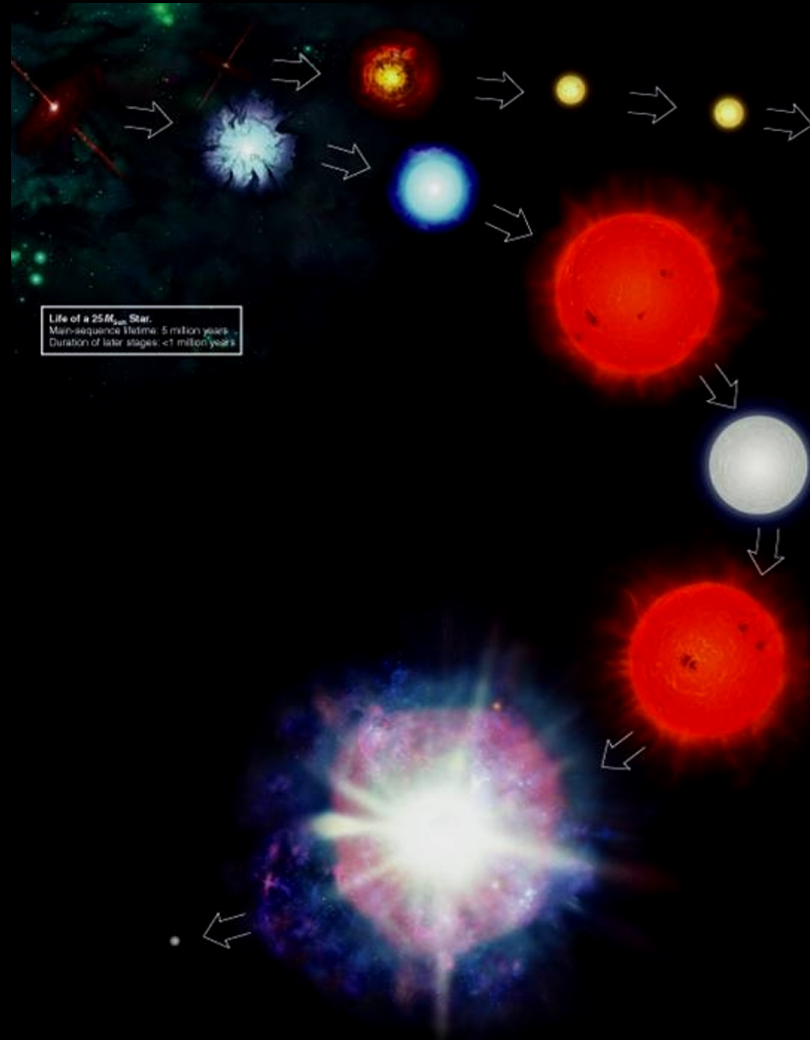


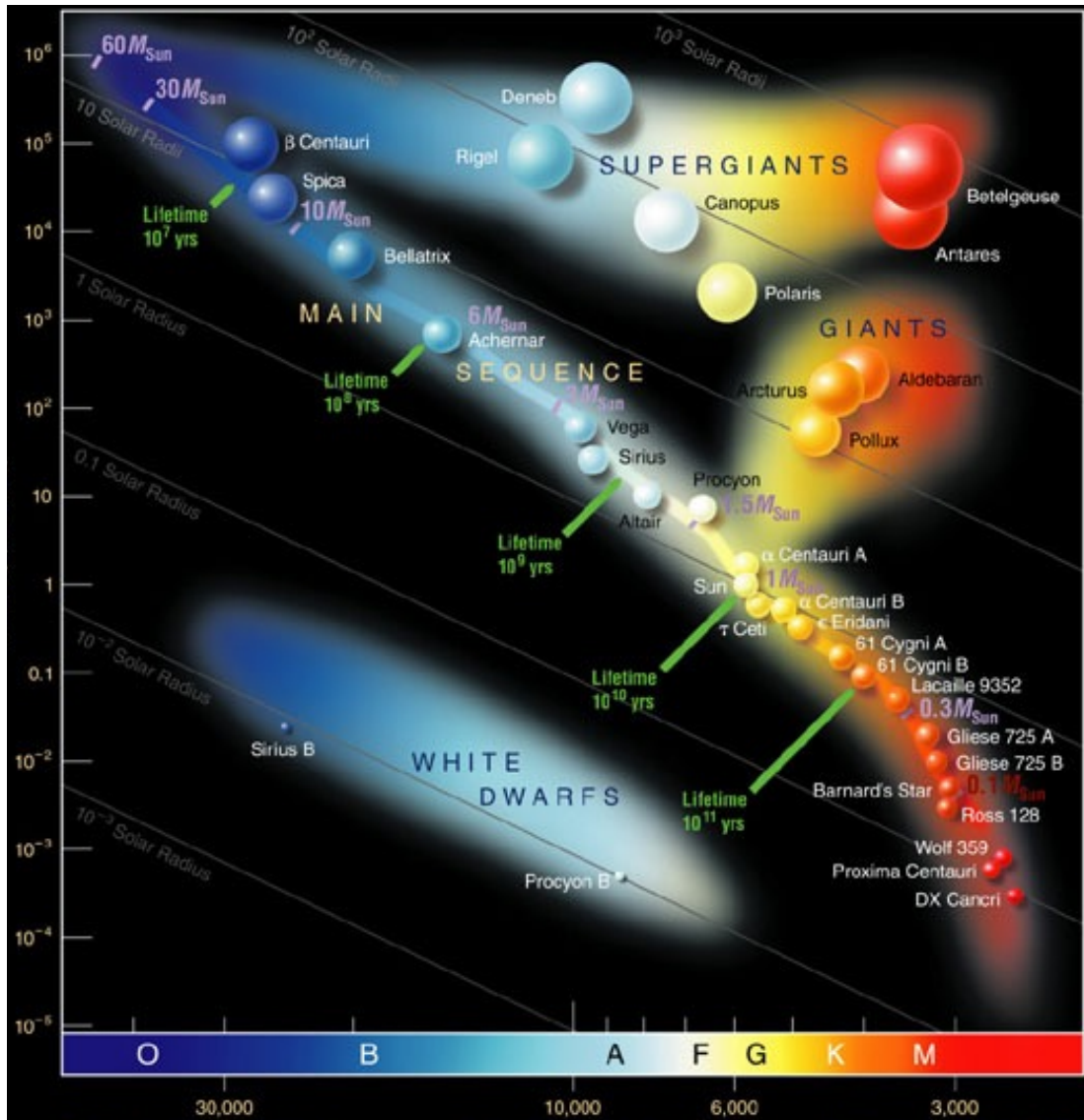
# Lecture 18: High Mass Stellar Evolution



# Life stages of a high-mass star



# Life Stages of High-Mass Stars



High mass stars leave MS quickly to become supergiants

# Think/Pair/Share

What happens when a high-mass star's core runs out of helium?

- A. The core collapses and the star explodes.
- B. Carbon fusion begins in the core.
- C. The core expands and cools off.
- D. Helium fuses in a shell around the core.

# Think/Pair/Share

What happens when a high-mass star's core runs out of helium?

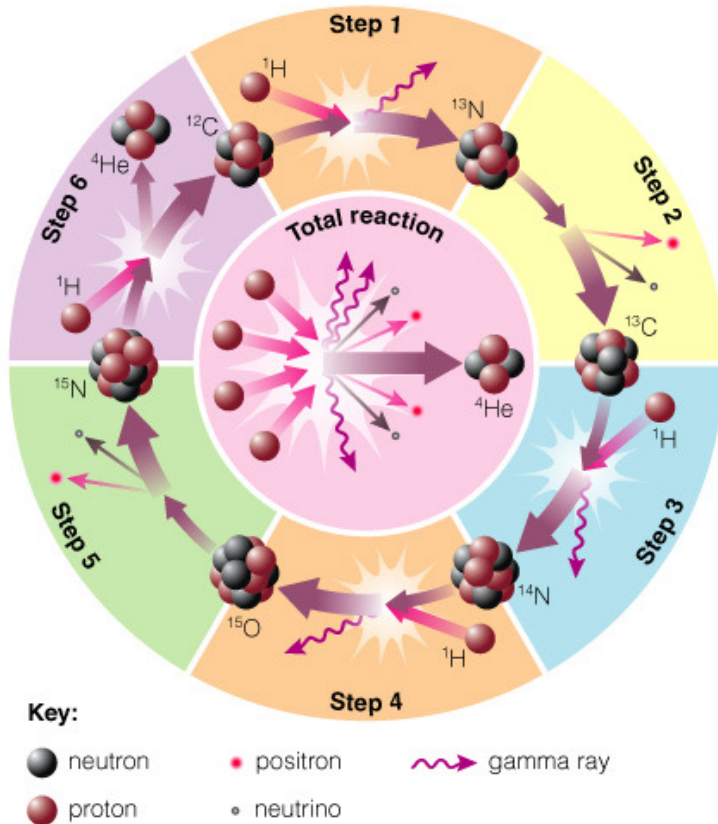
- A. The core collapses and the star explodes.
- B. Carbon fusion begins in the core.**
- C. The core expands and cools off.
- D. Helium fuses in a shell around the core.**

