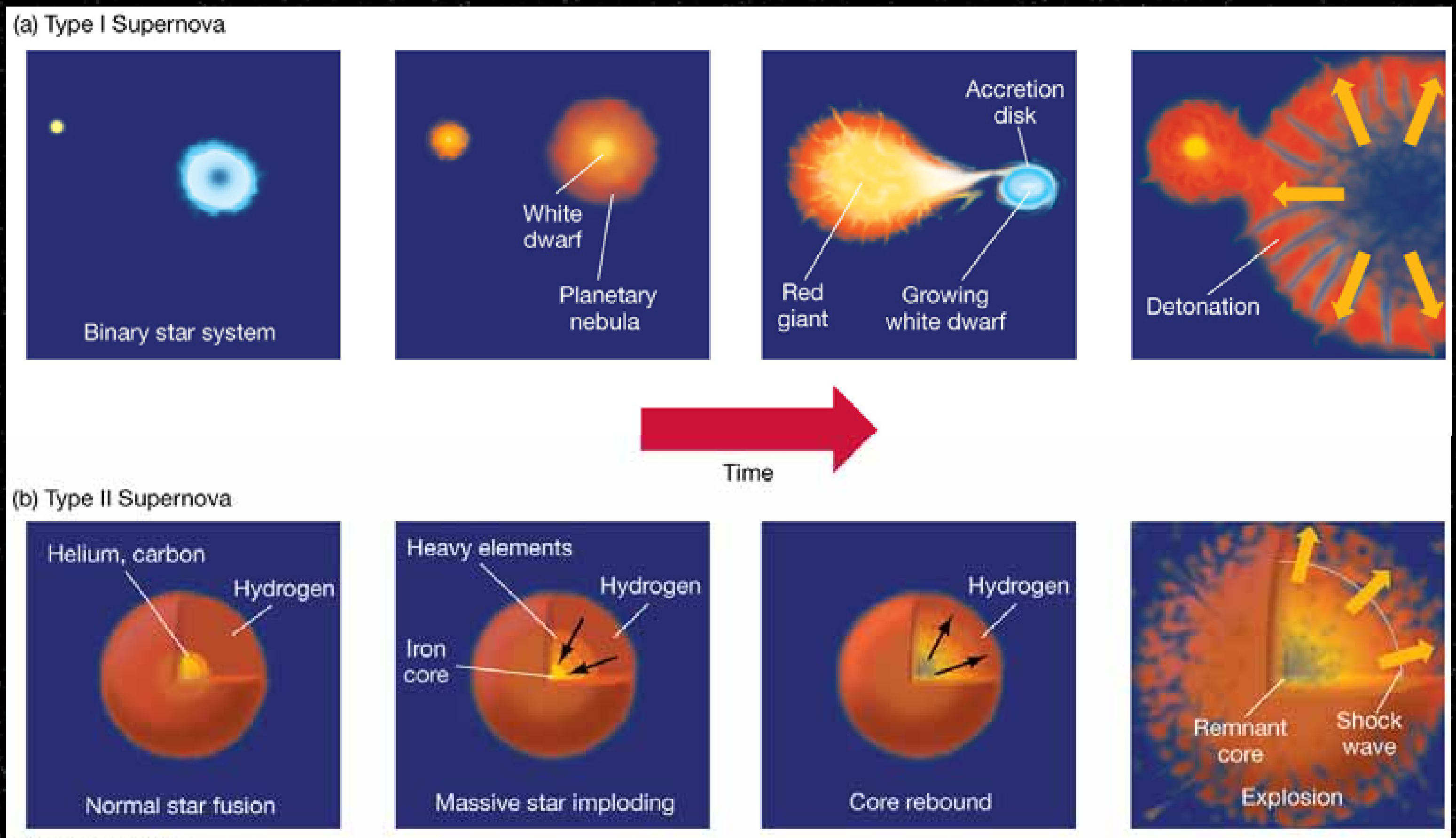
Carbon-detonation supernova: white dwarf that has accumulated too much mass from binary companion

If the white dwarf's mass exceeds 1.4 solar masses, electron degeneracy can no longer keep the core from collapsing.

Carbon fusion begins throughout the star almost simultaneously, resulting in a carbon explosion.

Supernovae

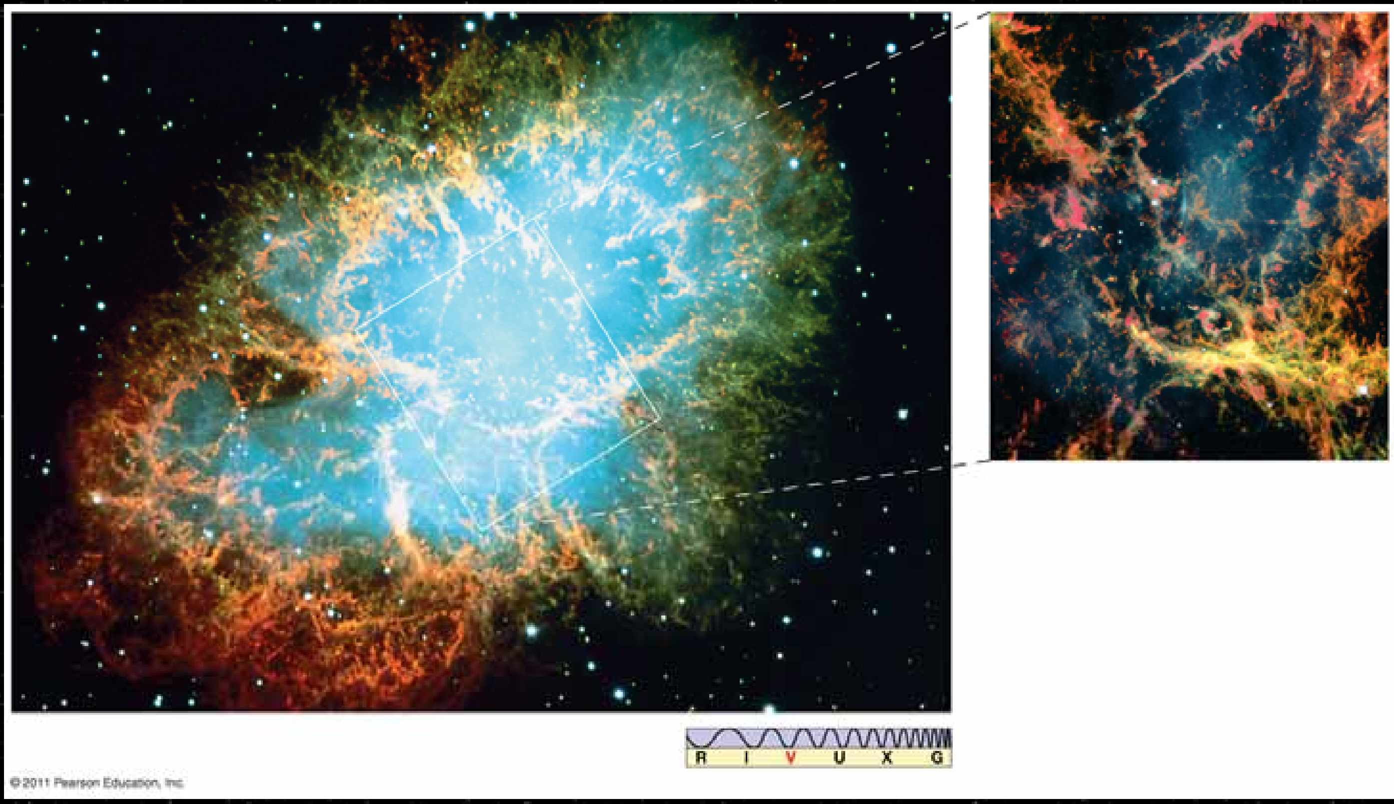
This graphic illustrates the two different types of supernovae:



Supernovae

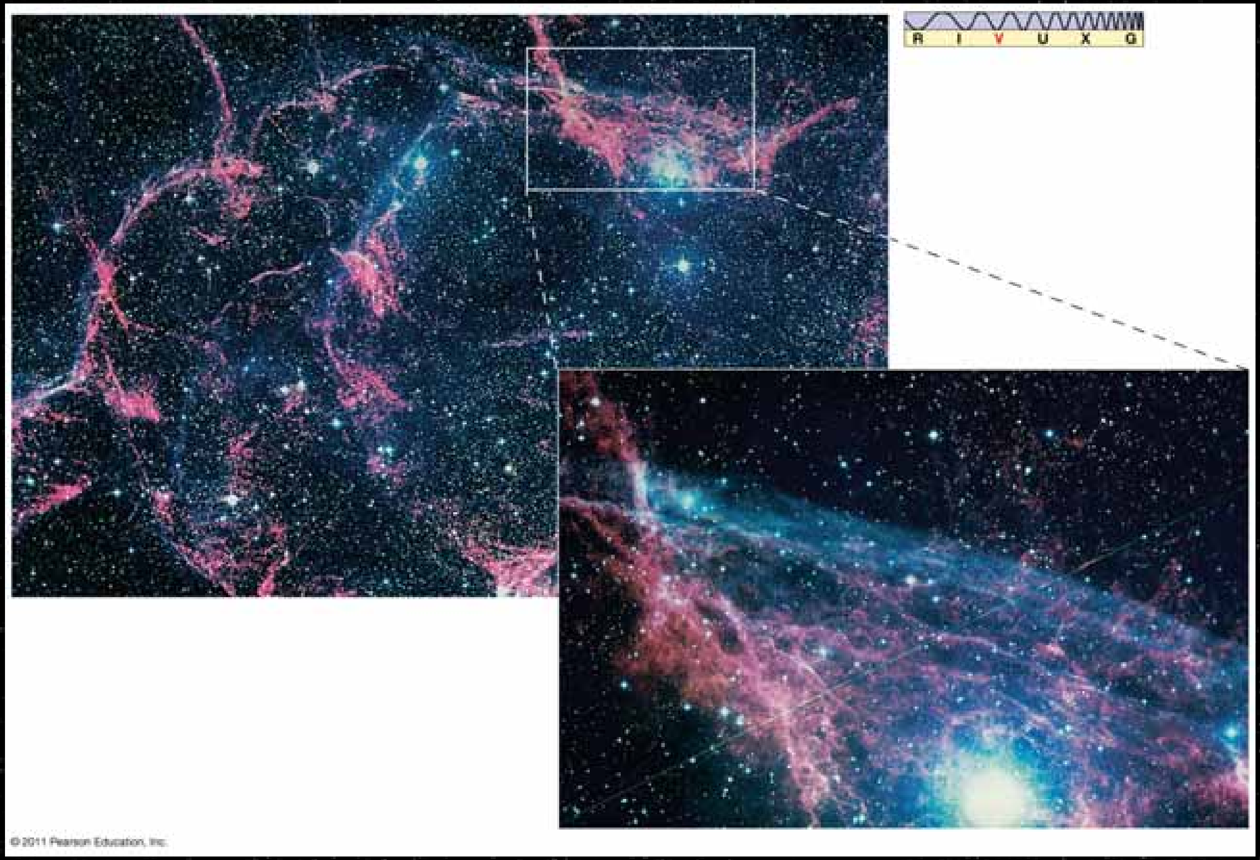
Supernovae leave remnants—the expanding clouds of material from the explosion.

