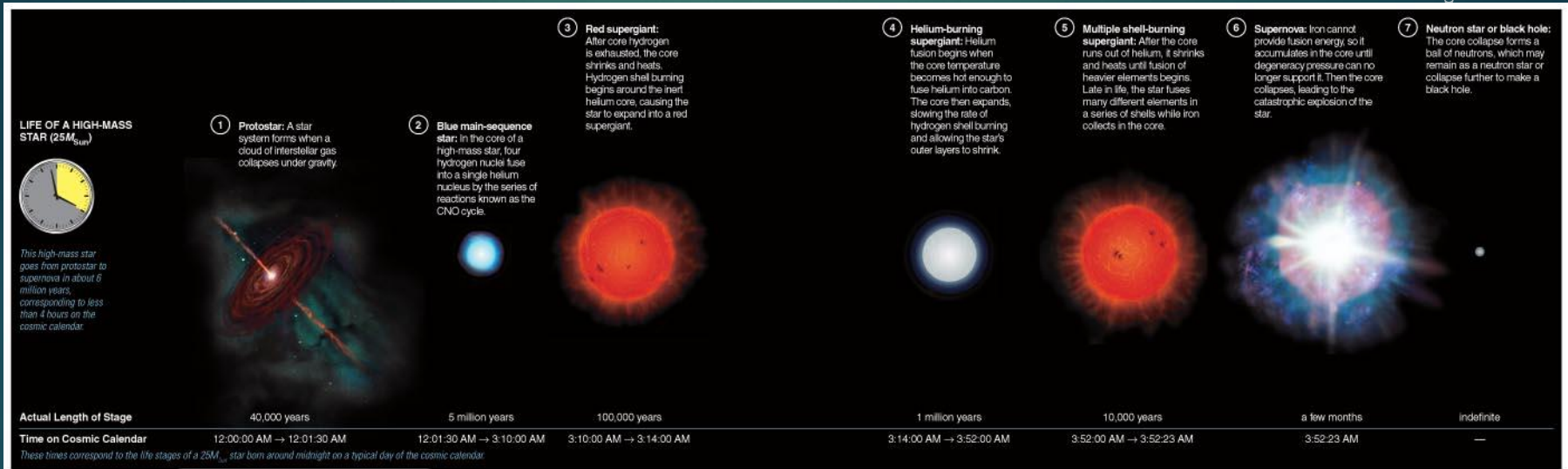


# 17.3 Life as a High-Mass Star

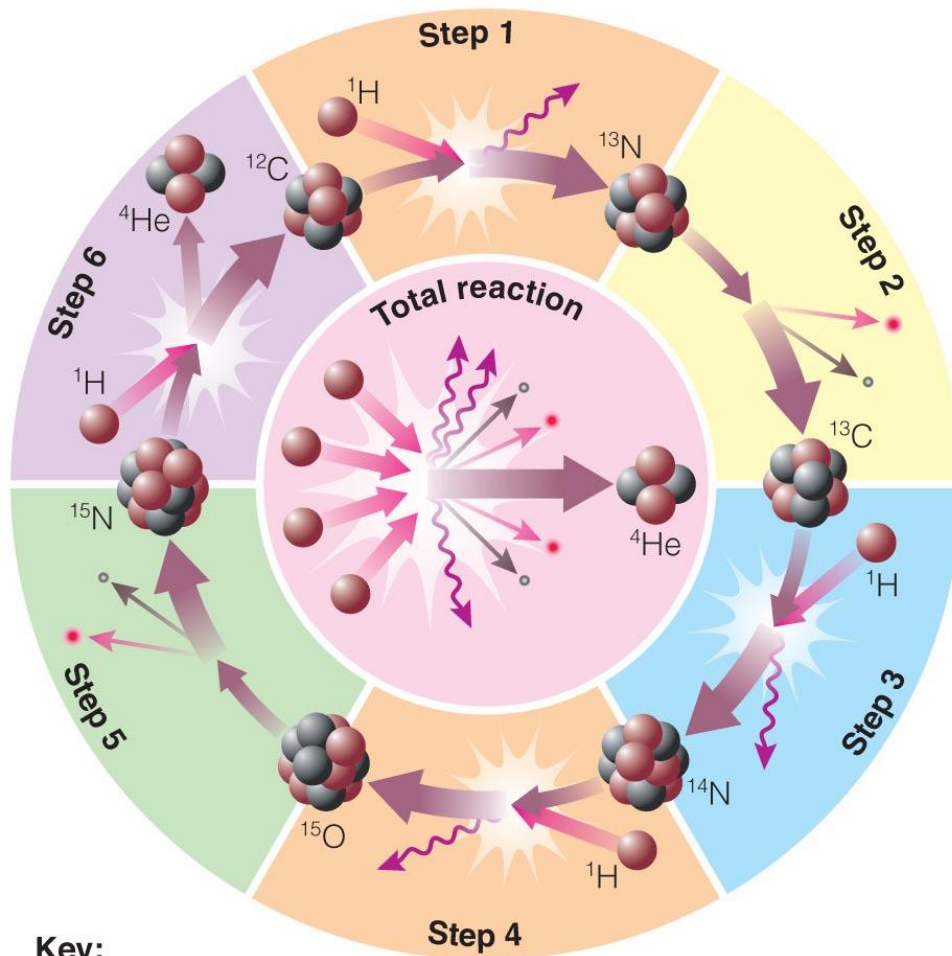
- ▶ Our goals for learning:
  - ▶ **What are the life stages of a high-mass star?**
  - ▶ **How do high-mass stars make the elements necessary for life?**
  - ▶ **How does a high-mass star die?**

# What are the life stages of a high-mass star?

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# CNO Cycle



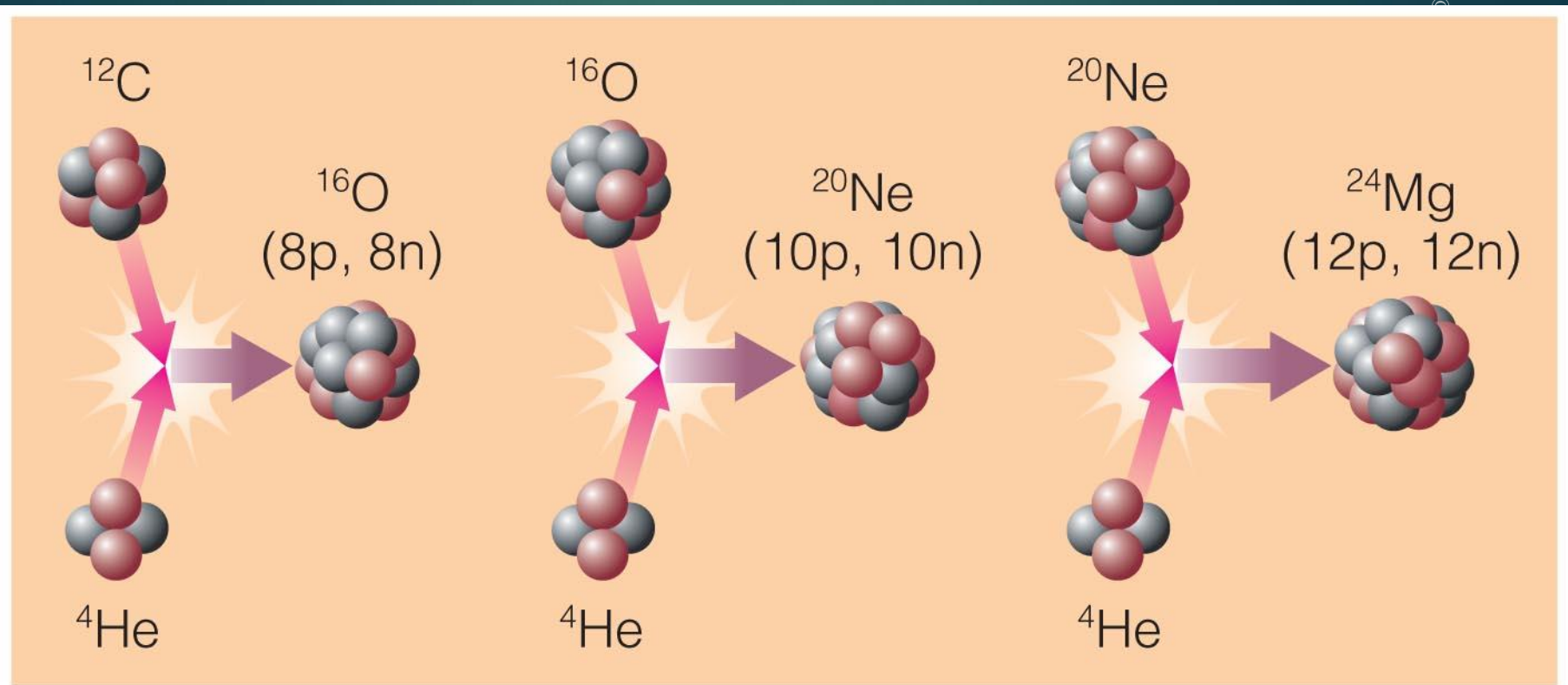
▶ High-mass main-sequence stars fuse H to He at a higher rate using carbon, nitrogen, and oxygen as catalysts.

▶ Greater core temperature enables hydrogen nuclei to overcome greater repulsion.

# Life Stages of High-Mass Stars

- ▶ Late life stages of high-mass stars are similar to those of low-mass stars:
  - ▶ Hydrogen core fusion (main sequence)
  - ▶ Hydrogen shell burning (supergiant)
  - ▶ Helium core fusion (supergiant)

# How do high-mass stars make the elements necessary for life?



a Helium-capture reactions.



### Key

12	Atomic number
<b>Mg</b>	Element's symbol
Magnesium	Element's name
24.305	Atomic mass*

\*Atomic masses are fractions because they represent a weighted average of atomic masses of different isotopes—in proportion to the abundance of each isotope on Earth.

