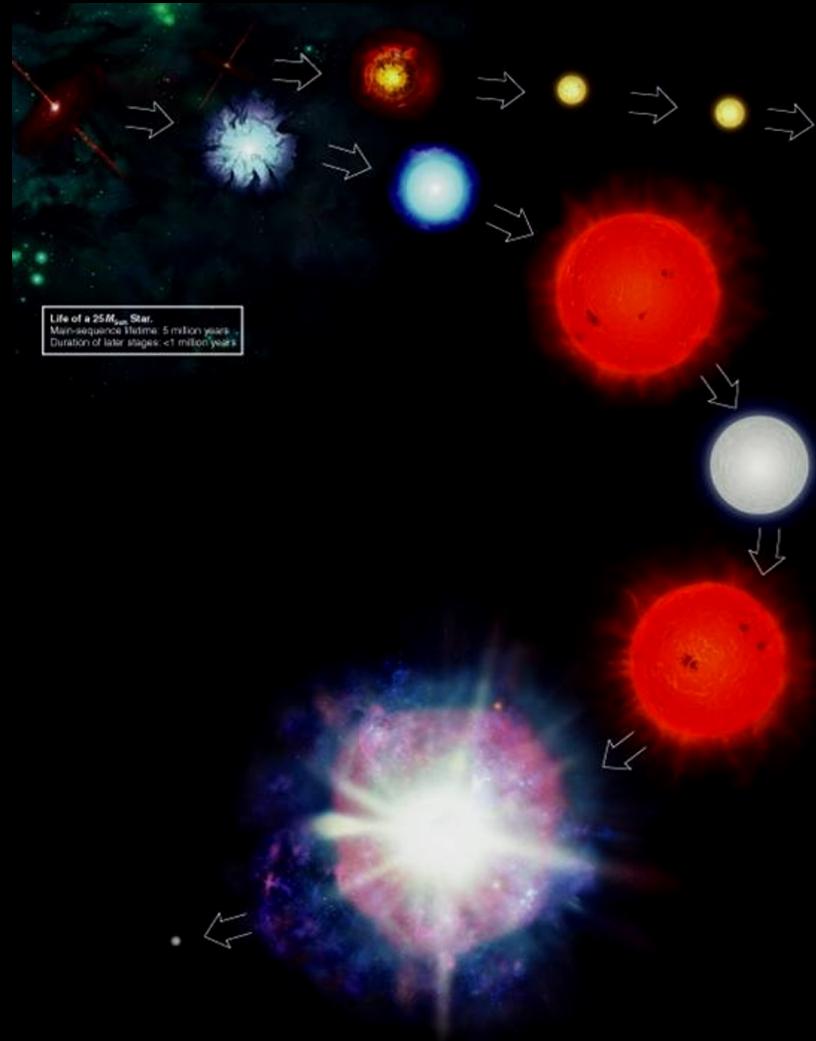
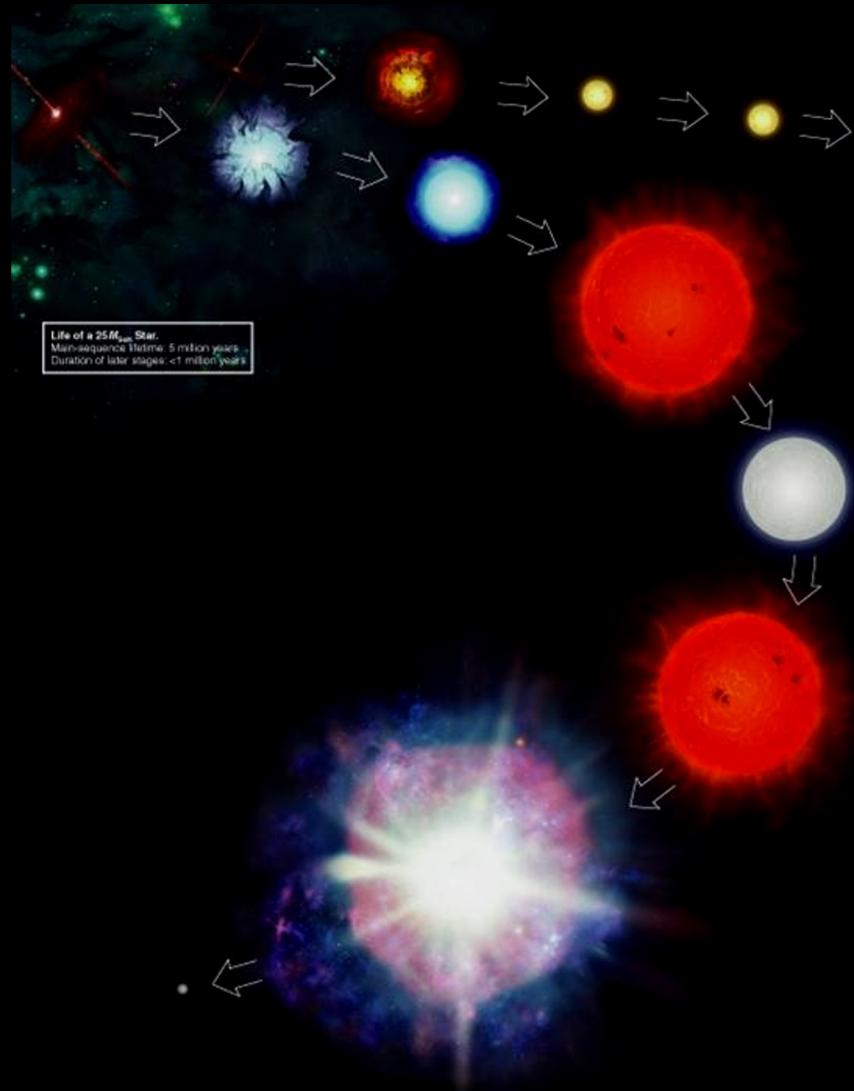


Lecture 18:

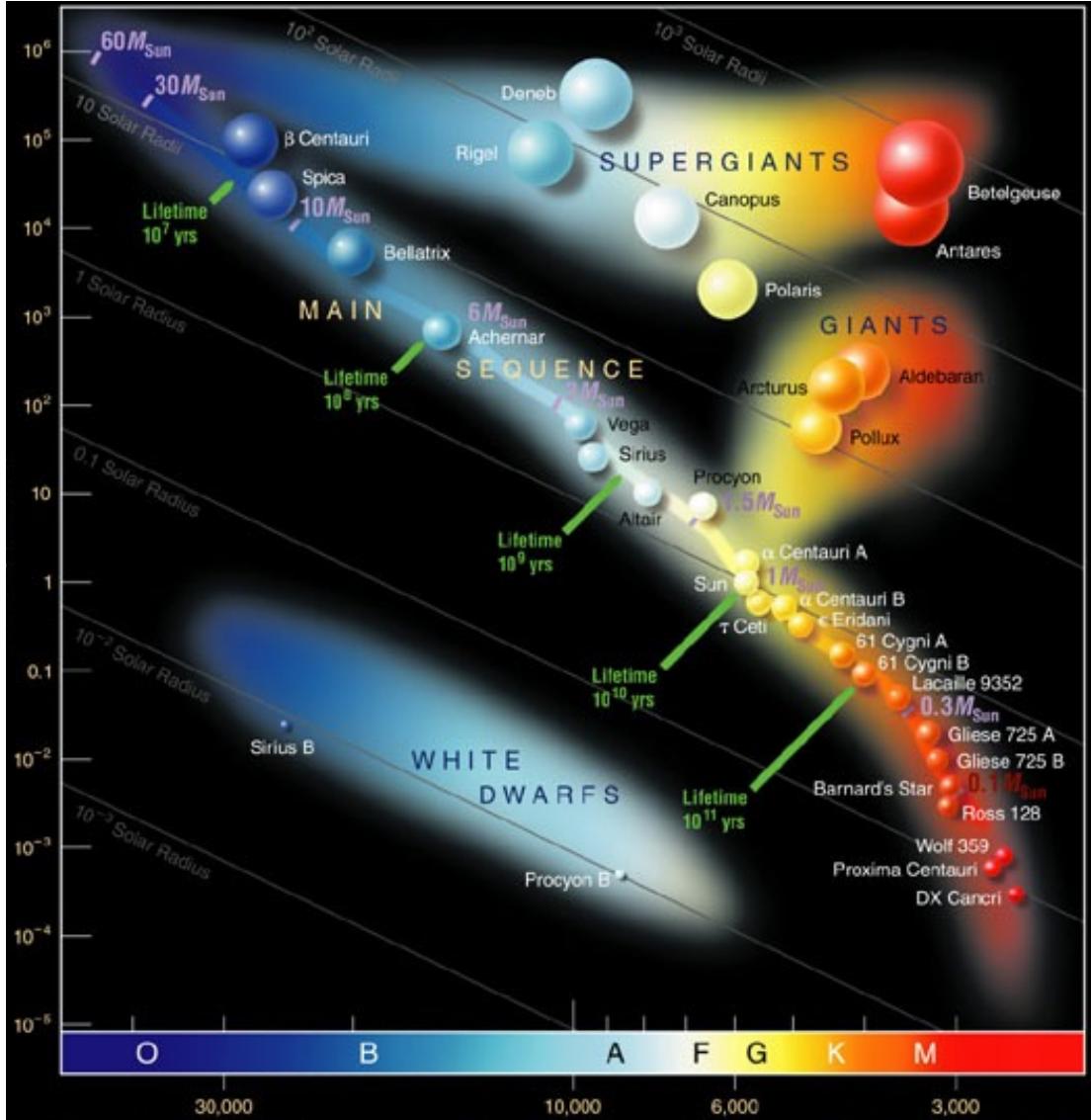
High Mass Stellar Evolution



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?

