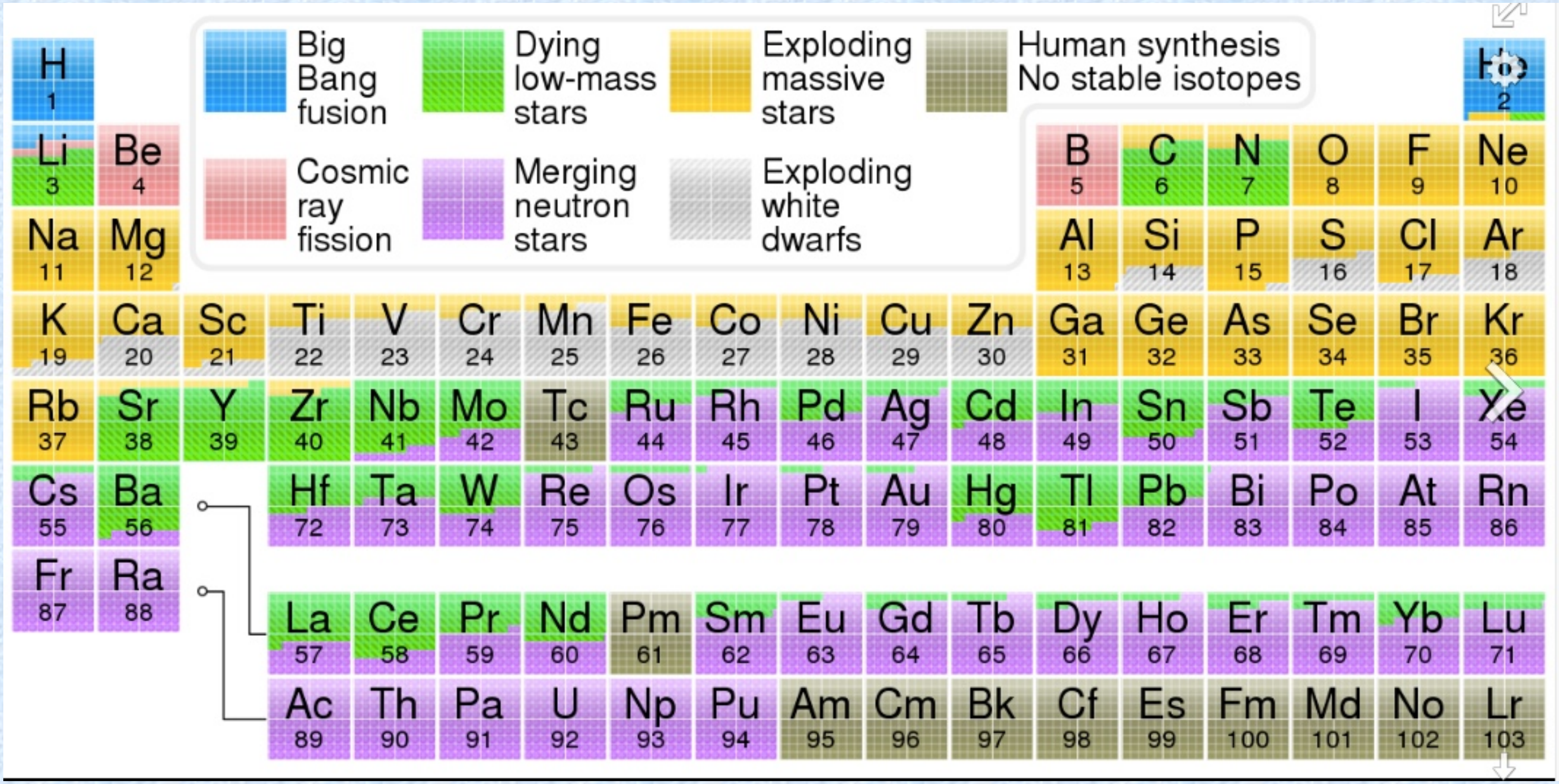
Astronomy 1 – Fall 2019



Lecture 12; November 18, 2019

Announcements

- **Professor Martin will be out of town Wednesday November 20th**
  - No office hours at 11am
  - No lecture 2-3:15pm
  - YES, TA Sections will meet Nov 20th and Nov 22nd
- **Yes, we will have lecture 2-3:15pm on Nov 27th.**
  - No, TA Sections will not meet Nov 27th and Nov 29th
- **Yes, you should go over the midterm solutions with Professor Martin or a TA before Thanksgiving Break.**
  - Someone has office hours each day.
  - No, we do not post the answer key. Mark the questions that you are unsure about and talk to an instructor.
- *Yes, it is possible to meet with Professor Martin on Tuesday; see me right after class.*

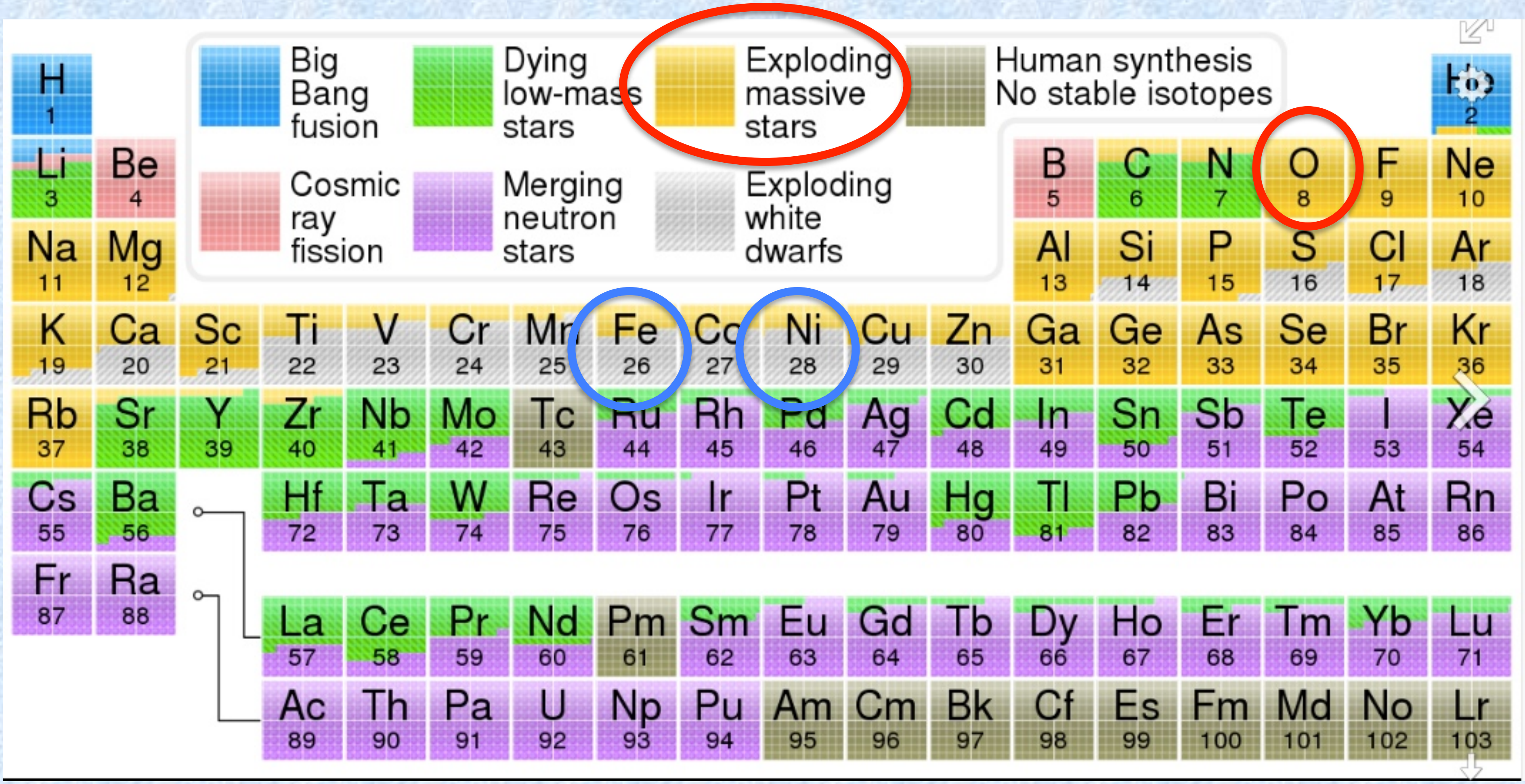
Previously on Astro 1

- The minimum mass of a star is about 0.08 M_0; less massive bodies do not get hot enough to fuse H nuclei into He.
- The maximum mass of a star is about 100 M_0; more massive bodies are unstable.
- The Main Sequence lifetimes of stars range from a few million years to much longer than the age of the Universe.
- **Stars move up the RGB when their core is contracting and the luminosity of the H burning shell is growing.**
- The main sequence turn off measured for a star cluster indicates the stellar mass of the most massive stars still burning H in their cores, thereby implying the cluster age.
- **Pauli exclusion principle and electron degeneracy pressure**
- **Production of C and O in He-burning stars**
- The luminosity of Cepheid stars increases with their period. Hence they are useful indicators of distance.

Today on Astro-1

- Late stages of evolution for low mass (0.4 to 4 M_0) stars.
  - The AGB, dredge up, and mass loss
  - Formation of white dwarfs
  - White dwarf mass – radius relation
  - Type Ia supernova explosions
- Evolution of high-mass stars (> 4 M_0)
  - Synthesis of elements with atomic number < 26
  - Why stars cannot burn iron.
  - Core-collapse (Type II) supernova
    - Neutron capture elements
    - Formation of neutron stars and black holes

Origin of the Elements



Stars more massive than about 1.3 $M_{\odot}$ burn hydrogen into helium via the CNO cycle.

Remember, the Sun burns hydrogen into helium via the proton-proton chain.

Why do we care? Well, for one thing, nitrogen would not be a common element without the CNO cycle.

The Carbon Nitrogen Oxygen Cycle

- ^{12}C nucleus captures a proton
- ^{13}N is unstable and beta decays to ^{13}C
- ^{13}C captures a proton and becomes ^{14}N
- ^{14}N captures another proton and becomes ^{15}O
- ^{15}O beta decays to ^{15}N
- ^{15}N captures a proton and produces a helium nucleus and ^{12}C

Hydrogen in

$$^{12}_{6}C + ^{1}_{1}H \longrightarrow ^{13}_{7}N + \gamma$$

$$^{13}_{7}N \longrightarrow ^{13}_{6}C + e^{+} + \nu$$

$$^{13}_{6}C + ^{1}_{1}H \longrightarrow ^{14}_{7}N + \gamma$$

$$^{14}_{7}N + ^{1}_{1}H \longrightarrow ^{15}_{8}O + \gamma$$

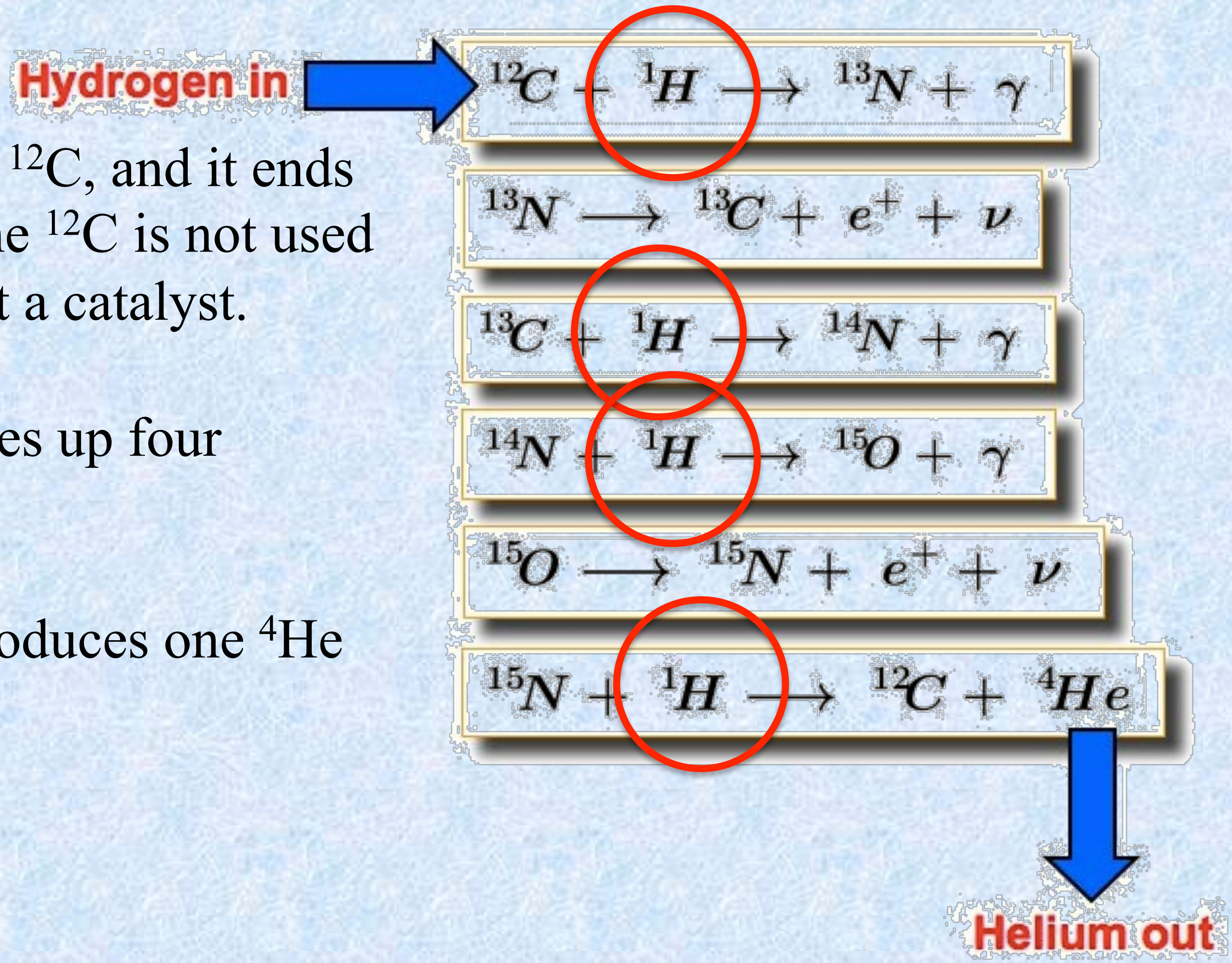
$$^{15}_{8}O \longrightarrow ^{15}_{7}N + e^{+} + \nu$$

$$^{15}_{7}N + ^{1}_{1}H \longrightarrow ^{12}_{6}C + ^{4}_{2}He$$

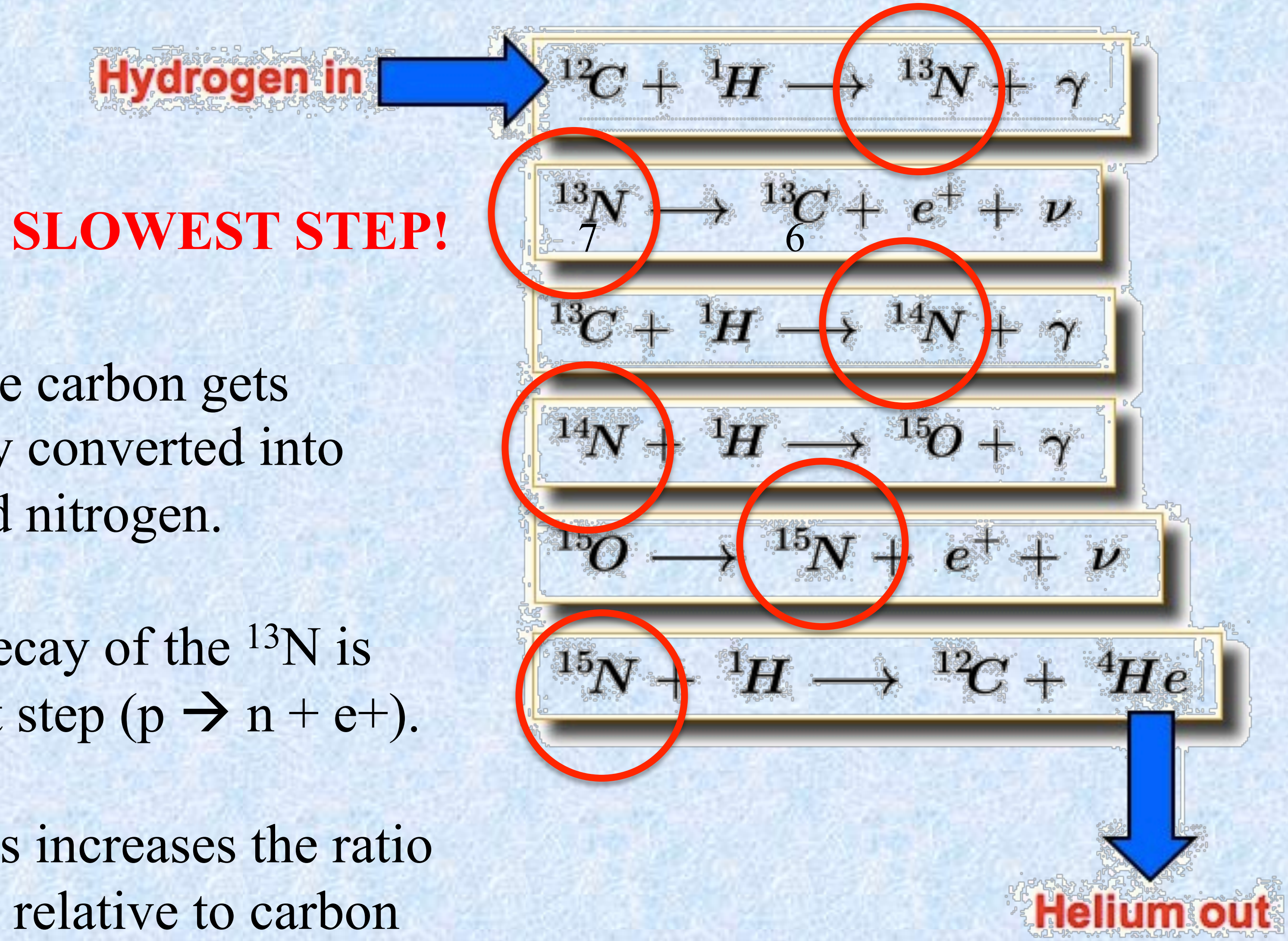
Helium out

The Carbon Nitrogen Oxygen Cycle

- It starts with ^{12}C, and it ends with ^{12}C. The ^{12}C is not used up. We call it a catalyst.
- The cycle uses up four protons.
- The cycle produces one ^{4}He nucleus.