# Life Stages of High-Mass Stars

- Life stages of high-mass stars are similar to those of low-mass stars:
  1. Hydrogen core fusion (main sequence)
  2. Hydrogen shell burning (*supergiant*)
  3. Helium core fusion (*supergiant*)
  4. ***Multiple***-shell burning beyond carbon

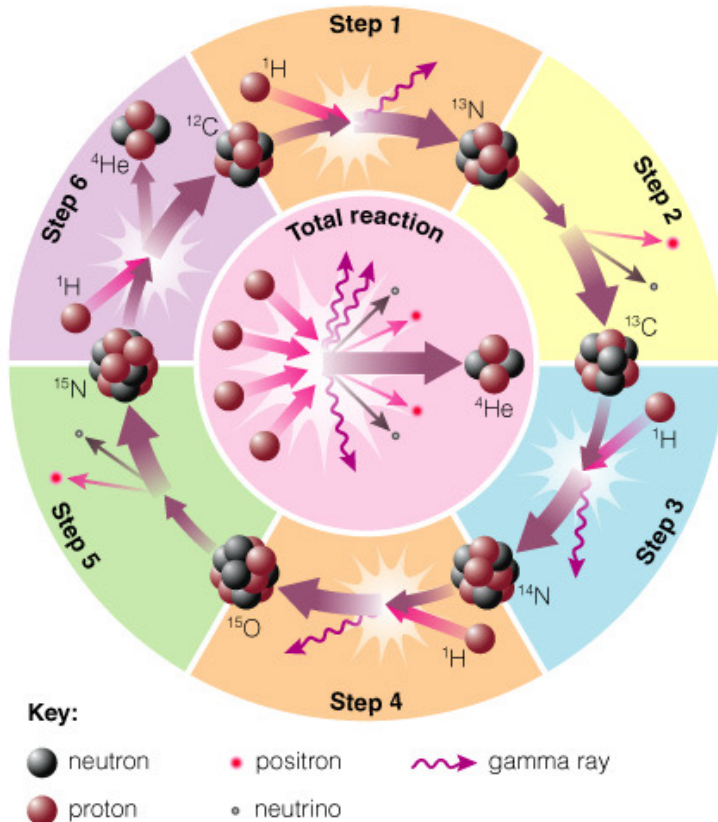
So how do high-mass stars make heavy elements?

# Fusion in a high mass star



- High-mass main sequence stars fuse H to He **at a higher rate** using carbon, nitrogen, and oxygen as catalysts (**CNO cycle**).
- Greater core temperature enables H nuclei to overcome greater repulsion of heavier elements in the process.
- *Higher fusion rate is why high-mass stars have a higher luminosity and shorter life than low-mass stars.*

# Fusion in a high mass star



- Hydrogen fuses to Helium in just a few million years
- Helium fuses to carbon in just a few hundred thousand years
- Core collapses further - temp, density, pressure increase further
- *Fusion of carbon and heavier elements can begin at 600 million K but only lasts a few hundred years!*

*How do high-mass stars make heavy elements?*



# The Periodic Table of Elements

## 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	4											5	6	7	8	9	10									
<b>Li</b>	<b>Be</b>											<b>B</b>	<b>C</b>	<b>N</b>	<b>O</b>	<b>F</b>	<b>Ne</b>									
Lithium	Beryllium											Boron	Carbon	Nitrogen	Oxygen	Fluorine	Neon									
6.941	9.01218											10.81	12.011	14.007	15.999	18.988	20.179									
11	12											13	14	15	16	17	18									
<b>Na</b>	<b>Mg</b>											<b>Al</b>	<b>Si</b>	<b>P</b>	<b>S</b>	<b>Cl</b>	<b>Ar</b>									
Sodium	Magnesium											Aluminum	Silicon	Phosphorus	Sulfur	Chlorine	Argon									
22.990	24.305											26.98	28.086	30.974	32.06	35.453	39.948									
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36									
<b>K</b>	<b>Ca</b>	<b>Sc</b>	<b>Ti</b>	<b>V</b>	<b>Cr</b>	<b>Mn</b>	<b>Fe</b>	<b>Co</b>	<b>Ni</b>	<b>Cu</b>	<b>Zn</b>	<b>Ga</b>	<b>Ge</b>	<b>As</b>	<b>Se</b>	<b>Br</b>	<b>Fr</b>									
Potassium	Calcium	Scandium	Titanium	Vanadium	Chromium	Manganese	Iron	Cobalt	Nickel	Copper	Zinc	Gallium	Germanium	Arsenic	Selenium	Bromine	Krypton									
39.098	40.08	44.956	47.88	50.94	51.996	54.938	55.847	58.9332	58.69	63.546	65.39	69.72	72.59	74.922	78.96	79.904	83.80									
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54									
<b>Rb</b>	<b>Sr</b>	<b>Y</b>	<b>Zr</b>	<b>Nb</b>	<b>Mo</b>	<b>Tc</b>	<b>Ru</b>	<b>Rh</b>	<b>Pd</b>	<b>Ag</b>	<b>Cd</b>	<b>In</b>	<b>Sn</b>	<b>Sb</b>	<b>Te</b>	<b>I</b>	<b>Xe</b>									
Rubidium	Strontium	Yttrium	Zirconium	Niobium	Molybdenum	Technetium	Ruthenium	Rhodium	Palladium	Silver	Cadmium	Indium	Tin	Antimony	Tellurium	Iodine	Xenon									
85.468	87.62	88.9059	91.224	92.91	95.94	(98)	101.07	102.906	106.42	107.868	112.41	114.82	118.71	121.75	127.60	126.905	131.29									
55	56											72	73	74	75	76	77	78	79	80	81	82	83	84	85	86
<b>Cs</b>	<b>Ba</b>											<b>Hf</b>	<b>Ta</b>	<b>W</b>	<b>Re</b>	<b>Os</b>	<b>Ir</b>	<b>Pt</b>	<b>Au</b>	<b>Hg</b>	<b>Tl</b>	<b>Pb</b>	<b>Bi</b>	<b>Po</b>	<b>At</b>	<b>Rn</b>
Cesium	Barium											Hafnium	Tantalum	Tungsten	Rhenium	Osmium	Iridium	Platinum	Gold	Mercury	Thallium	Lead	Bismuth	Polonium	Astatine	Radon
132.91	137.34											178.49	180.95	183.85	186.207	190.2	192.22	195.08	196.967	200.59	204.383	207.2	208.98	(209)	(210)	(222)
87	88											104	105	106	107	108	109	110	111	112						
<b>Fr</b>	<b>Ra</b>											<b>Rf</b>	<b>Db</b>	<b>Sg</b>	<b>Bh</b>	<b>Hs</b>	<b>Mt</b>	<b>Uun</b>	<b>Uuu</b>	<b>Uub</b>						
Francium	Radium											Rutherfordium	Dubnium	Seaborgium	Bohrium	Hassium	Meitnerium	Ununium	Ununium	Ununium						
(223)	226.0254											(261)	(262)	(263)	(262)	(265)	(266)	(269)	(272)	(277)						

## Lanthanide Series

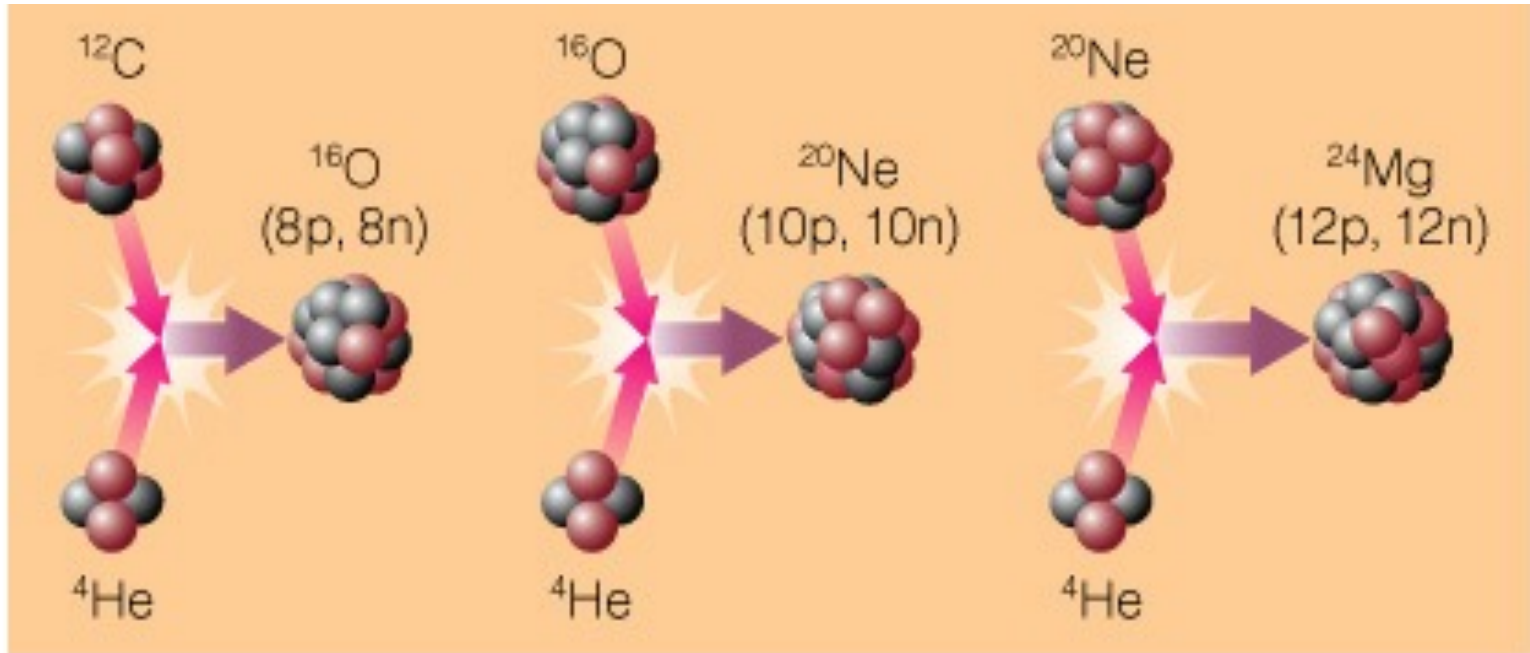
57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
<b>La</b>	<b>Ce</b>	<b>Pr</b>	<b>Nd</b>	<b>Pm</b>	<b>Sm</b>	<b>Eu</b>	<b>Gd</b>	<b>Tb</b>	<b>Dy</b>	<b>Ho</b>	<b>Er</b>	<b>Tm</b>	<b>Yb</b>	<b>Lu</b>
Lanthanum	Cerium	Praseodymium	Neodymium	Promethium	Samarium	Europium	Gadolinium	Terbium	Dysprosium	Holmium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