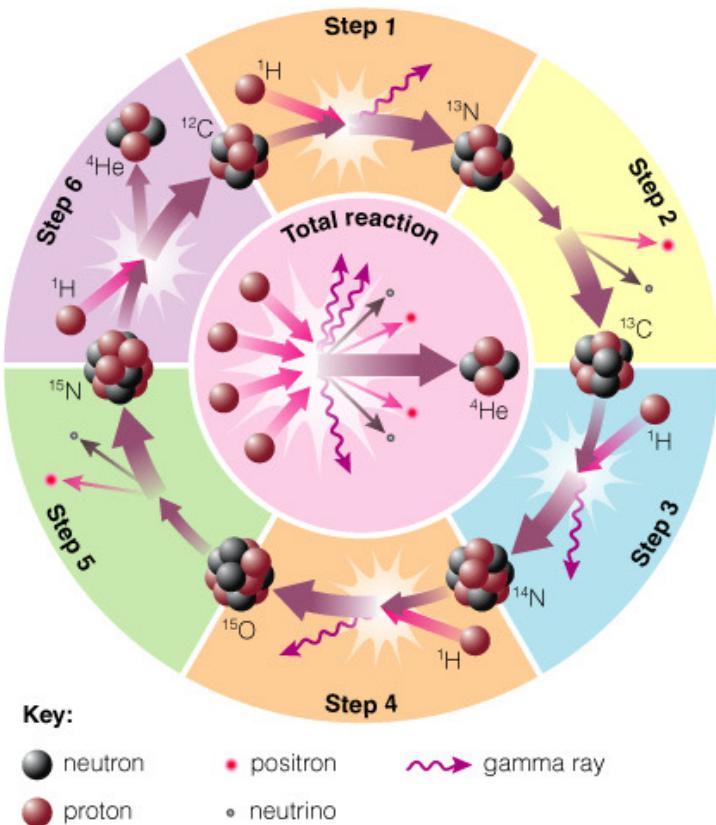
- A. The core collapses and the star explodes.
- B. Carbon fusion begins in the core.**
- C. The core expands and cools off.
- D. Helium fuses in a shell around the core.**

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**

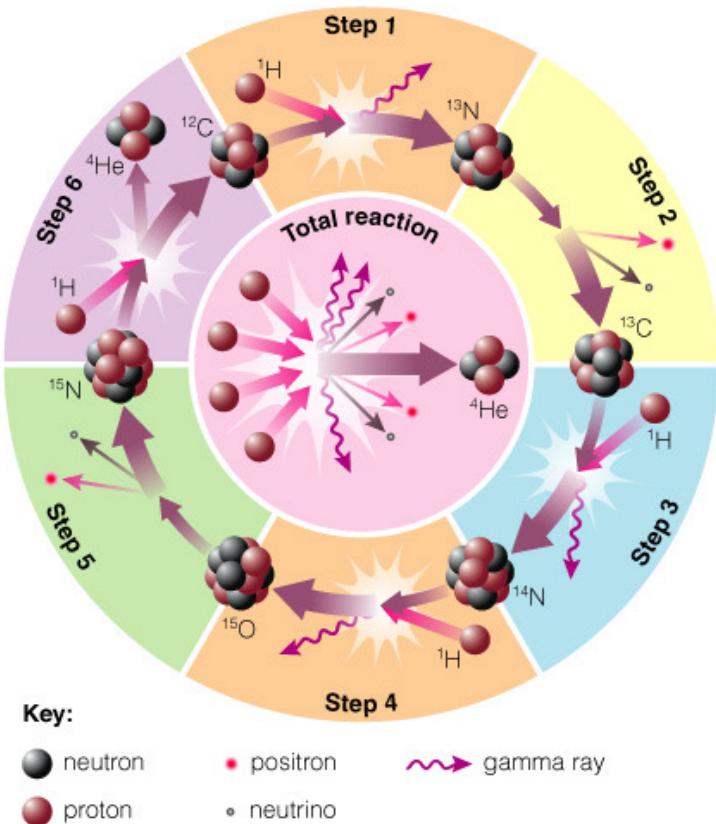
So how do high-mass stars make heavy elements?

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 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?

Key

12	Atomic number
Mg	Element's symbol
Magnesium	Element's name
24.305	Atomic mass*

1	H
Hydrogen	1.00794

3	Li
Lithium	6.941
11	Na
Sodium	22.990

12	Mg
Magnesium	24.305

19	K
Potassium	39.098
37	Rb
Rubidium	85.468

38	Sr
Strontium	87.62

20	Ca
Calcium	40.08
21	Sc
Scandium	44.956

22	Ti
Titanium	47.88
23	V
Vanadium	50.94

24	Cr
Chromium	51.996
25	Mn
Manganese	54.938

26	Fe
Iron	55.847
27	Co
Cobalt	58.9332

28	Ni
Nickel	58.69
29	Cu
Copper	63.546

30	Zn
Zinc	65.39
31	Ga
Gallium	69.72

32	Ge
Germanium	72.59
33	As
Arsenic	74.922

34	Se
Selenium	78.96
35	Br
Bromine	79.904

36	Fr
Krypton	83.80
37	Rb
Rubidium	85.468

38	Sr
Strontium	87.62
39	Y
Yttrium	88.9059

40	Zr
Zirconium	91.224
41	Nb
Niobium	92.91

42	Mo
Molybdenum	95.94
43	Tc
Technetium	(98)

44	Ru
Ruthenium	101.07
45	Rh
Rhodium	102.906

46	Pd
Palladium	106.42
47	Ag
Silver	107.868

48	Cd
Cadmium	112.41
49	In
Indium	114.82

50	Sn
Tin	118.71
51	Sb
Antimony	121.75

52	Te
Tellurium	127.60
53	I
Iodine	126.905

54	Xe
Xenon	131.29
55	Cs
Cesium	132.91

56	Ba
Barium	137.34
72	Hf
Hafnium	178.49

73	Ta
Tantalum	180.95
74	W
Tungsten	183.85

75	Re
Rhenium	186.207
76	Os
Osmium	190.2

77	Ir
Iridium	192.22
78	Pt
Platinum	195.08

79	Au
Gold	196.967
80	Hg
Mercury	200.59

81	Ti
Thallium	204.383
82	Pb
Lead	207.2

83	Bi
Bismuth	208.98
84	Po
Polonium	(209)

85	At
Astatine	(210)
86	Rn
Radon	(222)

5	B
Boron	10.81
6	C
Carbon	12.011

7	N
Nitrogen	14.007
8	O
Oxygen	15.999

9	F
Fluorine	18.988
10	Ne
Neon	20.179

The Periodic Table of Elements

2	He
Helium	4.003

*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.

The Lanthanide Series consists of the elements from lanthanum (La) to lutetium (Lu). They are often grouped together in the periodic table.

The Actinide Series consists of the elements from actinium (Ac) to lawrencium (Lr). They are often grouped together in the periodic table.