1 <b>H</b> Hydrogen 1.00794																	2 <b>He</b> Helium 4.003
3 <b>Li</b> Lithium 6.941	4 <b>Be</b> Beryllium 9.01218																
11 <b>Na</b> Sodium 22.990	12 <b>Mg</b> Magnesium 24.305																
19 <b>K</b> Potassium 39.098	20 <b>Ca</b> Calcium 40.08	21 <b>Sc</b> Scandium 44.956	22 <b>Ti</b> Titanium 47.88	23 <b>V</b> Vanadium 50.94	24 <b>Cr</b> Chromium 51.996	25 <b>Mn</b> Manganese 54.938	26 <b>Fe</b> Iron 55.847	27 <b>Co</b> Cobalt 58.9332	28 <b>Ni</b> Nickel 58.69	29 <b>Cu</b> Copper 63.546	30 <b>Zn</b> Zinc 65.39	31 <b>Ga</b> Gallium 69.72	32 <b>Ge</b> Germanium 72.59	33 <b>As</b> Arsenic 74.922	34 <b>Se</b> Selenium 78.96	35 <b>Br</b> Bromine 79.904	36 <b>Kr</b> Krypton 83.80
37 <b>Rb</b> Rubidium 85.468	38 <b>Sr</b> Strontium 87.62	39 <b>Y</b> Yttrium 88.9059	40 <b>Zr</b> Zirconium 91.224	41 <b>Nb</b> Niobium 92.91	42 <b>Mo</b> Molybdenum 95.94	43 <b>Tc</b> Technetium (98)	44 <b>Ru</b> Ruthenium 101.07	45 <b>Rh</b> Rhodium 102.906	46 <b>Pd</b> Palladium 106.42	47 <b>Ag</b> Silver 107.868	48 <b>Cd</b> Cadmium 112.41	49 <b>In</b> Indium 114.82	50 <b>Sn</b> Tin 118.71	51 <b>Sb</b> Antimony 121.75	52 <b>Te</b> Tellurium 127.60	53 <b>I</b> Iodine 126.905	54 <b>Xe</b> Xenon 131.29
55 <b>Cs</b> Cesium 132.91	56 <b>Ba</b> Barium 137.34	72 <b>Hf</b> Hafnium 178.49	73 <b>Ta</b> Tantalum 180.95	74 <b>W</b> Tungsten 183.85	75 <b>Re</b> Rhenium 186.207	76 <b>Os</b> Osmium 190.2	77 <b>Ir</b> Iridium 192.22	78 <b>Pt</b> Platinum 195.08	79 <b>Au</b> Gold 196.967	80 <b>Hg</b> Mercury 200.59	81 <b>Tl</b> Thallium 204.383	82 <b>Pb</b> Lead 207.2	83 <b>Bi</b> Bismuth 208.98	84 <b>Po</b> Polonium (209)	85 <b>At</b> Astatine (210)	86 <b>Rn</b> Radon (222)	
87 <b>Fr</b> Francium (223)	88 <b>Ra</b> Radium 226.0254	104 <b>Rf</b> Rutherfordium (263)	105 <b>Db</b> Dubnium (262)	106 <b>Sg</b> Seaborgium (266)	107 <b>Bh</b> Bohrium (267)	108 <b>Hs</b> Hassium (277)	109 <b>Mt</b> Meitnerium (268)	110 <b>Ds</b> Darmstadtium (281)	111 <b>Rg</b> Roentgenium (272)	112 <b>Cn</b> Copernicium (285)	113 <b>Uut</b> Ununtrium (284)	114 <b>Uuq</b> Ununquadium (289)	115 <b>Uup</b> Ununpentium (288)	116 <b>Uuh</b> Ununhexium (292)	117 <b>Uus</b> Ununseptium (294)	118 <b>Uuo</b> Ununoctium (294)	

### Lanthanide Series

57 <b>La</b> Lanthanum 138.906	58 <b>Ce</b> Cerium 140.12	59 <b>Pr</b> Praseodymium 140.908	60 <b>Nd</b> Neodymium 144.24	61 <b>Pm</b> Promethium (145)	62 <b>Sm</b> Samarium 150.36	63 <b>Eu</b> Europium 151.96	64 <b>Gd</b> Gadolinium 157.25	65 <b>Tb</b> Terbium 158.925	66 <b>Dy</b> Dysprosium 162.50	67 <b>Ho</b> Holmium 164.93	68 <b>Er</b> Erbium 167.26	69 <b>Tm</b> Thulium 168.934	70 <b>Yb</b> Ytterbium 173.04	71 <b>Lu</b> Lutetium 174.967
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### Actinide Series

89 <b>Ac</b> Actinium 227.028	90 <b>Th</b> Thorium 232.038	91 <b>Pa</b> Protactinium 231.036	92 <b>U</b> Uranium 238.029	93 <b>Np</b> Neptunium 237.048	94 <b>Pu</b> Plutonium (244)	95 <b>Am</b> Americium (243)	96 <b>Cm</b> Curium (247)	97 <b>Bk</b> Berkelium (247)	98 <b>Cf</b> Californium (251)	99 <b>Es</b> Einsteinium (252)	100 <b>Fm</b> Fermium (257)	101 <b>Md</b> Mendelevium (258)	102 <b>No</b> Nobelium (259)	103 <b>Lr</b> Lawrencium (260)
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► Big Bang made 75% H, 25% He; stars make everything else.

### Key

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Magnesium	Element's name
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37 <b>Rb</b> Rubidium 85.468	38 <b>Sr</b> Strontium 87.62	39 <b>Y</b> Yttrium 88.9059	40 <b>Zr</b> Zirconium 91.224	41 <b>Nb</b> Niobium 92.91	42 <b>Mo</b> Molybdenum 95.94	43 <b>Tc</b> Technetium (98)	44 <b>Ru</b> Ruthenium 101.07	45 <b>Rh</b> Rhodium 102.906	46 <b>Pd</b> Palladium 106.42	47 <b>Ag</b> Silver 107.868	48 <b>Cd</b> Cadmium 112.41	49 <b>In</b> Indium 114.82	50 <b>Sn</b> Tin 118.71	51 <b>Sb</b> Antimony 121.75	52 <b>Te</b> Tellurium 127.60	53 <b>I</b> Iodine 126.905	54 <b>Xe</b> Xenon 131.29
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► Helium fusion can make carbon in low-mass stars.



### Key

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<b>Mg</b>	Element's symbol
Magnesium	Element's name
24.305	Atomic mass*

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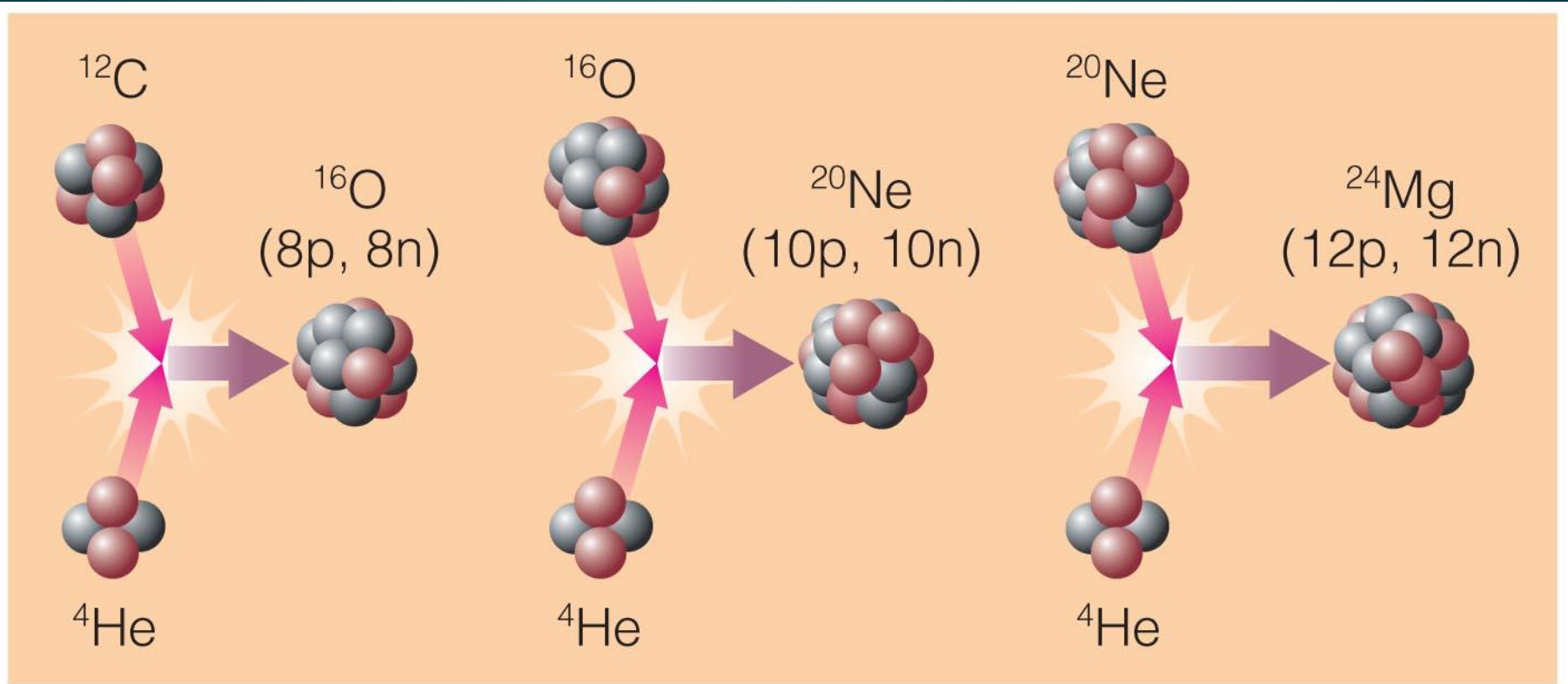
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► CNO cycle can change carbon into nitrogen and oxygen.