## Actinide Series

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

- Big Bang made 75% H, 25% He – *stars make all other elements*
- Helium fusion can make carbon in low-mass stars.

# Helium Capture



- Very high core temperatures in high mass stars allow helium to fuse with heavier elements.

# The Periodic Table of Elements

## 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																	10 <b>Ne</b> Neon 20.179
11 <b>Na</b> Sodium 22.990	12 <b>Mg</b> Magnesium 24.305																	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>Fr</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																	86 <b>Rn</b> Radon (222)
87 <b>Fr</b> Francium (223)	88 <b>Ra</b> Radium 226.0254																	
		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)			
		104 <b>Rf</b> Rutherfordium (261)	105 <b>Db</b> Dubnium (262)	106 <b>Sg</b> Seaborgium (263)	107 <b>Bh</b> Bohrium (262)	108 <b>Hs</b> Hassium (265)	109 <b>Mt</b> Meitnerium (266)	110 <b>Uun</b> Ununnilium (269)	111 <b>Uuu</b> Unununium (272)	112 <b>Uub</b> Ununbium (277)								

## Lanthanide Series

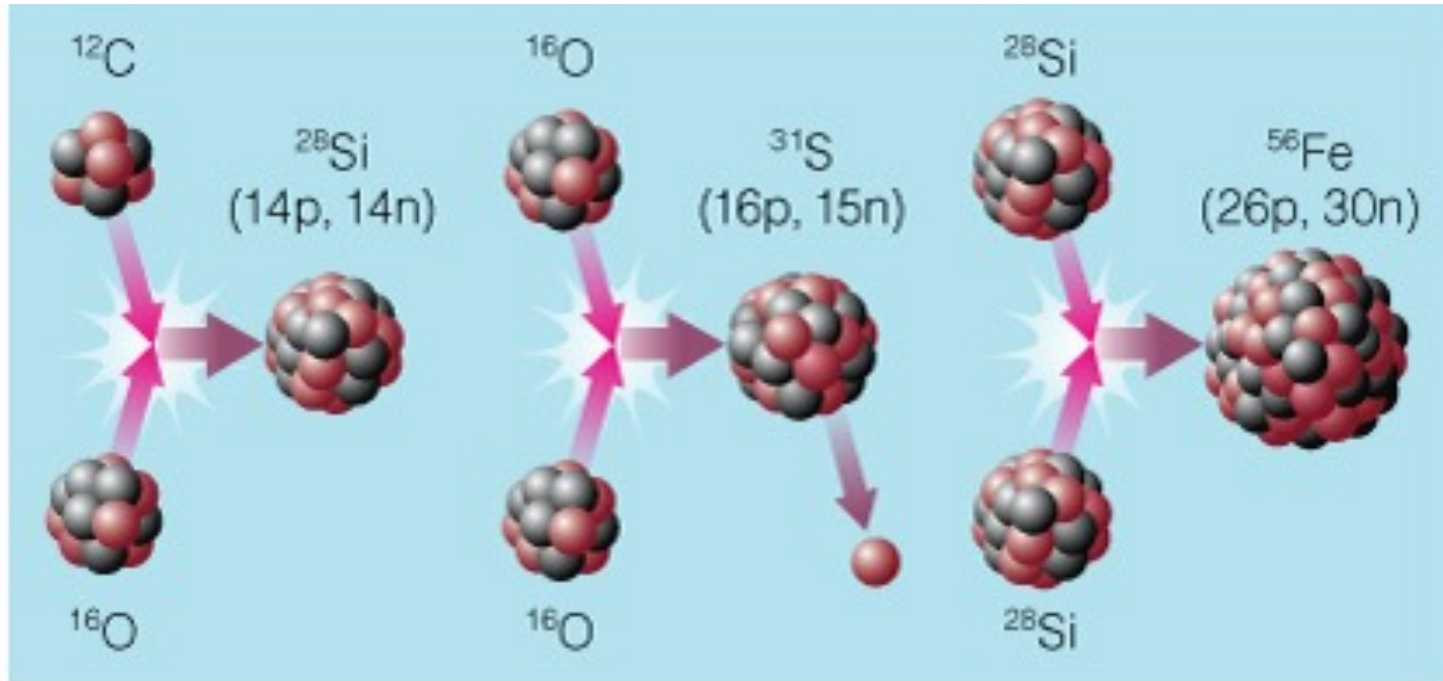
57 <b>La</b> Lanthanum 138.906	58 <b>Ce</b> Cerium 140.12	59 <b>Pr</b> Praseodymium 140.908	60 <b>Nd</b> Neodymium 144.24	61 <b>Pm</b> Promethium (145)	62 <b>Sm</b> Samarium 150.36	63 <b>Eu</b> Europium 151.96	64 <b>Gd</b> Gadolinium 157.25	65 <b>Tb</b> Terbium 158.925	66 <b>Dy</b> Dysprosium 162.50	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
---	-------------------------------------	--	--	--	---------------------------------------	---------------------------------------	---	---------------------------------------	---	--------------------------------------	-------------------------------------	---------------------------------------	--	--

## 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)
--	---------------------------------------	--	--------------------------------------	---	---------------------------------------	---------------------------------------	------------------------------------	---------------------------------------	---	---	--------------------------------------	--	---------------------------------------	---

Helium capture can change C into O, O into Ne, Ne to Mg.

# Advanced Nuclear Burning



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

# The Periodic Table of Elements

## 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																	10 <b>Ne</b> Neon 20.179
11 <b>Na</b> Sodium 22.990	12 <b>Mg</b> Magnesium 24.305																	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>Fr</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																	86 <b>Rn</b> Radon (222)
87 <b>Fr</b> Francium (223)	88 <b>Ra</b> Radium 226.0254																	
		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)		
		104 <b>Rf</b> Rutherfordium (261)	105 <b>Db</b> Dubnium (262)	106 <b>Sg</b> Seaborgium (263)	107 <b>Bh</b> Bohrium (262)	108 <b>Hs</b> Hassium (265)	109 <b>Mt</b> Meitnerium (266)	110 <b>Uun</b> Ununnilium (269)	111 <b>Uuu</b> Unununium (272)	112 <b>Uub</b> Ununbium (277)								