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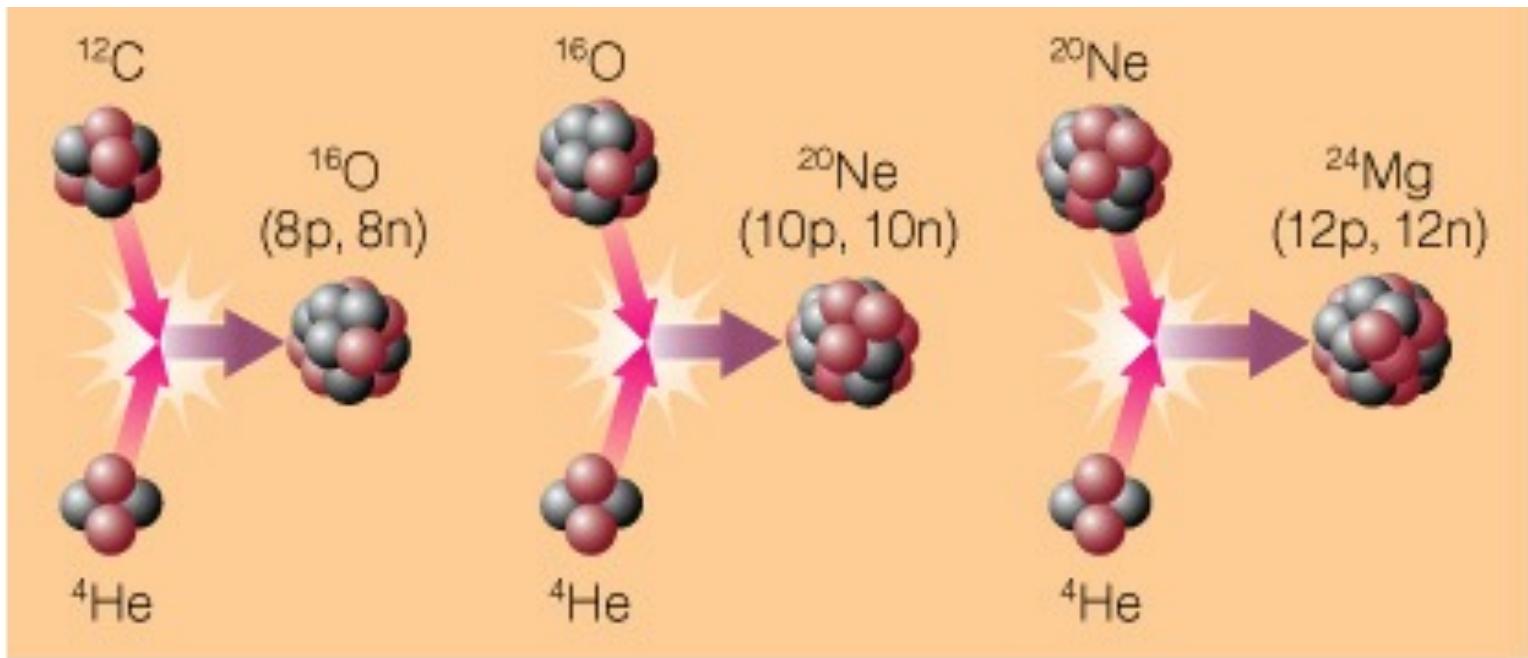
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The Actinide Series consists of the elements from actinium (Ac) to lawrencium (Lr). They are often grouped together in the periodic table.

- 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.

H Hydrogen 1.00794	Li Lithium 6.941	Be Beryllium 9.01218
Na Sodium 22.990	Mg Magnesium 24.305	
K Potassium 39.098	Ca Calcium 40.08	
Rb Rubidium 85.468	Sr Strontium 87.62	
Cs Cesium 132.91	Ba Barium 137.34	
Fr Francium (223)	Ra Radium 226.0254	

Key

12	Atomic number
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Magnesium	Element's name
24.305	Atomic mass*

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The Periodic Table of Elements

Table of Elements						
2 He Helium 4.003						
5 B Boron 10.81	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.988	10 Ne Neon 20.179	
13 Al Aluminum 26.98	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.06	17 Cl Chlorine 35.453	18 Ar Argon 39.948	
31 Ga Gallium 69.72	32 Ge Germanium 72.59	33 As Arsenic 74.922	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Fr Krypton 83.80	
49 In Indium 114.82	50 Sn Tin 118.71	51 Sb Antimony 121.75	52 Te Tellurium 127.60	53 I Iodine 126.905	54 Xe Xenon 131.29	
81 Tl Thallium 204.363	82 Pb Lead 207.2	83 Bi Bismuth 208.98	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)	

Lanthanide Series

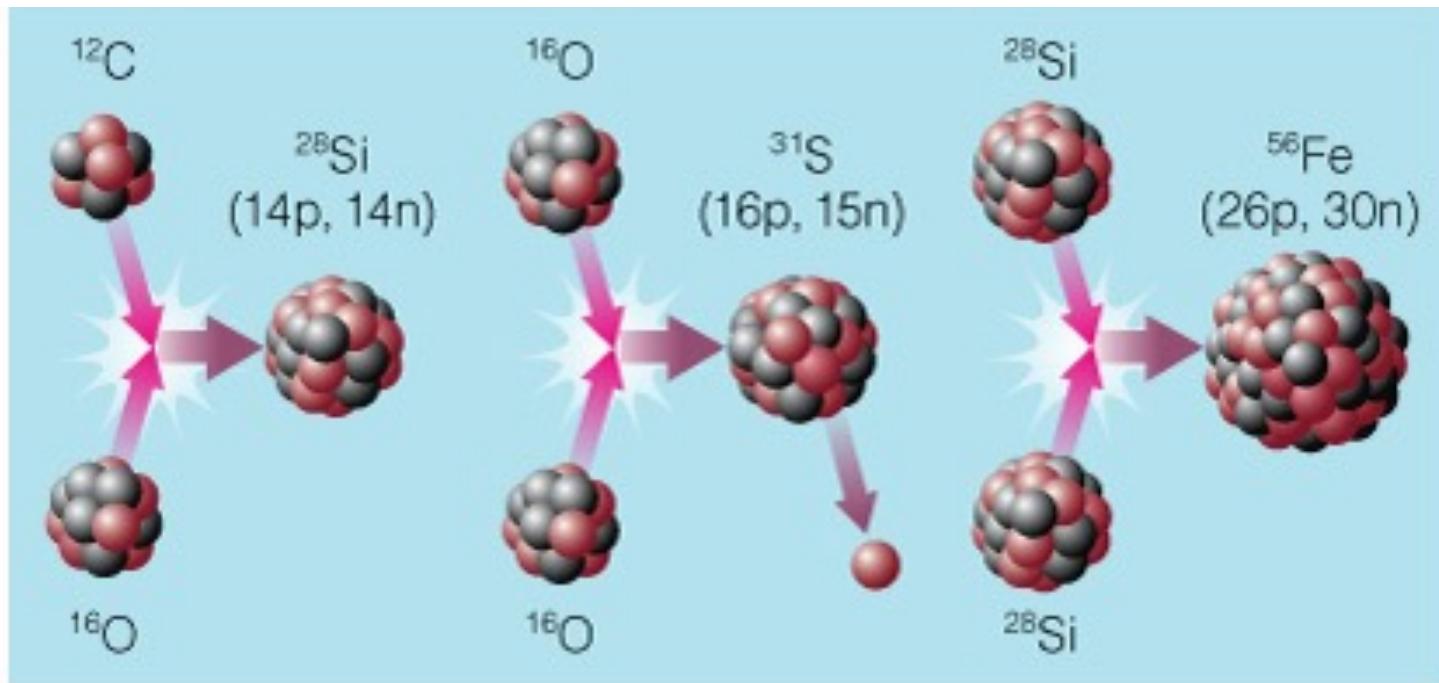
57 La Lanthanum 138.906	58 Ce Cerium 140.12	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.96	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93	68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium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

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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*!

H Hydrogen 1.00794
Li Lithium 6.941
Be Beryllium 9.01218
Mg Magnesium 24.305
Na Sodium 22.990
K Potassium 39.098
Rb Rubidium 85.468
Sr Strontium 87.62
Cs Cesium 132.91
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Si Silicon 28.086
P Phosphorus 30.974
S Sulfur 32.06
Cl Chlorine 35.453
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In Indium 114.82
Tl Thallium 120.383
Sn Tin 118.71
Sb Antimony 121.75
Te Tellurium 127.60
I Iodine 126.905
Rb Rutherfordium (261)
Db Dubnium (262)
Sg Seaborgium (263)
Bh Bohrium (262)
Hs Hassium (265)
Mt Meitnerium (266)
Uun Ununnilium (269)
Uuu Unununium (272)
Uub Ununbium (277)
La Lanthanum 138.906
Ce Cerium 140.12
Pr Praseodymium 140.908
Nd Neodymium 144.24
Pm Promethium (145)
Sm Samarium 150.36
Eu Europium 151.96
Gd Gadolinium 157.25
Tb Terbium 158.925
Dy Dysprosium 162.50
Ho Holmium 164.93
Er Erbium 167.26
Tm Thulium 168.934
Yb Ytterbium 173.04
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Lanthanide Series