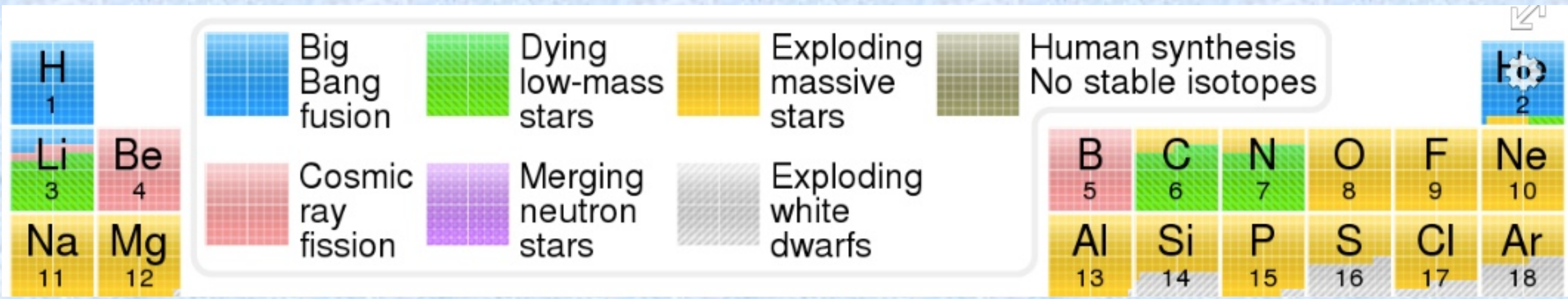


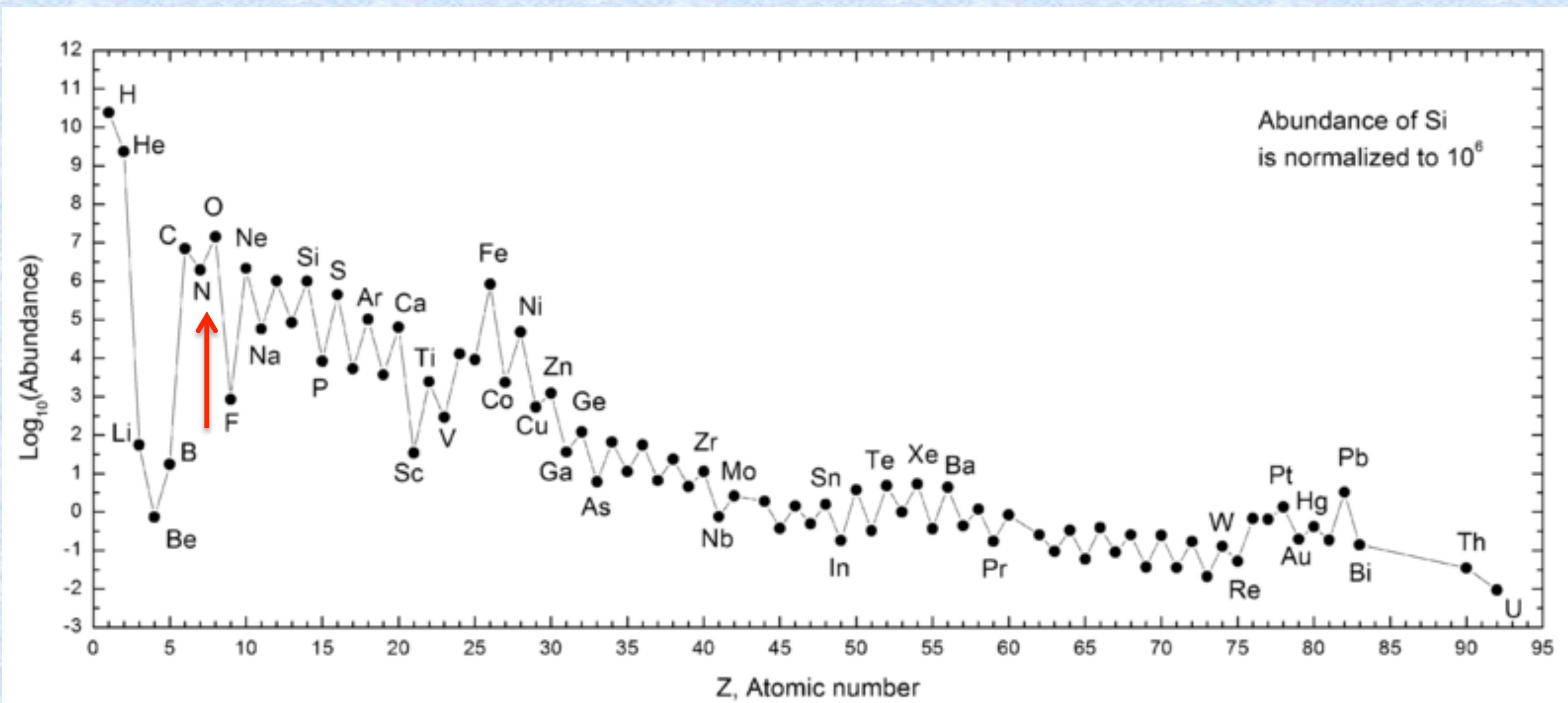
The Carbon Nitrogen Oxygen Cycle



- Some of the carbon gets temporarily converted into oxygen and nitrogen.
- The beta decay of the ^{13}N is the slowest step (p → n + e+).
- The process increases the ratio of nitrogen relative to carbon and oxygen.

CNO Cycle Increases Cosmic Nitrogen Abundance





Elements in a Typical 70 kg Human

Bulk Elements (kg)		Macrominerals (g)	
oxygen	44	calcium	1700
carbon	12.6	phosphorus	680
hydrogen	6.6	potassium	250
nitrogen	1.8	chlorine	115
sulfur	0.1	sodium	70
		magnesium	42

Late Stages of Low Mass Stars

Structure of Low-Mass AGB Star

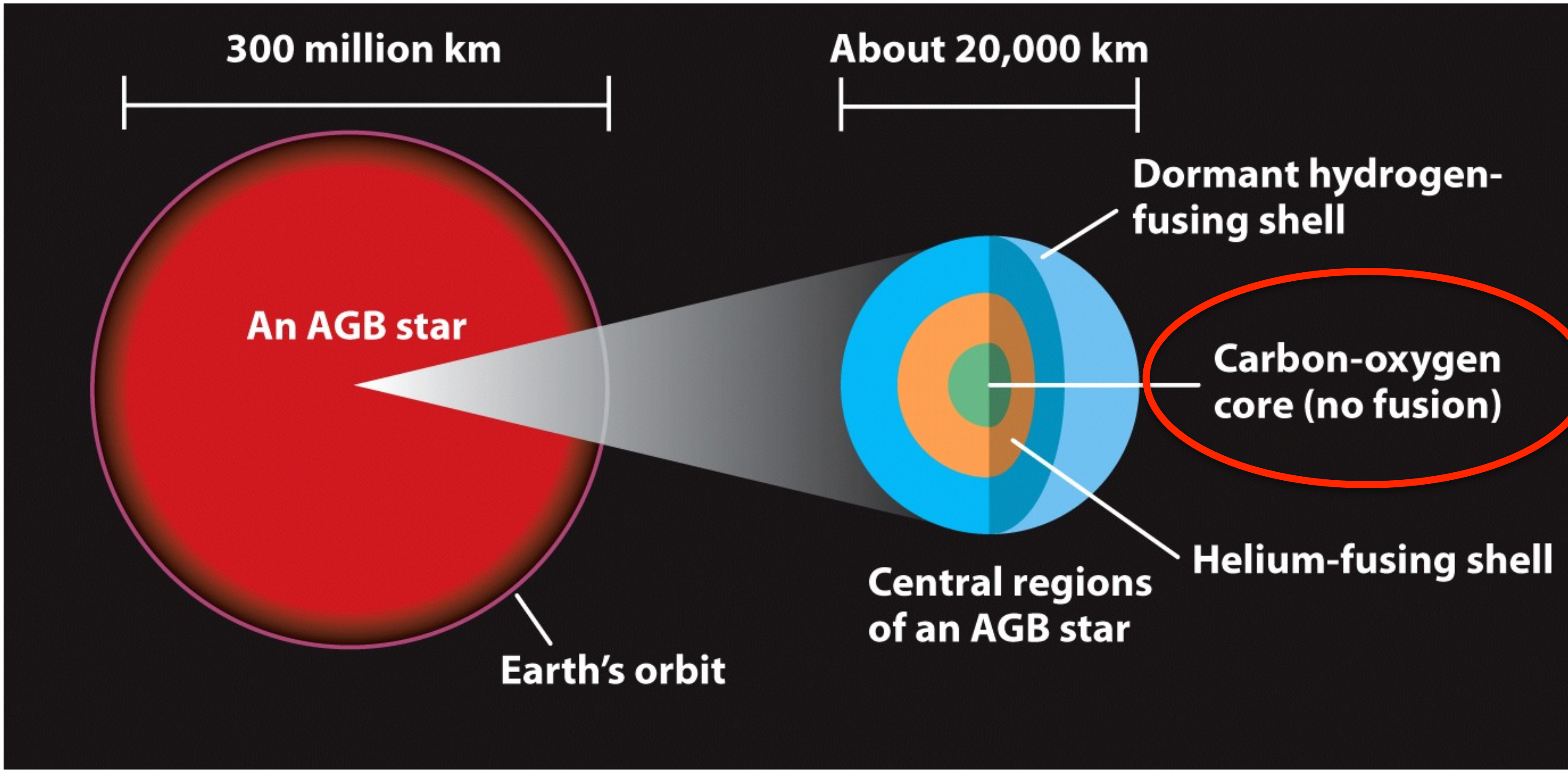


Figure 20-2
Universe, Tenth Edition

Late Phases of Stellar Evolution: Asymptotic Giant Branch (AGB)