## Lanthanide Series

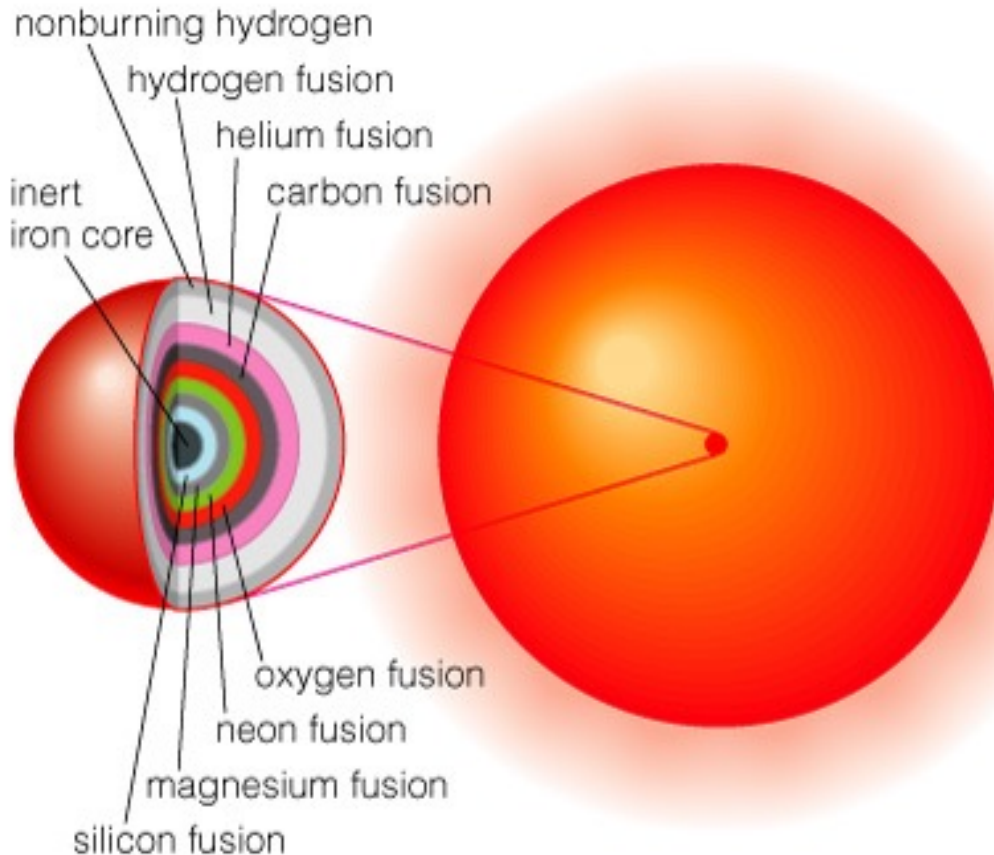
57 <b>La</b> Lanthanum 138.906	58 <b>Ce</b> Cerium 140.12	59 <b>Pr</b> Praseodymium 140.908	60 <b>Nd</b> Neodymium 144.24	61 <b>Pm</b> Promethium (145)	62 <b>Sm</b> Samarium 150.36	63 <b>Eu</b> Europium 151.96	64 <b>Gd</b> Gadolinium 157.25	65 <b>Tb</b> Terbium 158.925	66 <b>Dy</b> Dysprosium 162.50	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
---	-------------------------------------	--	--	--	---------------------------------------	---------------------------------------	---	---------------------------------------	---	--------------------------------------	-------------------------------------	---------------------------------------	--	--

## 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)
--	---------------------------------------	--	--------------------------------------	---	---------------------------------------	---------------------------------------	------------------------------------	---------------------------------------	---	---	--------------------------------------	--	---------------------------------------	---

Advanced reactions in stars make elements like Si, S, Ca, and Fe.

# Multiple-Shell Burning

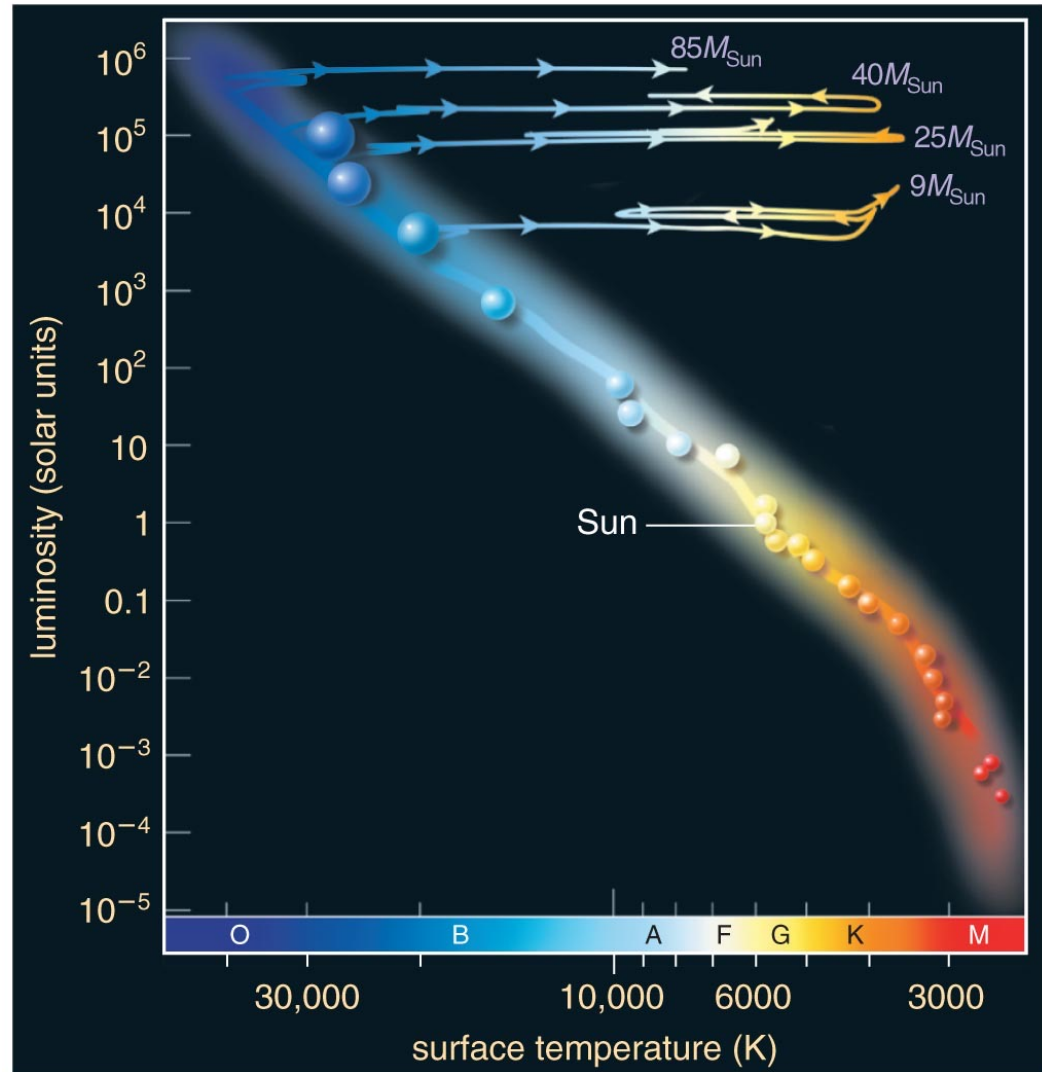


- Advanced nuclear fusion proceeds in a series of nested shells.
- Progressively heavier elements are created by fusion: *nucleosynthesis*.
- Ignition of next heavier element in core (and new shell) do what to star?

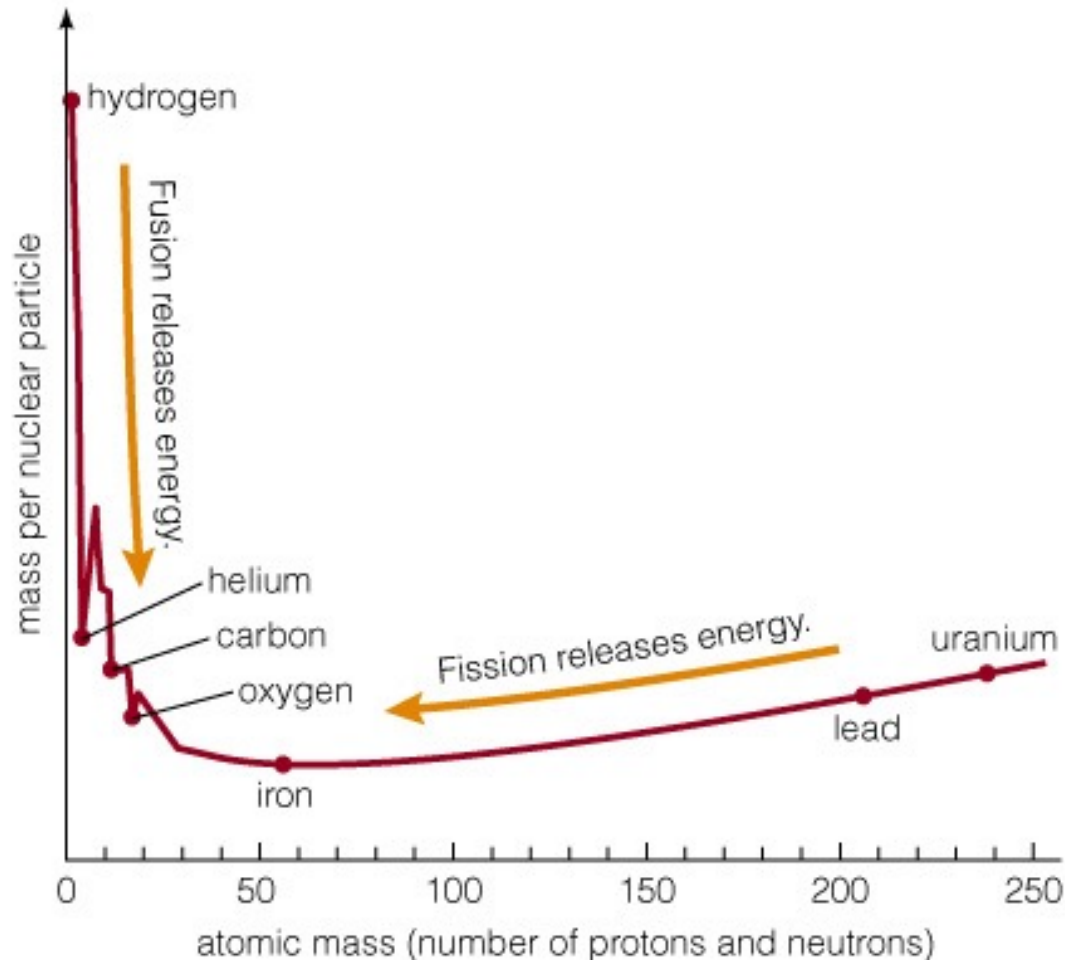
# High mass life tracks

High mass stars change from red to blue supergiants – and back!