# Helium Capture



a Helium-capture reactions.

- ▶ High core temperatures allow helium to fuse with heavier elements.

### Key

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3 <b>Li</b> Lithium 6.941	4 <b>Be</b> Beryllium 9.01218																	5 <b>B</b> Boron 10.81	6 <b>C</b> Carbon 12.011	7 <b>N</b> Nitrogen 14.007	8 <b>O</b> Oxygen 15.999	9 <b>F</b> Fluorine 18.988	10 <b>Ne</b> Neon 20.179									
11 <b>Na</b> Sodium 22.990	12 <b>Mg</b> Magnesium 24.305																	13 <b>Al</b> Aluminum 26.98	14 <b>Si</b> Silicon 28.086	15 <b>P</b> Phosphorus 30.974	16 <b>S</b> Sulfur 32.06	17 <b>Cl</b> Chlorine 35.453	18 <b>Ar</b> Argon 39.948									
19 <b>K</b> Potassium 39.098	20 <b>Ca</b> Calcium 40.08	21 <b>Sc</b> Scandium 44.956	22 <b>Ti</b> Titanium 47.88	23 <b>V</b> Vanadium 50.94	24 <b>Cr</b> Chromium 51.996	25 <b>Mn</b> Manganese 54.938	26 <b>Fe</b> Iron 55.847	27 <b>Co</b> Cobalt 58.9332	28 <b>Ni</b> Nickel 58.69	29 <b>Cu</b> Copper 63.546	30 <b>Zn</b> Zinc 65.39	31 <b>Ga</b> Gallium 69.72	32 <b>Ge</b> Germanium 72.59	33 <b>As</b> Arsenic 74.922	34 <b>Se</b> Selenium 78.96	35 <b>Br</b> Bromine 79.904	36 <b>Kr</b> Krypton 83.80															
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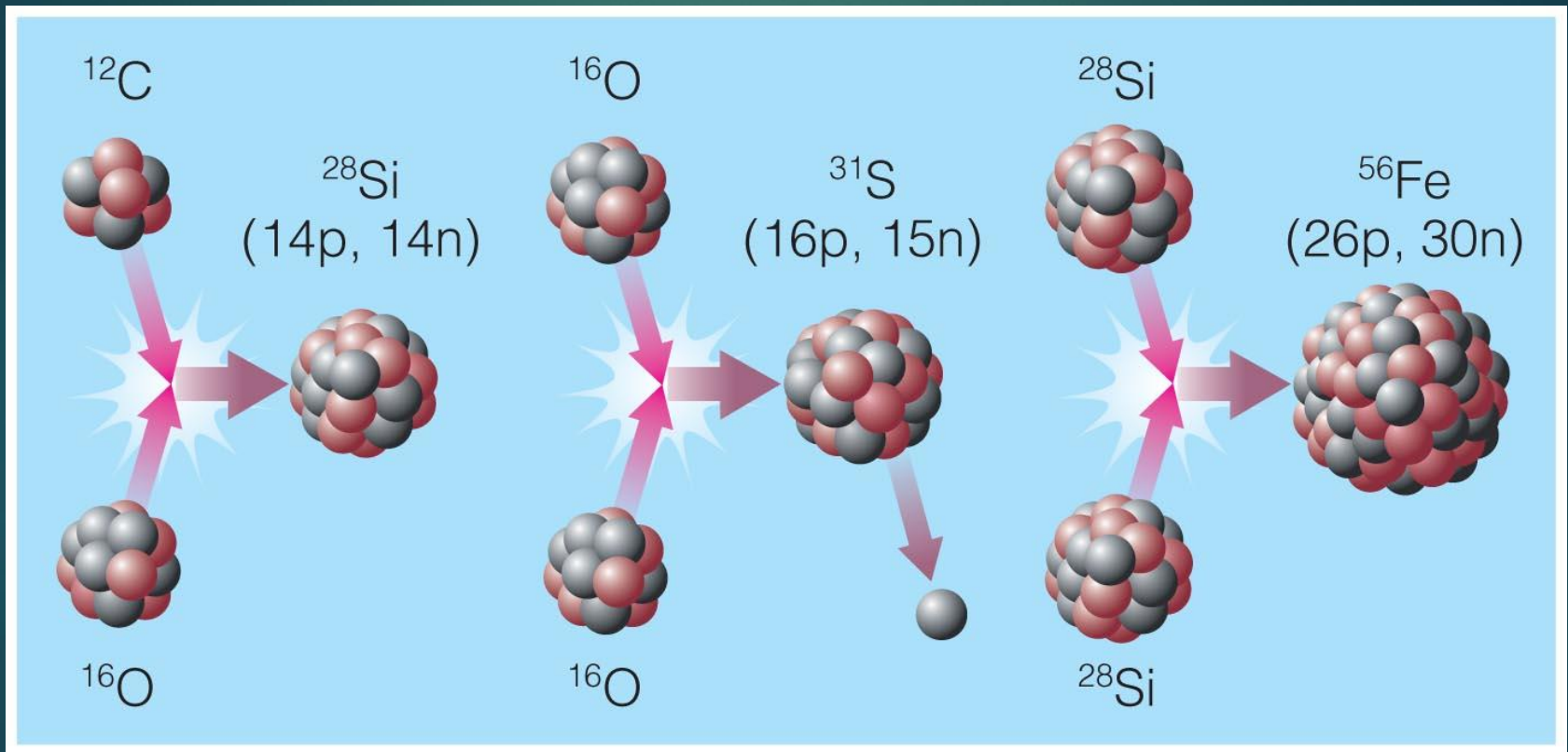
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► Helium capture builds carbon into oxygen, neon, magnesium, and other elements.

# Advanced Nuclear Burning

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- ▶ Core temperatures in stars with  $>8M_{\text{Sun}}$  allow fusion of elements as heavy as iron.



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1 <b>H</b> Hydrogen 1.00794																	2 <b>He</b> Helium 4.003															
3 <b>Li</b> Lithium 6.941	4 <b>Be</b> Beryllium 9.01218																	5 <b>B</b> Boron 10.81	6 <b>C</b> Carbon 12.011	7 <b>N</b> Nitrogen 14.007	8 <b>O</b> Oxygen 15.999	9 <b>F</b> Fluorine 18.988	10 <b>Ne</b> Neon 20.179									
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19 <b>K</b> Potassium 39.098	20 <b>Ca</b> Calcium 40.08	21 <b>Sc</b> Scandium 44.956	22 <b>Ti</b> Titanium 47.88	23 <b>V</b> Vanadium 50.94	24 <b>Cr</b> Chromium 51.996	25 <b>Mn</b> Manganese 54.938	26 <b>Fe</b> Iron 55.847	27 <b>Co</b> Cobalt 58.9332	28 <b>Ni</b> Nickel 58.69	29 <b>Cu</b> Copper 63.546	30 <b>Zn</b> Zinc 65.39	31 <b>Ga</b> Gallium 69.72	32 <b>Ge</b> Germanium 72.59	33 <b>As</b> Arsenic 74.922	34 <b>Se</b> Selenium 78.96	35 <b>Br</b> Bromine 79.904	36 <b>Kr</b> Krypton 83.80															
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### Lanthanide Series

57 <b>La</b> Lanthanum 138.906	58 <b>Ce</b> Cerium 140.12	59 <b>Pr</b> Praseodymium 140.908	60 <b>Nd</b> Neodymium 144.24	61 <b>Pm</b> Promethium (145)	62 <b>Sm</b> Samarium 150.36	63 <b>Eu</b> Europium 151.96	64 <b>Gd</b> Gadolinium 157.25	65 <b>Tb</b> Terbium 158.925	66 <b>Dy</b> Dysprosium 162.50	67 <b>Ho</b> Holmium 164.93	68 <b>Er</b> Erbium 167.26	69 <b>Tm</b> Thulium 168.934	70 <b>Yb</b> Ytterbium 173.04	71 <b>Lu</b> Lutetium 174.967
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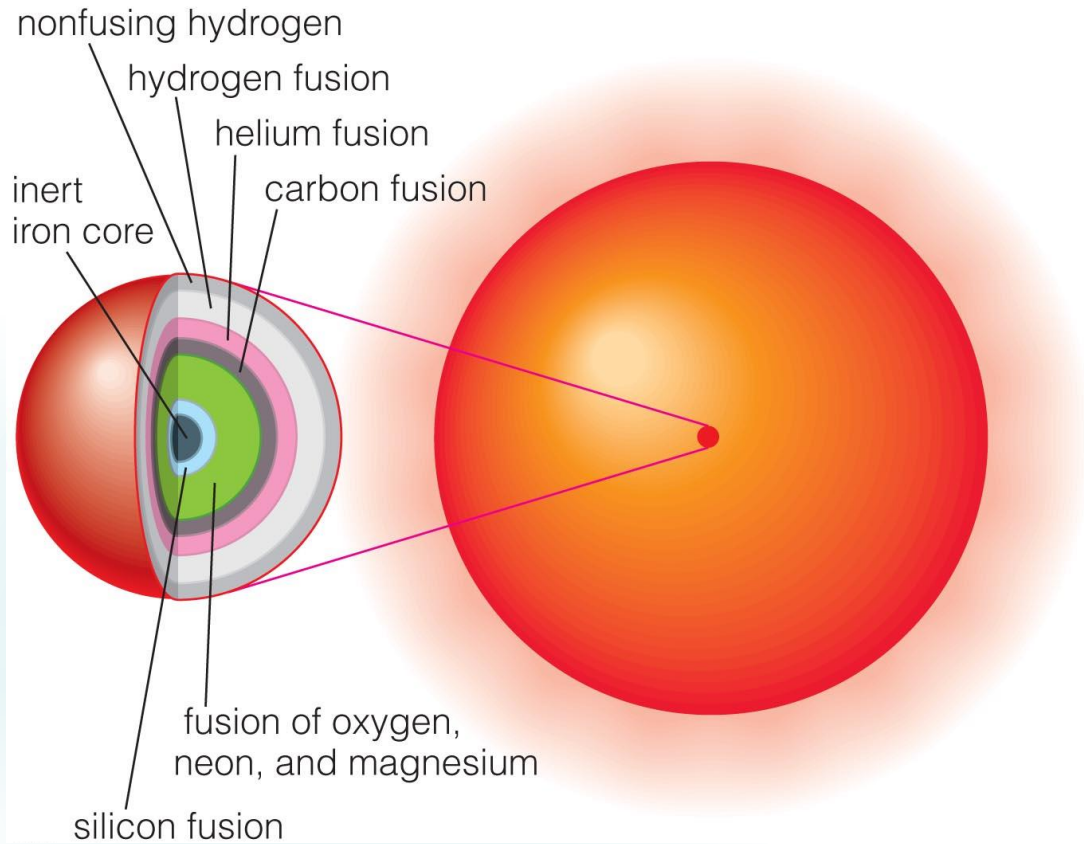
### Actinide Series