The Crab nebula is a remnant from a supernova explosion that occurred in the year 1054.



Supernovae

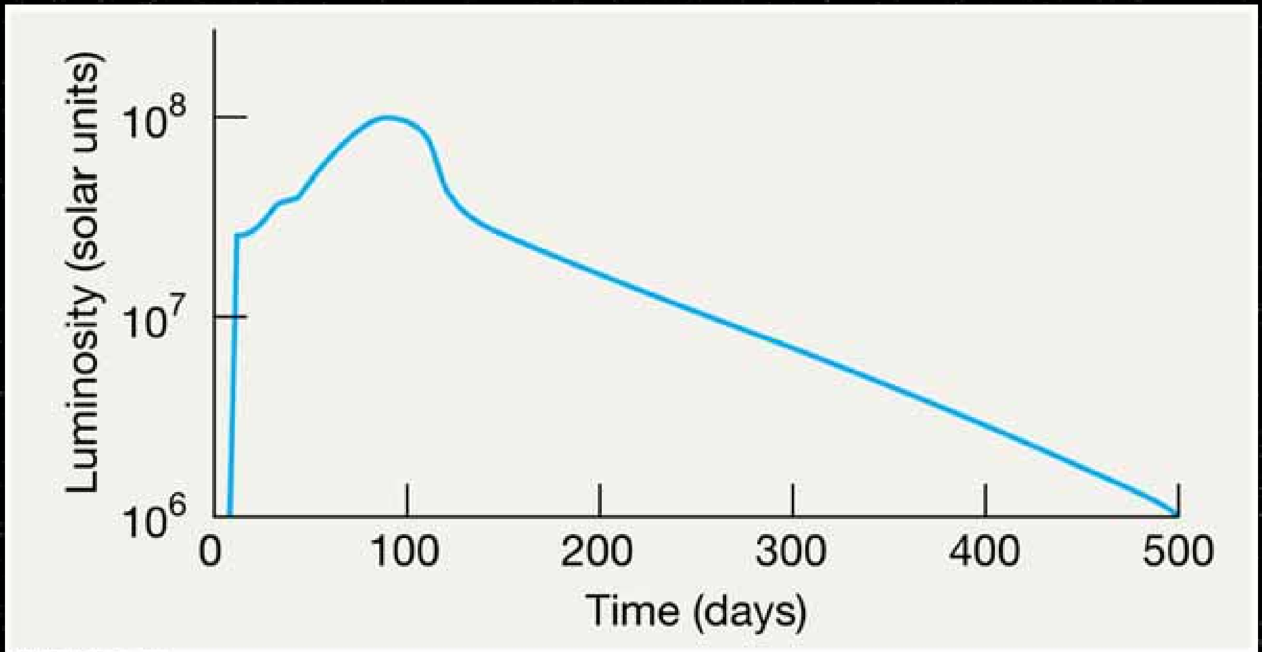
This is the Vela supernova remnant: Extrapolation shows it exploded about 9000 BCE



Supernova 1987A

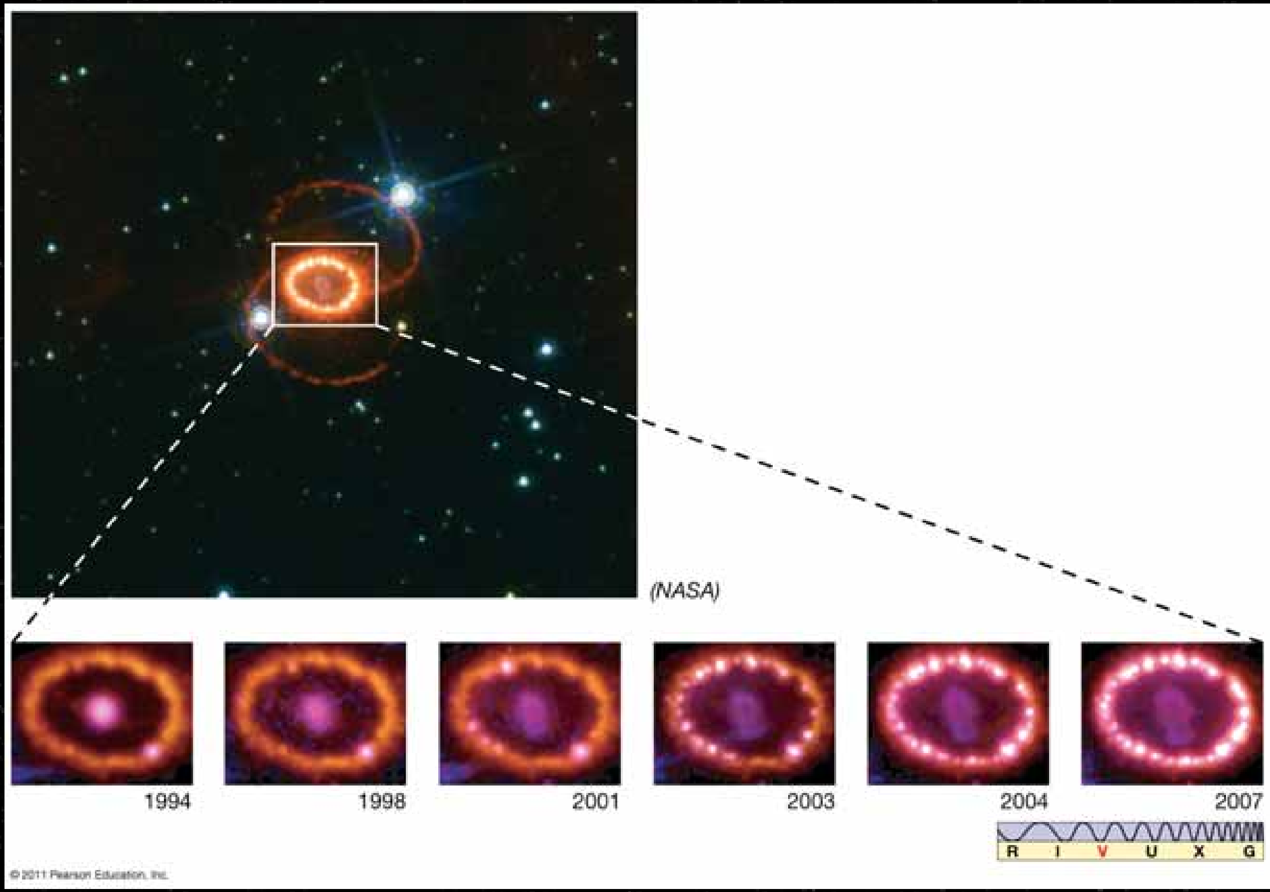
Supernovae are rare; there has not been one in our galaxy for about 400 years.

A supernova, called SN1987A, did occur in the Large Magellanic Cloud, a neighboring galaxy, in 1987. Its light curve is somewhat atypical:



Supernova 1987A

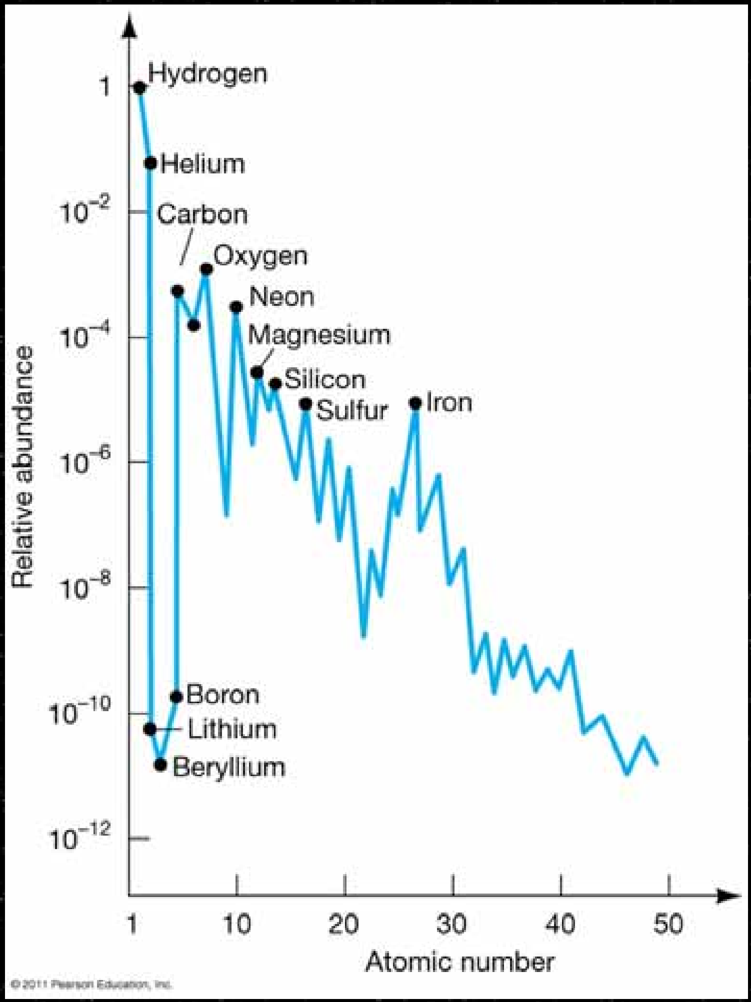
A cloud of glowing gas is now visible around SN1987A, and a small central object is becoming discernible:



The Formation of the Elements

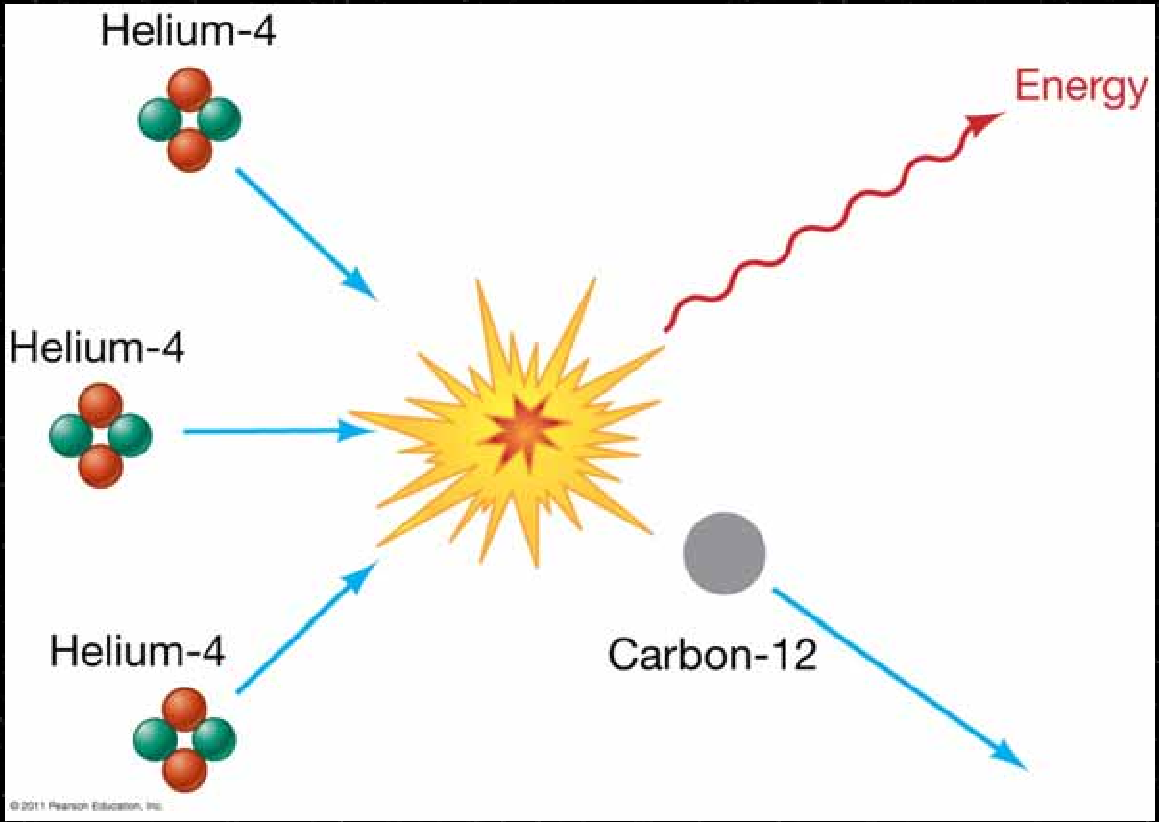
There are 81 stable and 10 radioactive elements that exist on our planet. Where did they come from?