- Core ignites fusion of new element and fusion of new shell – increased luminosity expands star, cools surface.
- Core finishes fusion of element – decreased luminosity contracts star, heats surface.



# Iron - ~~fusion~~



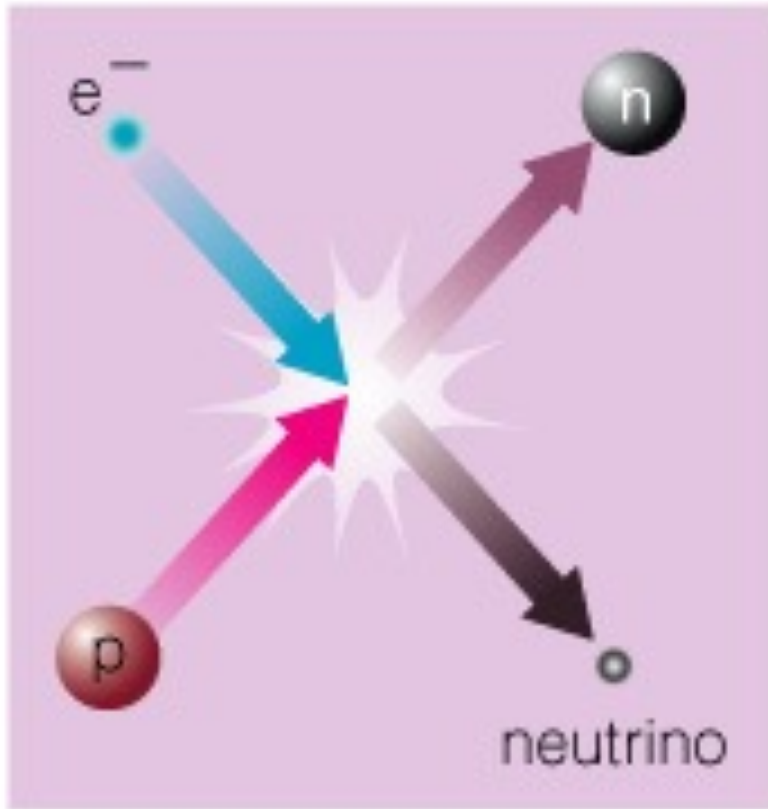
- Fusion releases energy because source elements have greater mass than elements created
- Iron is a dead end for fusion because *nuclear reactions involving iron do not release energy*
- Elements heavier than iron can only release energy via fission



How does a high-mass star die?

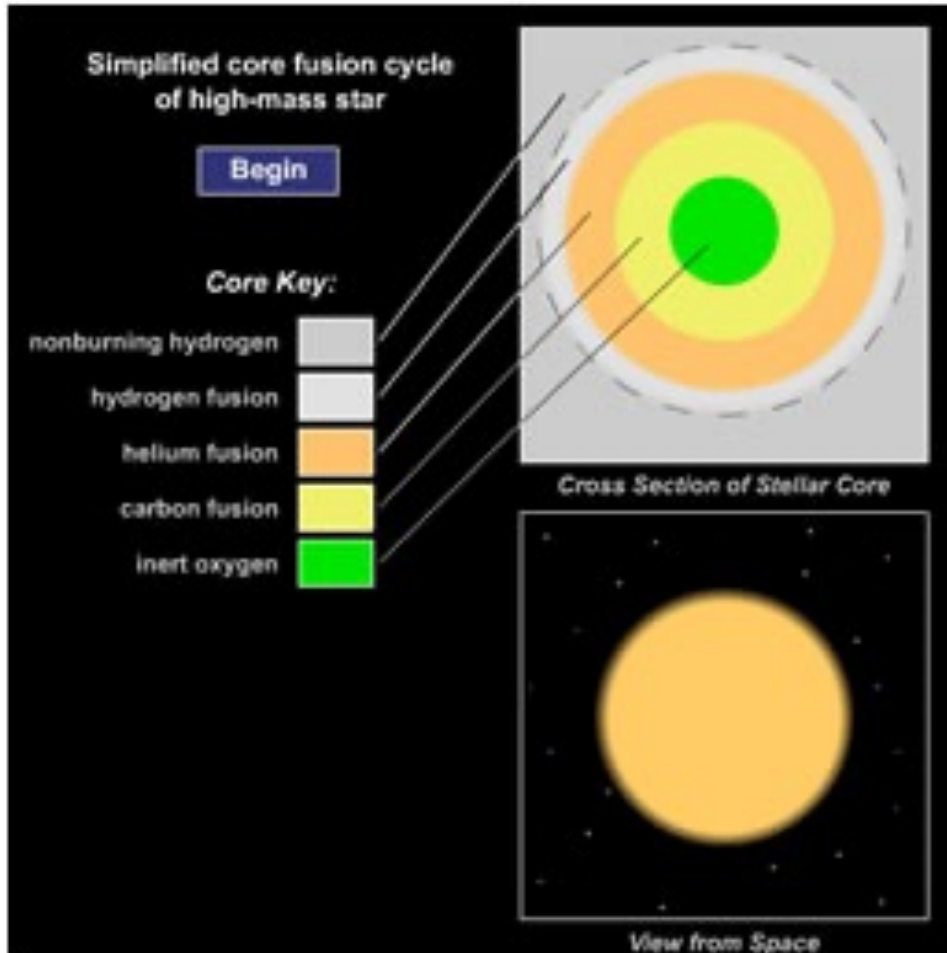


# Core collapse



- Iron builds up in the core until electron degeneracy pressure can no longer resist gravity.
- Gravity overcomes the electron degeneracy pressure.
- *Electrons are forced to combine with protons, making neutrons (and neutrinos).*

# Supernova!



- With no support, core suddenly collapses.
- Only *neutron* degeneracy can stop collapse of most supergiants.
- Core “bounces”, creating a titanic **supernova** explosion.
- Iron core collapses into a **neutron star** just a few km across!

### 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																	10 <b>Ne</b> Neon 20.179
11 <b>Na</b> Sodium 22.990	12 <b>Mg</b> Magnesium 24.305																	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>Fr</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																	86 <b>Rn</b> Radon (222)
87 <b>Fr</b> Francium (223)	88 <b>Ra</b> Radium 226.0254																	
		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)			
		104 <b>Rf</b> Rutherfordium (261)	105 <b>Db</b> Dubnium (262)	106 <b>Sg</b> Seaborgium (263)	107 <b>Bh</b> Bohrium (262)	108 <b>Hs</b> Hassium (265)	109 <b>Mt</b> Meitnerium (266)	110 <b>Uun</b> Ununnilium (269)	111 <b>Uuu</b> Unununium (272)	112 <b>Uub</b> Ununbium (277)								

### 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
---	-------------------------------------	--	--	--	---------------------------------------	---------------------------------------	---	---------------------------------------	---	--------------------------------------	-------------------------------------	---------------------------------------	--	--

### 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)
--	---------------------------------------	--	--------------------------------------	---	---------------------------------------	---------------------------------------	------------------------------------	---------------------------------------	---	---	--------------------------------------	--	---------------------------------------	---

Vast amounts of energy (100x Sun's *lifetime* energy!) and neutrons are released enabling elements heavier than iron such as Au and U to form.

# The Formation of the Elements

H B																		He B					
Li C	Be C																	B C	C S L	N S L	O S L	F L	Ne S L
Na L	Mg L																	Al \$ L	Si \$ L	P L	S S L	Cl L	Ar L
K L	Ca L	Sc L	Ti \$ L	V \$ L	Cr L	Mn L	Fe \$ L	Co \$	Ni \$	Cu L	Zn L	Ga \$	Ge \$	As L	Se \$	Br \$	Kr \$						
Rb \$	Sr L	Y L	Zr L	Nb L	Mo \$ L	Tc L	Ru \$ L	Rh \$	Pd \$ L	Ag \$ L	Cd \$ L	In \$ L	Sn \$ L	Sb \$	Te \$	I \$	Xe \$						
Cs \$	Ba L	Hf \$ L		Ta \$ L	W \$ L	Re \$	Os \$	Ir \$	Pt \$	Au \$	Hg \$ L	Tl \$ L	Pb \$	Bi \$	Po \$	At \$	Rn \$						
Fr \$	Ra \$																						
		La L	Ce L	Pr \$ L	Nd \$ L	Pm \$ L	Sm \$ L	Eu \$	Gd \$	Tb \$	Dy \$	Ho \$	Er \$	Tm \$	Yb \$ L	Lu \$							
		Ac \$	Th \$	Pa \$	U \$	Np \$	Pu \$	Am M	Cm M	Bk M	Cf M	Es M	Fm M	Md M	No M	Lr M							

<div style="background-color: #ccccff; border: 1px solid black; padding: 2px; display: inline-block;">B</div> Big Bang	<div style="background-color: #90ee90; border: 1px solid black; padding: 2px; display: inline-block;">L</div> Large stars	<div style="background-color: #ffcc99; border: 1px solid black; padding: 2px; display: inline-block;">\$</div> Supernovae	
<div style="background-color: #add8e6; border: 1px solid black; padding: 2px; display: inline-block;">C</div> Cosmic rays	<div style="background-color: #ffff00; border: 1px solid black; padding: 2px; display: inline-block;">S</div> Small stars	<div style="background-color: #cc99ff; border: 1px solid black; padding: 2px; display: inline-block;">M</div> Man-made	

# Supernova Remnant



- Energy released by the collapse of the core drives outer layers into space.
- The Crab Nebula is the remnant of a supernova seen in A.D. 1054.
- Expanding material (heavy elements) enriches the ISM.