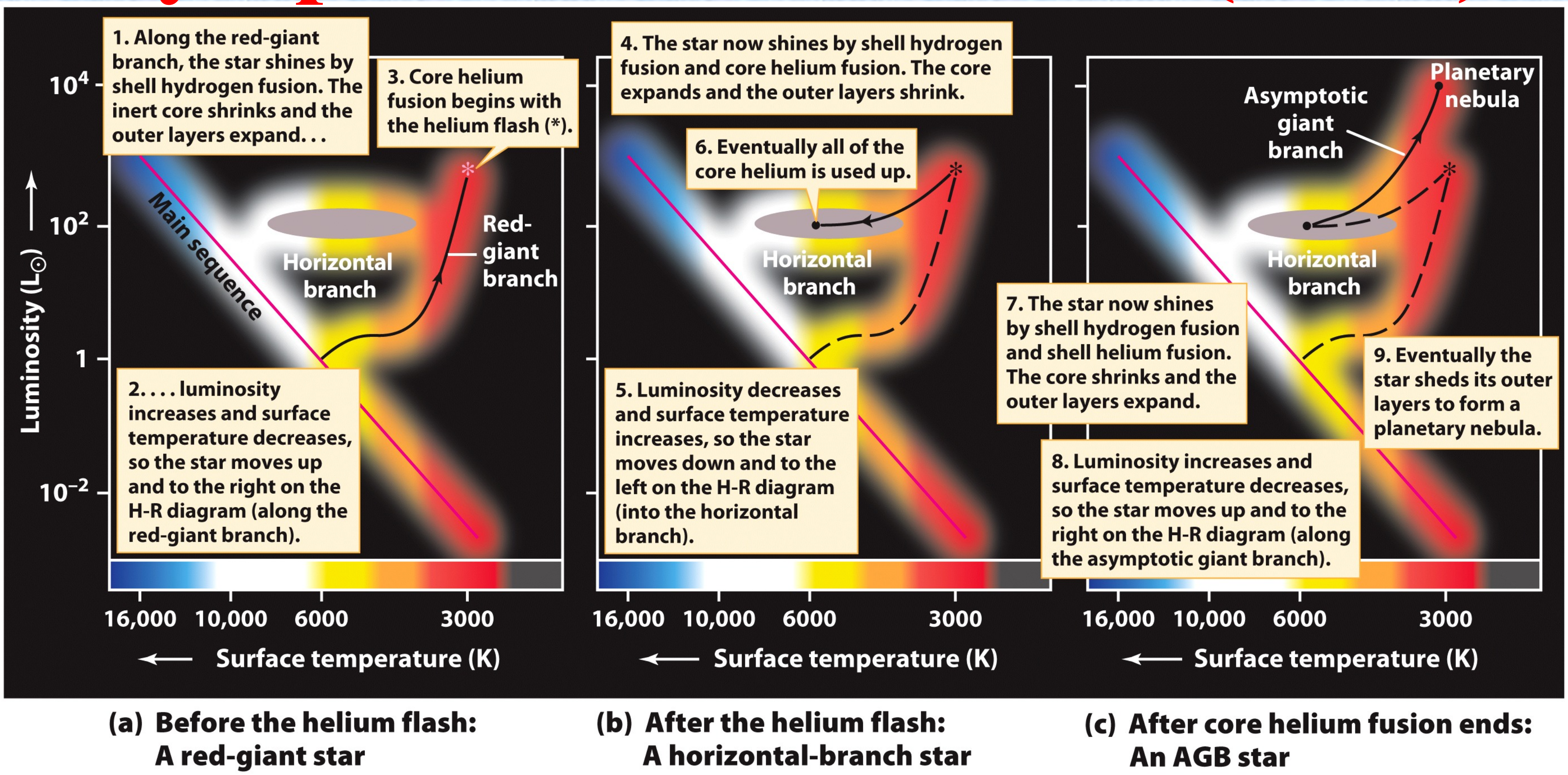


Figure 20-1
Universe, Tenth Edition

Convection, Dredge Up, & Thermal Pulses

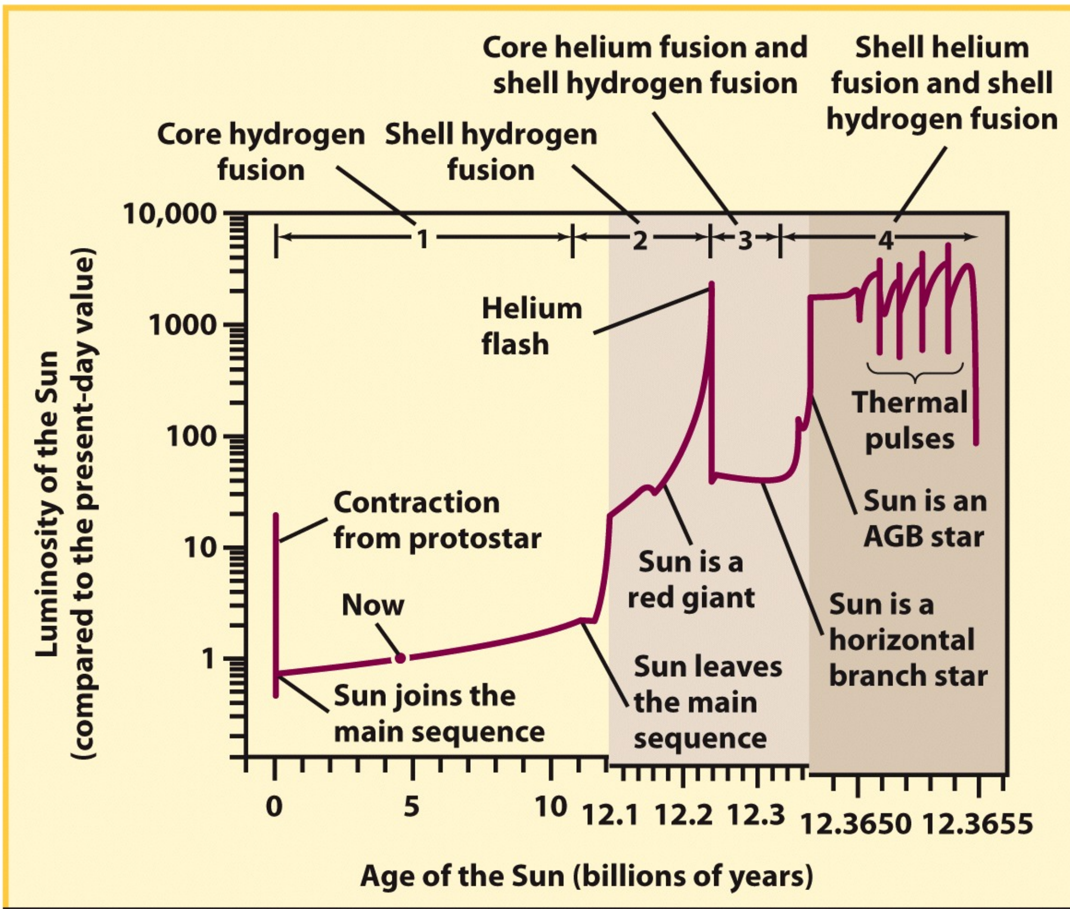


Figure 20-6
Universe, Tenth Edition

Carbon Pollution (Enrichment?) of the Interstellar Medium

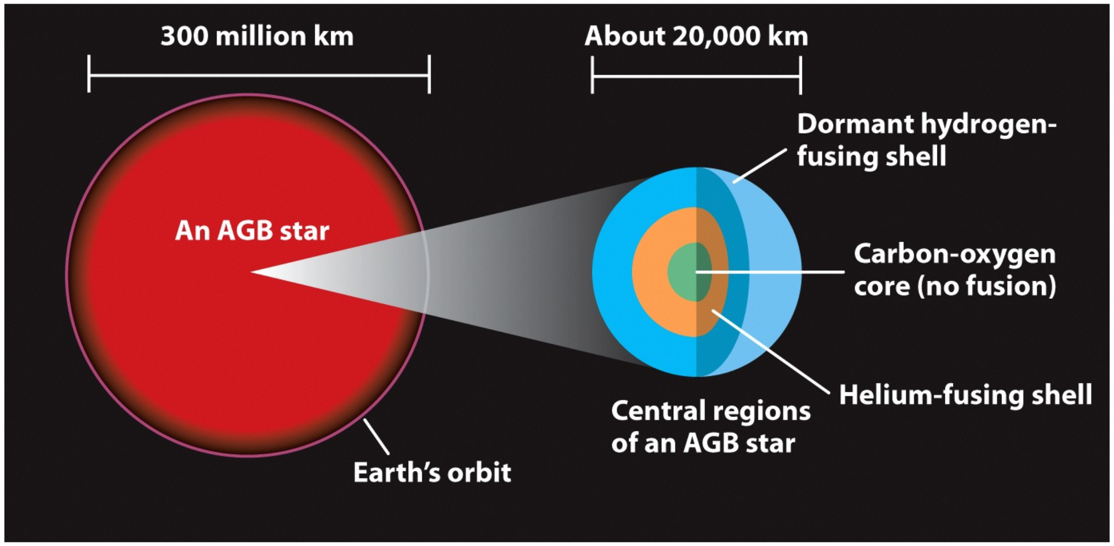


Figure 20-2
Universe, Tenth Edition

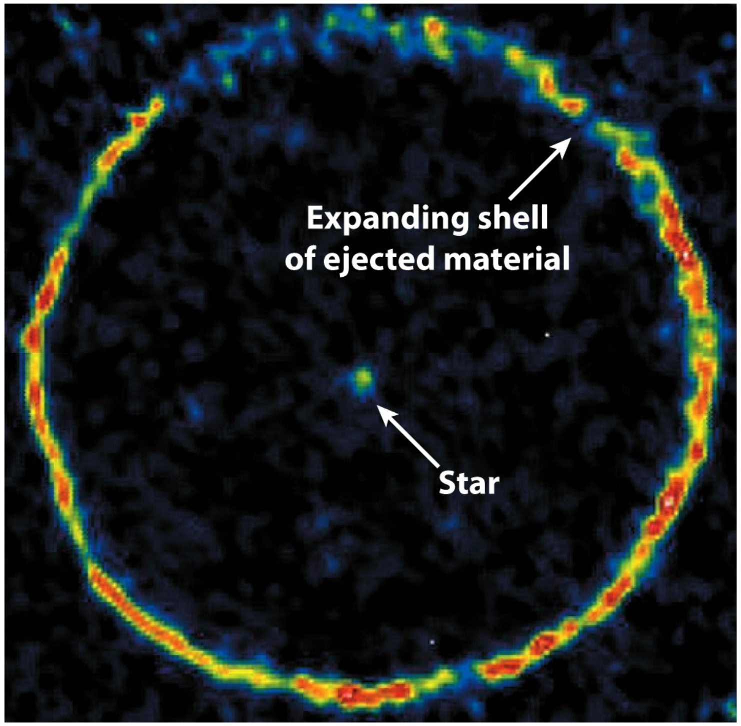


Figure 20-4
Universe, Tenth Edition
H. Olofsson, Stockholm Observatory, et al./NASA

The End State of Low Mass Stars: White Dwarfs

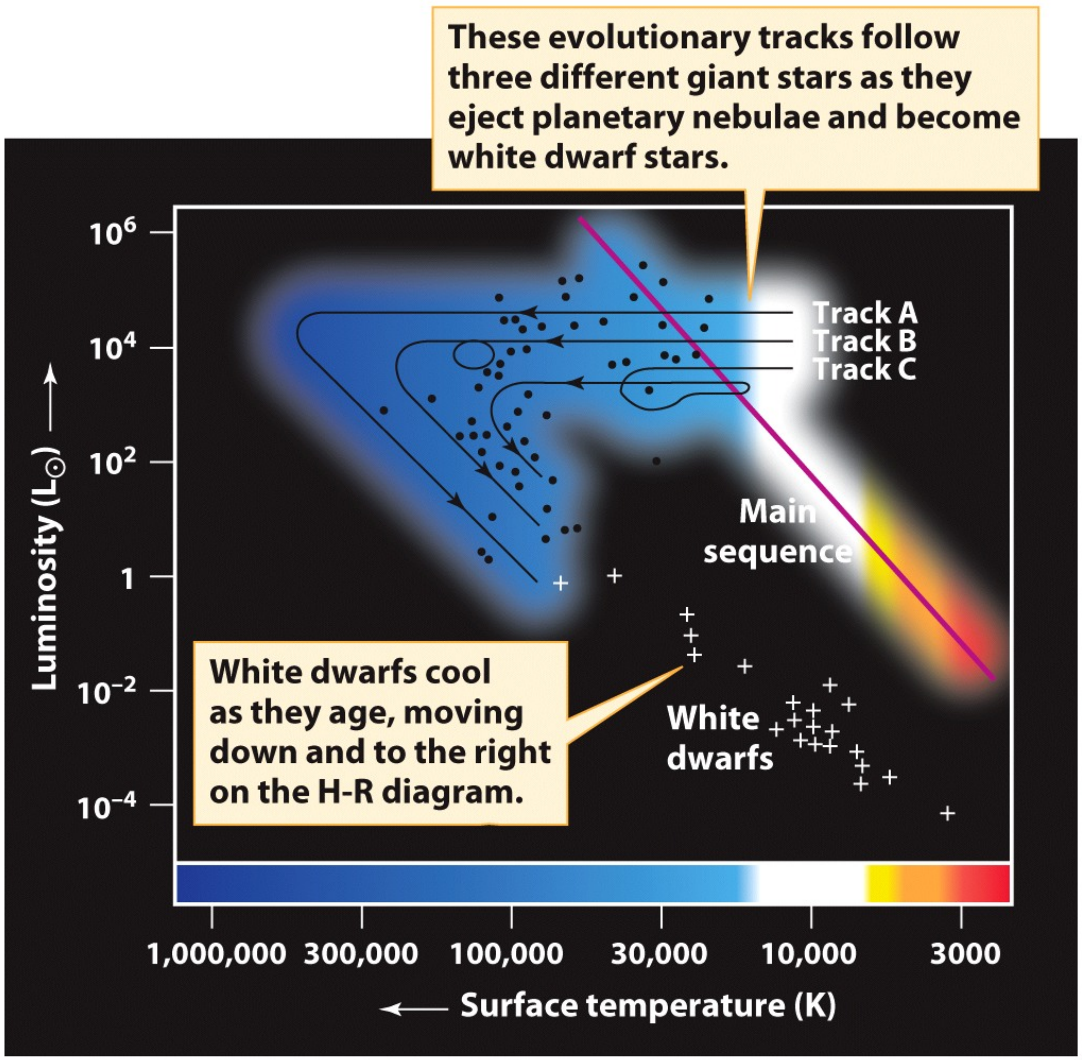


Figure 20-11a
Universe, Tenth Edition

	Mass ($M_\odot$)		
	Giant star	Ejected nebula	White dwarf
A	3.0	1.8	1.2
B	1.5	0.7	0.8
C	0.8	0.2	0.6

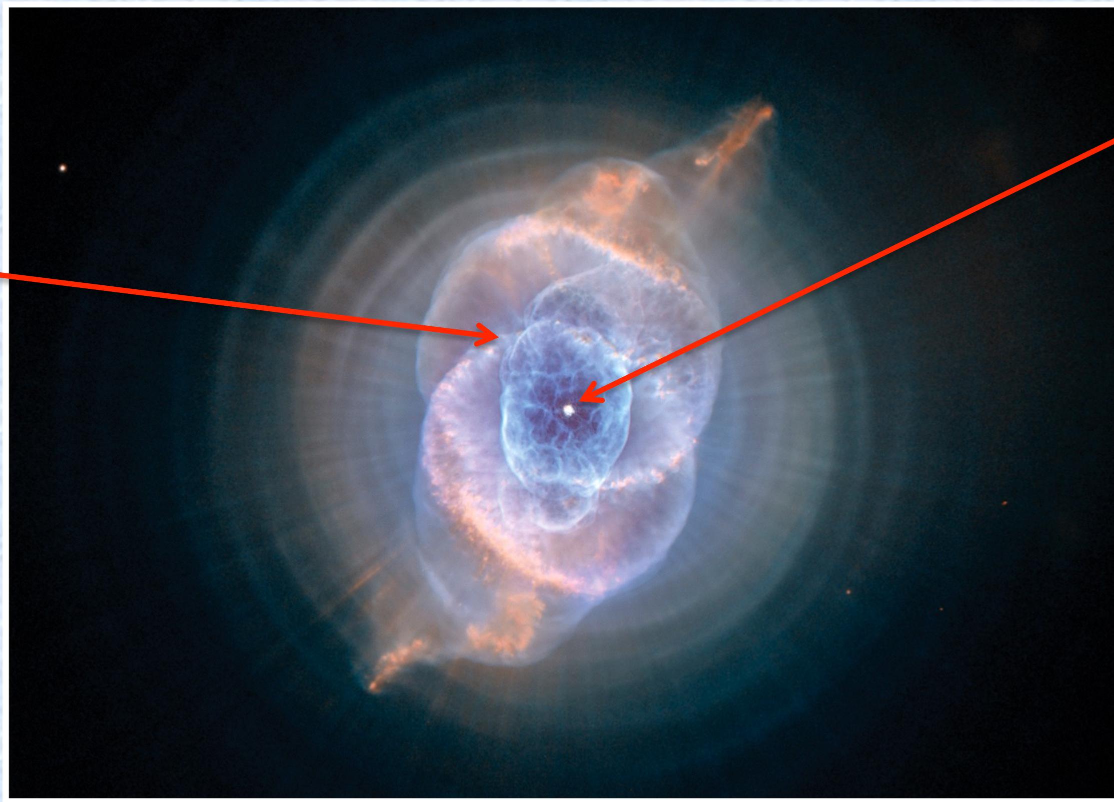
Figure 20-1
Universe, Ter

- A white dwarf is not really a star. There is no nuclear fusion in its core.
- It is a glowing ember held up be the pressure of **degenerate electrons**.

The Exposed Core of a Star

- This ‘planetary nebula’ is powered by a white dwarf.
- It is an example of an emission nebula.

Ejected outer layers of the star.



Exposed stellar core $10^4\ L_0$

Figure 20-5
Universe, Tenth Edition
NASA, ESA, HEIC, The Hubble Heritage Team STScI/AURA

White dwarfs usually have surface temperatures well above 10,000 K, yet they have extremely low luminosity. Why is this?

A. They are very far away.

B. They have a very large surface area.

C. They emit most of their radiation in the far infrared.

D. They emit most of their radiation in the ultraviolet.

E. They have a very small surface area.

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Degenerate "Stars" Have Some Peculiar Properties: More Massive WDs are Smaller!

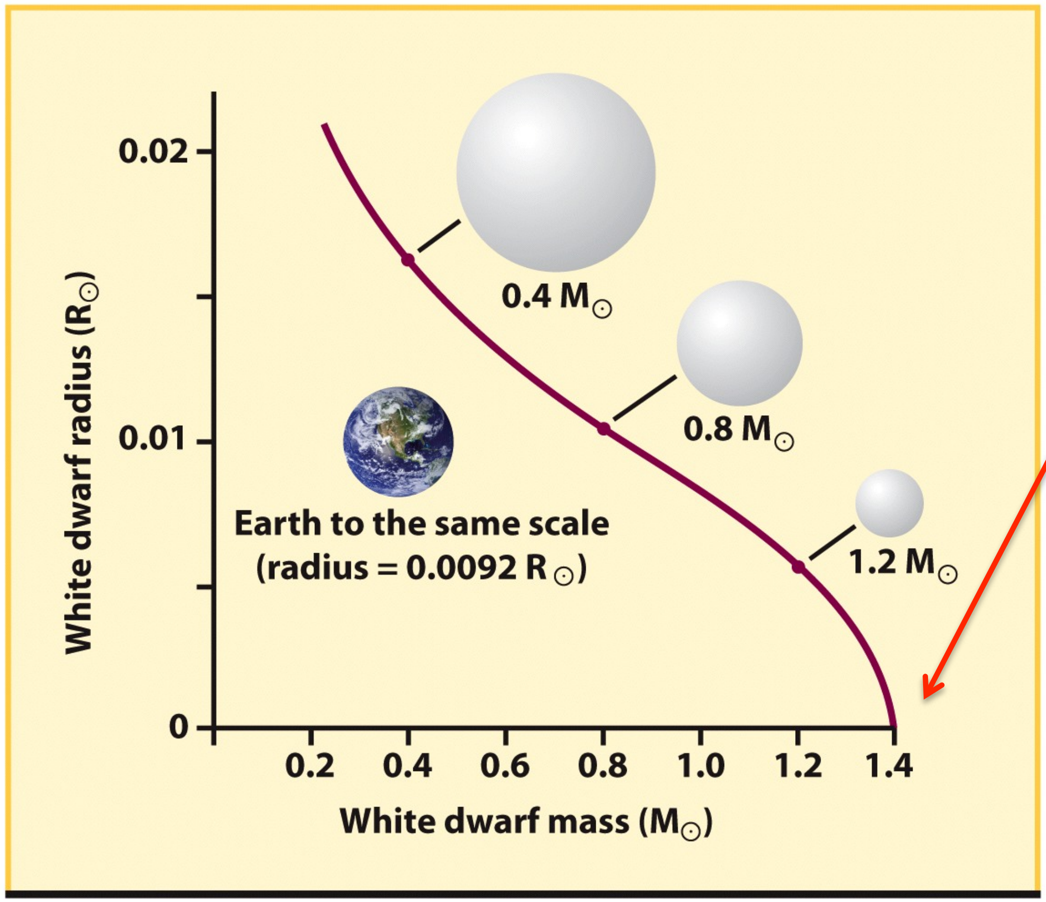


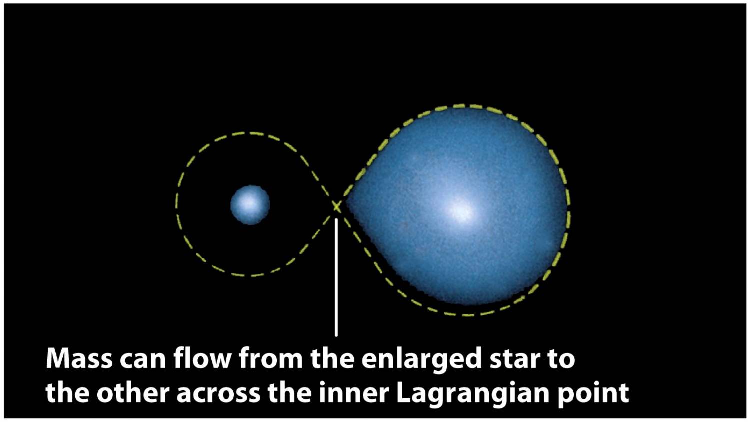
Figure 20-10
Universe, Tenth Edition

Interesting!

We call this mass the Chandrasekhar limit.

What happens when the companion of a 1.39 M_0 white dwarf becomes a red giant and begins to transfer mass to the white dwarf?