This graph shows the relative abundances of different elements in the universe:



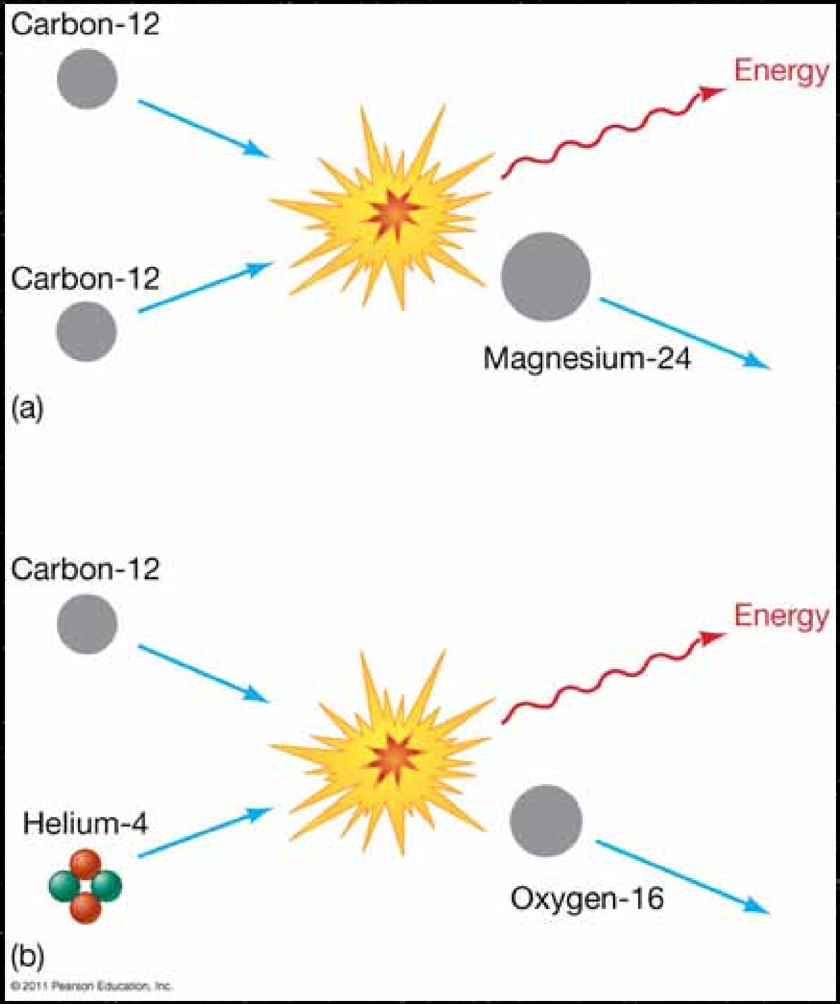
The Formation of the Elements

Some of these elements are formed during normal stellar fusion. Here, three helium nuclei fuse to form carbon:



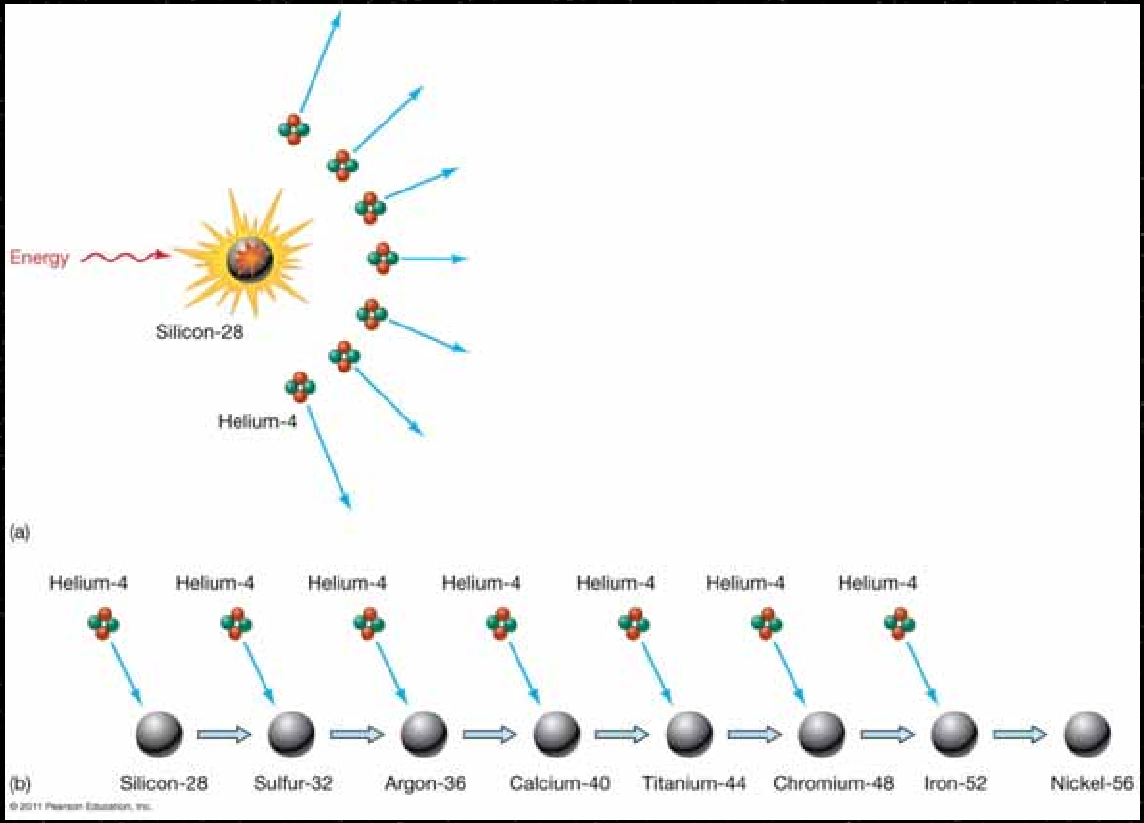
The Formation of the Elements

Carbon can then fuse, either with itself or with alpha particles, to form more nuclei:



The Formation of the Elements

The elements that can be formed through successive alpha-particle fusion are more abundant than those created by other fusion reactions:



The Formation of the Elements

The last nucleus in the alpha-particle chain is nickel-56, which is unstable and quickly decays to cobalt-56 and then to iron-56.

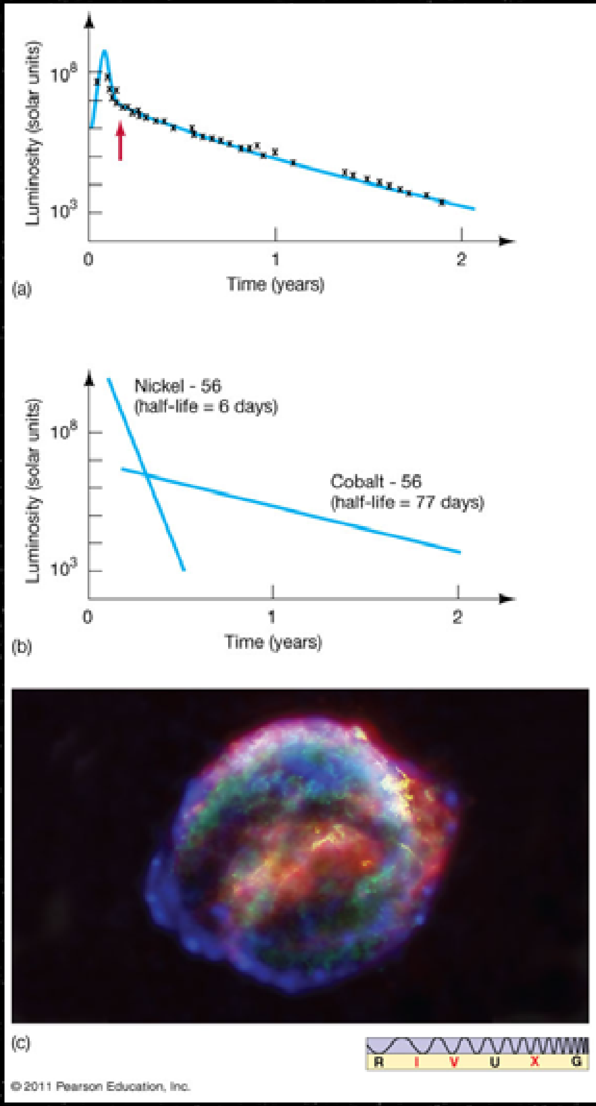
Iron-56 is the most stable nucleus, so it neither fuses nor decays.

However, within the cores of the most massive stars, neutron capture can create heavier elements, all the way up to bismuth-209.

The heaviest elements are made during the first few seconds of a supernova explosion.

The Formation of the Elements

This theory of formation of new elements in supernova explosions produces a light curve that agrees quite well with observed curves:



The Cycle of Stellar Evolution

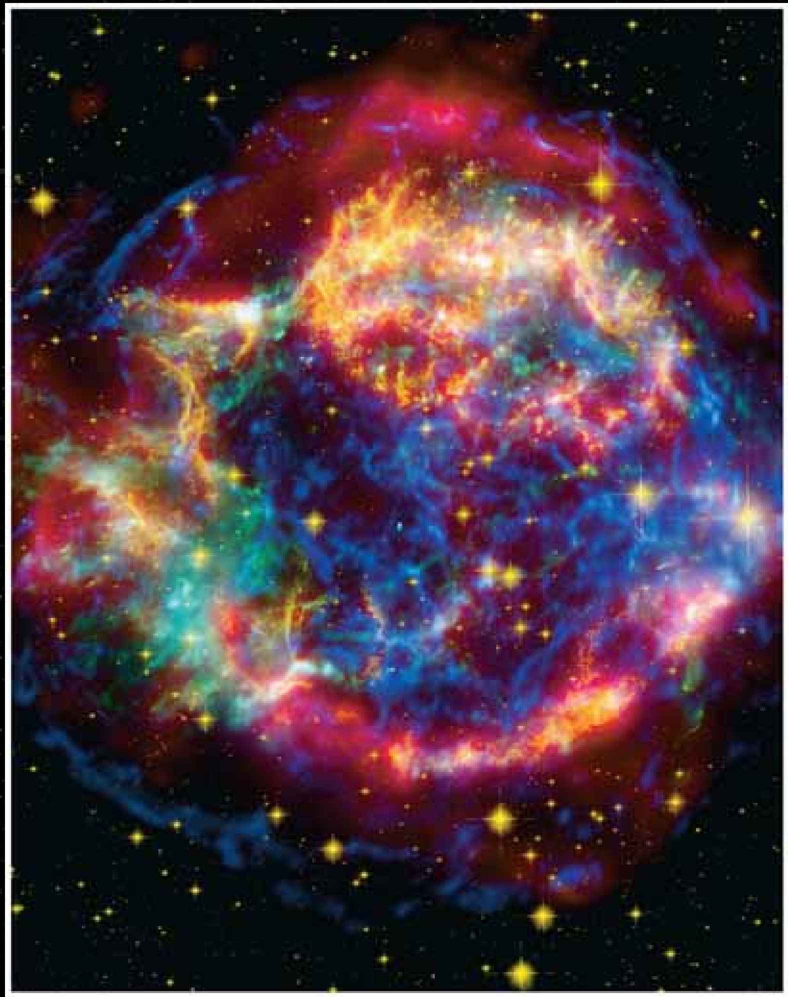
Star formation is cyclical: Stars form, evolve, and die.