PLAY

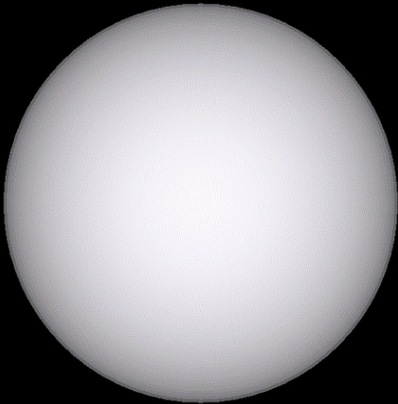
Multiwavelength Crab Nebula

# Supernova 1987A



- The closest supernova in the last four centuries was seen in 1987; it taught us much about SN.
- SN are seen on other galaxies regularly.

# Neutron stars

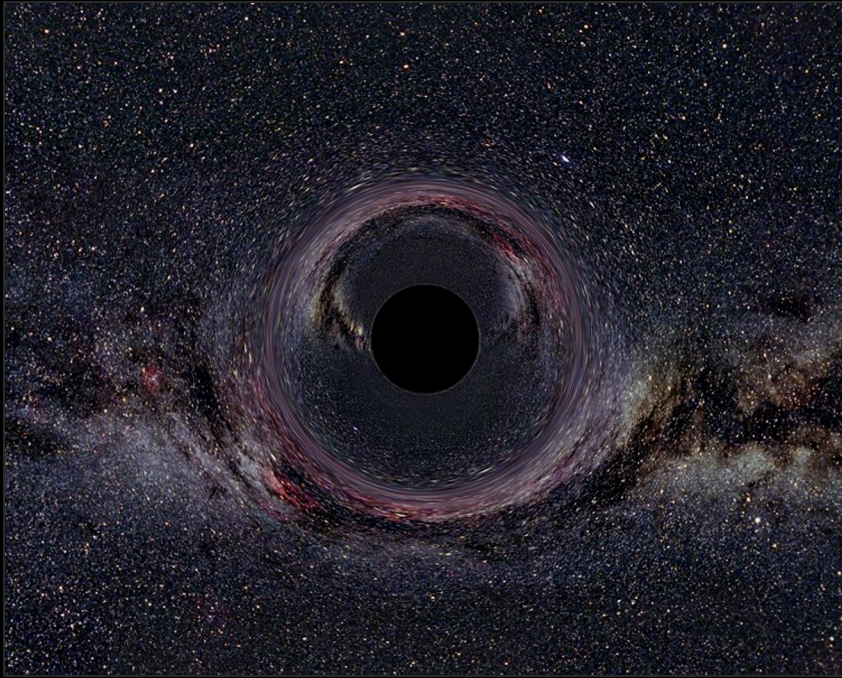


$M = 1.5 M_{\text{sun}}$   
 $R \approx 10 \text{ km}$   
 $V_{\text{esc}} \approx 0.7c$

- Gravity crushes the core (about the size of Earth and the mass of the Sun) to unimaginable density – entire star is of nuclear density just 10 km across!
- One  $\text{cm}^3$  would weigh 100 *million* tons!
- In most massive stars, **neutron** degeneracy finally stops the collapse.
- The star is literally a giant atomic nucleus – a ball of neutrons about 10 km in diameter.



# Black holes



- In a few of the most massive stars ( $> 30 M_{\text{Sun}}$ ), even neutron degeneracy cannot stop the collapse.
- Gravity ultimately crushes the star out of the observable universe!
- Gravity is so strong that even light can no longer escape.
- No physical surface but enormous gravity source remains.

# What have we learned?

Begin 3 minute review

# 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 (main sequence, red *supergiant*, etc).

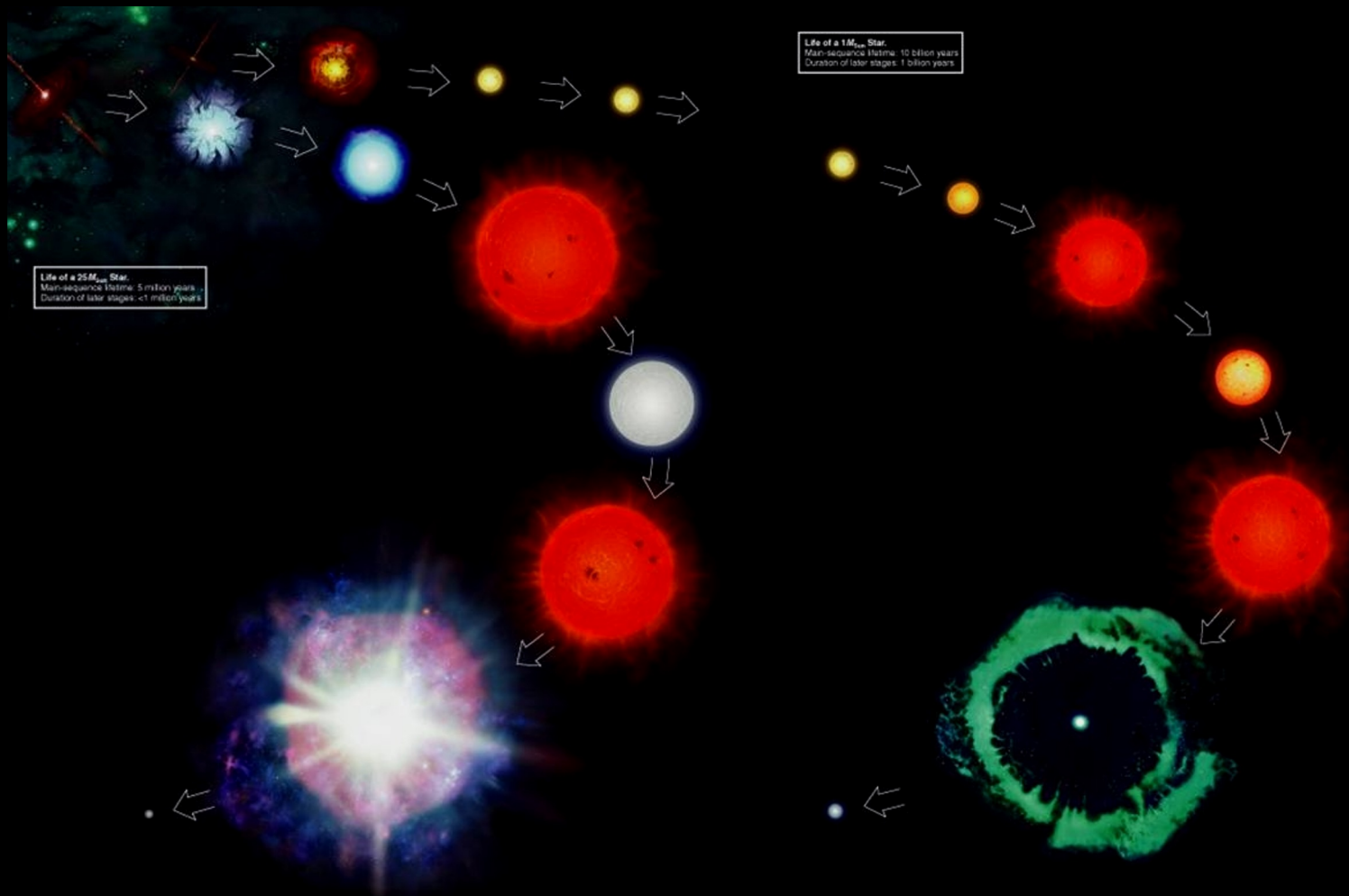
How do high-mass stars make heavy elements?

Higher masses produce much higher core temperatures that enable fusion of heavier elements - *nucleosynthesis*

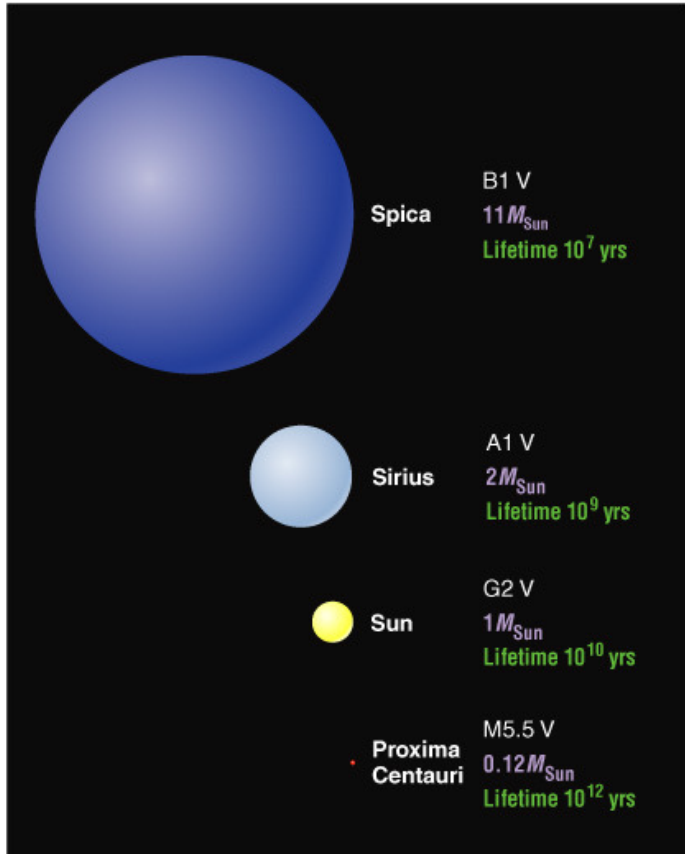
How does a high-mass star die?