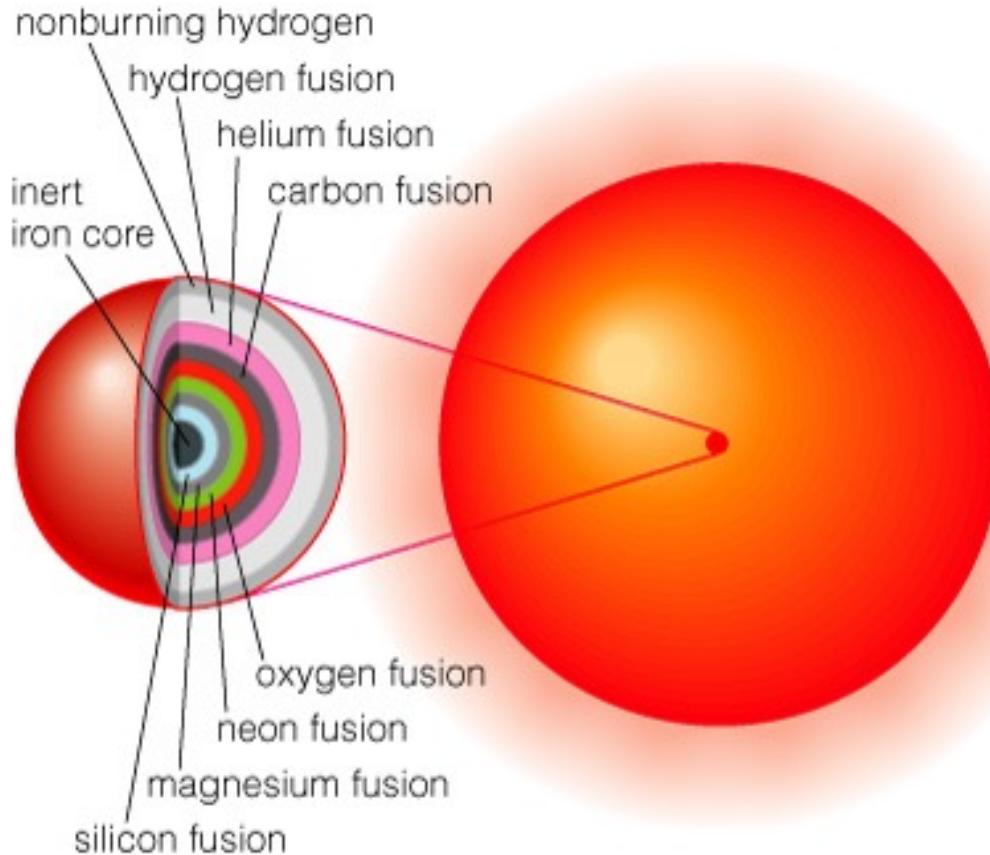
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Cm Curium (247)
Bk Berkelium (247)
Cf Californium (251)
Esn Einsteinium (252)
Fm Fermium (257)
Md Mendelevium (258)
No Nobelium (259)
Lr Lawrencium (260)

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

Multiple-Shell Burning

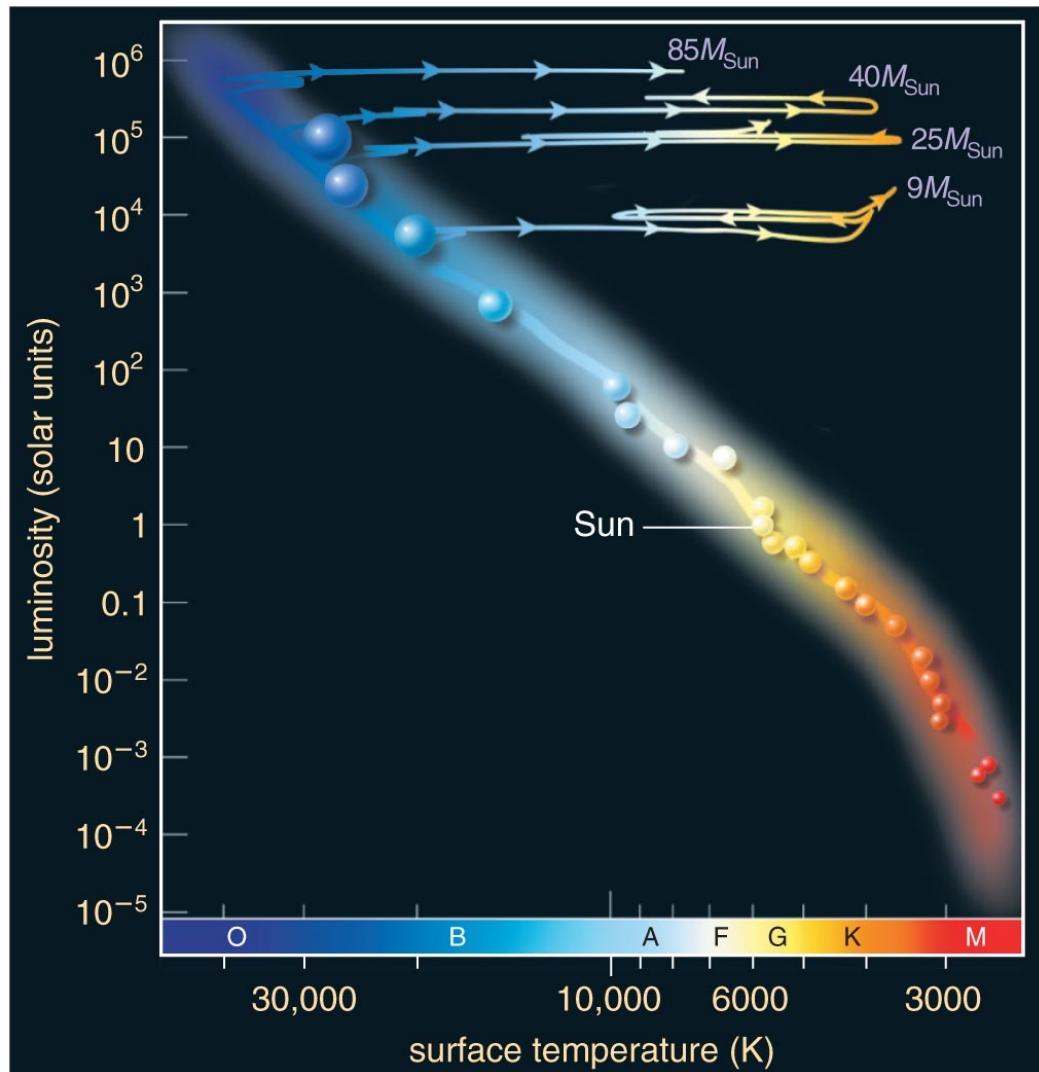


- Advanced nuclear fusion proceeds in a series of nested shells.
- Progressively heavier elements are created by fusion: *nucleosynthesis*.
- Ignition of next heavier element in core (and new shell) do what to star?