In dying, they send heavy elements into the interstellar medium.

These elements then become parts of new stars.

And so it goes.

Neutron Stars and Black Holes



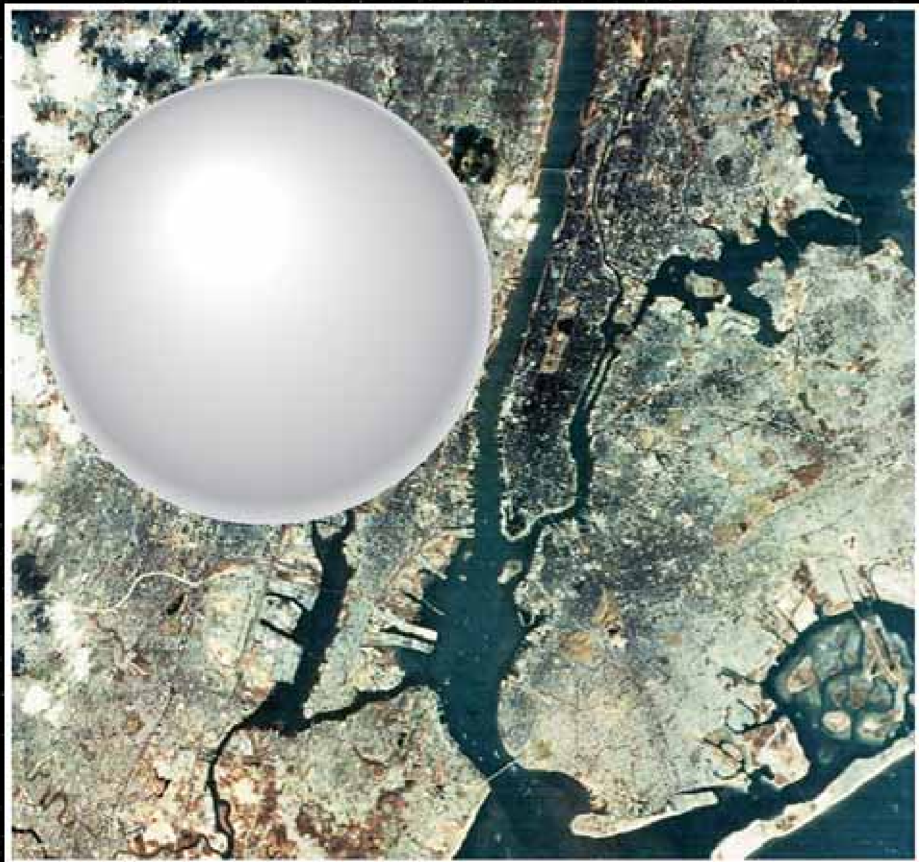
Neutron Stars

After a Type I supernova, little or nothing remains of the original star.

After a Type II supernova, part of the core may survive. It is very dense—as dense as an atomic nucleus—and is called a neutron star.

Neutron Stars

Neutron stars, although they have 1–3 solar masses, are so dense that they are very small. This image shows a 1-solar-mass neutron star, about 10 km in diameter, compared to Manhattan:



Neutron Stars

Other important properties of neutron stars (beyond mass and size):

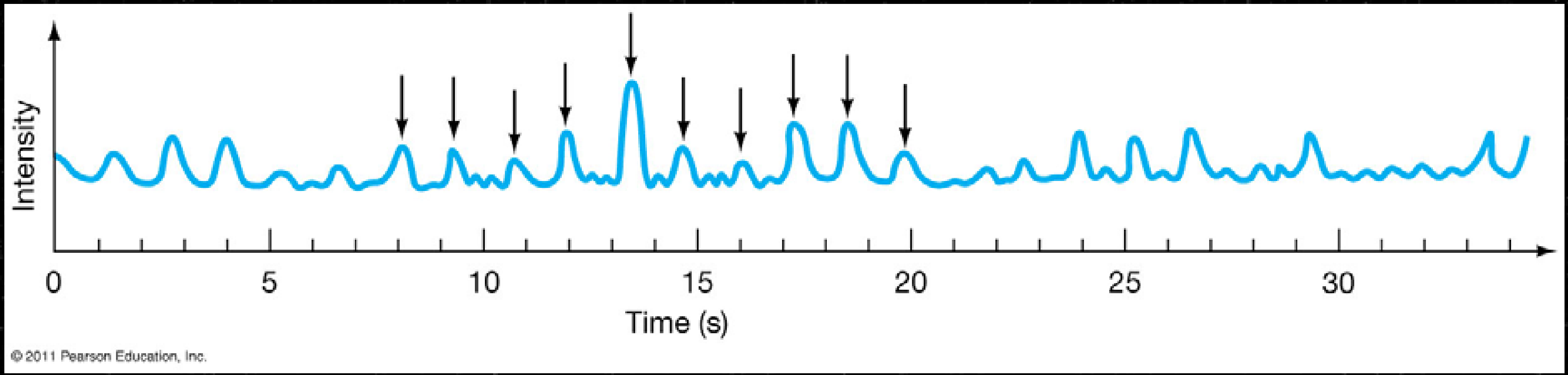
• Rotation—as the parent star collapses, the neutron core spins very rapidly, conserving angular momentum. Typical periods are fractions of a second.

• Magnetic field—again as a result of the collapse, the neutron star's magnetic field becomes enormously strong.

Pulsars

The first pulsar was discovered in 1967. It emitted extraordinarily regular pulses; nothing like it had ever been seen before.

After some initial confusion, it was realized that this was a neutron star, spinning very rapidly.

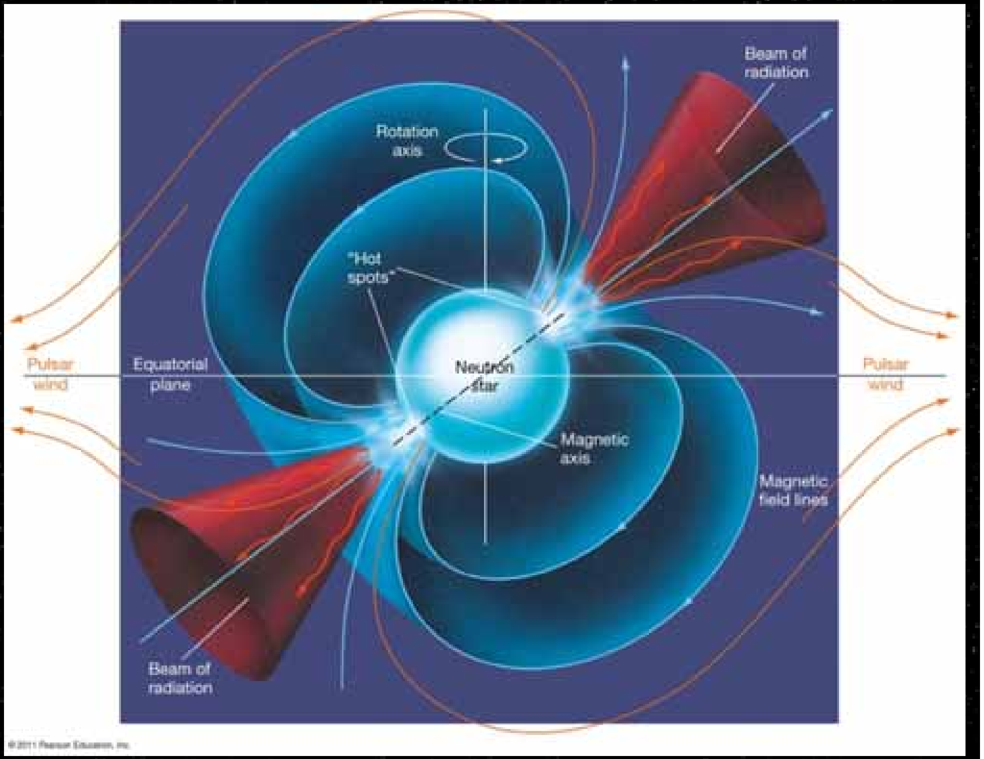


Pulsars

But why would a neutron star flash on and off?

This figure illustrates the lighthouse effect responsible:

Strong jets of matter are emitted at the magnetic poles. If the rotation axis is not the same as the magnetic axis, the two beams will sweep out circular paths. If the Earth lies in one of those paths, we will see the star pulse.



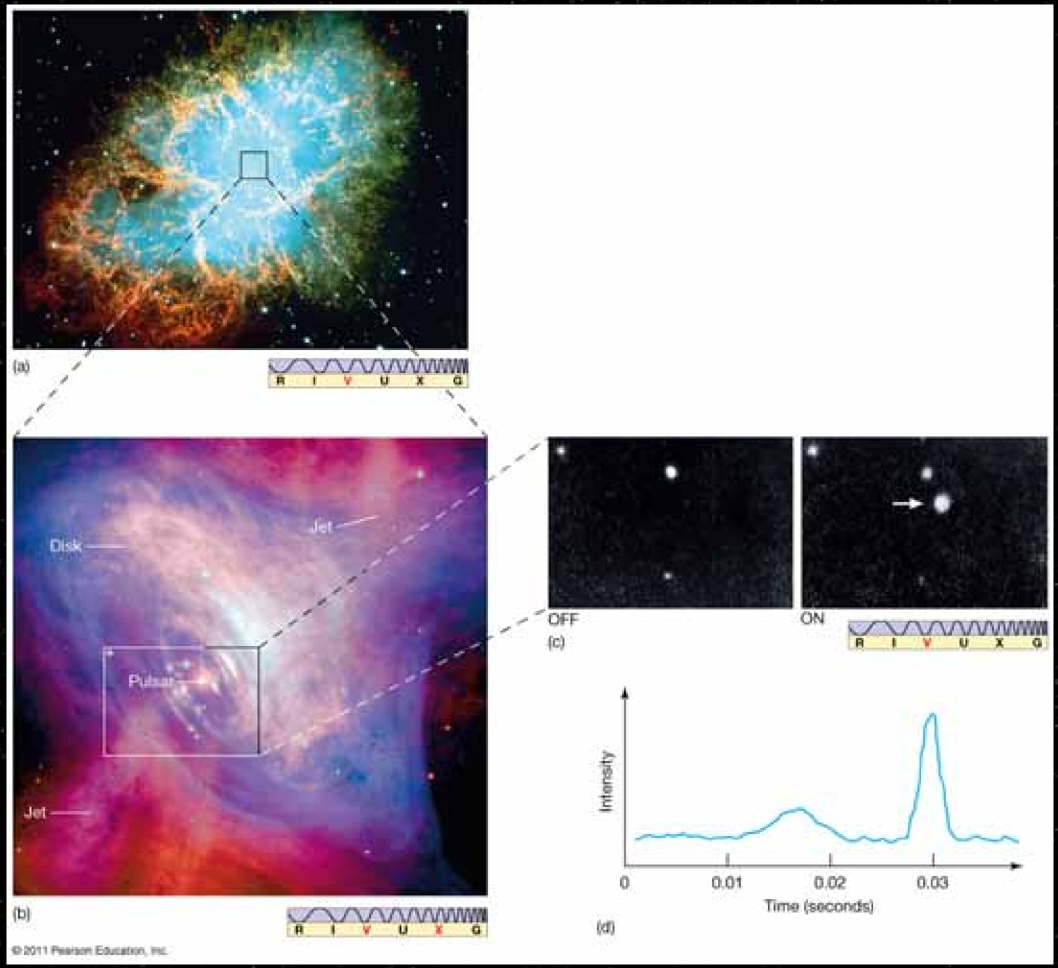
Pulsars

Pulsars radiate their energy away quite rapidly; the radiation weakens and stops in a few tens of millions of years, making the neutron star virtually undetectable.