The iron core collapses and bounces, leading to a supernova explosion.

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

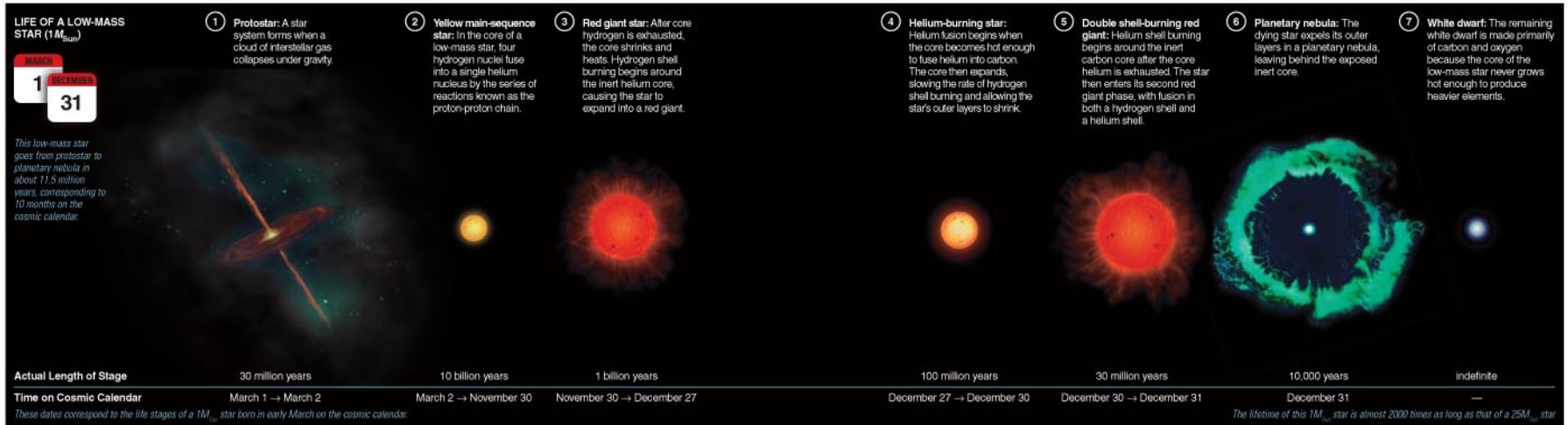


# Role of Mass



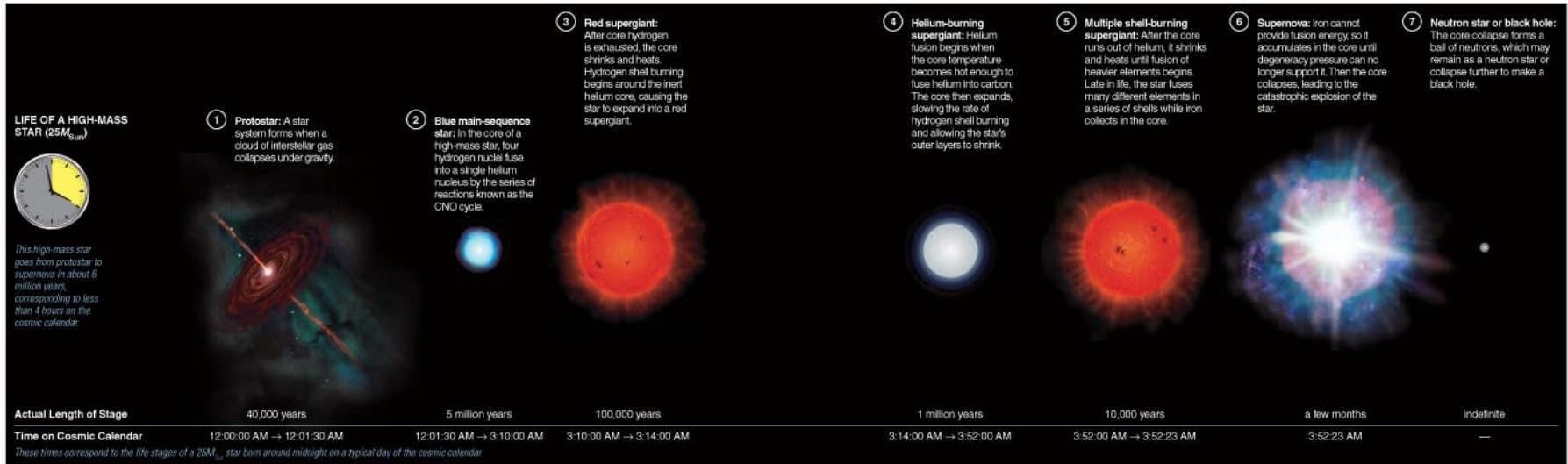
- *A star's mass determines its entire life story because it determines its core temperature.*
- **High-mass stars have short lives**, eventually becoming hot enough to make iron, and end in supernova explosions and neutron stars.
- **Low-mass stars have long lives**, never become hot enough to fuse carbon nuclei, and end as white dwarfs.

# Life stages of Low-Mass stars



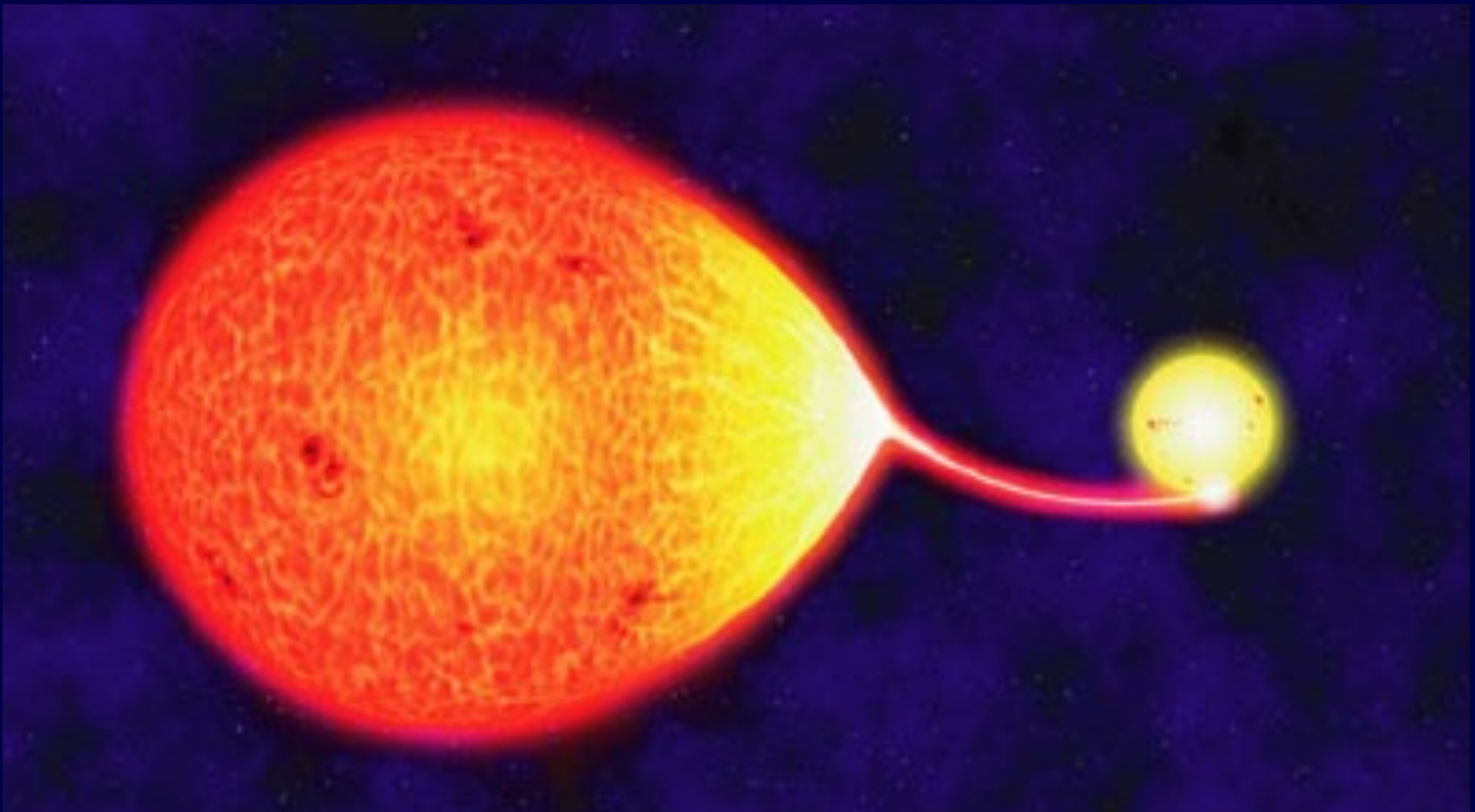
1. Protostar: Interstellar cloud collapse under gravity and heats up.
2. Main sequence: H fuses to He in core.
3. Red giant: H fuses to He in shell around inert He core.
4. Helium core burning: He fuses to C in core while H fuses to He in shell around the core.
5. Red Giant (again). Double shell burning: H and He both fuse in shells around an inert carbon core.
6. Planetary nebula: outer layers blown off.
7. White dwarf: primarily carbon, some oxygen.