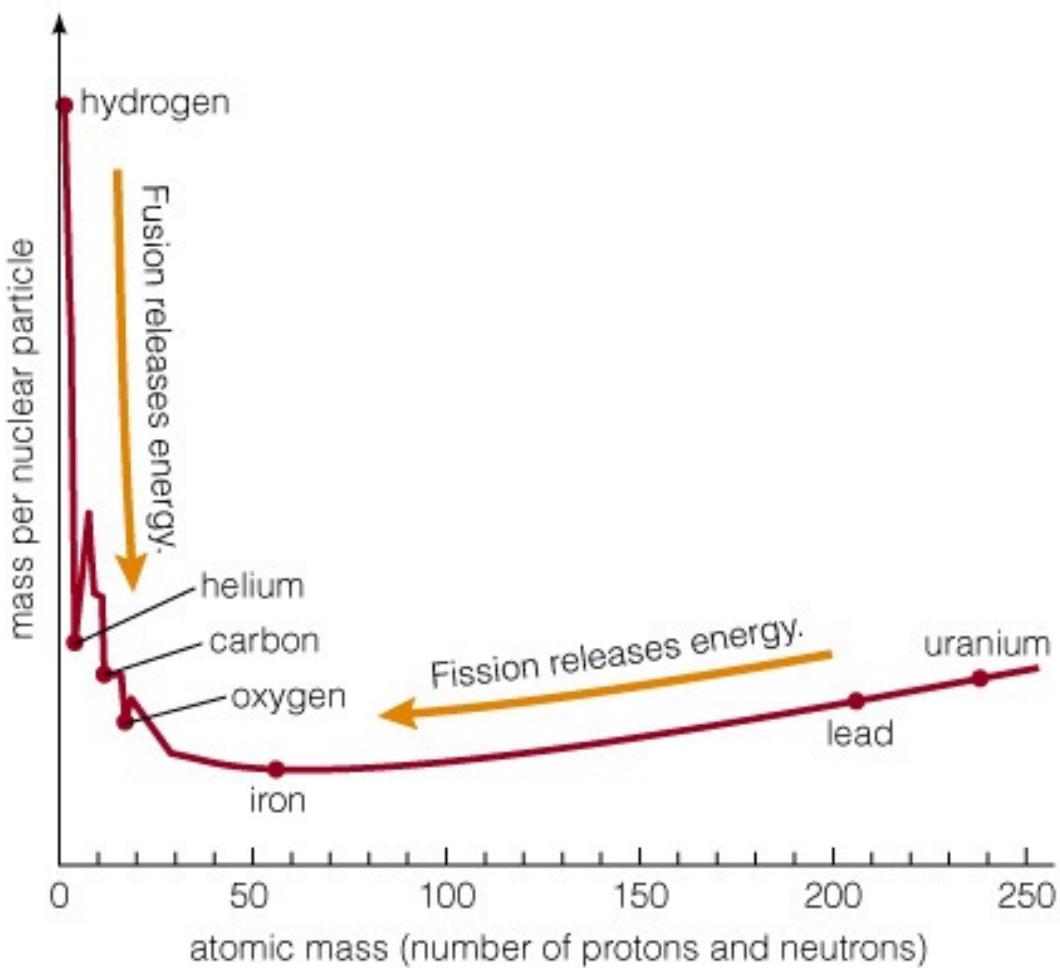
High mass life tracks

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~~

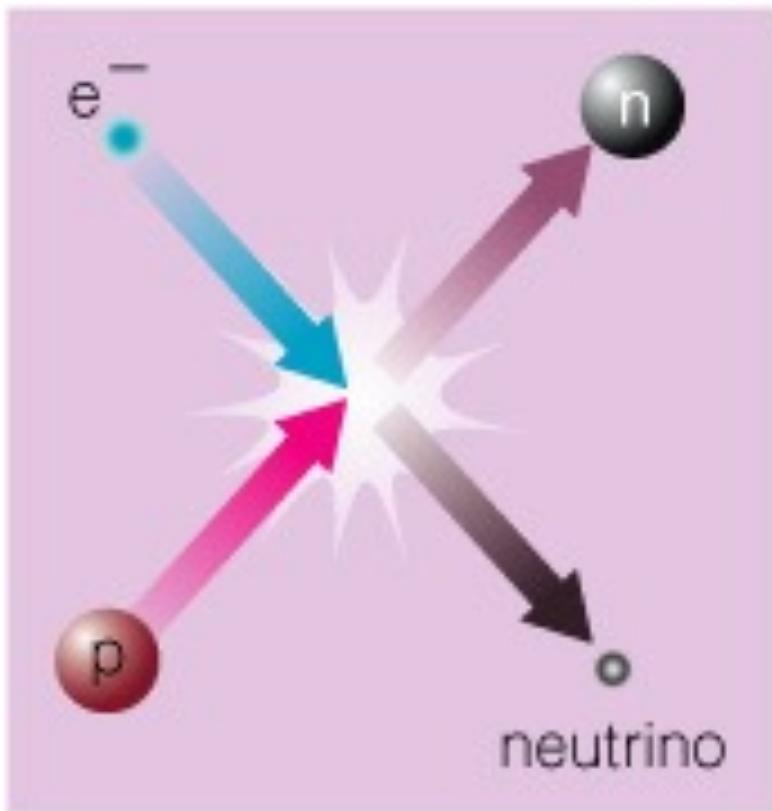


- Fusion releases energy because source elements have greater mass than elements created
- Iron is a dead end for fusion because *nuclear reactions involving iron do not release energy*
- Elements heavier than iron can only release energy via fission

How does a high-mass star die?

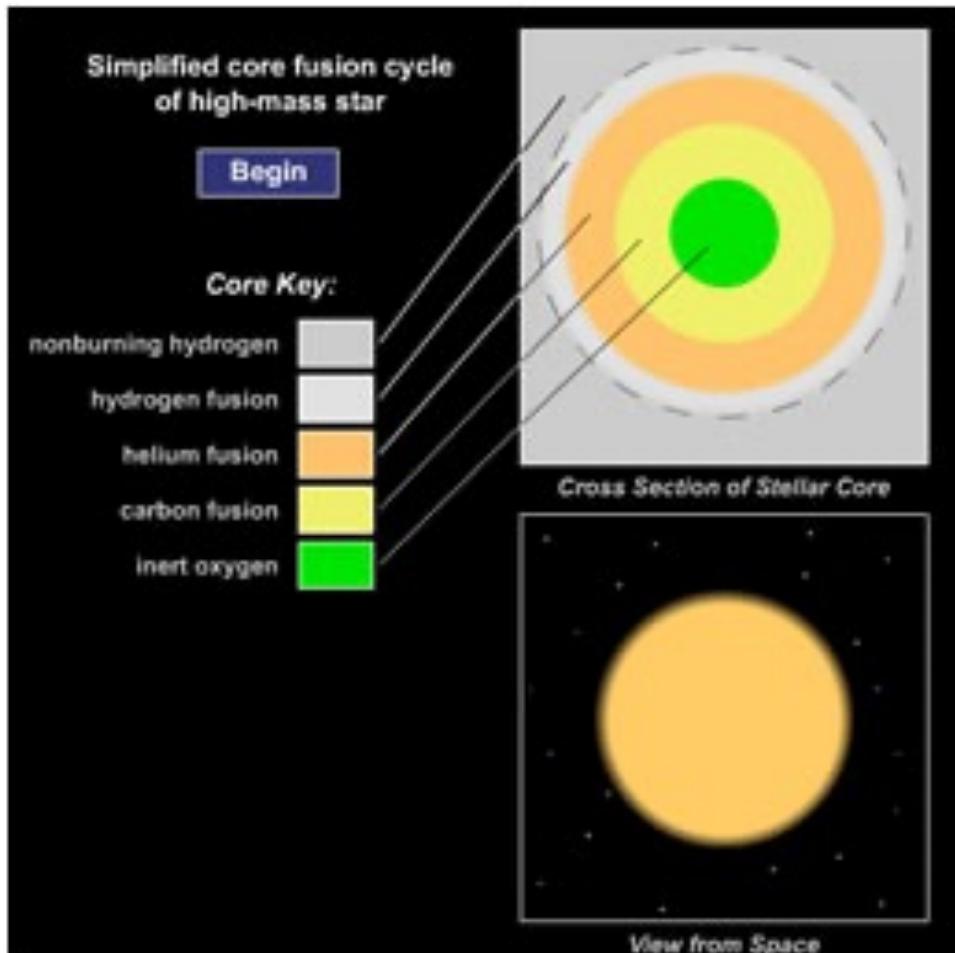


Core collapse



- 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!

H Hydrogen 1.00794	Mg Magnesium 24.305	12 Atomic number Mg Element's symbol Magnesium Element's name 24.305 Atomic mass*
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	Os Osmium 190.2	Ir Iridium 192.22
	Pt Platinum 195.08	Pt Platinum 195.08
	Au Gold 196.007	Au Gold 196.007
	Hg Mercury 200.59	Hg Mercury 200.59
	Tl Thallium 204.383	Tl Thallium 204.383
	Pb Lead 207.2	Pb Lead 207.2
	Bi Bismuth (209)	Bi Bismuth (209)
	Po Polonium (210)	Po Polonium (210)
	At Astatine (210)	At Astatine (210)
	Rn Radon (222)	Rn Radon (222)