Pulsars also will not be visible on Earth if their jets are not pointing our way.

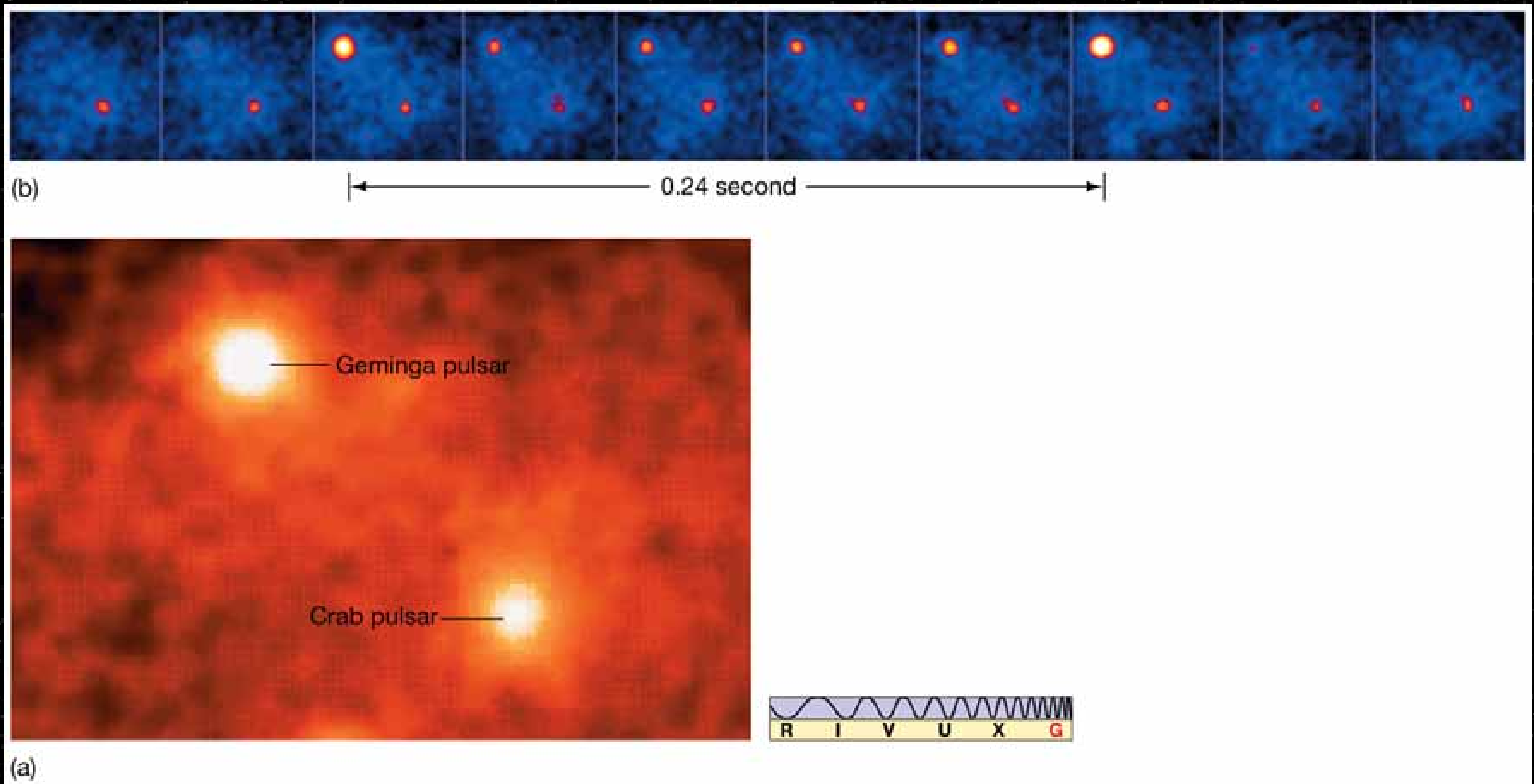
Pulsars

There is a pulsar at the center of the Crab Nebula; the images show it in the "off" and "on" states. The disk and jets are also visible:



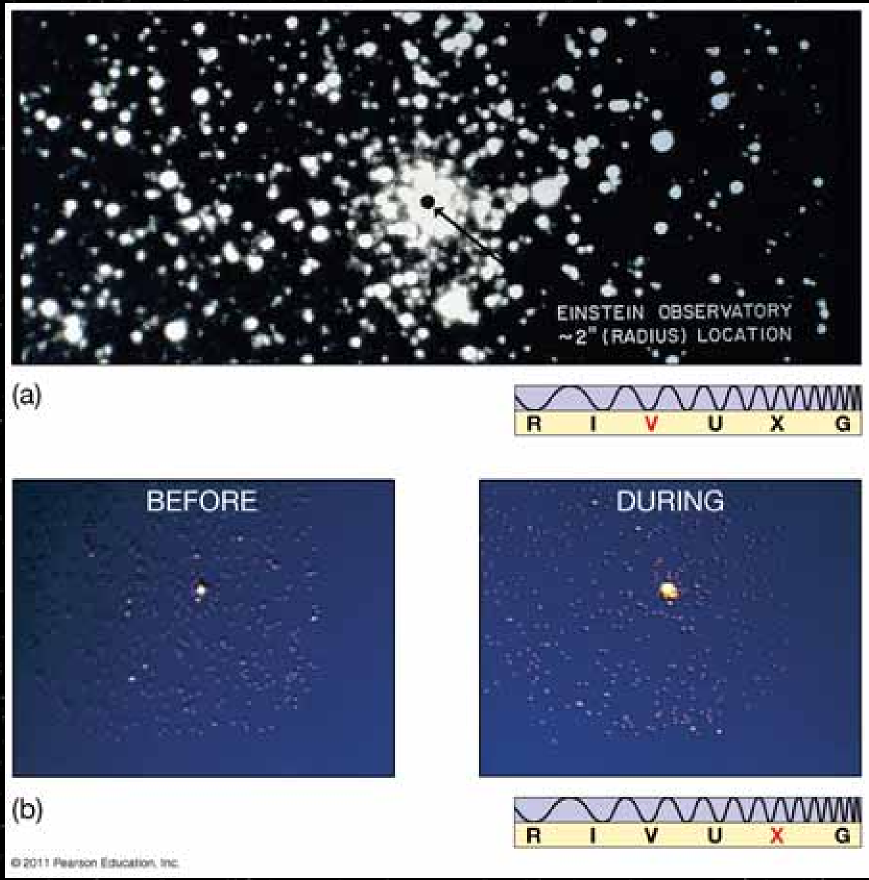
Pulsars

The Crab pulsar also pulses in the gamma-ray spectrum:



Neutron-Star Binaries

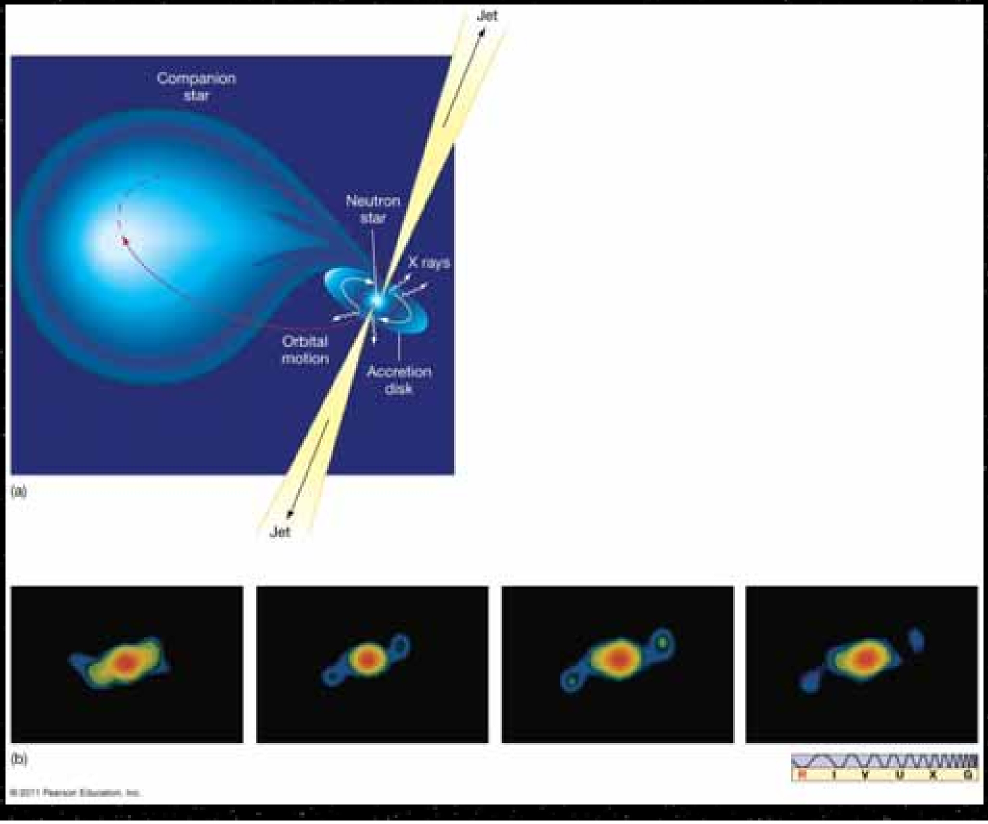
Bursts of X-rays have been observed near the center of our galaxy. A typical one appears below, as imaged in the X-ray spectrum:



Neutron-Star Binaries

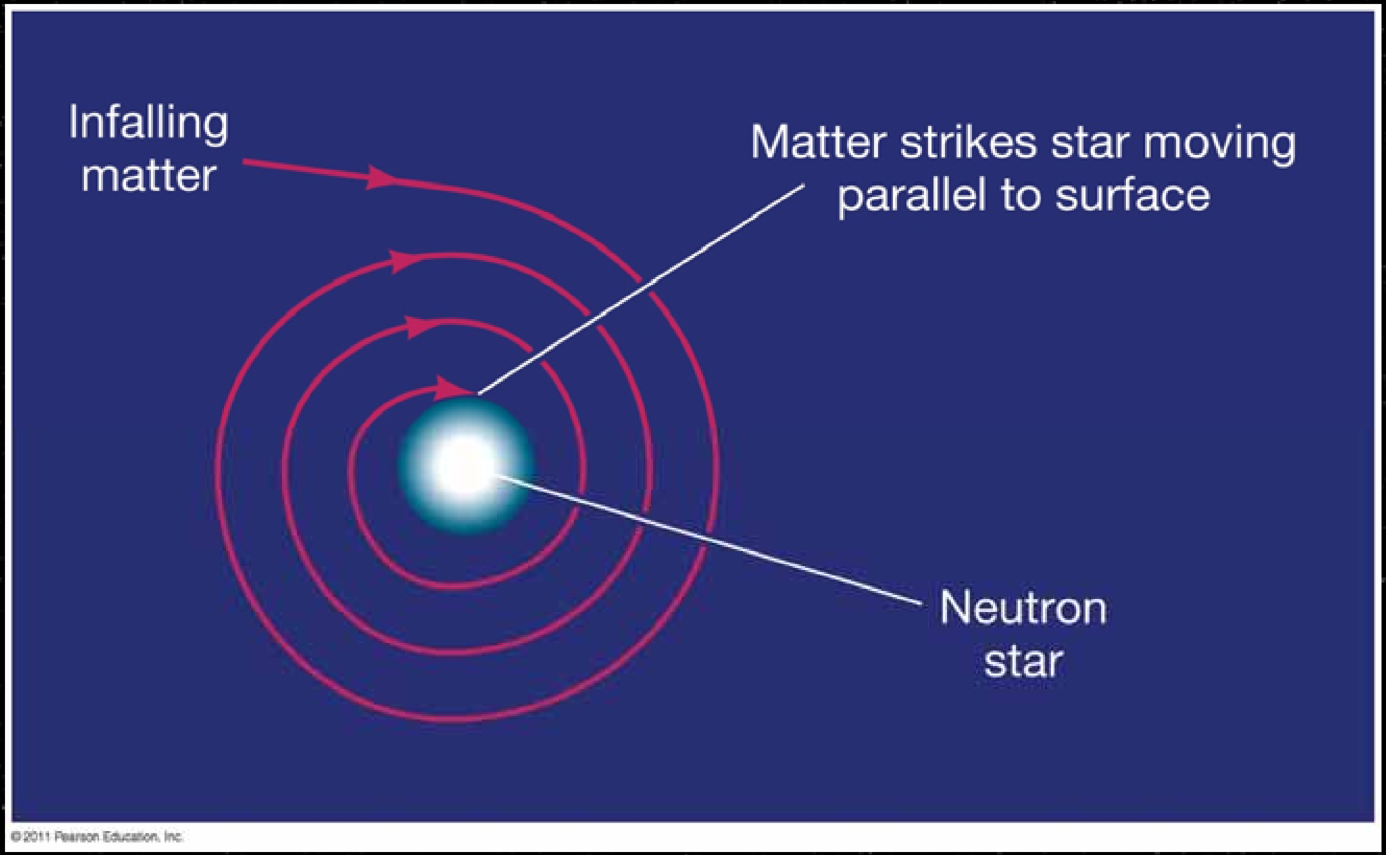
These X-ray bursts are thought to originate on neutron stars that have binary partners.

The process is similar to a nova, but much more energy is emitted due to the extremely strong gravitational field of the neutron star.



Neutron-Star Binaries

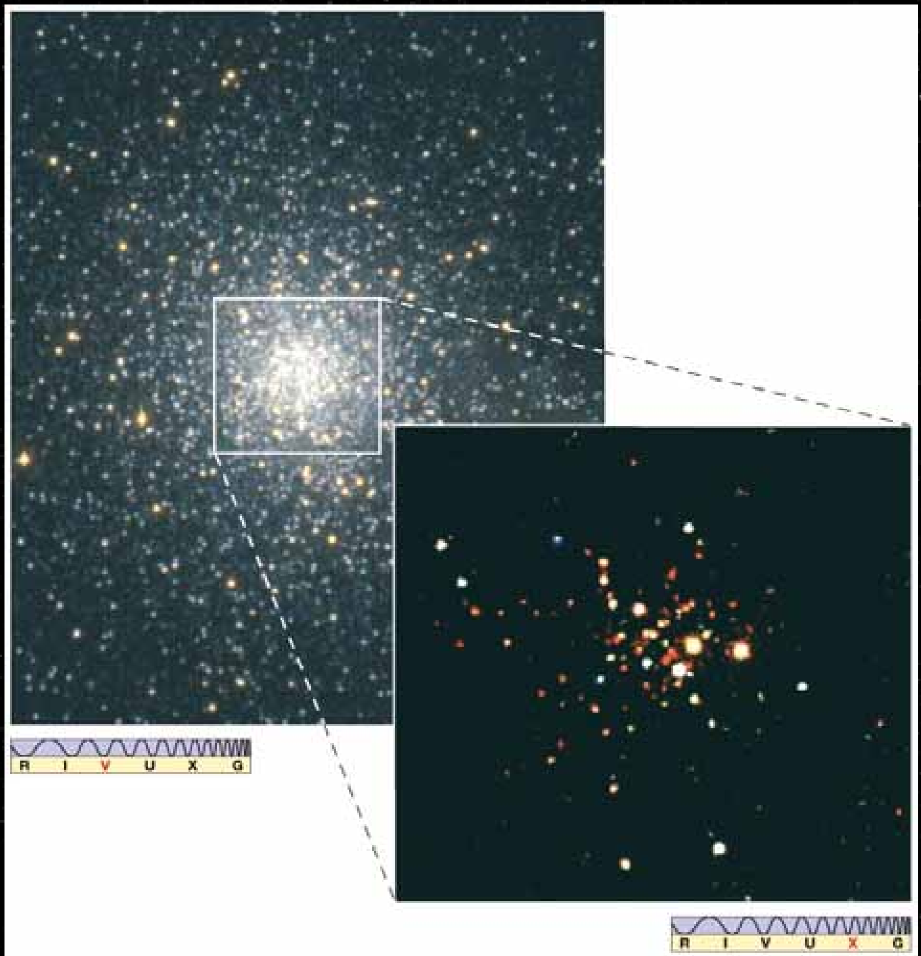
Most pulsars have periods between 0.03 and 0.3 seconds, but a new class of pulsar was discovered in the early 1980s: the millisecond pulsar.



Neutron-Star Binaries

Millisecond pulsars are thought to be "spun-up" by matter falling in from a companion.

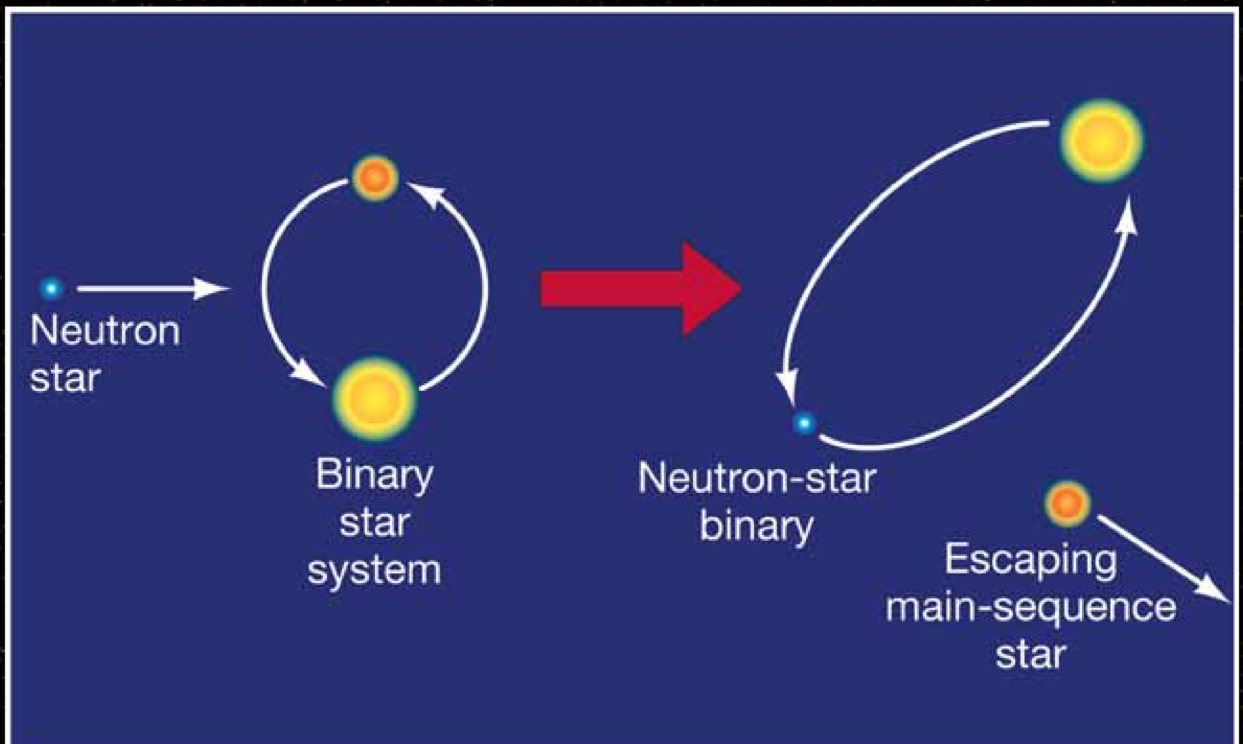
This globular cluster has been found to have 108 separate X-ray sources, about half of which are thought to be millisecond pulsars:



Neutron-Star Binaries

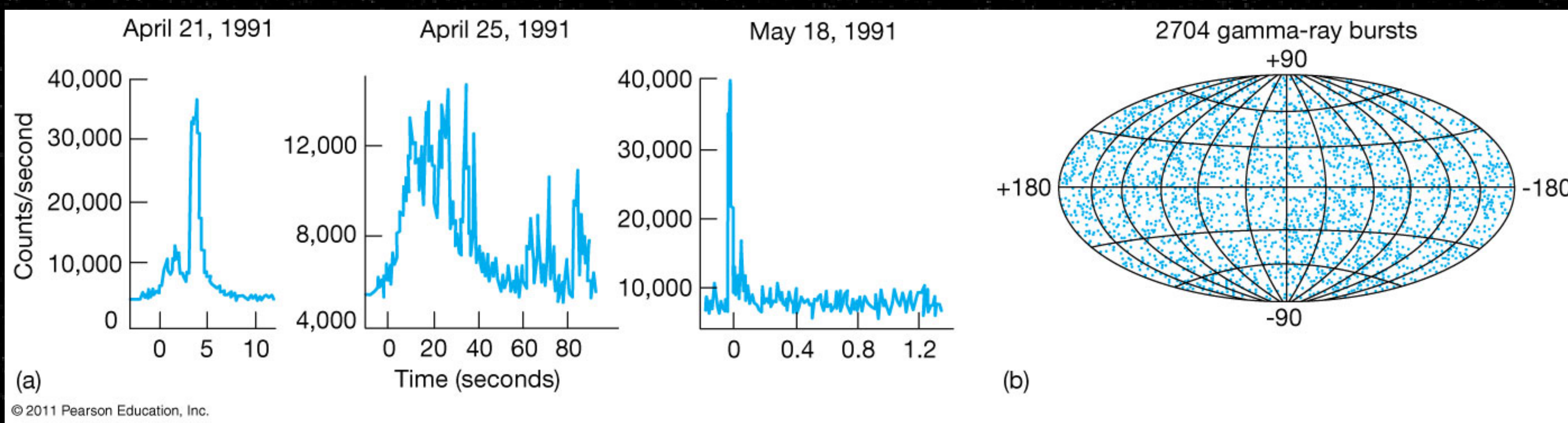
In 1992, a pulsar was discovered whose period had unexpected, but very regular, variations.