89 <b>Ac</b> Actinium 227.028	90 <b>Th</b> Thorium 232.038	91 <b>Pa</b> Protactinium 231.036	92 <b>U</b> Uranium 238.029	93 <b>Np</b> Neptunium 237.048	94 <b>Pu</b> Plutonium (244)	95 <b>Am</b> Americium (243)	96 <b>Cm</b> Curium (247)	97 <b>Bk</b> Berkelium (247)	98 <b>Cf</b> Californium (251)	99 <b>Es</b> Einsteinium (252)	100 <b>Fm</b> Fermium (257)	101 <b>Md</b> Mendelevium (258)	102 <b>No</b> Nobelium (259)	103 <b>Lr</b> Lawrencium (260)
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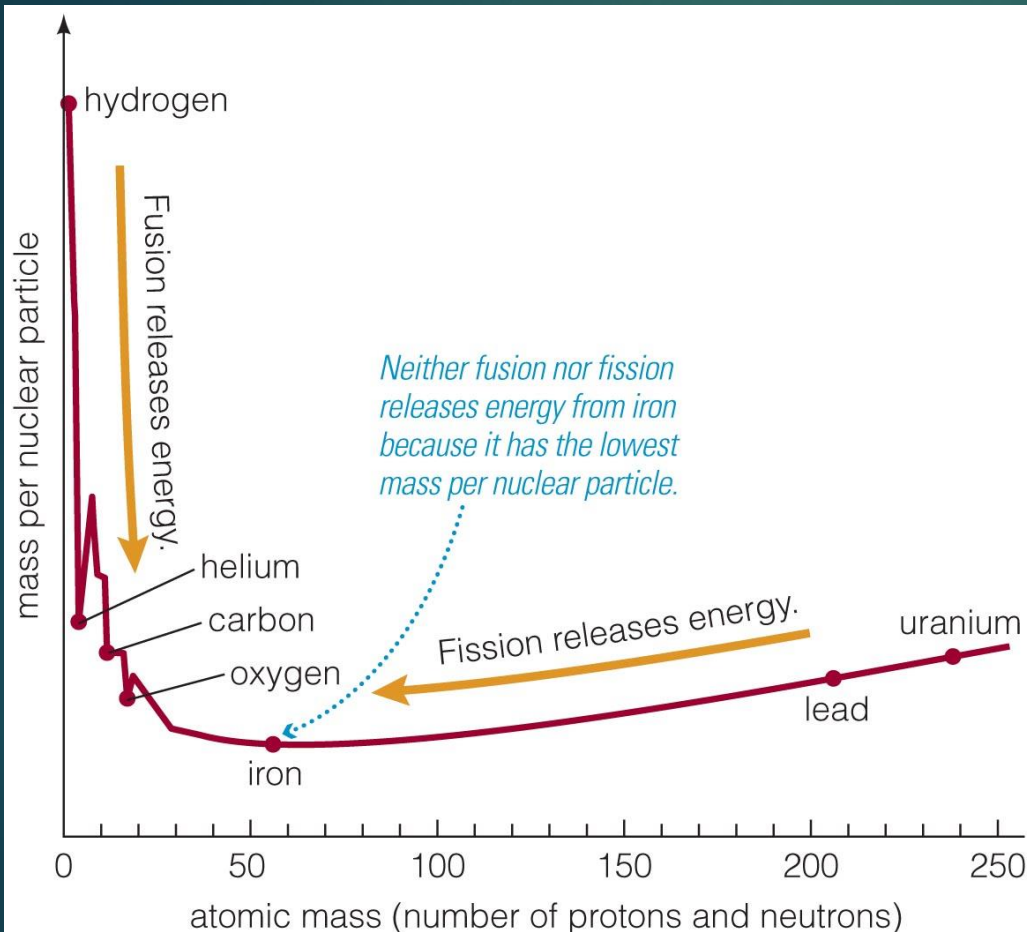
► Advanced reactions in stars make elements like Si, S, Ca, Fe.



# Multiple Shell Burning

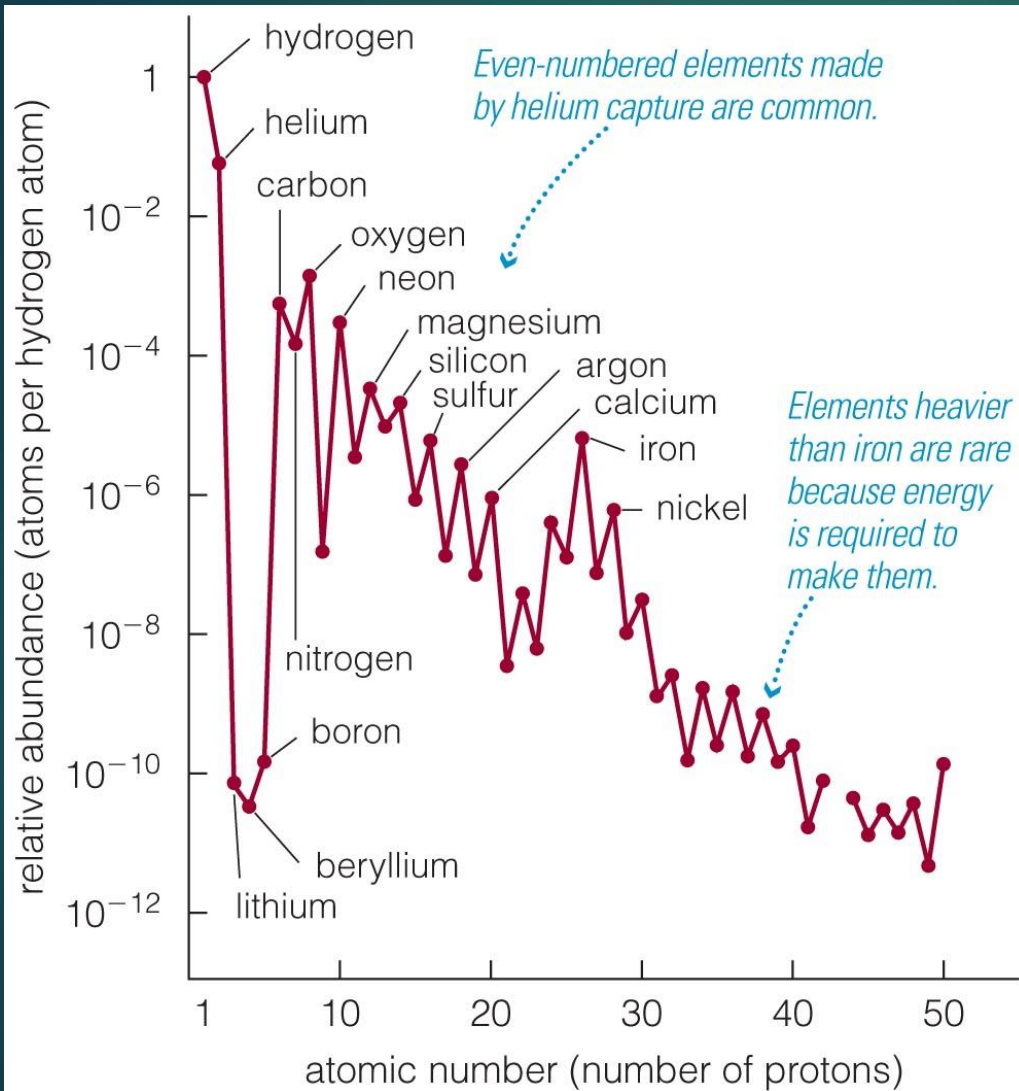


- ▶ Advanced nuclear burning proceeds in a series of nested shells.