Lanthanide Series

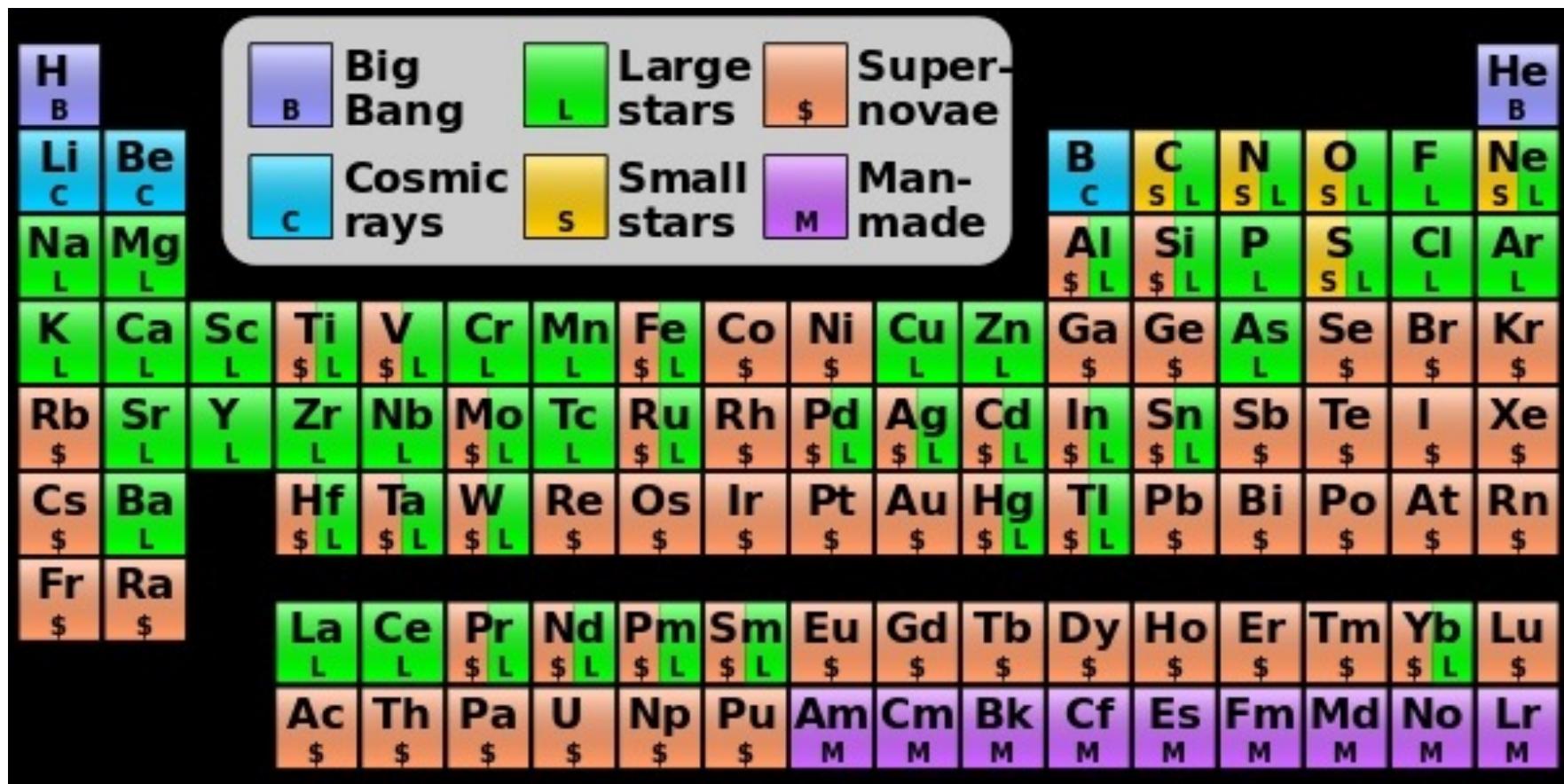
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Vast amounts of energy (100x Sun's *lifetime* energy!) and neutrons are released enabling elements heavier than iron such as Au and U to form.

The Formation of the Elements



Supernova Remnant

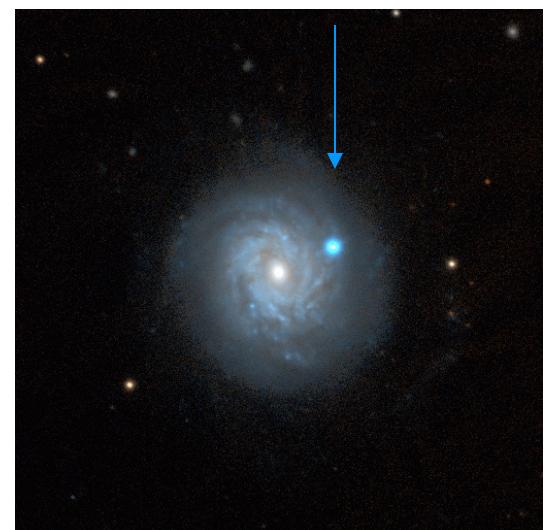
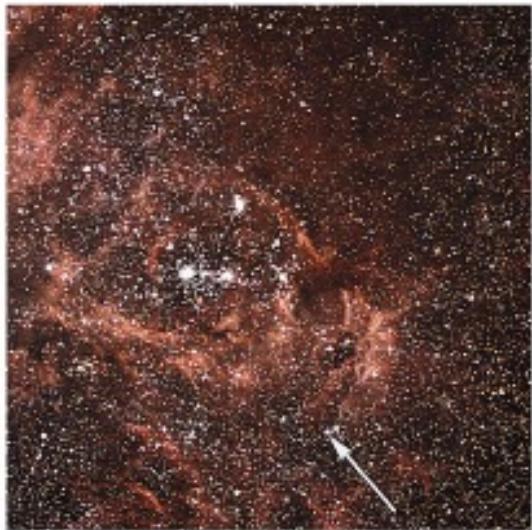


- Energy released by the collapse of the core drives outer layers into space.
- The Crab Nebula is the remnant of a supernova seen in A.D. 1054.
- Expanding material (heavy elements) enriches the ISM.

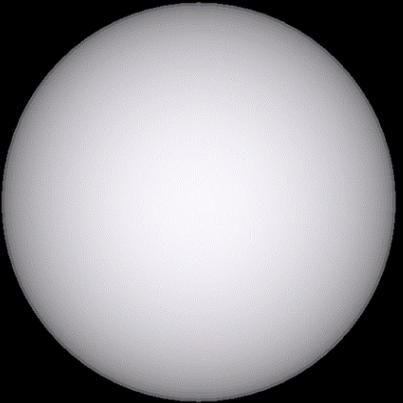
PLAY

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.

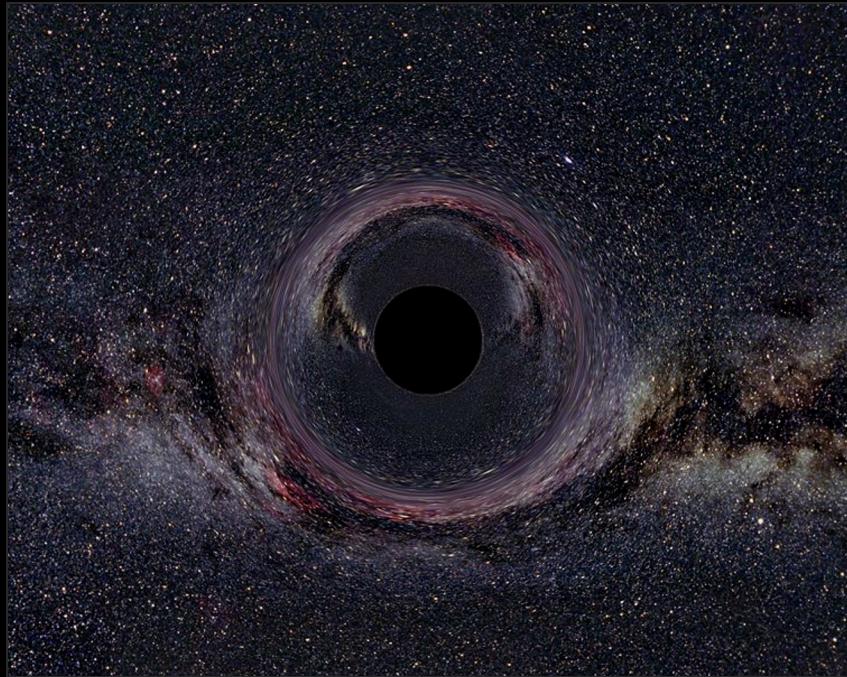


Neutron stars

- 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 cm^3 would weigh 100 *million* tons!
- In most massive stars, **neutron** degeneracy finally stops the collapse.
- The star a literally a giant atomic nucleus – a ball of neutrons about 10 km in diameter.

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

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).