These variations were thought to be consistent with a planet, which must have been picked up by the neutron star, not the progenitor star:



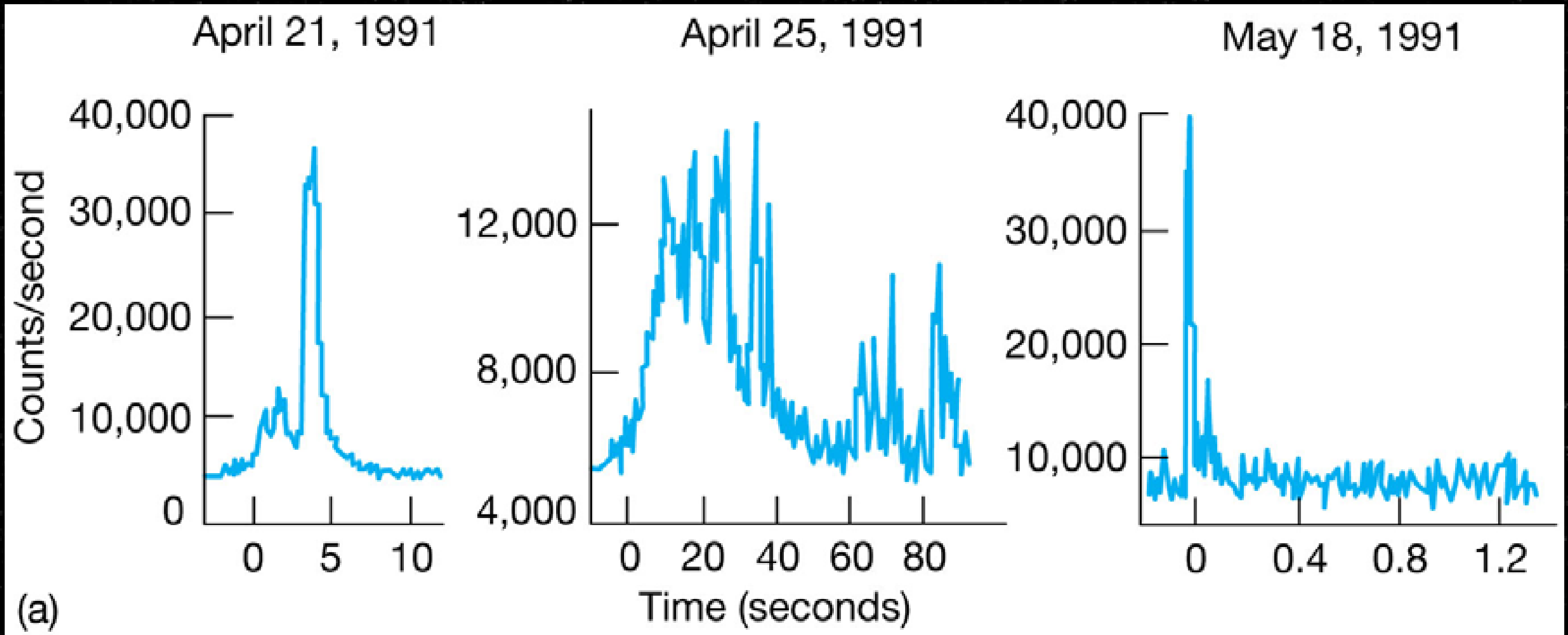
Gamma-Ray Bursts

Gamma-ray bursts also occur, and were first spotted by satellites looking for violations of nuclear test-ban treaties. This map of where the bursts have been observed shows no "clumping" of bursts anywhere, particularly not within the Milky Way. Therefore, the bursts must originate from outside our Galaxy.



Gamma-Ray Bursts

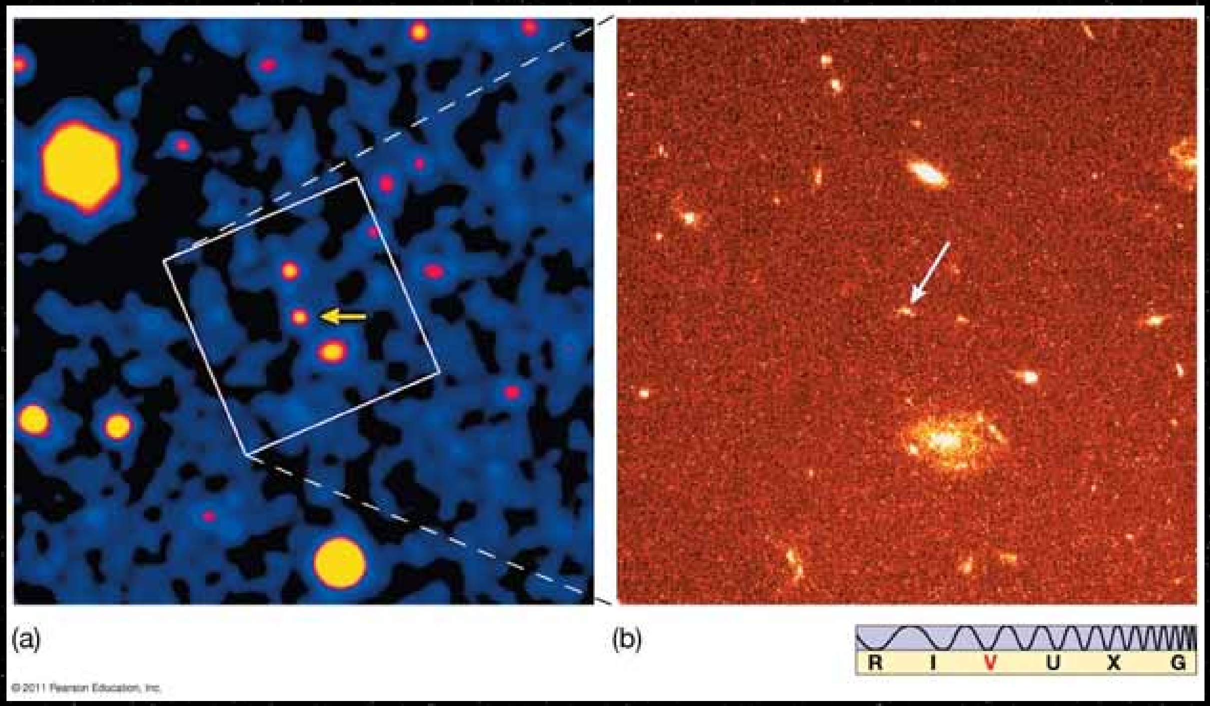
These are some sample luminosity curves for gamma-ray bursts:



Gamma-Ray Bursts

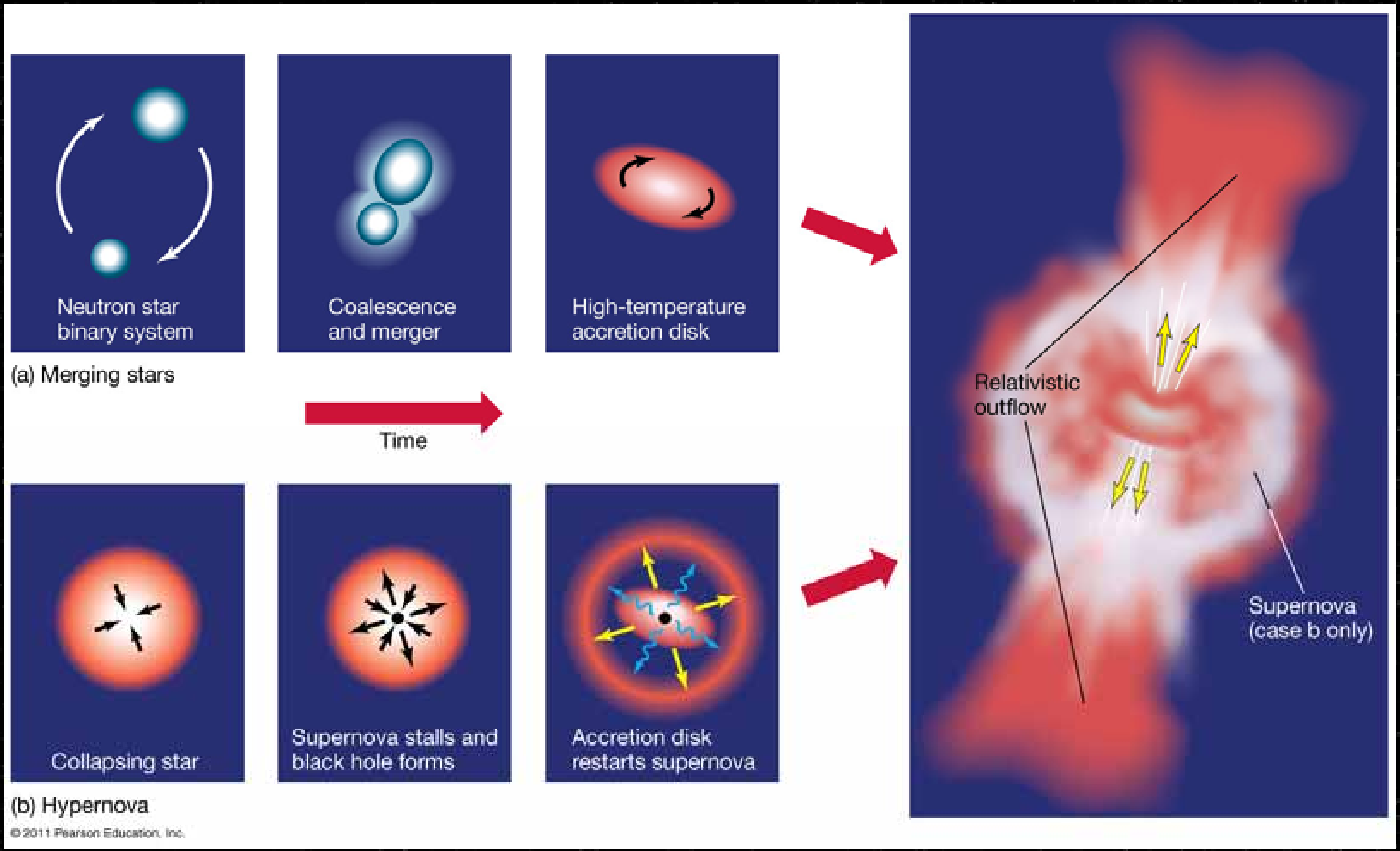
Distance measurements of some gamma bursts show them to be very far away—2 billion parsecs for the first one measured.