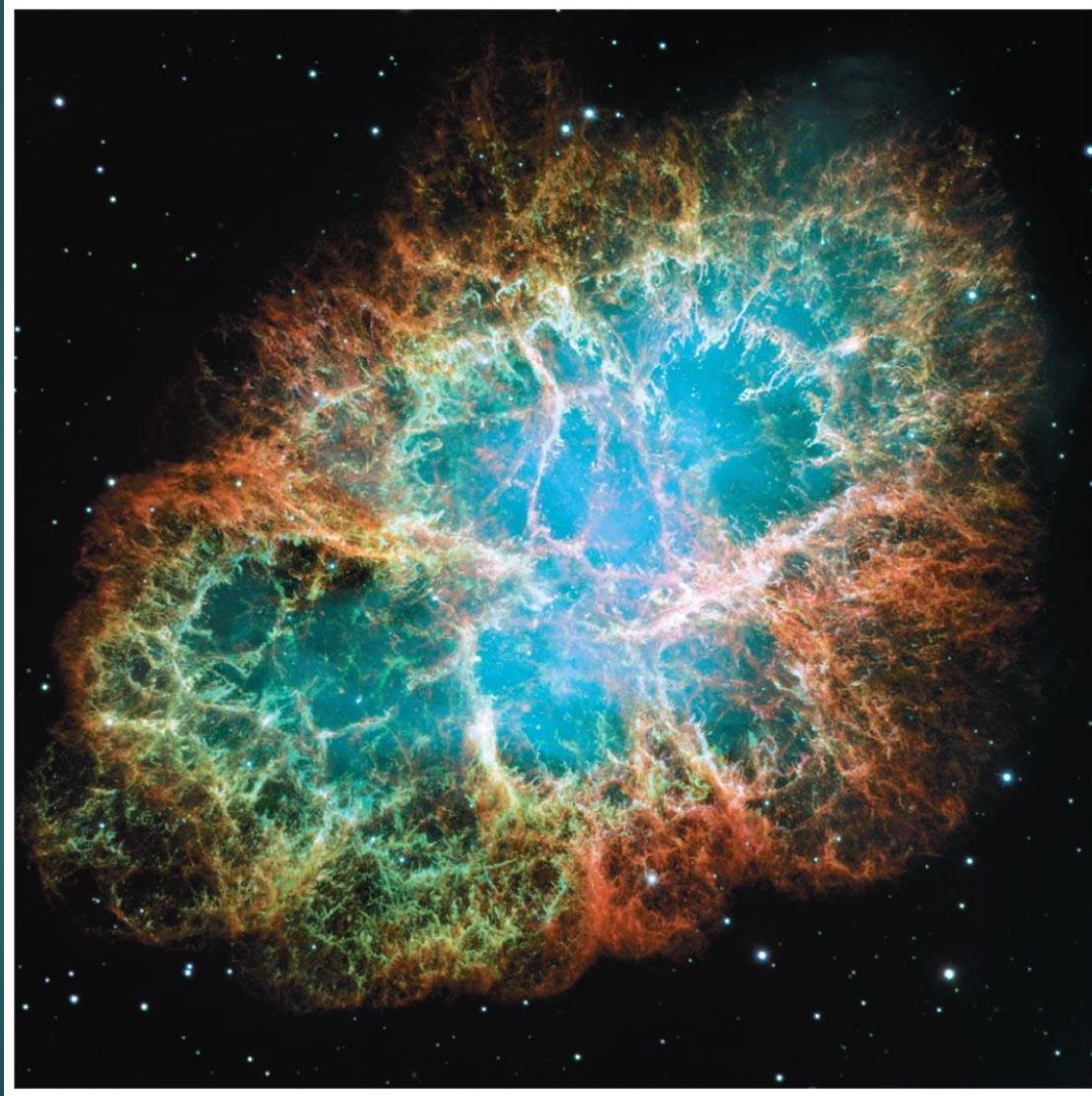
► Iron is a dead end for fusion because nuclear reactions involving iron do not release energy.

► (This is because iron has lowest mass per nuclear particle.)



- ▶ Evidence for helium capture:
- ▶ Higher abundances of elements with even numbers of protons

# How does a high-mass star die?





## The Death Sequence of a High-Mass Star

### Simplified core fusion cycle of high-mass star

Begin

#### Core Key:

nonburning hydrogen



hydrogen fusion



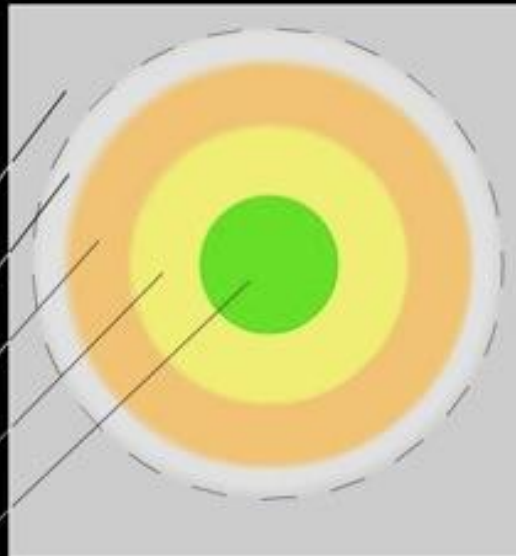
helium fusion



carbon fusion



inert oxygen



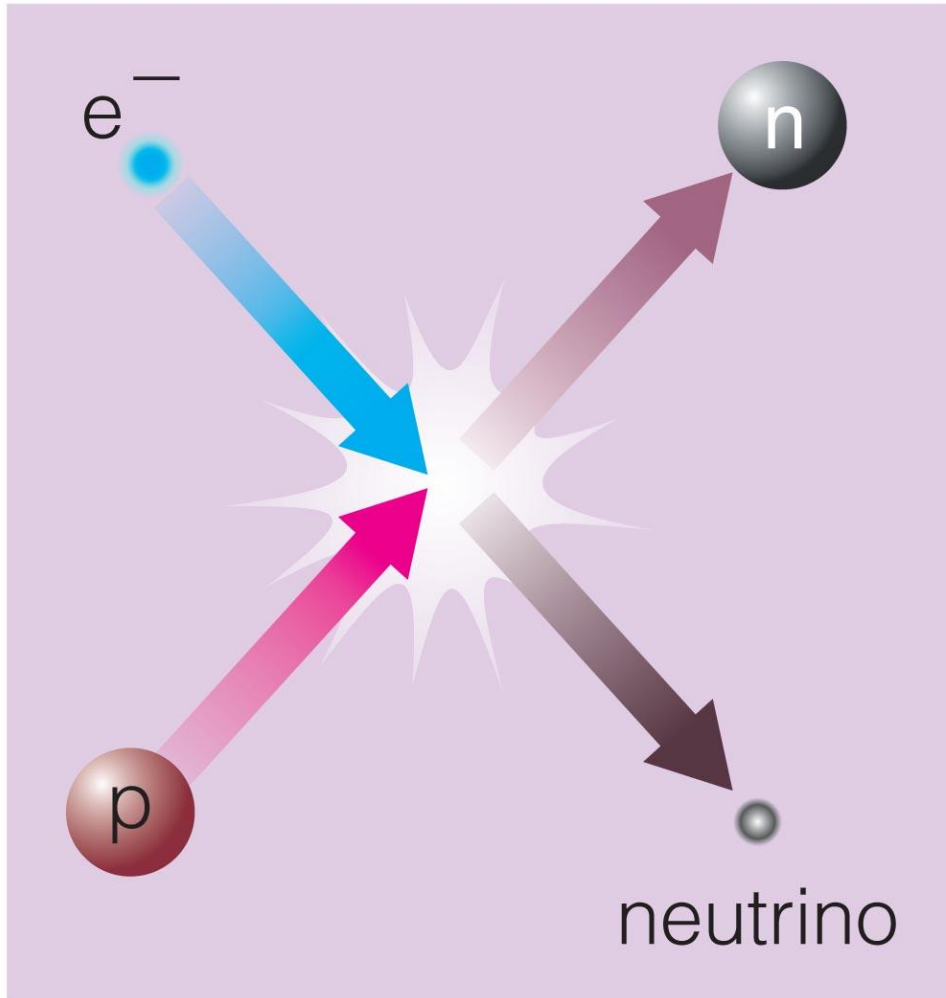
Cross Section of Stellar Core



View from Space

- ▶ Iron builds up in core until degeneracy pressure can no longer resist gravity.
- ▶ The core then suddenly collapses, creating a supernova explosion.

# Supernova Explosion



- ▶ Core degeneracy pressure goes away because electrons combine with protons, making neutrons and neutrinos.
- ▶ Neutrons collapse to the center, forming a **neutron star**.

### Key

12	Atomic number
<b>Mg</b>	Element's symbol
Magnesium	Element's name
24.305	Atomic mass*

\*Atomic masses are fractions because they represent a weighted average of atomic masses of different isotopes—in proportion to the abundance of each isotope on Earth.

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### Lanthanide Series

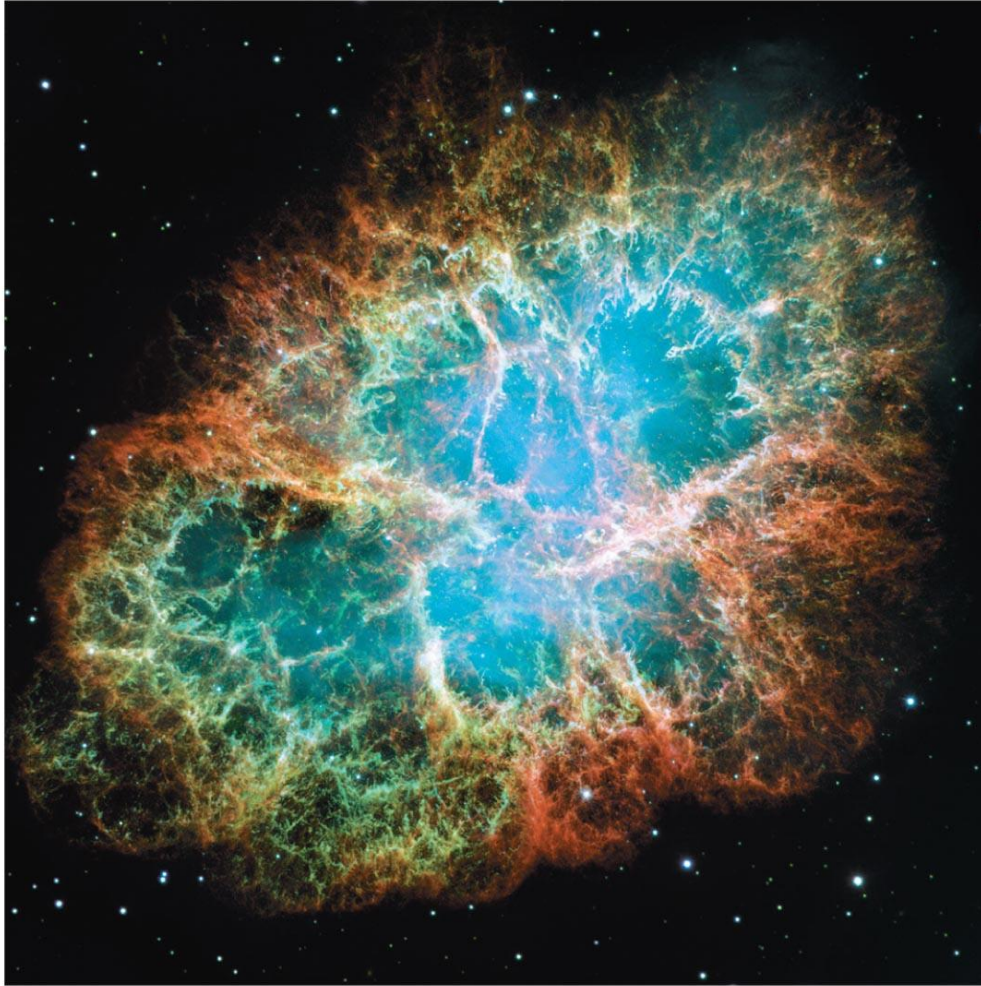
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► Energy and neutrons released in supernova explosion enable elements heavier than iron to form, including gold and uranium.