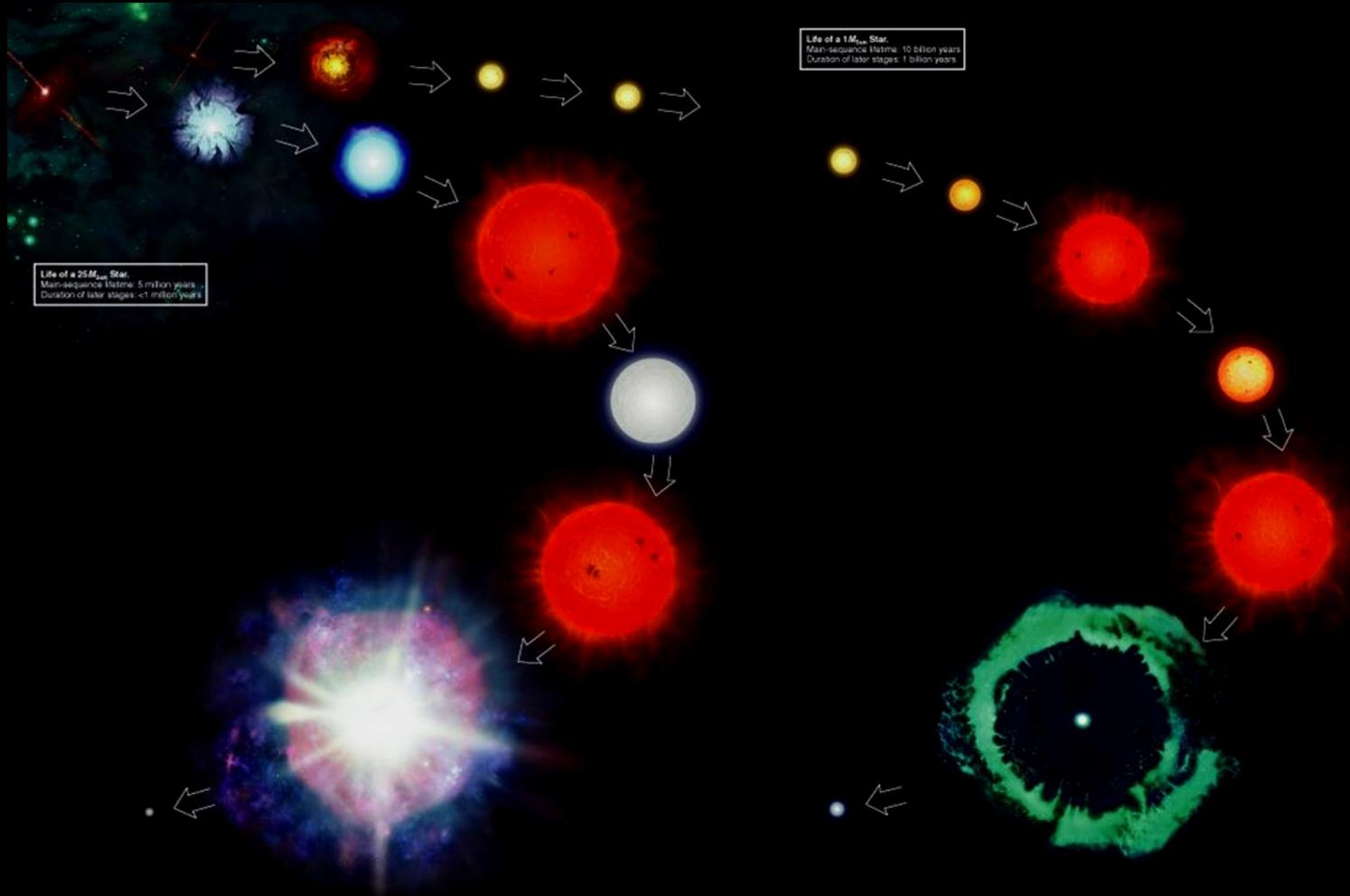
How do high-mass stars make heavy elements?

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

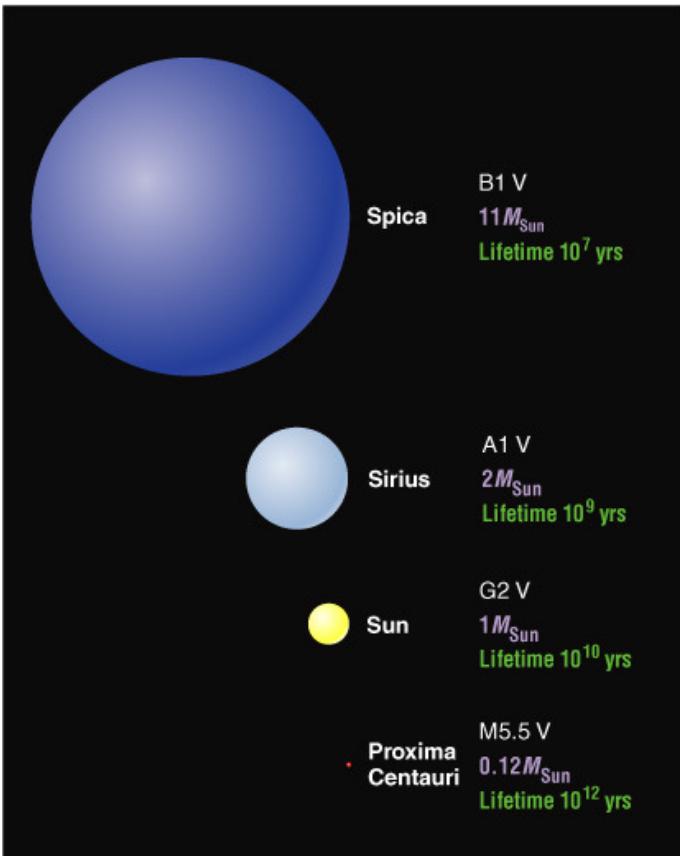
How does a high-mass star die?

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

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

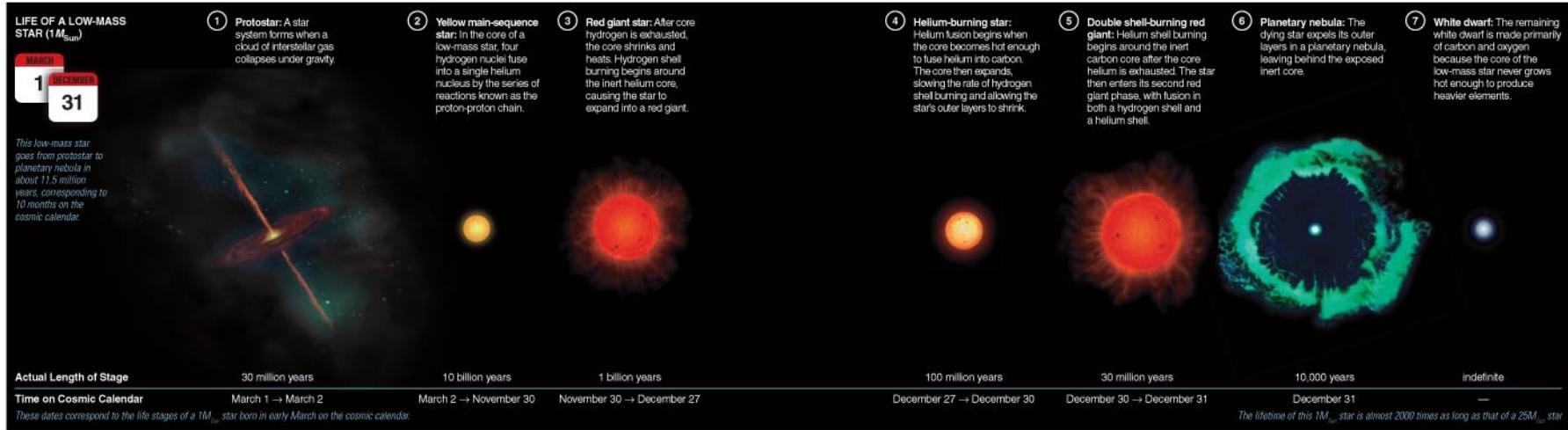


Role of Mass



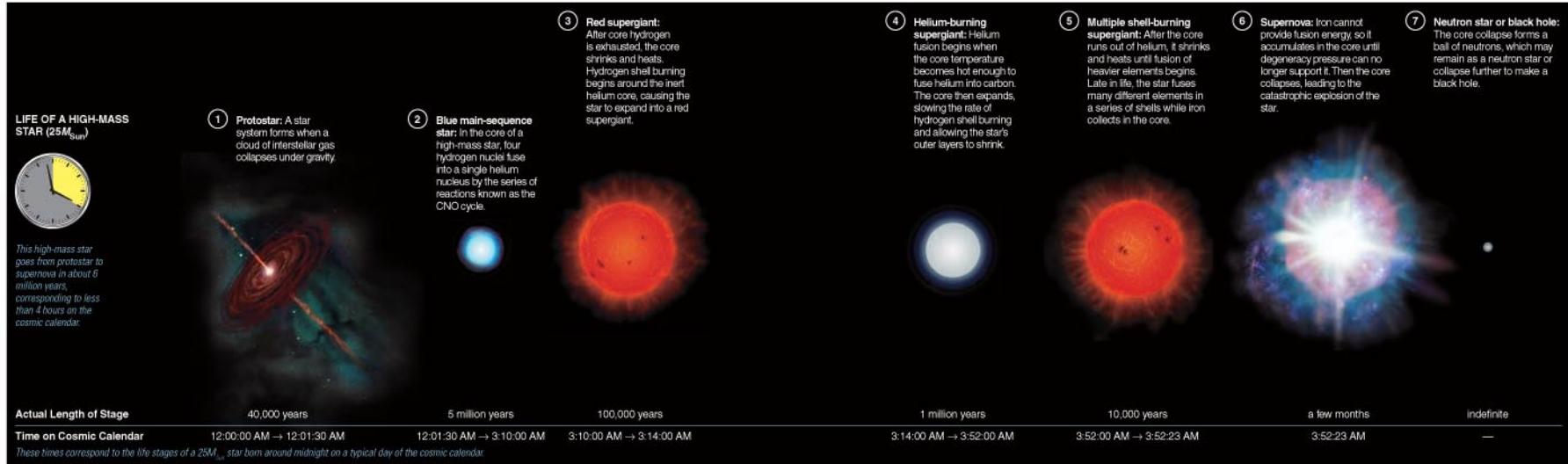
- *A star's mass determines its entire life story because it determines its core temperature.*
- **High-mass stars have short lives,** eventually becoming hot enough to make iron, and end in supernova explosions and neutron stars.
- **Low-mass stars have long lives,** never become hot enough to fuse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