Occasionally the spectrum of a burst can be measured, allowing distance determination:



Gamma-Ray Bursts

Two models—merging neutron stars or a hypernova—have been proposed as the source of gamma-ray bursts:



Black Holes

The mass of a neutron star cannot exceed about 3 solar masses. If a core remnant is more massive than that, nothing will stop its collapse, and it will become smaller and smaller and denser and denser.

Eventually, the gravitational force is so intense that even light cannot escape. The remnant has become a black hole.

Black Holes

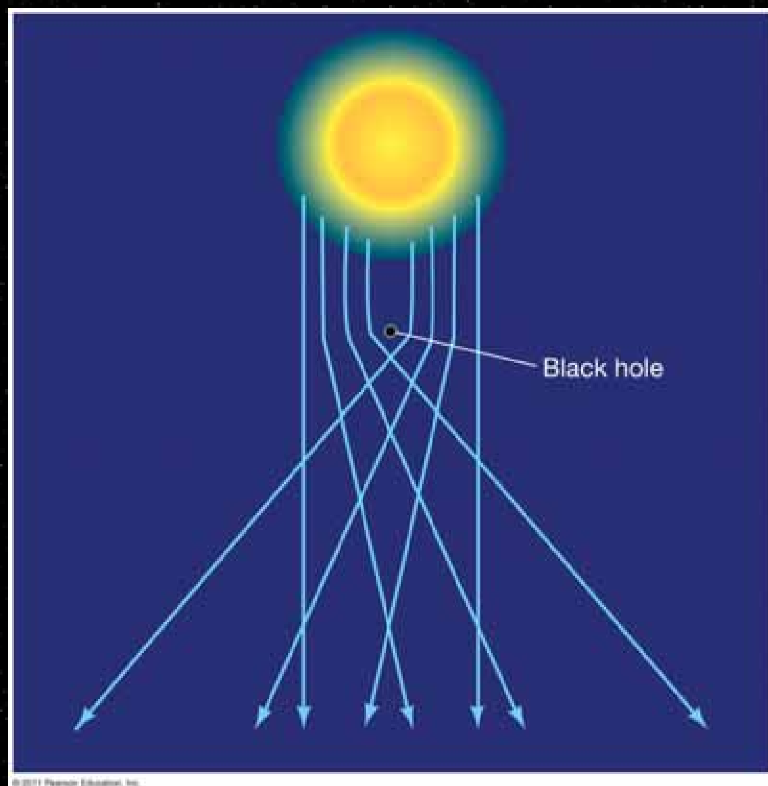
The radius at which the escape speed from the black hole equals the speed of light is called the Schwarzschild radius.

The Earth's Schwarzschild radius is about a centimeter; the Sun's is about 3 km.

Once the black hole has collapsed, the Schwarzschild radius takes on another meaning—it is the event horizon. Nothing within the event horizon can escape the black hole.

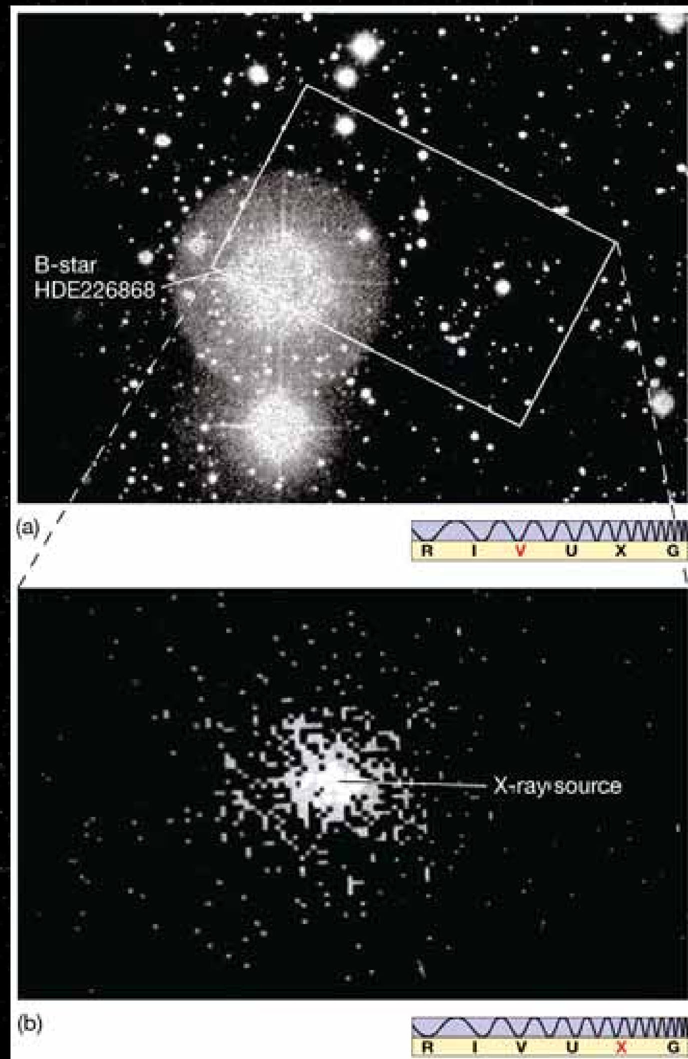
Observational Evidence for Black Holes

Black holes cannot be observed directly, as their gravitational fields will cause light to bend around them.



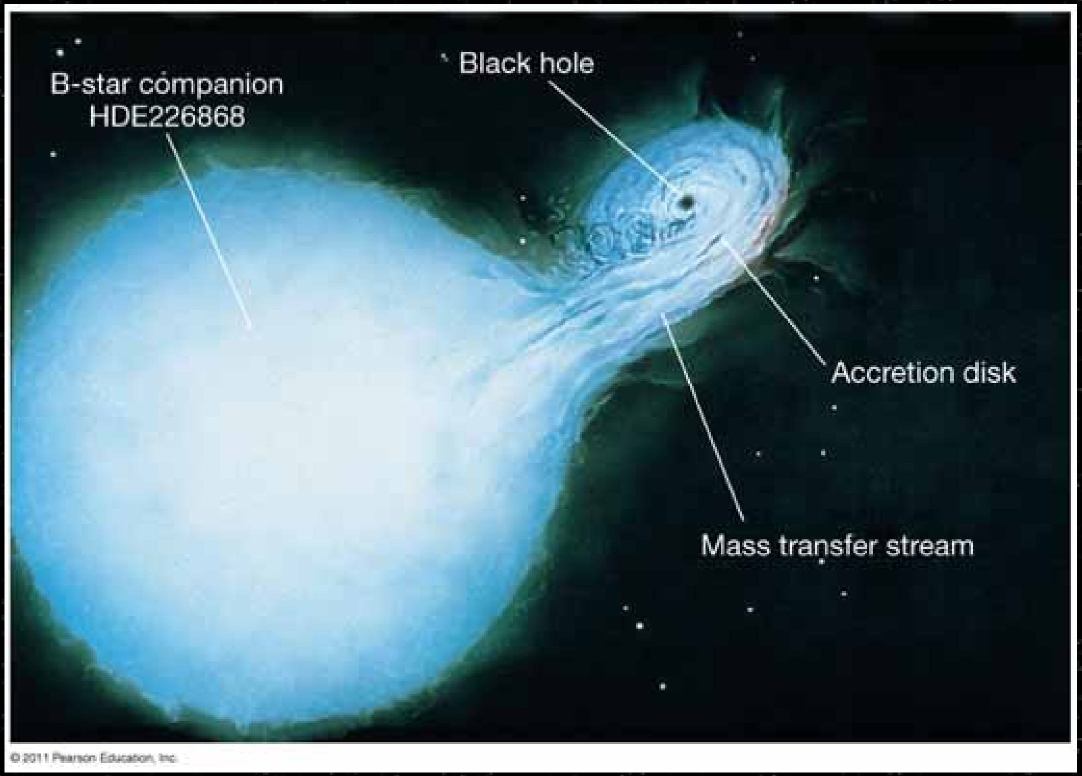
Observational Evidence for Black Holes

This bright star has an unseen companion that is a strong X-ray emitter called Cygnus X-1, which is thought to be a black hole:



22.8 Observational Evidence for Black Holes

The existence of black-hole binary partners for ordinary stars can be inferred by the effect the holes have on the star's orbit, or by radiation from infalling matter.



Observational Evidence for Black Holes

Cygnus X-1 is a very strong black-hole candidate:

• Its visible partner is about 25 solar masses.

• The system's total mass is about 35 solar masses, so the X-ray source must be about 10 solar masses.

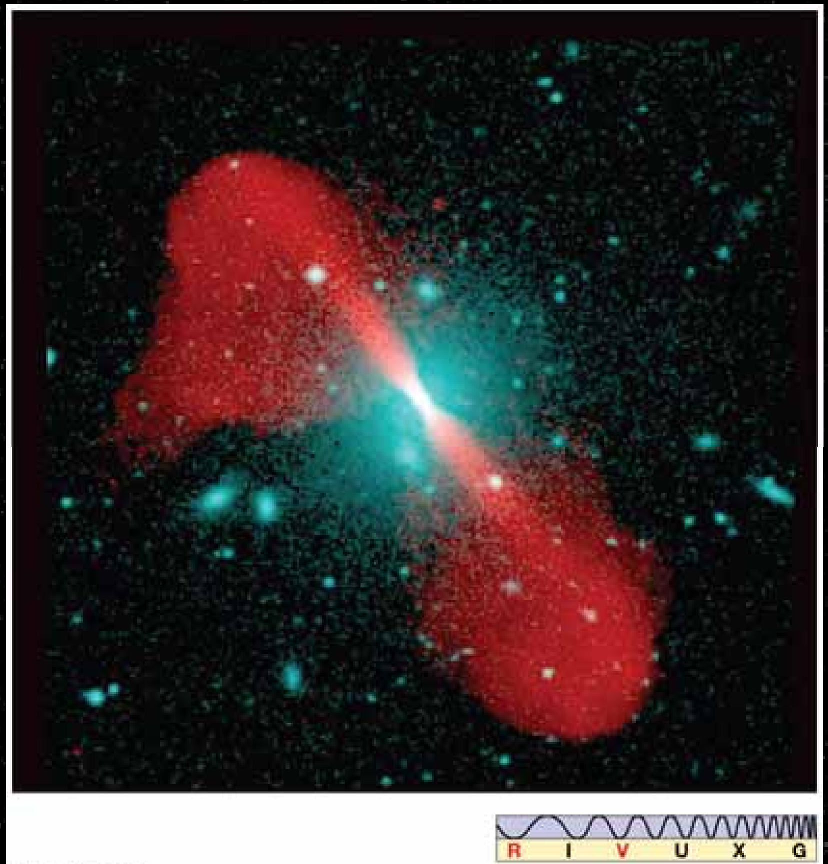
• Hot gas appears to be flowing from the visible star to an unseen companion.

• Short time-scale variations indicate that the source must be very small.

Observational Evidence for Black Holes

There are several other black-hole candidates as well, with characteristics similar to those of Cygnus X-1.

The centers of many galaxies contain supermassive black holes—about 1 million solar masses.



Observational Evidence for Black Holes

Recently, evidence for intermediate-mass black holes has been found; these are about 100 to 1000 solar masses. Their origin is not well understood.