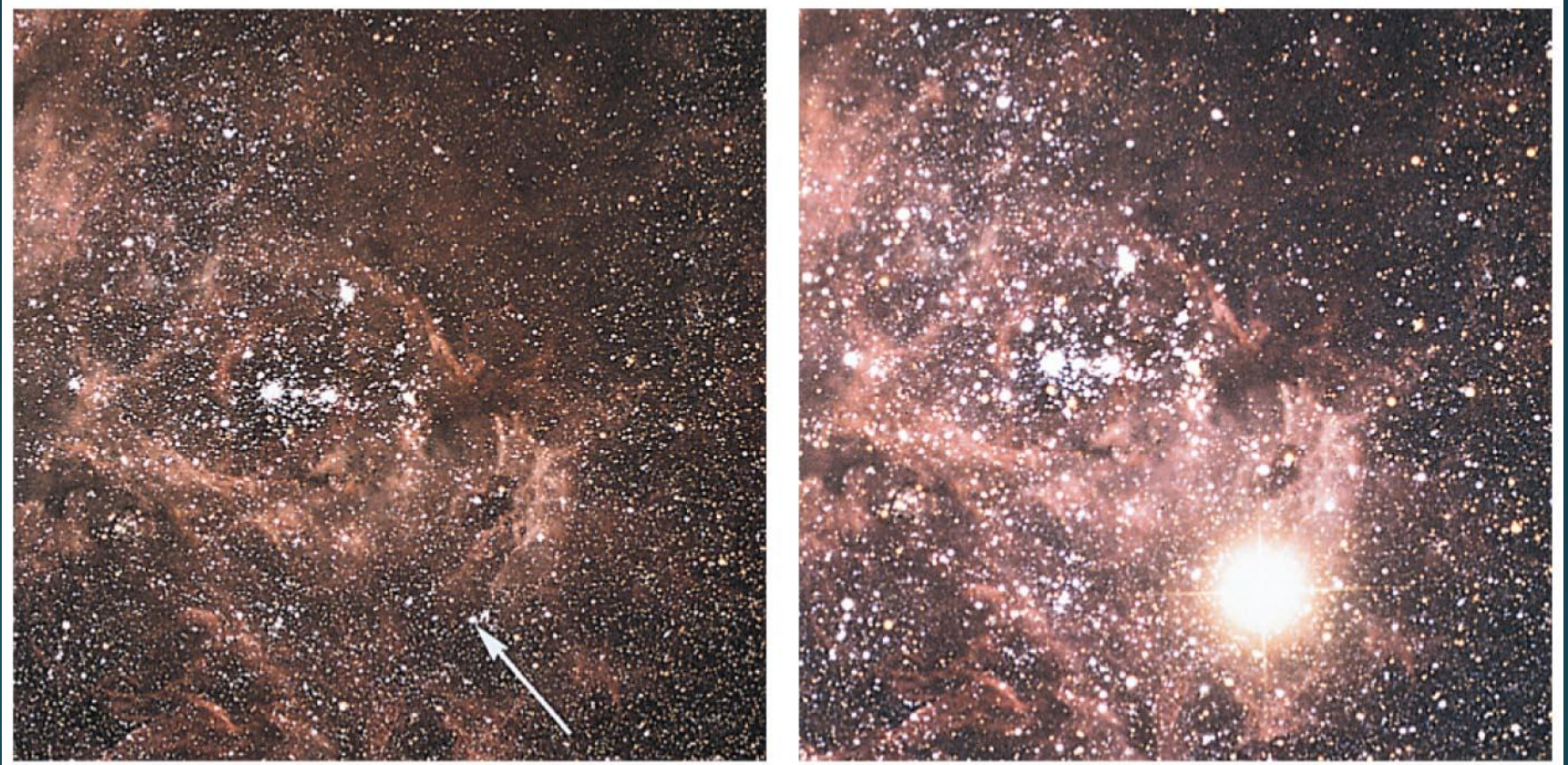
# Supernova Remnant



- ▶ Energy released by the collapse of the core drives the star's outer layers into space.
- ▶ The Crab Nebula is the remnant of the supernova seen in A.D. 1054.



# Supernova 1987A



- ▶ The closest supernova in the last four centuries was seen in 1987.



# Rings around Supernova 1987A



- ▶ The supernova's flash of light caused rings of gas around the supernova to glow.

# Impact of Debris with Rings



- ▶ More recent observations show the inner ring lighting up as debris crashes into it.

# What have we learned?

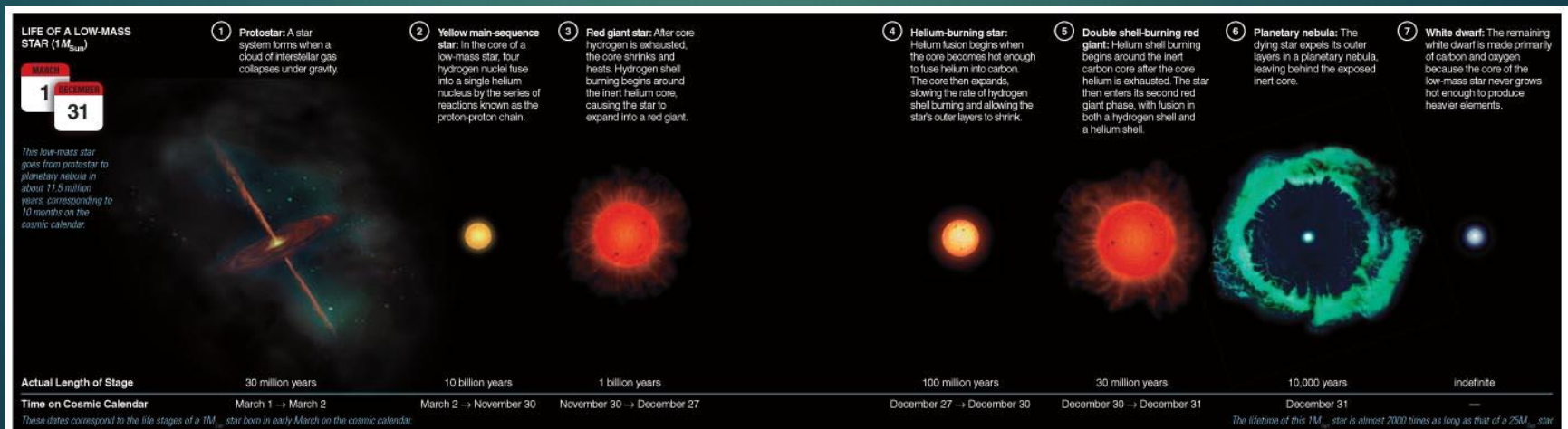
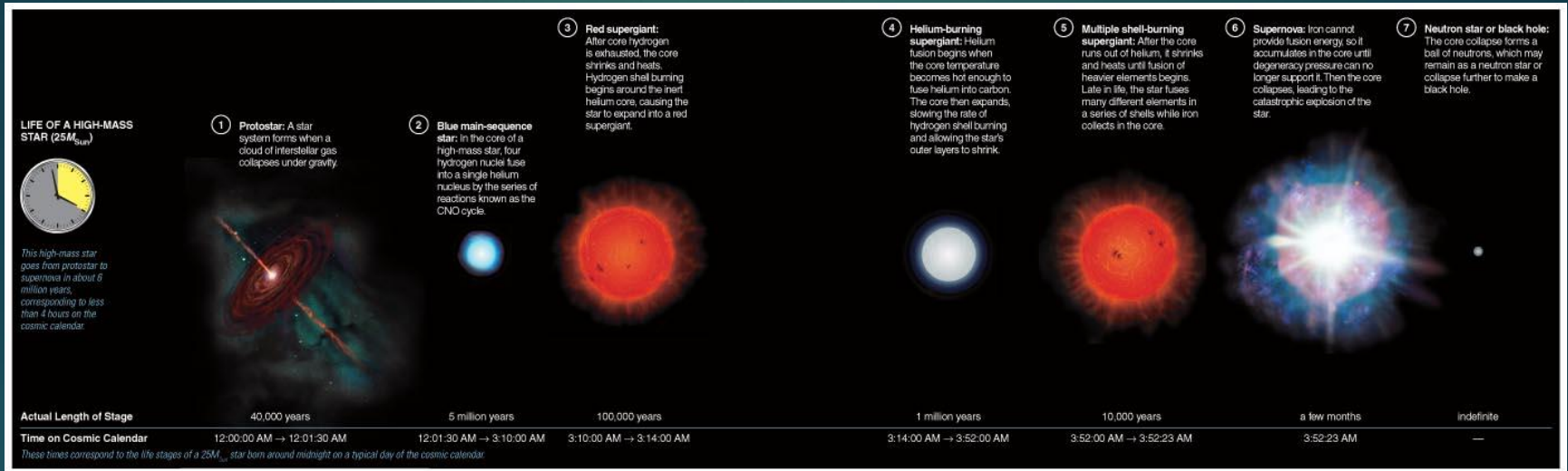
- ▶ **What are the life stages of a high-mass star?**
  - ▶ They are similar to the life stages of a low-mass star.
- ▶ **How do high-mass stars make the elements necessary for life?**
  - ▶ Higher masses produce higher core temperatures that enable fusion of heavier elements.
- ▶ **How does a high-mass star die?**
  - ▶ Its iron core collapses, leading to a supernova.