A. The white dwarf collapses into a black hole, and its radius goes to zero.
B. The white dwarf vaporizes, and its mass becomes zero.
C. The pressure increases in the white dwarf's core and carbon nuclei begin to fuse.
D. The white dwarf explodes.
E. Combination of C & D.



Semi-detached binary: One star fills its Roche lobe.

Figure 19-21b
Universe, Tenth Edition

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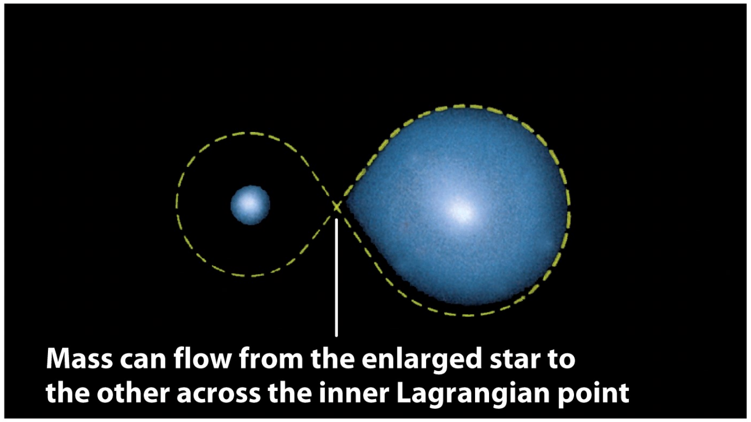


Semi-detached binary: One star fills its Roche lobe.

Figure 19-21b
Universe, Tenth Edition

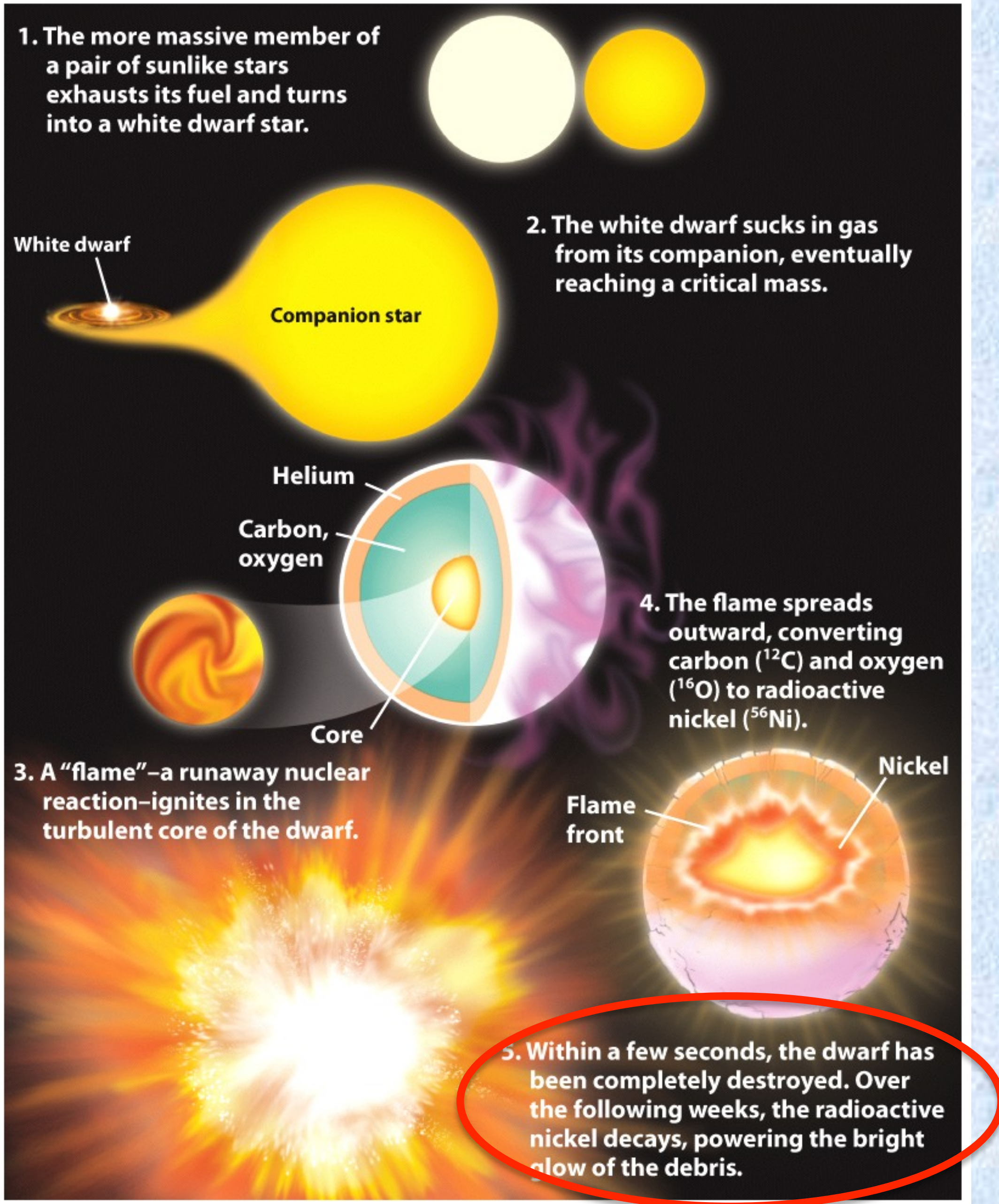


Figure 20-19
Universe, Tenth Edition
Illustration by Don Dixon, adapted from Wolfgang Hillebrandt, Hans-Thomas Janka, and Ewald Müller, "How to Blow Up a Star," *Scientific American*, October 2006

Degeneracy pressure holds up the white dwarf against gravity.

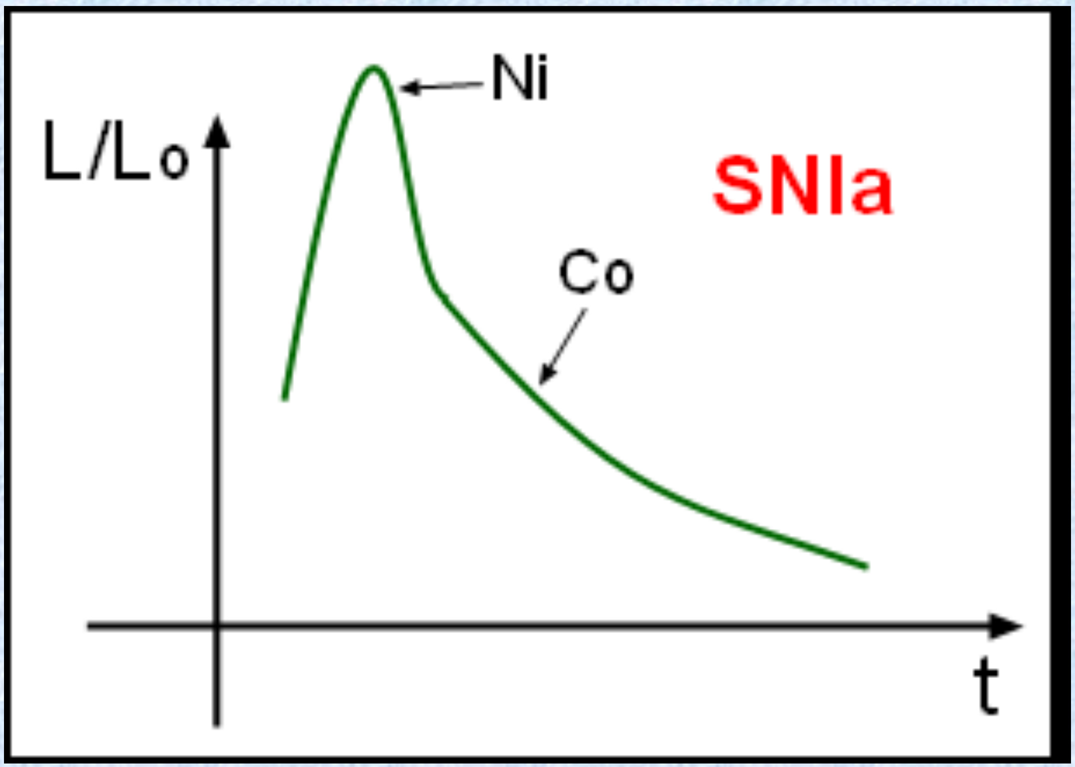
The temperature can increase without causing the pressure to increase – no thermostat.

The inside gets really hot and carbon fusion ignites.

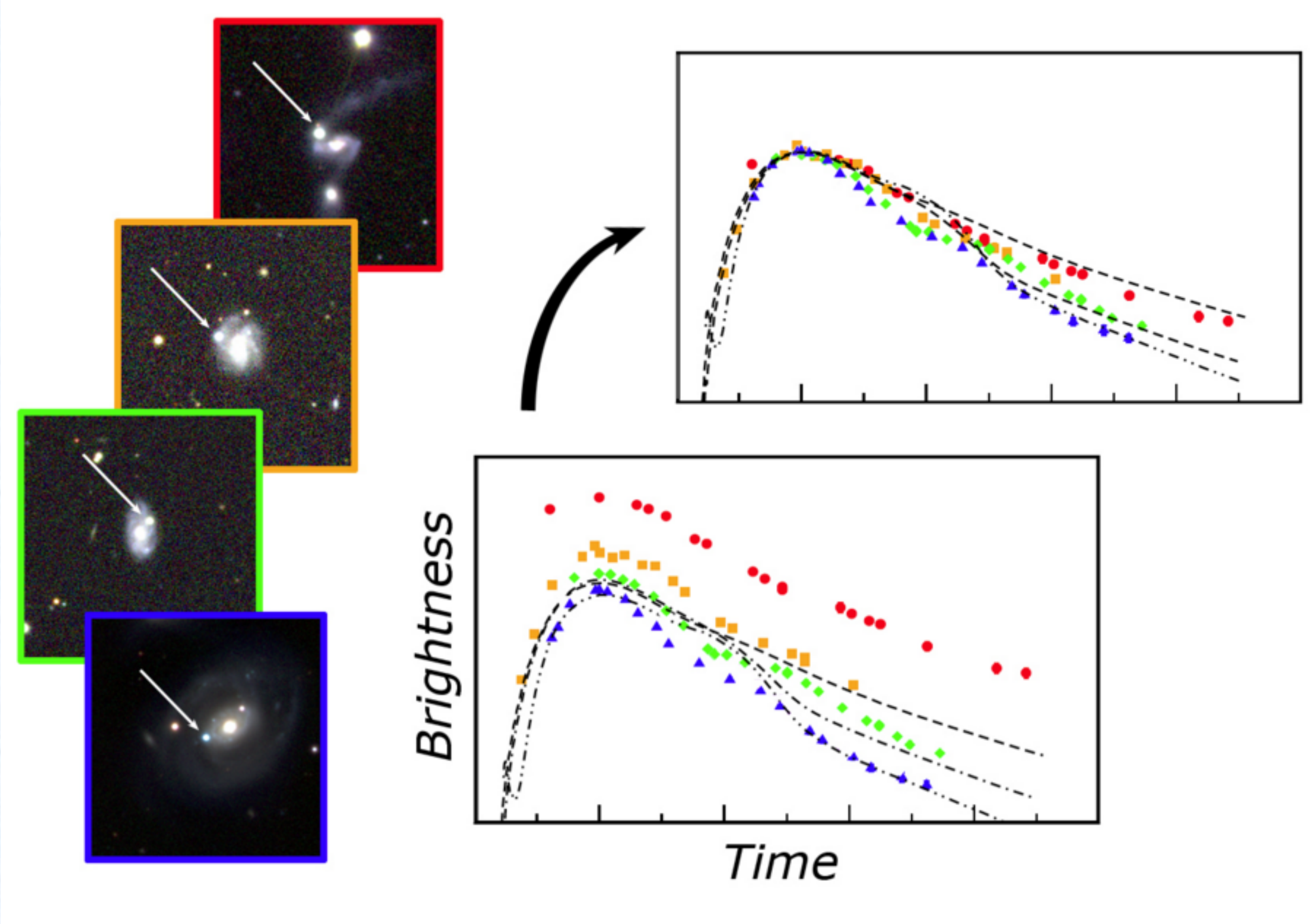
The result is a Type Ia supernova.

Exploding White Dwarfs are Standard Candels

- Nucleosynthesis produces many elements near the iron peak.
- Weeks after the explosion, the supernova glows due to the radioactive decay of these elements.
- ^{56}Ni ($\tau_{1/2}$ = 6 days) → ^{56}Co ($\tau_{1/2}$ = 271 days) → ^{56}Fe



Exploding White Dwarfs are Standard Candels



Spectrum of a Type Ia Supernova

(a) Type Ia supernova

- **The spectrum has no hydrogen or helium lines, but does have a strong absorption line of ionized silicon (Si II).**
- **Produced by runaway carbon fusion in a white dwarf in a close binary system (the ionized silicon is a by-product of carbon fusion).**

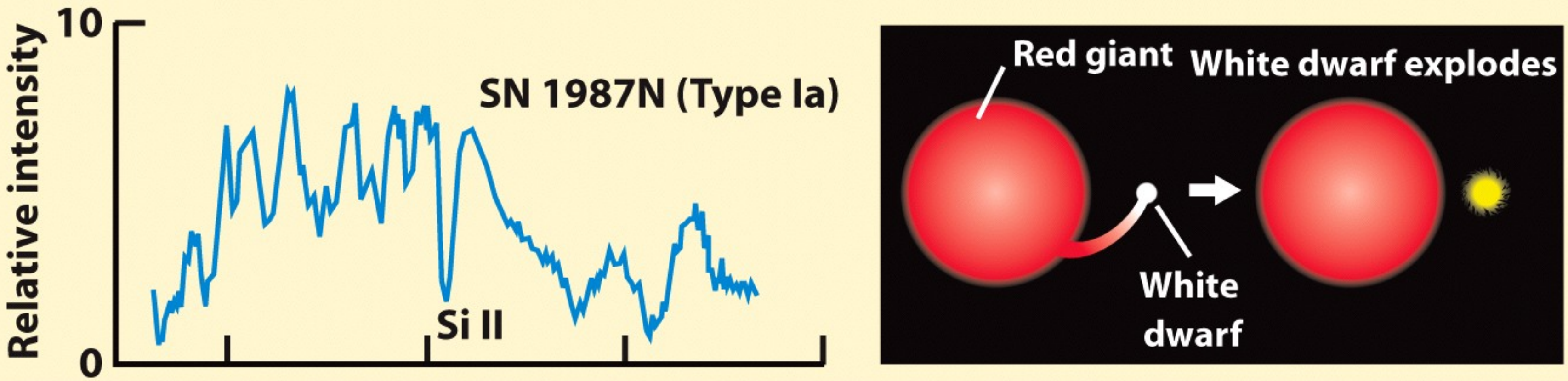


Figure 20-18a
Universe, Tenth Edition

A Type Ia supernova does not show any hydrogen or helium emission lines. Such a supernova is thought to occur when

A. a white dwarf in a binary system accumulates mass from its companion, eventually causing runaway fusion in the white dwarf.
B. a red supergiant loses its surface layers and its core of helium collapses.
C. a supergiant fuses elements all the way up to silicon to produce an iron core, which then collapses.
D. a red supergiant loses its surface layers and its core of carbon collapses.

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Two Types Supernovae

- Type Ia supernovae are exploding white dwarfs.
  - White dwarfs are the end stage of low mass stars.
  - Their spectra do **not** show lines from hydrogen. Why?
  - These explosions have a standard luminosity. Why?
- Type II supernovae are exploding high mass stars.
  - They leave behind a neutron star or black hole.
  - Their spectra do show hydrogen lines.
- Supernova remnants can have either origin.