# Life Stages of High-Mass Star

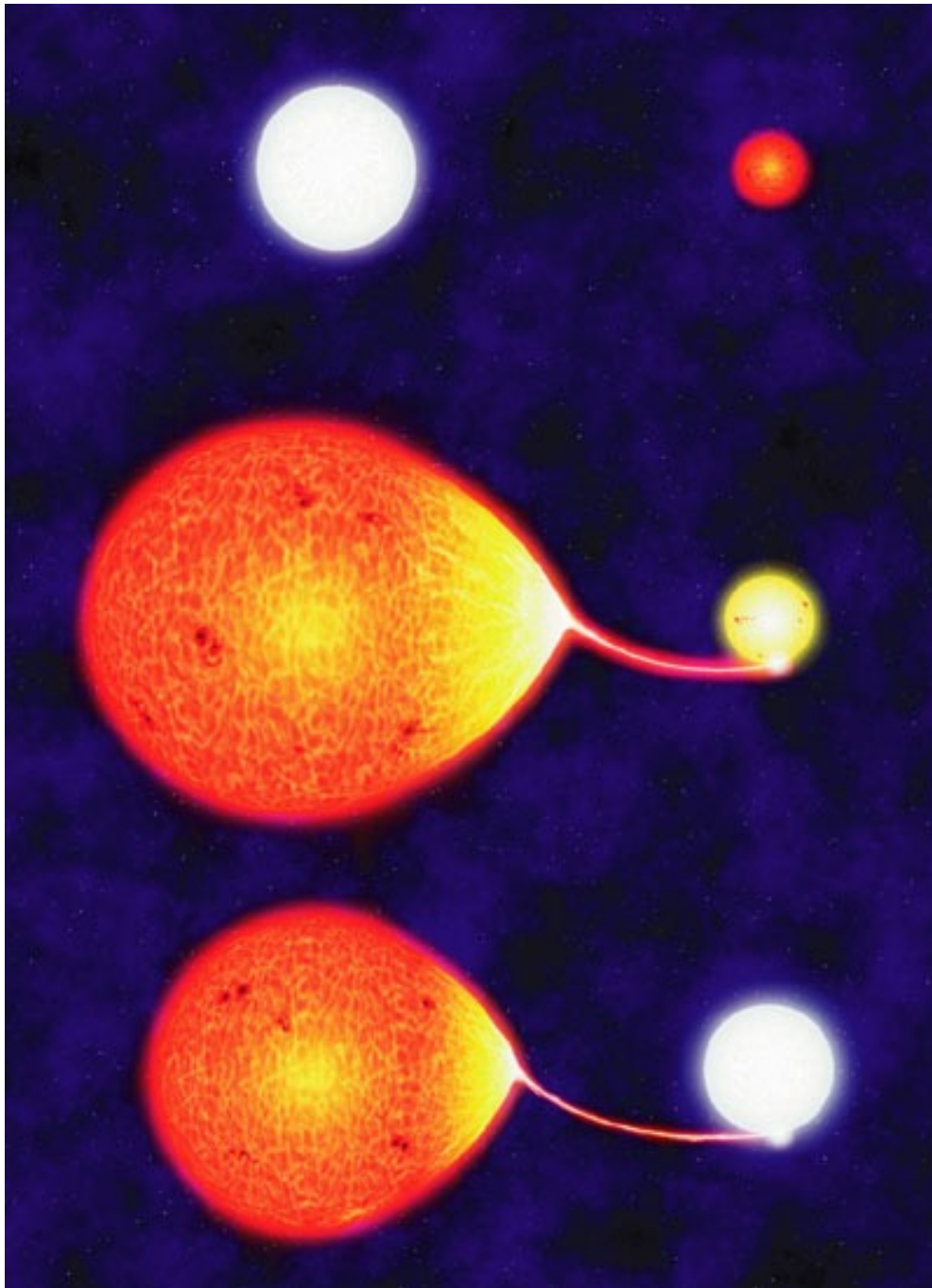


1. Protostar: Interstellar cloud collapse under gravity and heats up.
2. Main sequence: H fuses to He in core.
3. Red supergiant: H fuses to He in shell around inert He core.
4. Helium core burning supergiant: He fuses to C in core while H fuses to He in shell around the core.
5. Red supergiant (again). *Multiple* shell burning: H, He, C and heavier elements fuse in shells around an inert iron core.
6. Supernova: Titanic explosion as outer blown away by the rebound of the collapsing iron core. Heavy elements beyond synthesized.
7. leaves neutron star (or black hole) behind.

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

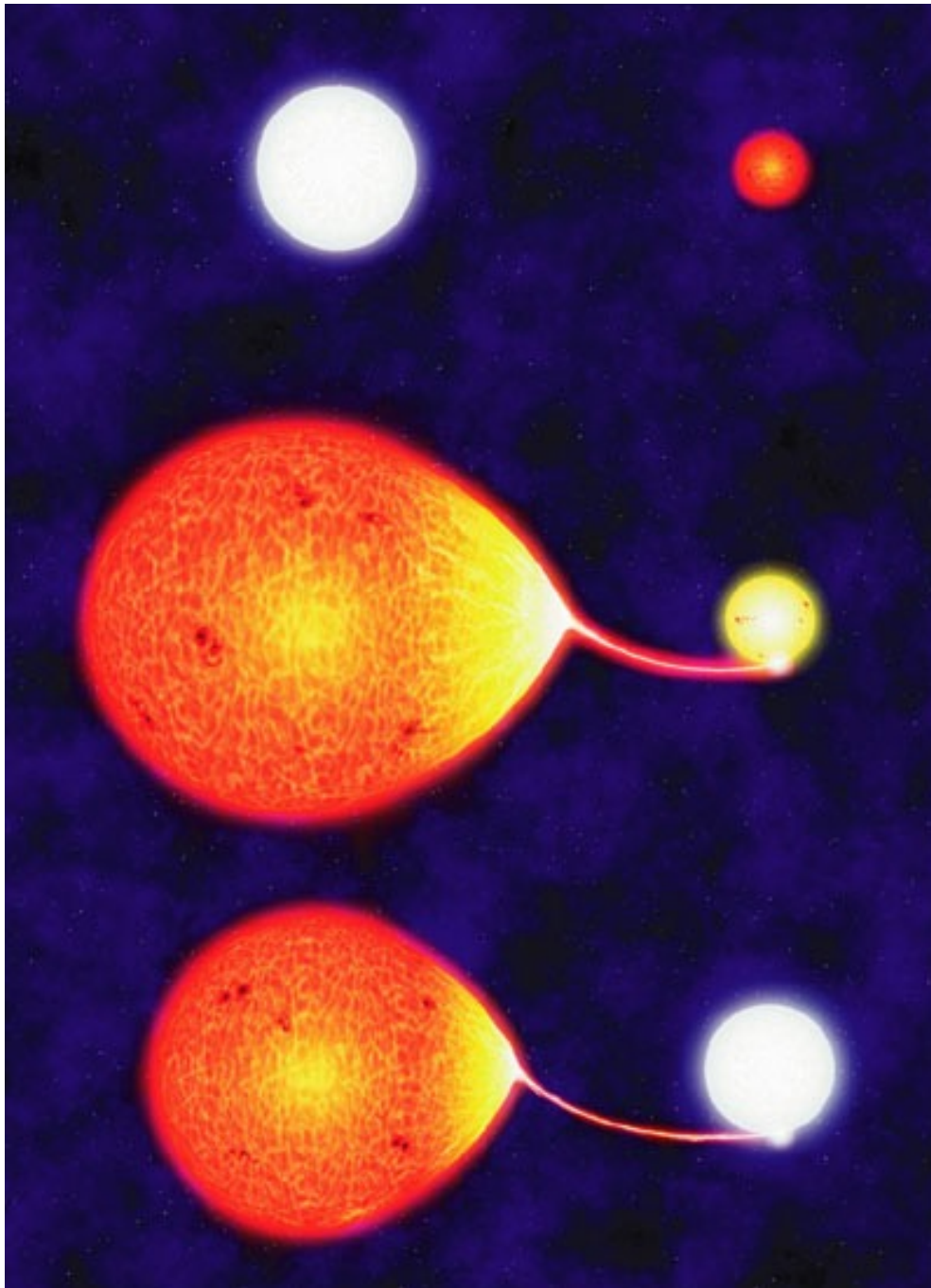






# Mass Transfer

Stars can be close enough that *matter can flow* from the subgiant onto the main-sequence star.



# Mass Transfer

- The star that is now a subgiant was originally more massive.
- As it reached the end of its life and started to grow, it transferred mass to its companion (*mass exchange*).
- Now the companion star is more massive, may even evolve faster!

# What have we learned?

Begin 3 minute review

# 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.