# 17.4 The Roles of Mass and Mass Exchange

- ▶ Our goals for learning:
  - ▶ **How does a star's mass determine its life story?**
  - ▶ **How are the lives of stars with close companions different?**

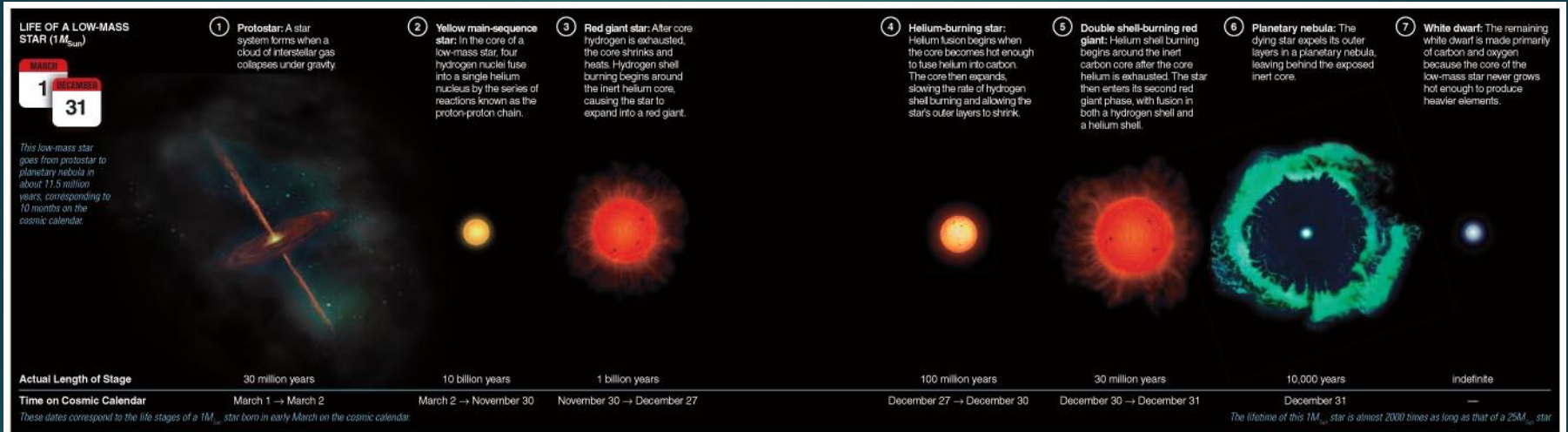
# How does a star's mass determine its life story?



# Role of Mass

- ▶ A star's mass determines its entire life story because it determines its core temperature.
- ▶ High-mass stars with  $> 8M_{\text{Sun}}$  have short lives, eventually becoming hot enough to make iron, and end in supernova explosions.
- ▶ Low-mass stars with  $< 2M_{\text{Sun}}$  have long lives, never become hot enough to fuse carbon nuclei, and end as white dwarfs.
- ▶ Intermediate-mass stars can make elements heavier than carbon but end as white dwarfs.

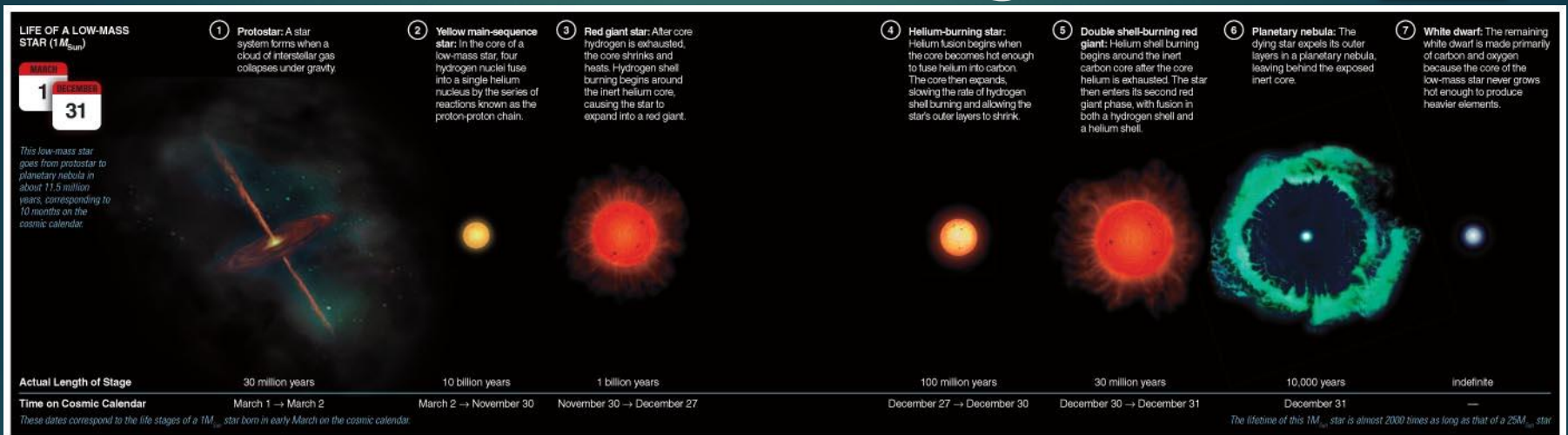
# Low-Mass Star Summary



1. Main sequence: H fuses to He in core.
2. Red giant: H fuses to He in shell around He core.
3. Helium core burning: He fuses to C in core while H fuses to He in shell.
4. Double shell burning: H and He both fuse in shells.
5. Planetary nebula leaves white dwarf behind.