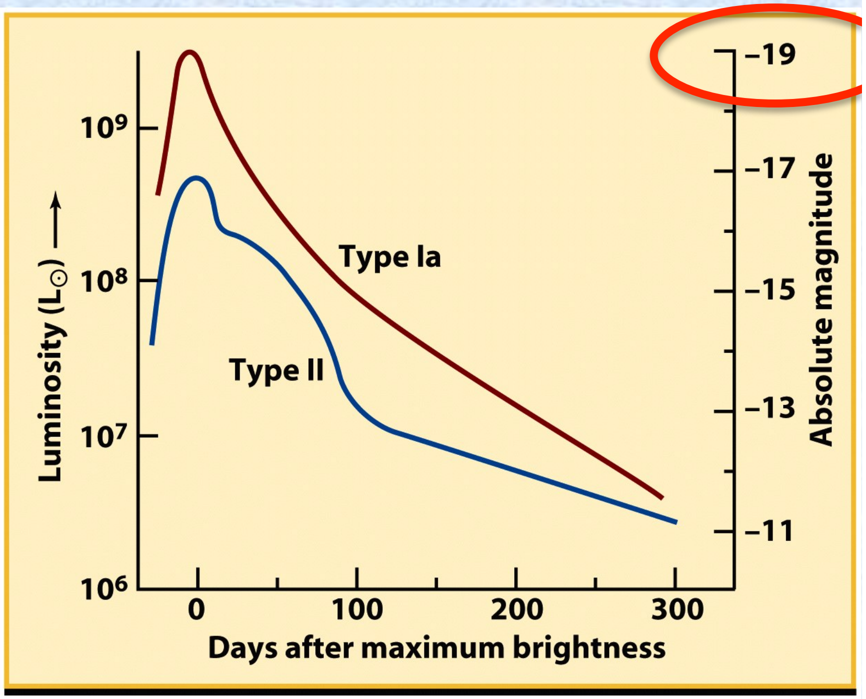
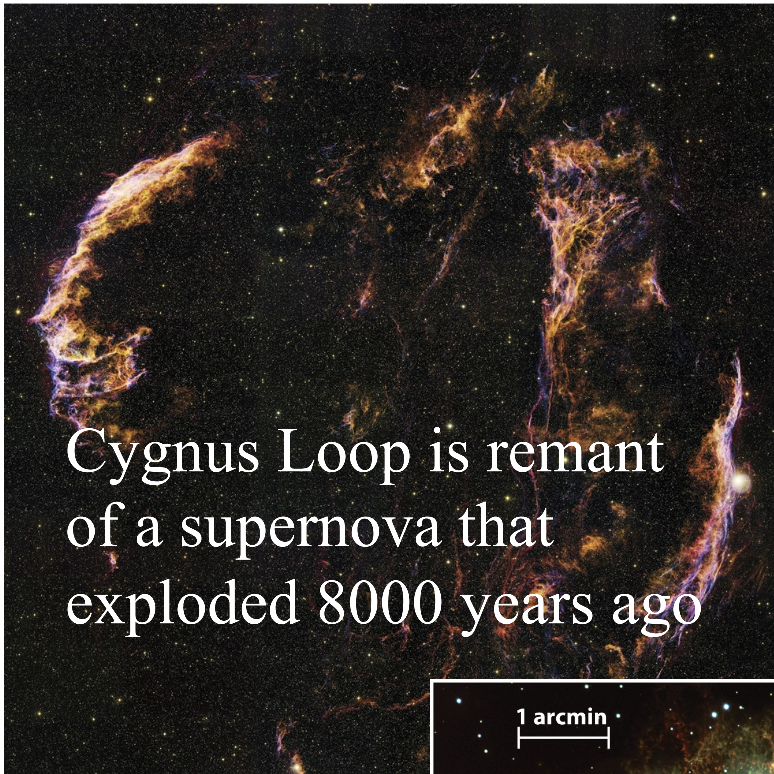


Figure 20-22
Universe, Eighth Edition

The type of supernova can also be distinguished by the light curve.

Gallery of Supernova Remnants



Cygnus Loop is remant of a supernova that exploded 8000 years ago

Figure 20-21
Universe, Tenth Edition
National Optical Astronomy Observatory [NOAO] and WIYN partners

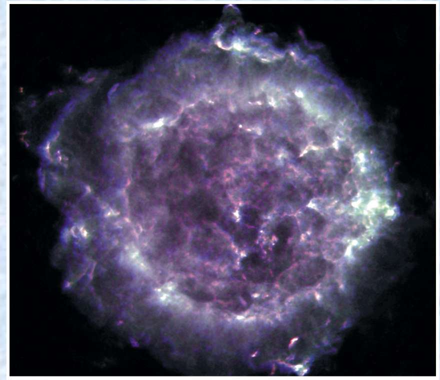
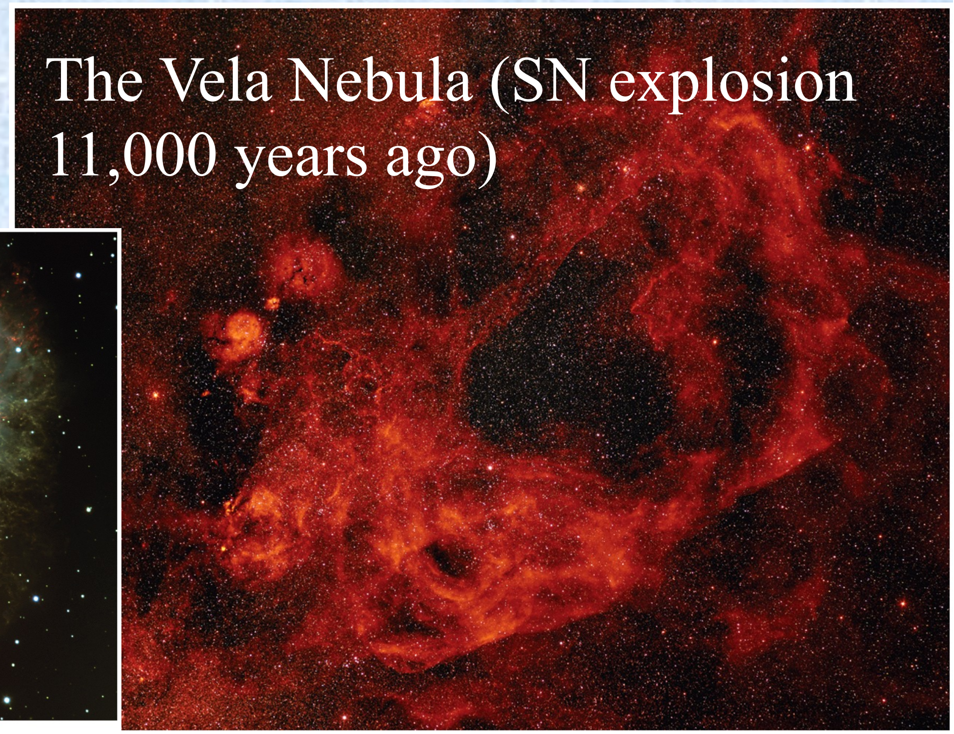


Figure 20-23
Universe, Tenth Edition
NRAO/AUI

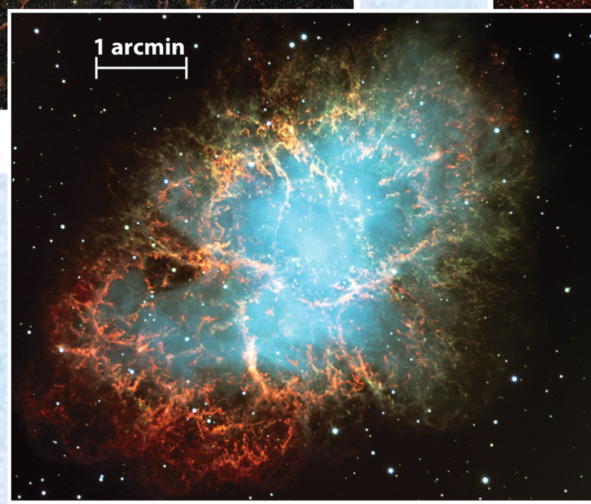
Cass A (previous HW problem) − remnant of an explosion 300 years ago.



The Vela Nebula (SN explosion 11,000 years ago)

tion

Crab Nebula: Definitely the remnant of a massive star!



The Crab Nebula
Figure 20-26a
Universe, Tenth Edition
The FORS Team, VLT, European Southern Observatory

High Mass Stars ($M > 8\ M_o$)

High mass stars: *Life in the fast lane*

We have seen that the surfaces of high-mass stars generate strong stellar winds, which remove roughly 50% of the stars initial mass. The winds are driven by radiation pressure.

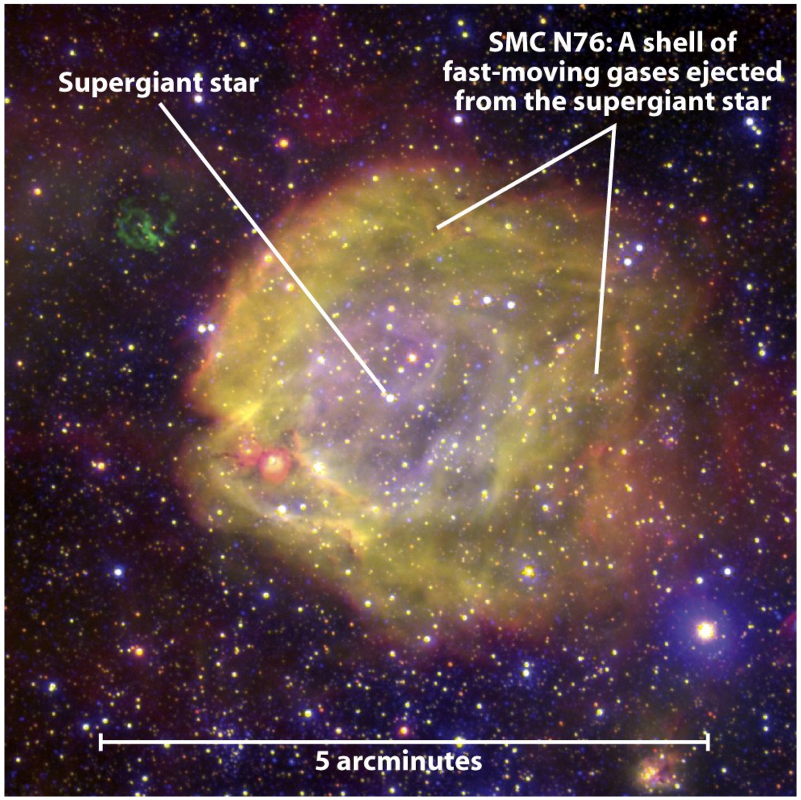
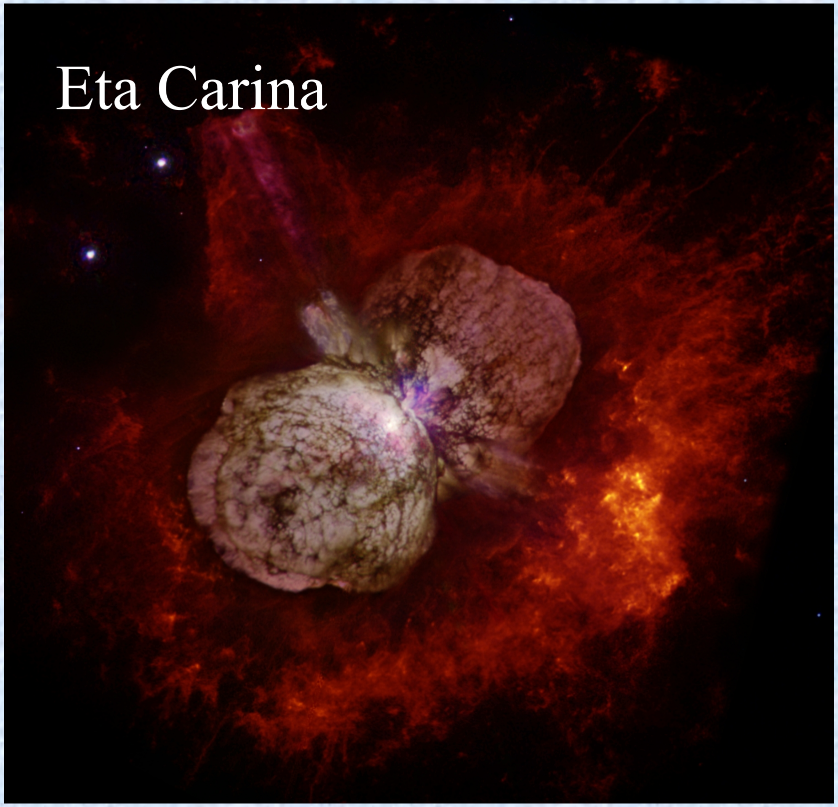


Figure 20-12
Universe, Eighth Edition



Nuclear Fusion in a Massive Star

Higher atomic number ➔ More repulsion between nuclei
➔ Requires more kinetic energy (i.e., higher T) to fuse

Coulomb's Law

$$F_e = k_e \frac{q_1 q_2}{r^2}$$

where

- F_e is the force
- k_e is the Coulomb's constant (8.987×10^9 N.m^2.C^{-2})
- q_1 and q_2 are the signed magnitudes of the charges
- r is the distance between the charges

Table 20-1 Evolutionary Stages of a 25-$M_\odot$ Star

Stage	Core temperature (K)	Core density (kg/m^3)	Duration of stage
Hydrogen fusion	4×10^7	5×10^3	7×10^6 years
Helium fusion	2×10^8	7×10^5	7×10^5 years
Carbon fusion	6×10^8	2×10^8	600 years
Neon fusion	1.2×10^9	4×10^9	1 year
Oxygen fusion	1.5×10^9	10^{10}	6 months
Silicon fusion	2.7×10^9	3×10^{10}	1 day
Core collapse	5.4×10^9	3×10^{12}	$^1/_4$ second
Core bounce	2.3×10^{10}	4×10^{15}	milliseconds
Explosive (supernova)	about 10^9	varies	10 seconds

High Mass Stars Create Heavy Elements Up to Atomic Number 26 by Fusion

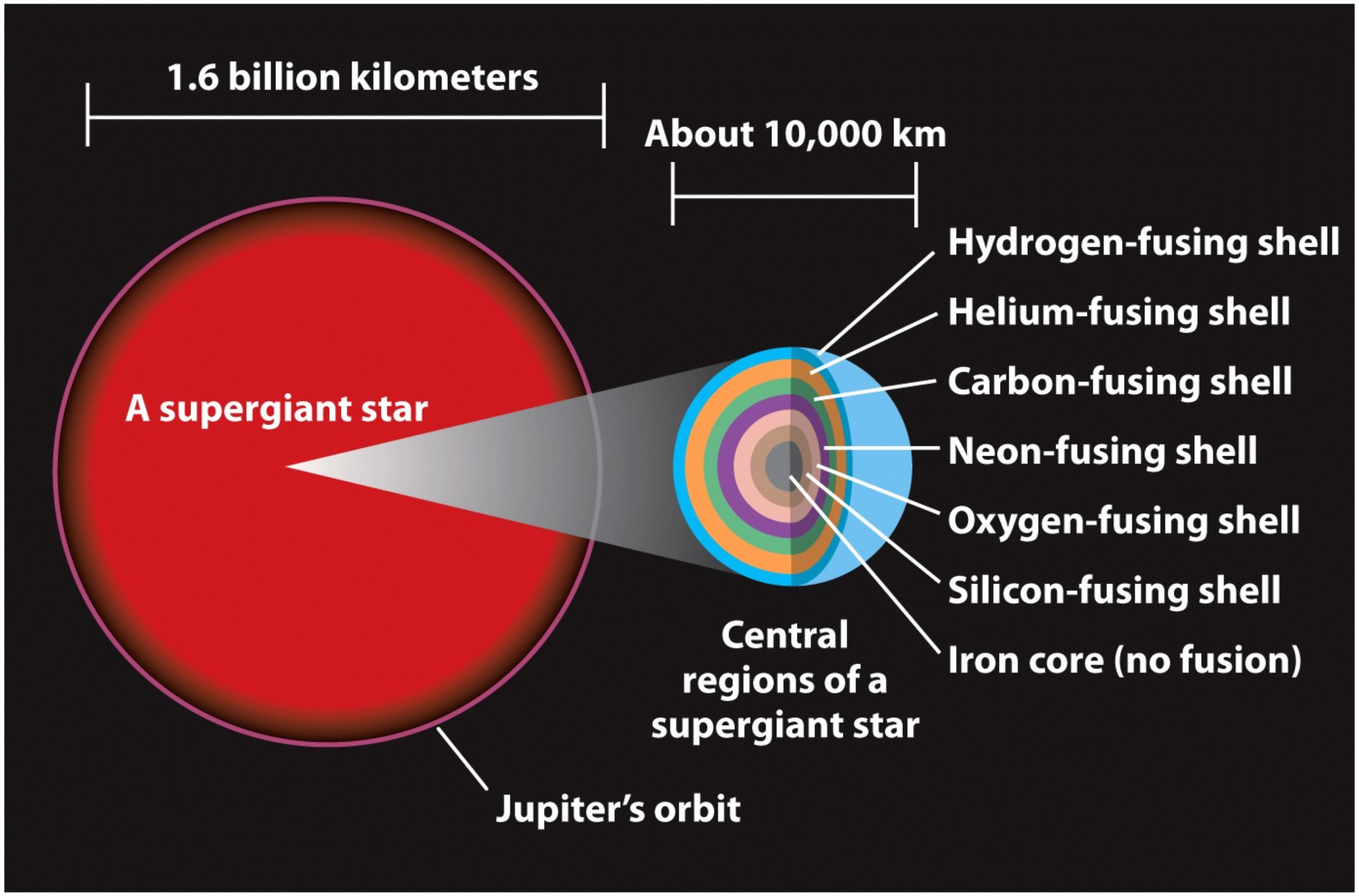
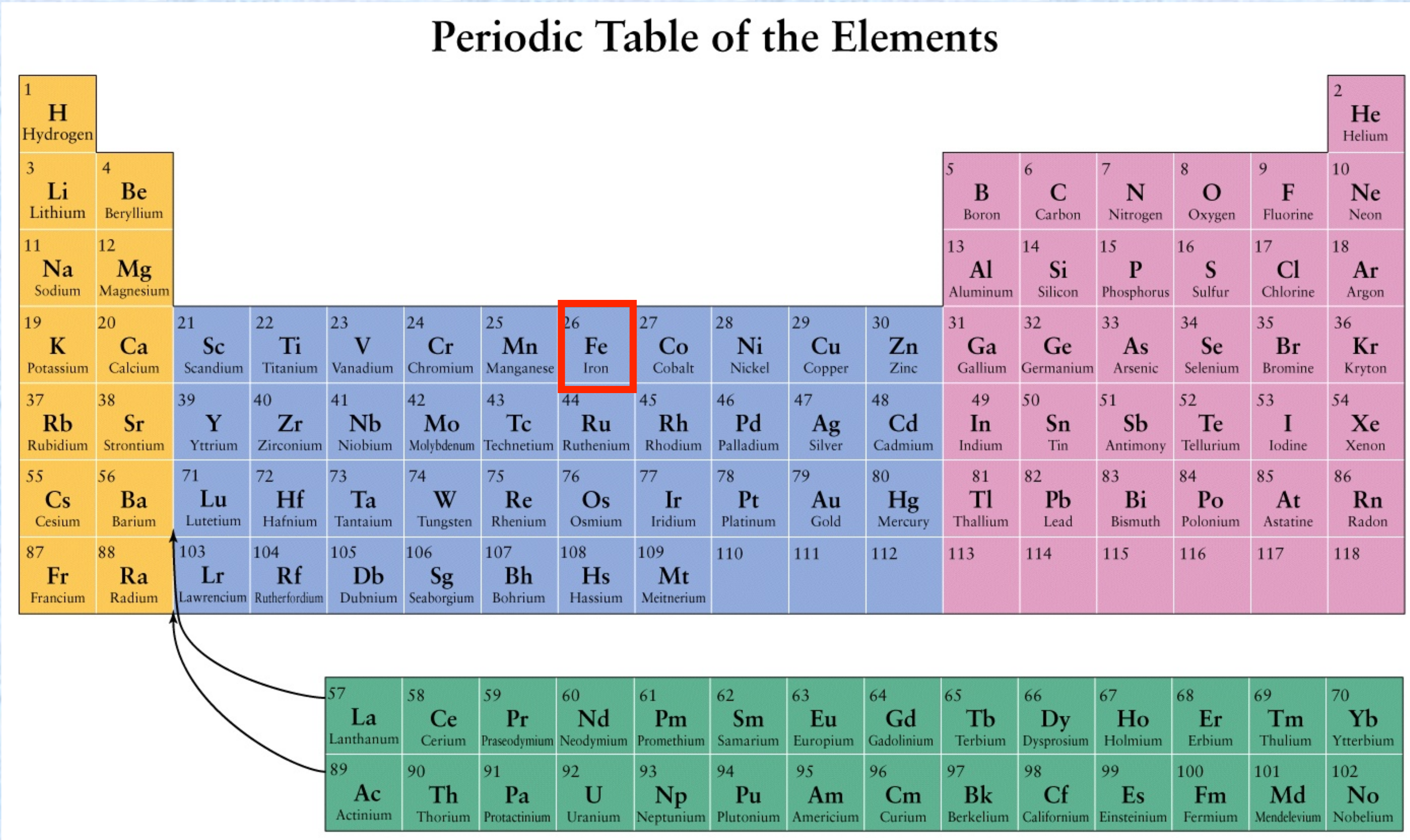


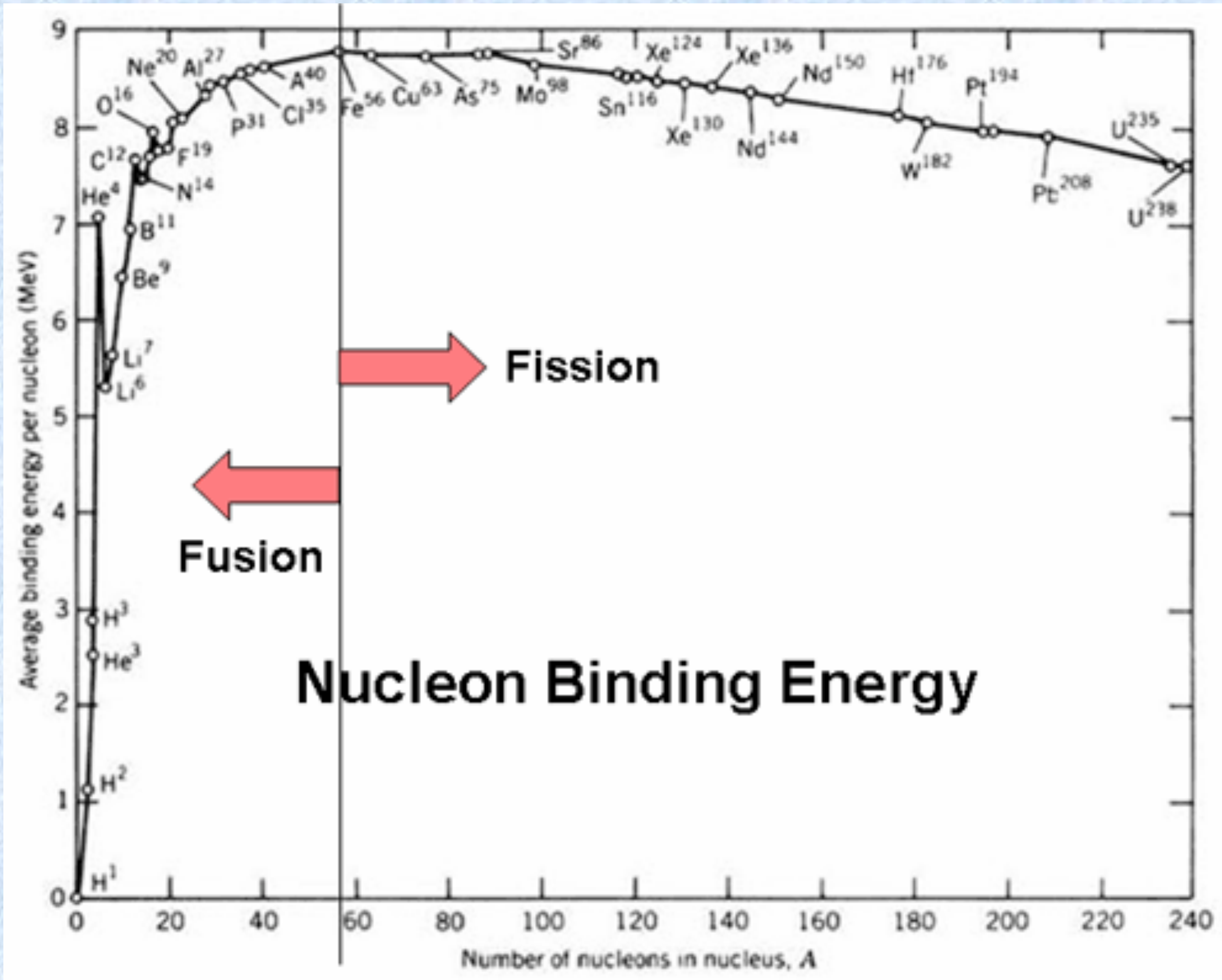
Figure 20-13
Universe, Tenth Edition

Stars much more massive than the Sun:

Reactions produce elements up to iron (Fe, 26 protons, 30 neutrons)

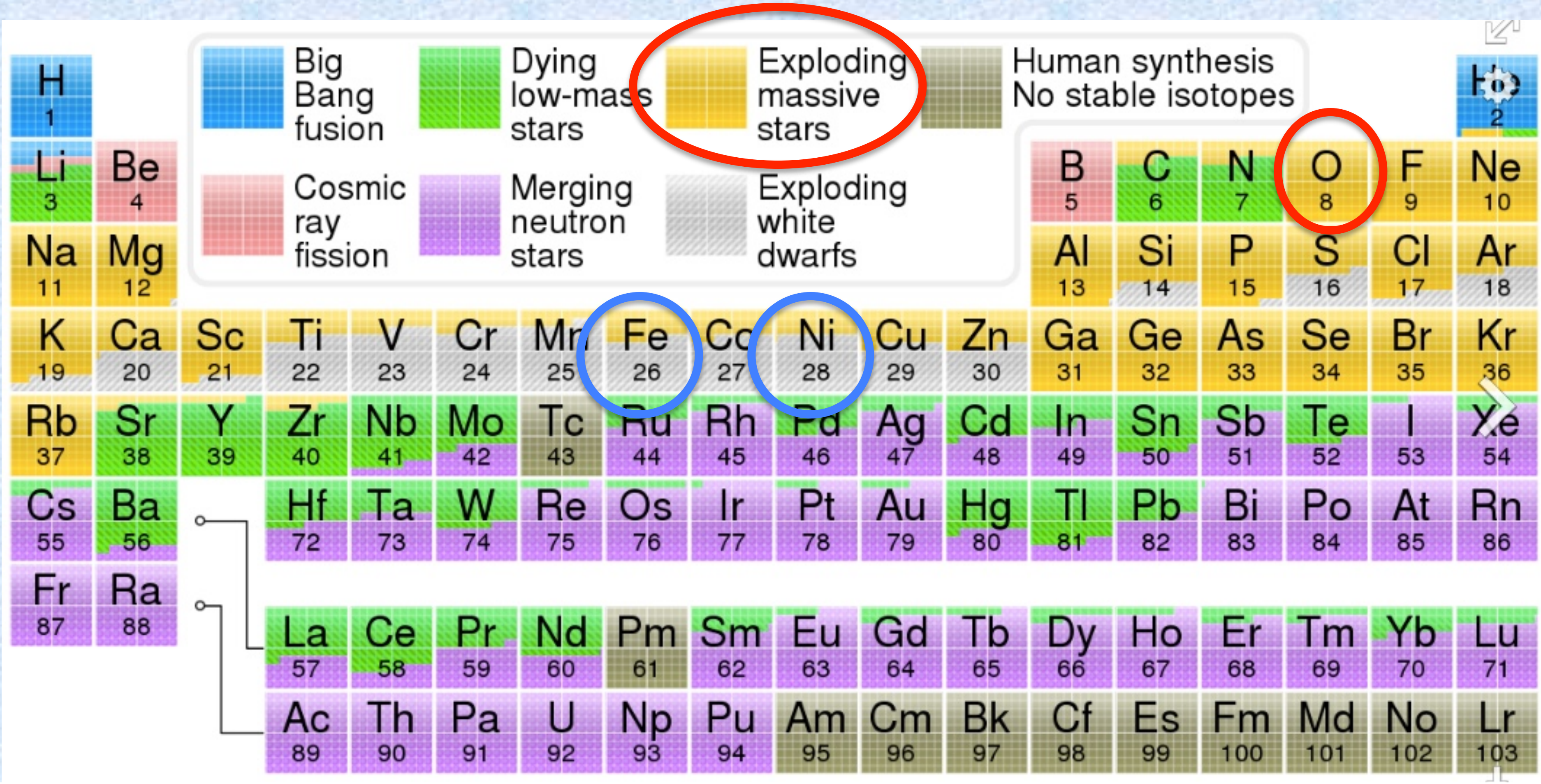


Why Stop at Iron?



Nuclei Heavier than Iron Are Produced During the Explosion

- Make a series of elements by adding ^{4}He nuclei, reaching Fe.
- These elements capture neutrons during the supernova explosion, building heavier elements.



The existence of carbon-based life (such as humans) on Earth tells us that carbon was present in the solar nebula. This carbon was created by

A. fusion of hydrogen in the core of a red giant.

B. fusion of helium in the core of a red giant.

C. fusion of helium in the core of a neutron star.

D. fusion of hydrogen in a shell inside a red giant.

E. fusion of hydrogen in the core of a main-sequence star.

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Massive stars burn a series of fuels (elements) in concentric shells. As more “ash” is added to the iron core, what happens to the star?

A. The radius of the core becomes enormous due to pressure of degenerate electrons.
B. The iron ignites and begins to fuse thereby setting off a supernova explosion.
C. The core expands due to the added iron, and the outer layers fall inwards due to the added mass in the core.
D. The core contracts due to the added weight, and the outer layers expand because energy is released at a rapid rate by shell burning.

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When the Core Reaches Nuclear Densities, It Cannot Contract Further!

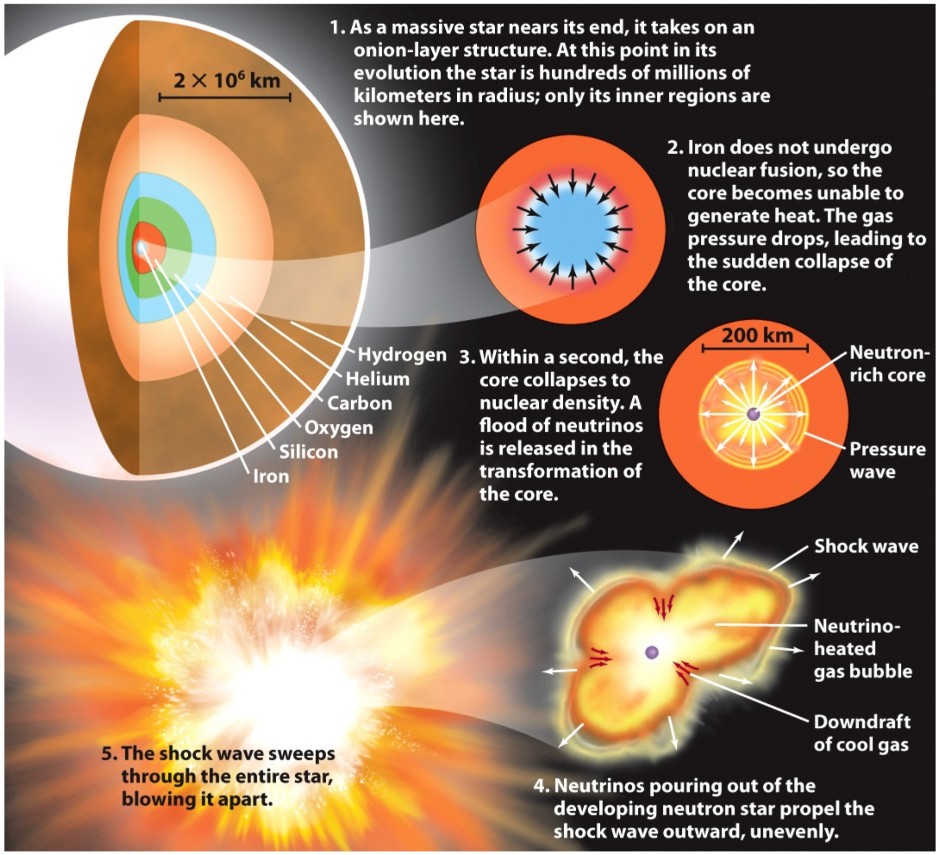


Figure 20-14
Universe, Tenth Edition
Illustration by Don Dixon, adapted from Wolfgang Hillebrandt, Hans- Thomas Janka, and Ewald Müller, "How to Blow Up a Star," *Scientific American*, October 2006

Signatures of Core Collapse:

1. Neutrino Burst
2. Neutron Star (or Black Hole) Remnant

Formation of a Black Hole

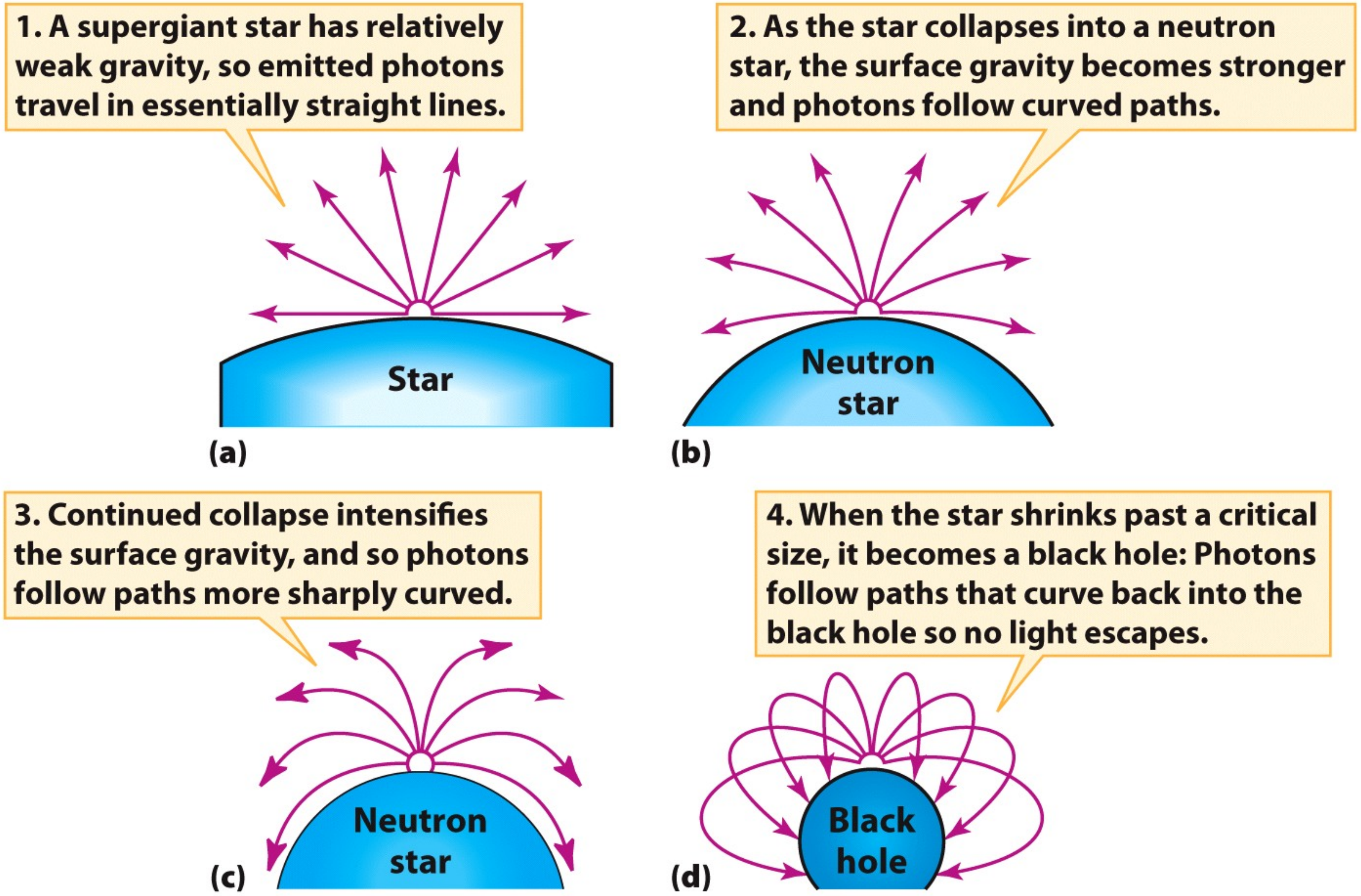


Figure 21-8
Universe, Tenth Edition

Summary of Stellar Remnants

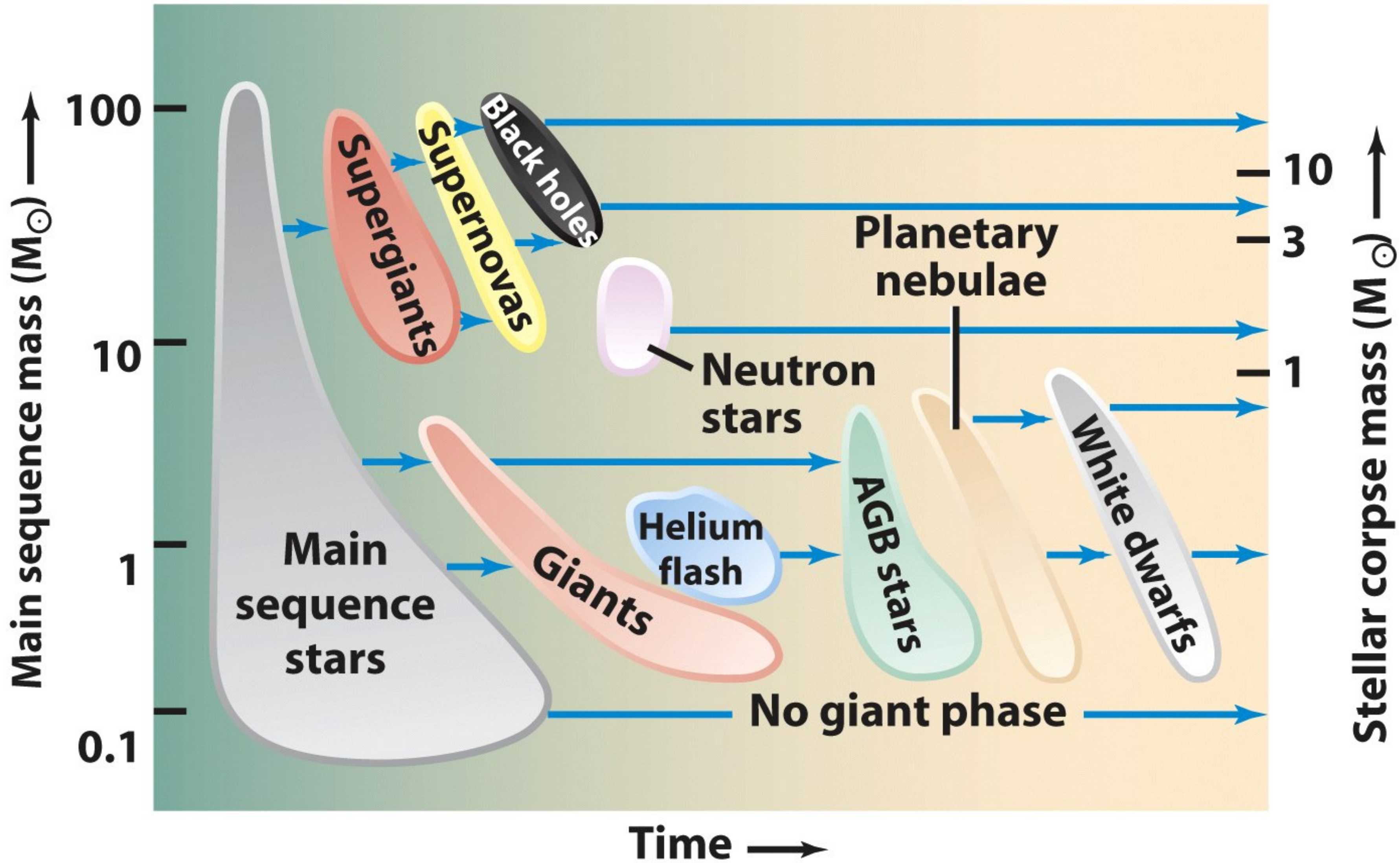
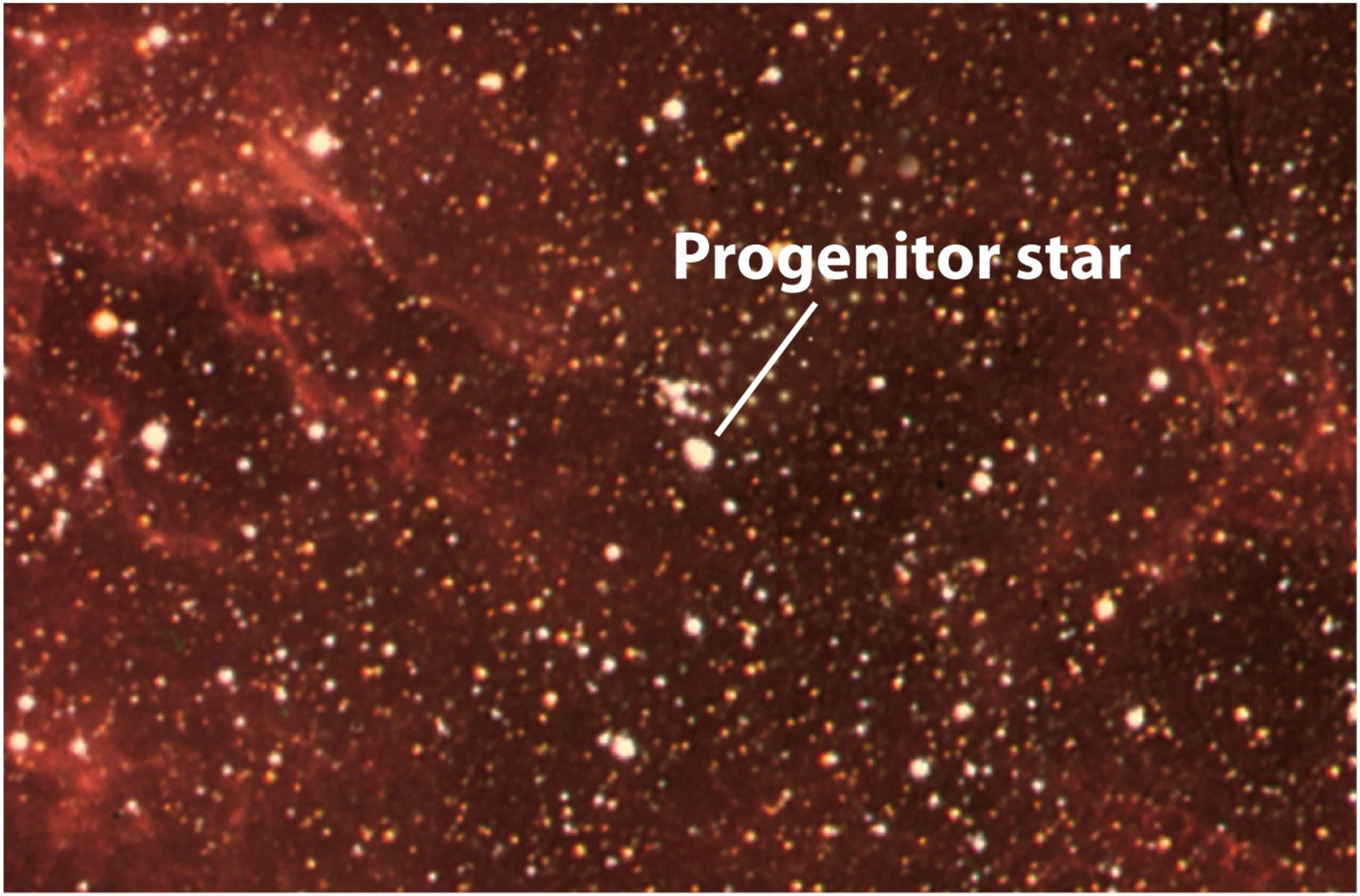


Figure 20-26a
Universe, Eighth Edition

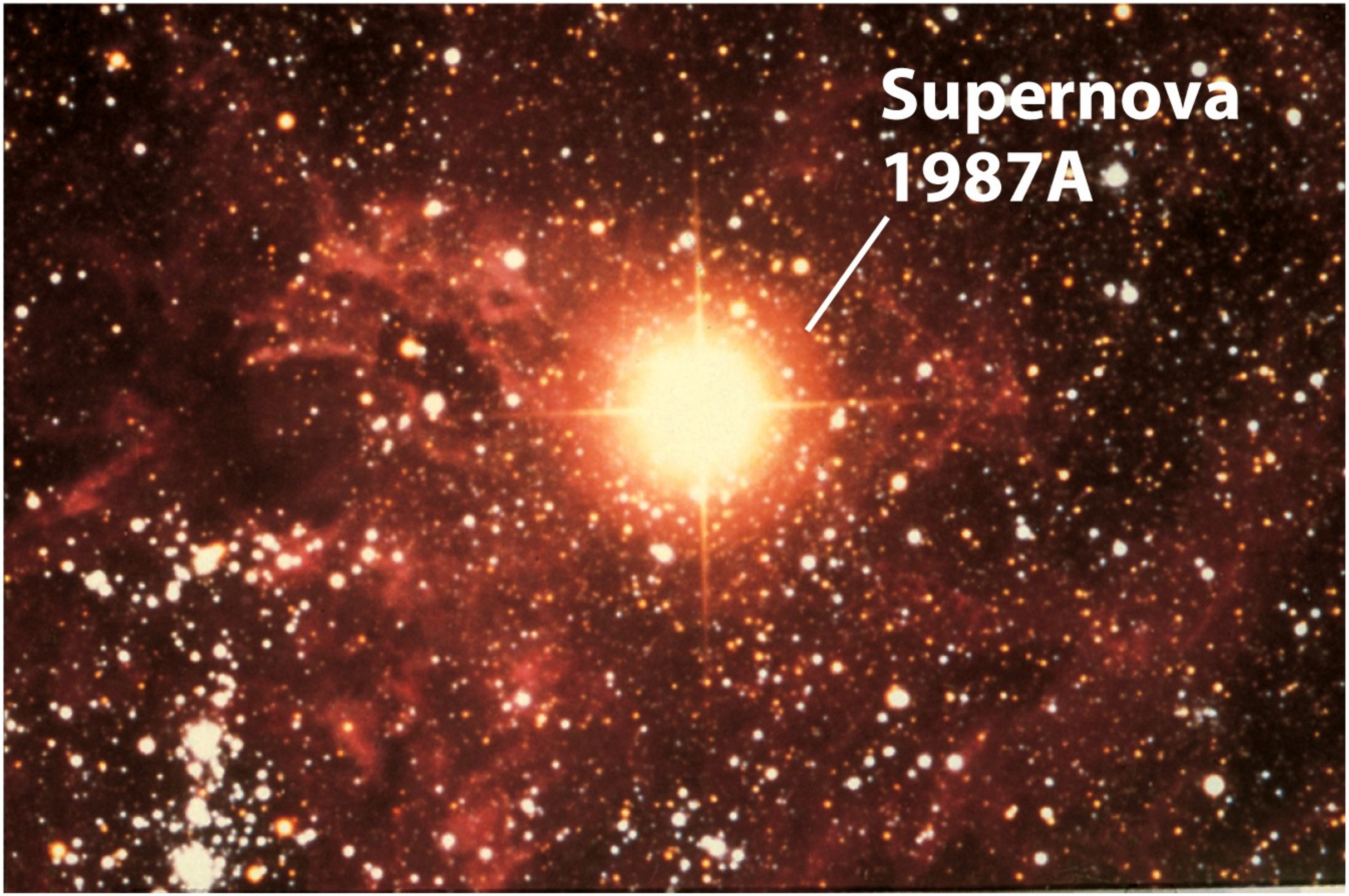
Neutron "Stars"

- Density similar to atomic nuclei
- Neutron degeneracy pressure holds the star up against gravity.
- 1 teaspoon would weigh 10^8 tons!
- A 1.4 M_O NS has a radius of just 10 km.
- Only possible in a small range
  - < 1.44 M_O, get a white dwarf instead
  - > 3-4 M_O, collapse continues to black hole



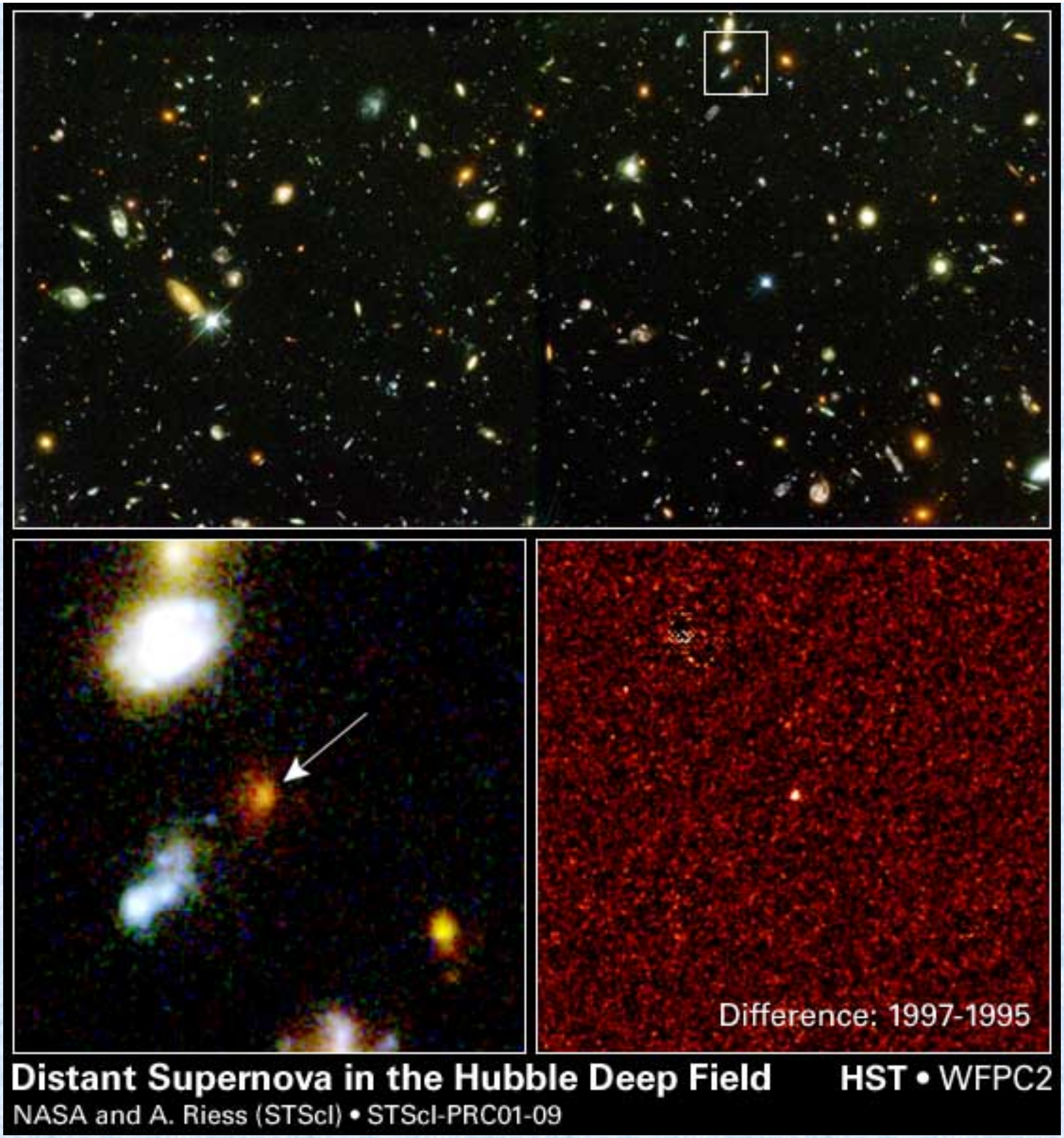
Before the star exploded

Figure 20-16a
Universe, Tenth Edition
Australian Astronomical Observatory/David Malin Images



After the star exploded

Figure 20-16b
Universe, Tenth Edition
Australian Astronomical Observatory/David Malin Images



The most distant supernova. Supernovae are so bright (~7 billion solar luminosities) that you can see them very far away. This one was dates from 10 billion years ago.