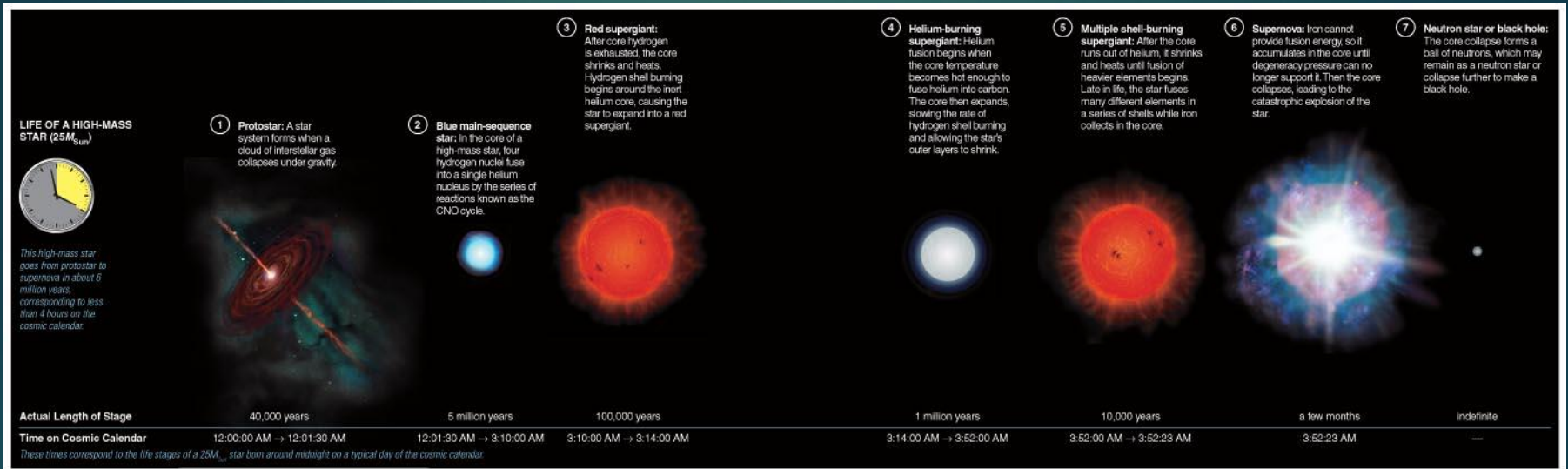


# Reasons for Life Stages



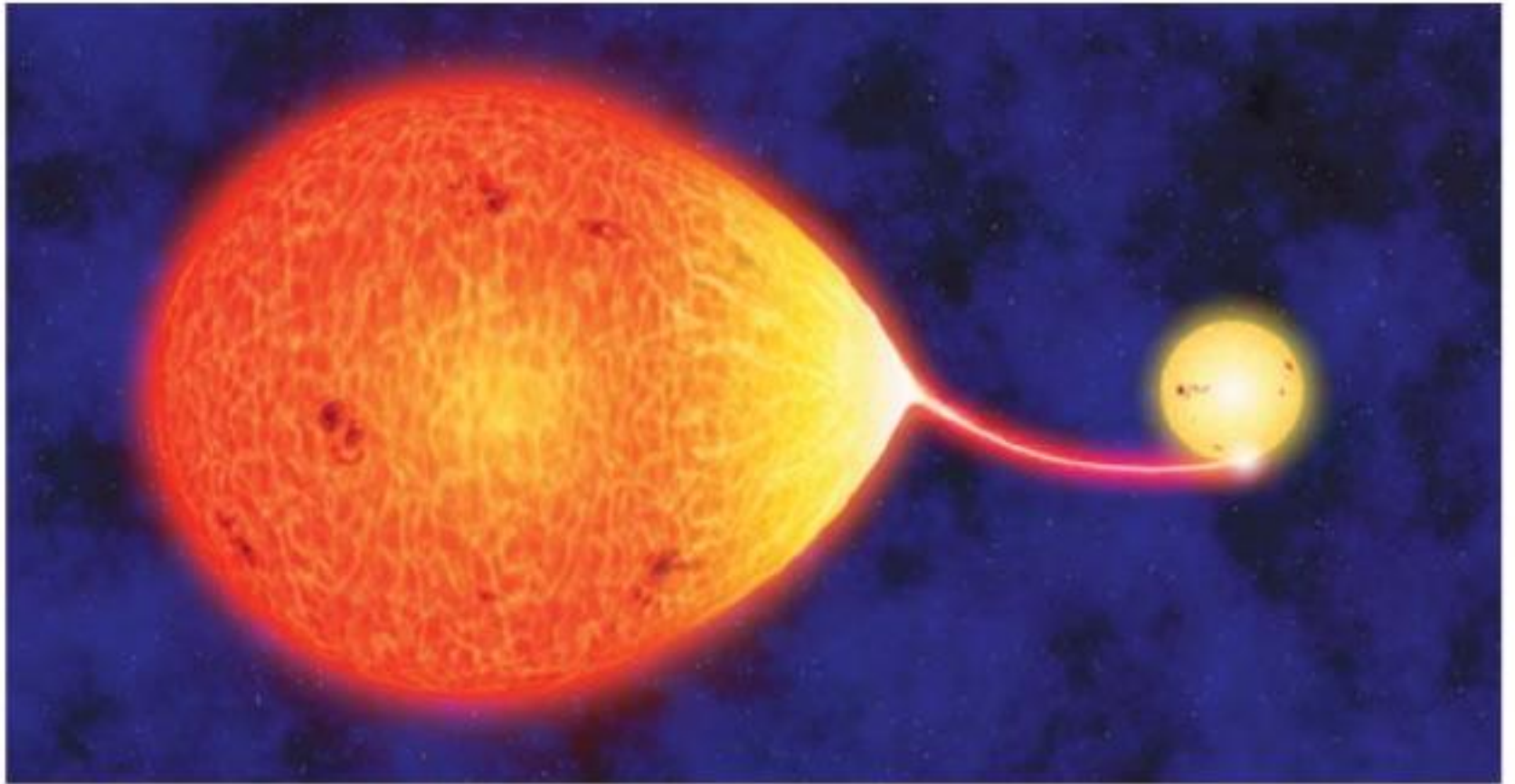
- ▶ Core shrinks and heats until it's hot enough for fusion.
- ▶ Nuclei with larger charge require higher temperature for fusion.
- ▶ Core thermostat is broken while core is not hot enough for fusion (shell burning).
- ▶ Core fusion can't happen if degeneracy pressure keeps core from shrinking.

# Life Stages of High-Mass



1. Main sequence: H fuses to He in core.
2. Red supergiant: H fuses to He in shell around He core.
3. Helium core burning:
4. He fuses to C in core while H fuses to He in shell.
5. Multiple shell burning:
6. Many elements fuse in shells.
7. Supernova leaves neutron star behind.

# How are the lives of stars with close companions different?



Algol at onset of mass transfer. When the more massive star expanded into a red giant, it began losing some of its mass to its normal, hydrogen core fusion companion.

# Thought Question

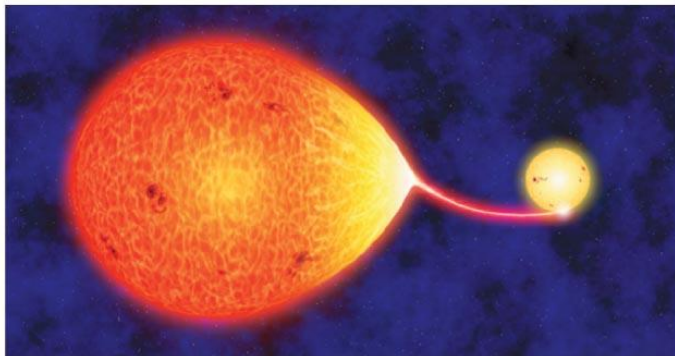
- ▶ The binary star Algol consists of a  $3.7M_{\text{Sun}}$  main-sequence star and a  $0.8M_{\text{Sun}}$  subgiant star.
- ▶ What's strange about this pairing?
- ▶ How did it come about?



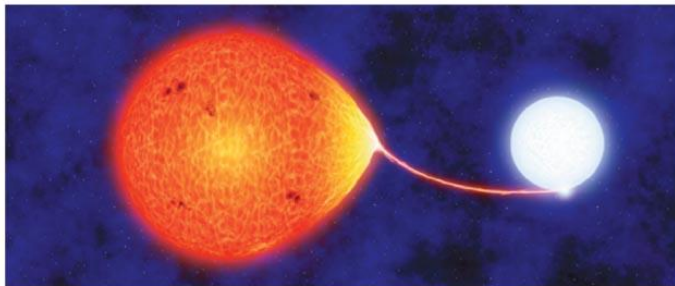
# Thought Question Answers



Algol shortly after its birth. The higher-mass star (left) evolved more quickly than its lower-mass companion (right).



Algol at onset of mass transfer. When the more massive star expanded into a red giant, it began losing some of its mass to its normal, hydrogen core fusion companion.

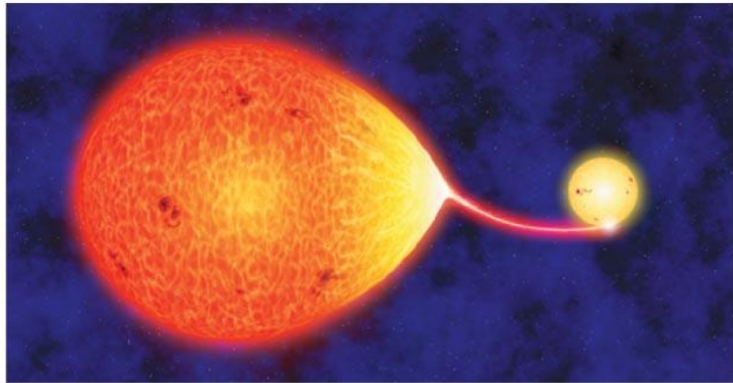


Algol today. As a result of the mass transfer, the red giant has shrunk to a subgiant, and the normal star on the right is now the more massive of the two stars.

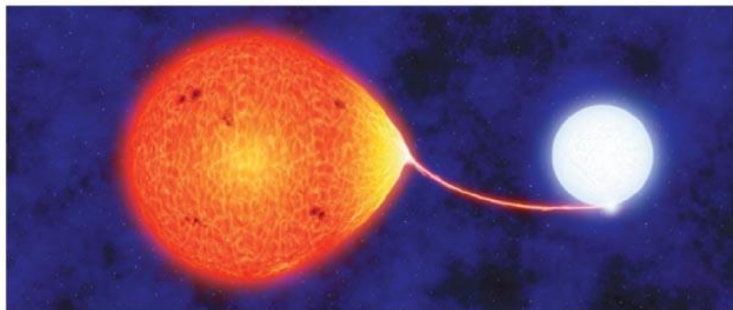
- ▶ The stars in Algol are close enough that matter can flow from the subgiant onto the main-sequence star.



Algol shortly after its birth. The higher-mass star (left) evolved more quickly than its lower-mass companion (right).



Algol at onset of mass transfer. When the more massive star expanded into a red giant, it began losing some of its mass to its normal, hydrogen core fusion companion.

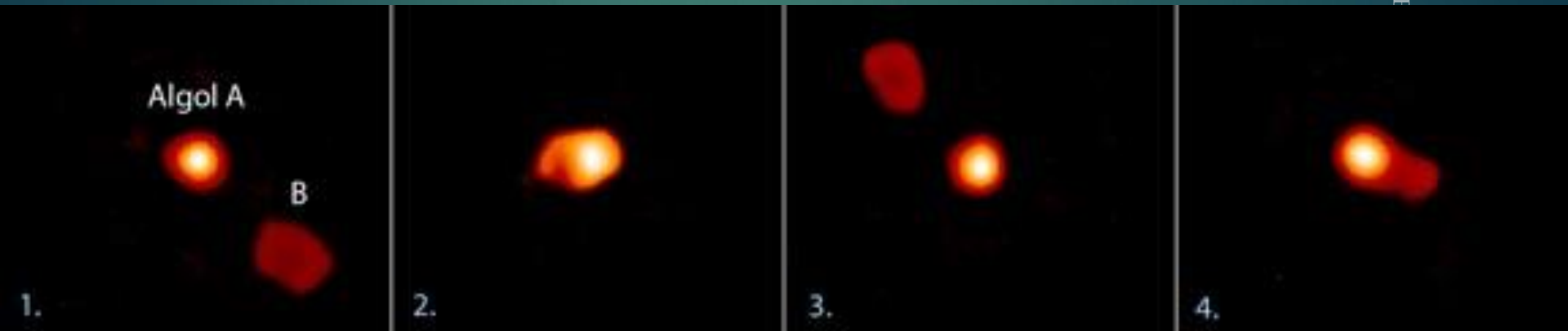


Algol today. As a result of the mass transfer, the red giant has shrunk to a subgiant, and the normal star on the right is now the more massive of the two stars.

- ▶ The star that is now a subgiant was originally more massive.
- ▶ As it reached the end of its life and started to grow, it began to transfer mass to its companion (*mass exchange*).
- ▶ Now the companion star is more massive.

# Images of Algol

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# What have we learned?

- ▶ **How does a star's mass determine its life story?**
  - ▶ Mass determines how high a star's core temperature can rise and therefore determines how quickly a star uses its fuel and what kinds of elements it can make.
- ▶ **How are the lives of stars with close companions different?**
  - ▶ Stars with close companions can exchange mass, altering the usual life stories of stars.