The Spectra of Core-Collapse Supernova Differ from the Thermonuclear Explosion of a WD

(d) Type II supernova

- The spectrum has prominent hydrogen lines such as H_α.
- Produced by core collapse in a massive star whose outer layers were largely intact.

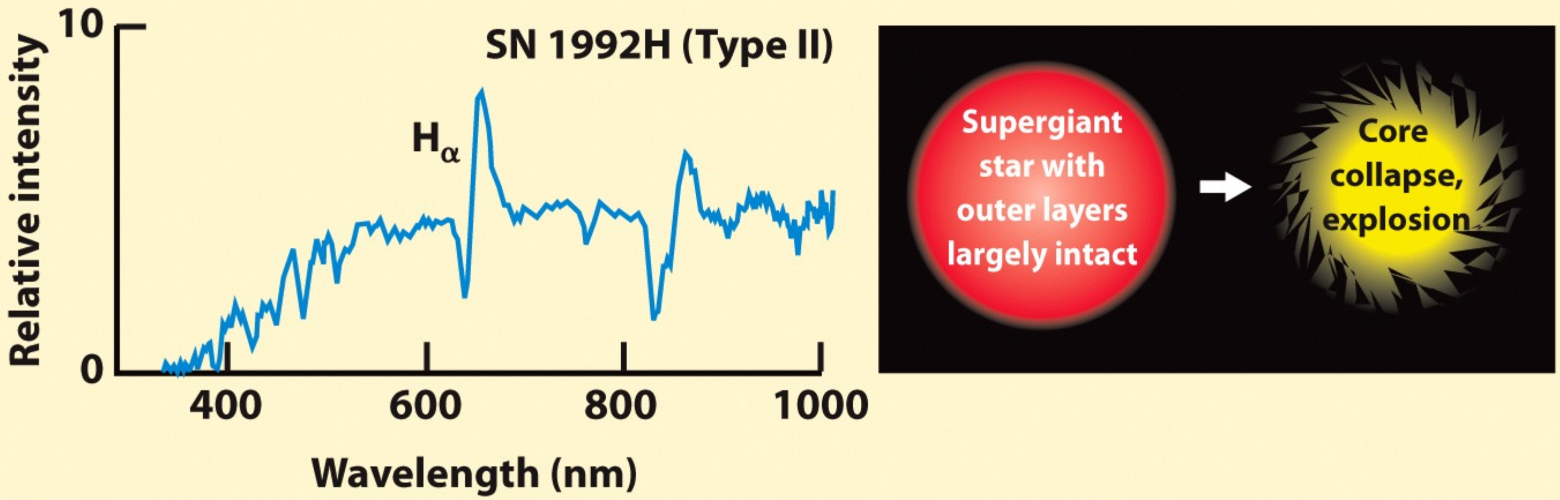
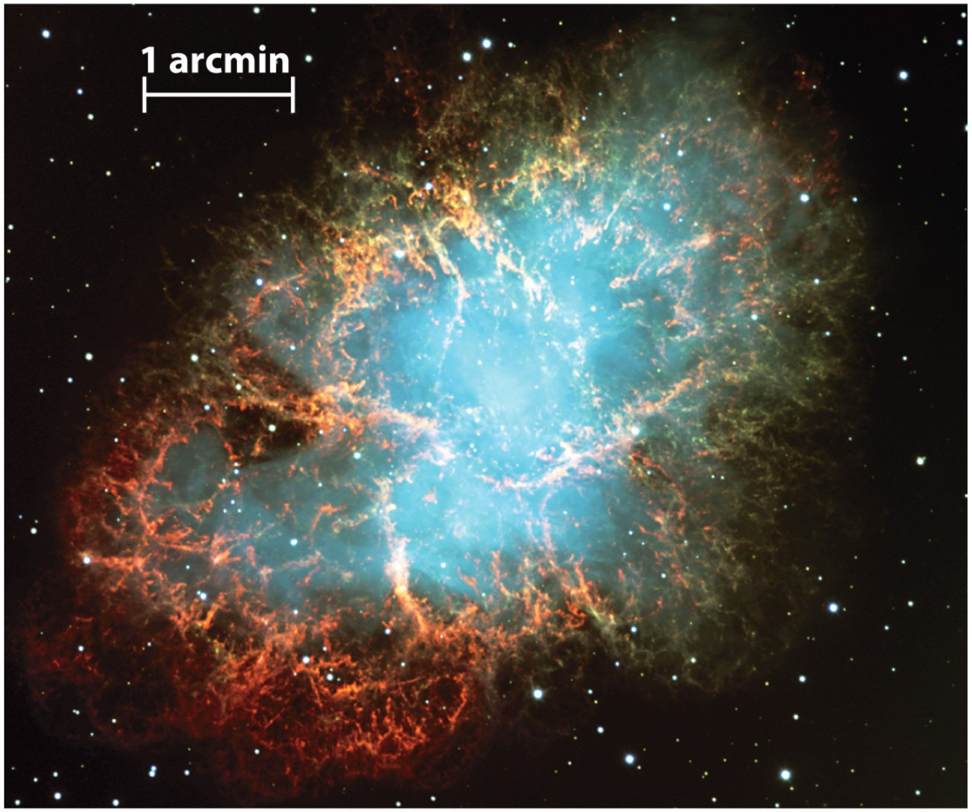


Figure 20-18d
Universe, Tenth Edition

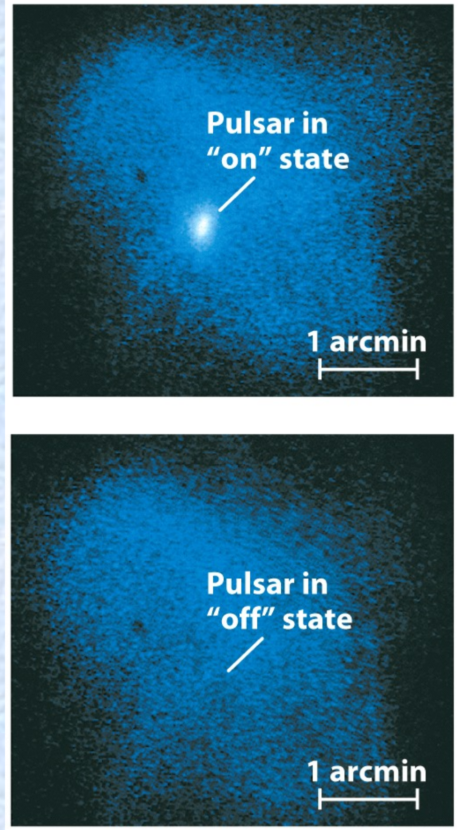
A Record of a Supernova Explosion from the 11th Century

Figure 20-25
Universe, Tenth Edition
Courtesy of National Parks Service



The Crab Nebula

Figure 20-26a
Universe, Tenth Edition
The FORS Team, VLT, European Southern Observatory



The Crab pulsar in X-rays

Figure 20-26c
Universe, Tenth Edition
Harvard-Smithsonian Center for Astrophysics

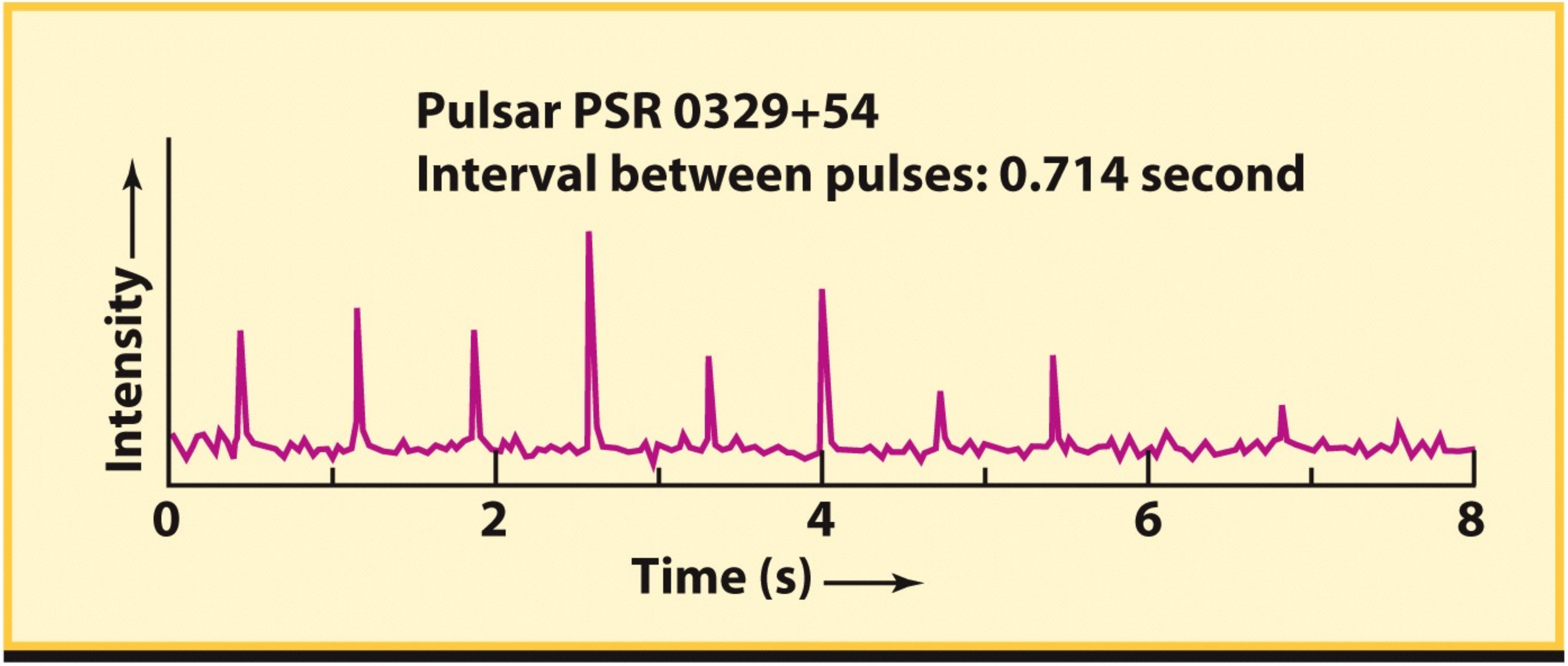
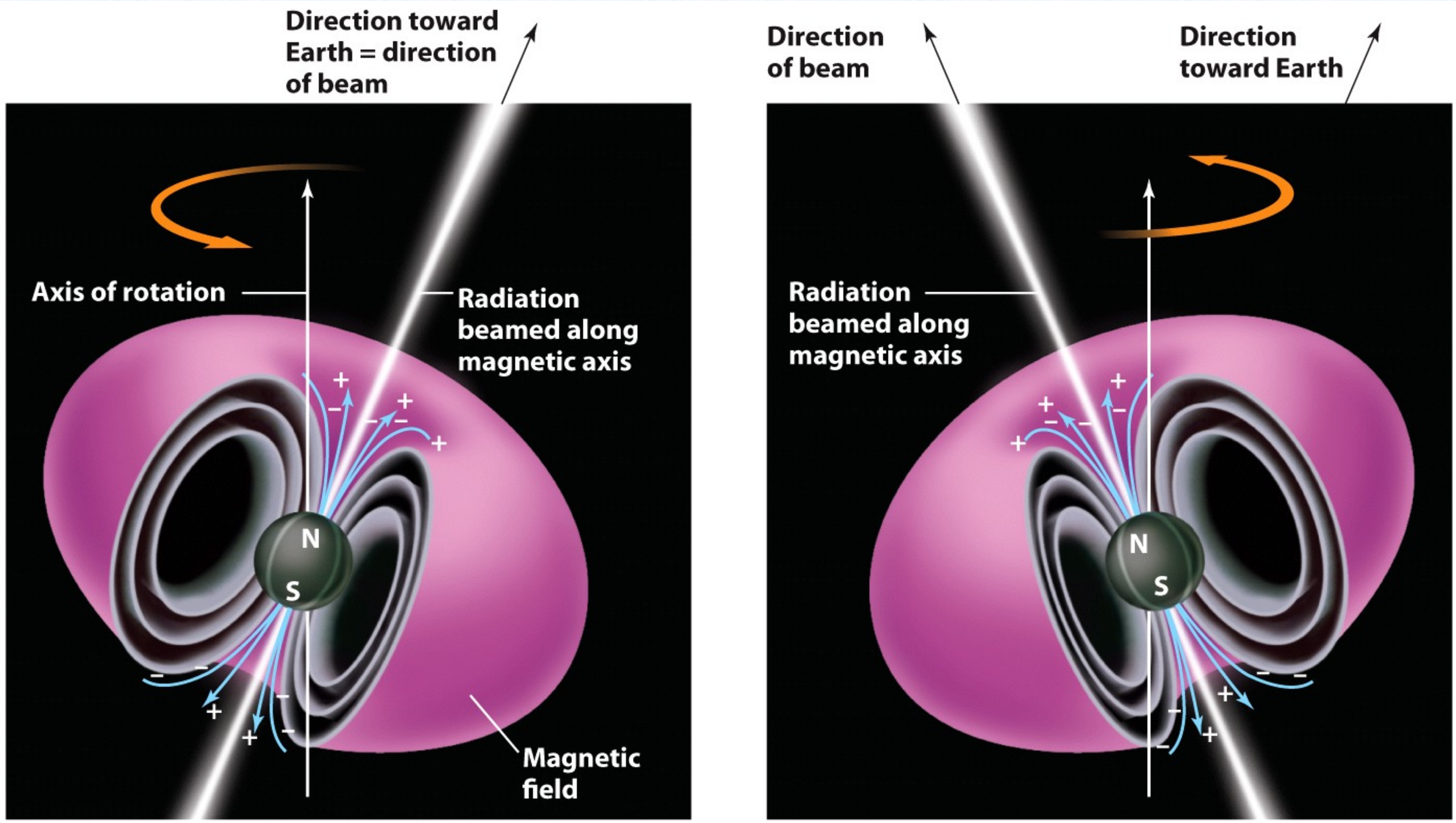


Figure 20-27
Universe, Tenth Edition



(a) One of the beams from the rotating neutron star is aimed toward Earth: We detect a pulse of radiation.

(b) Half a rotation later, neither beam is aimed toward Earth: We detect that the radiation is "off."

Figure 20-29
Universe, Tenth Edition

Elements heavier than iron are produced by nuclear reactions

A. in a white dwarf.
B. in a neutron star.
C. during a supernova explosion of a massive star.
D. in the shells around the core of a massive star.
E. in the core of a massive star just before it explodes as a supernova.

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A20.8

A neutron star can be

A. left behind after a Type Ia supernova explosion.
B. created if a star stops burning hydrogen and contracts.
C. created if a star stops burning helium and contracts.
D. left behind after a Type II supernova explosion.
E. left behind after a star of $M < 1.4\ M_{\odot}$ experiences a planetary nebula.

A neutron star can be

A. left behind after a Type Ia supernova explosion.
B. created if a star stops burning hydrogen and contracts.
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D. left behind after a Type II supernova explosion.
E. left behind after a star of $M < 1.4\ M_{\odot}$ experiences a planetary nebula.

A neutron star

A. spins very rapidly, because the star from which it evolved was spinning very rapidly.
B. spins very slowly, because the star from which it evolved was spinning very slowly.
C. spins very rapidly, because as the star from which it evolved underwent collapse, its rotation rate speeded up to conserve angular momentum.
D. spins very rapidly, because as the star from which it evolved underwent collapse, its angular momentum dissipated.
E. spins very slowly, because the star from which it evolved was spinning very rapidly.

A neutron star

A. spins very rapidly, because the star from which it evolved was spinning very rapidly.
B. spins very slowly, because the star from which it evolved was spinning very slowly.
C. spins very rapidly, because as the star from which it evolved underwent collapse, its rotation rate speeded up to conserve angular momentum.
D. spins very rapidly, because as the star from which it evolved underwent collapse, its angular momentum dissipated.
E. spins very slowly, because the star from which it evolved was spinning very rapidly.

Summary

- Late evolution and death of intermediate-mass stars (about 0.4 $M_\odot$ to about 4 $M_\odot$):
  - red giant when shell hydrogen fusion begins,
  - a horizontal-branch star when core helium fusion begins
  - asymptotic giant branch star when the no more helium core fusion and shell helium fusion begins.
  - Then alf of the mass of the star is ejected exposing the CO core of the star. The core is a white dwarf the envelope a planetary nebula.
- Late Evolution and death of High-Mass Star (>4 $M_\odot$)
  - Can undergo carbon fusion, neon fusion, oxygen fusion, and silicon fusion, etc
  - The highest mass stars eventually find themselves with a iron-rich core surrounded by burning shells (>8 $M_\odot$). The star dies in a violent cataclysm in which its core collapses and most of its matter is ejected into space: a supernova!! 99% of the energy can come out in neutrinos!