Life stages of Low-Mass stars



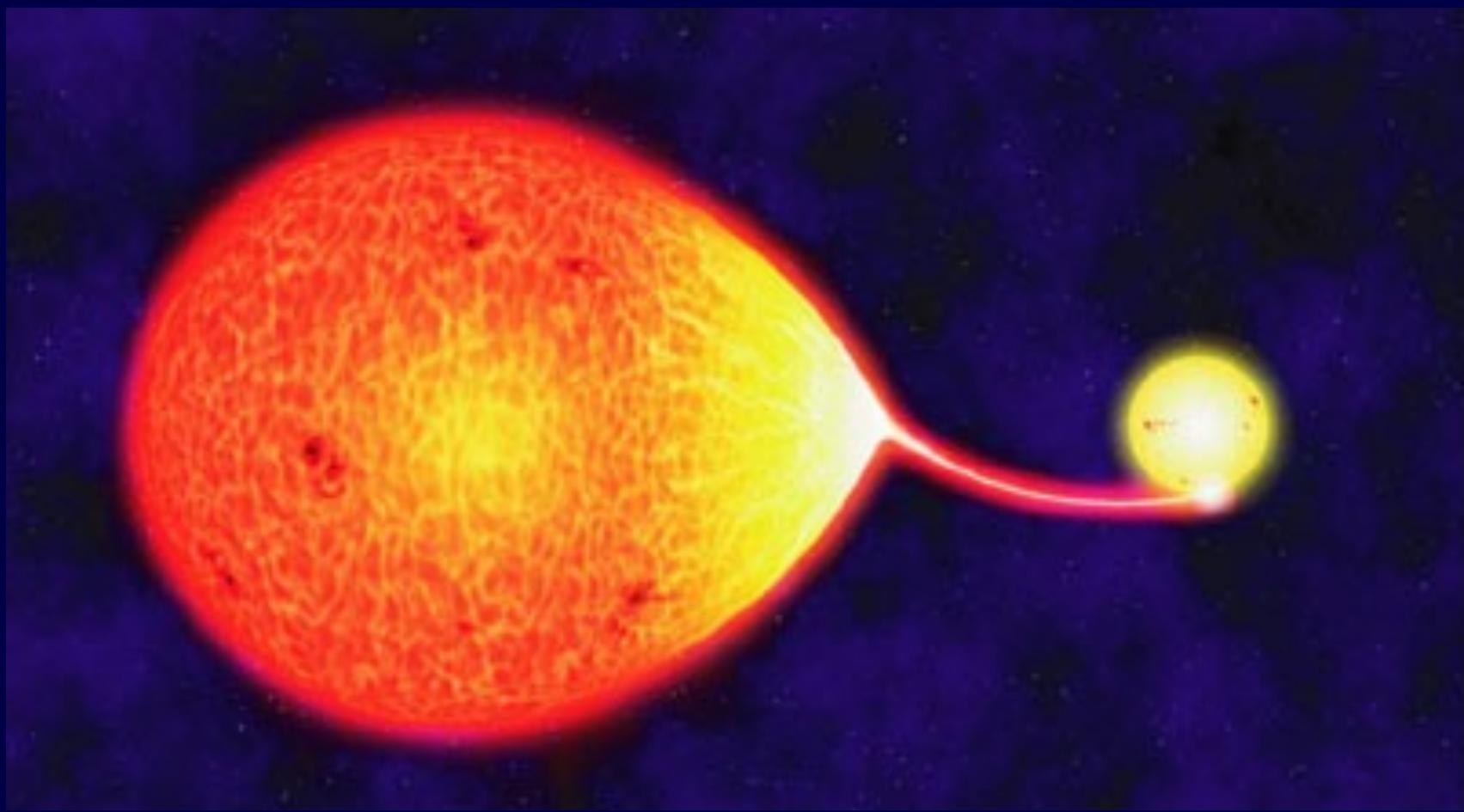
1. Protostar: Interstellar cloud collapse under gravity and heats up.
2. Main sequence: H fuses to He in core.
3. Red giant: H fuses to He in shell around inert He core.
4. Helium core burning: He fuses to C in core while H fuses to He in shell around the core.
5. Red Giant (again). Double shell burning: 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.

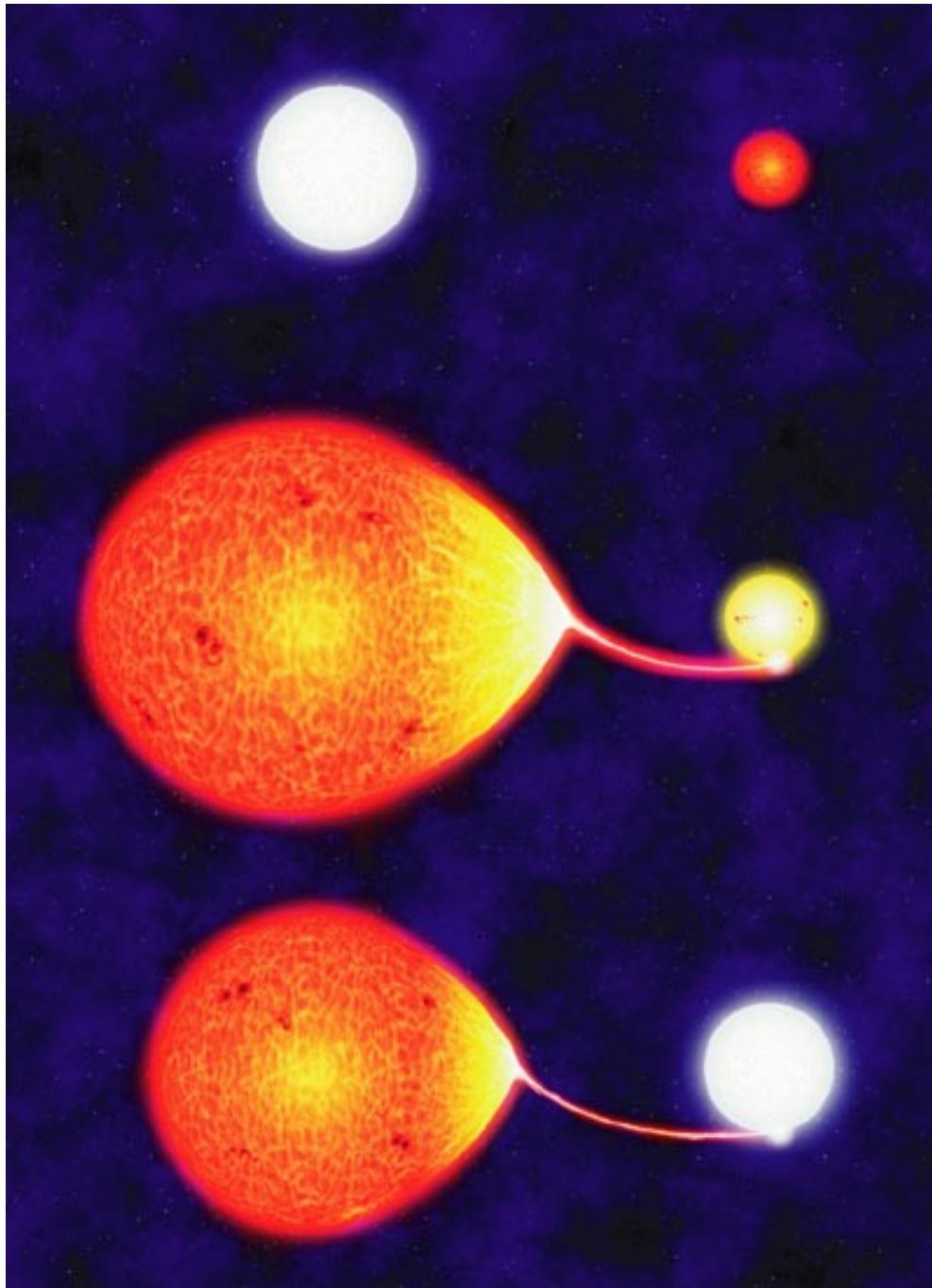
Life Stages of High-Mass Star



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?



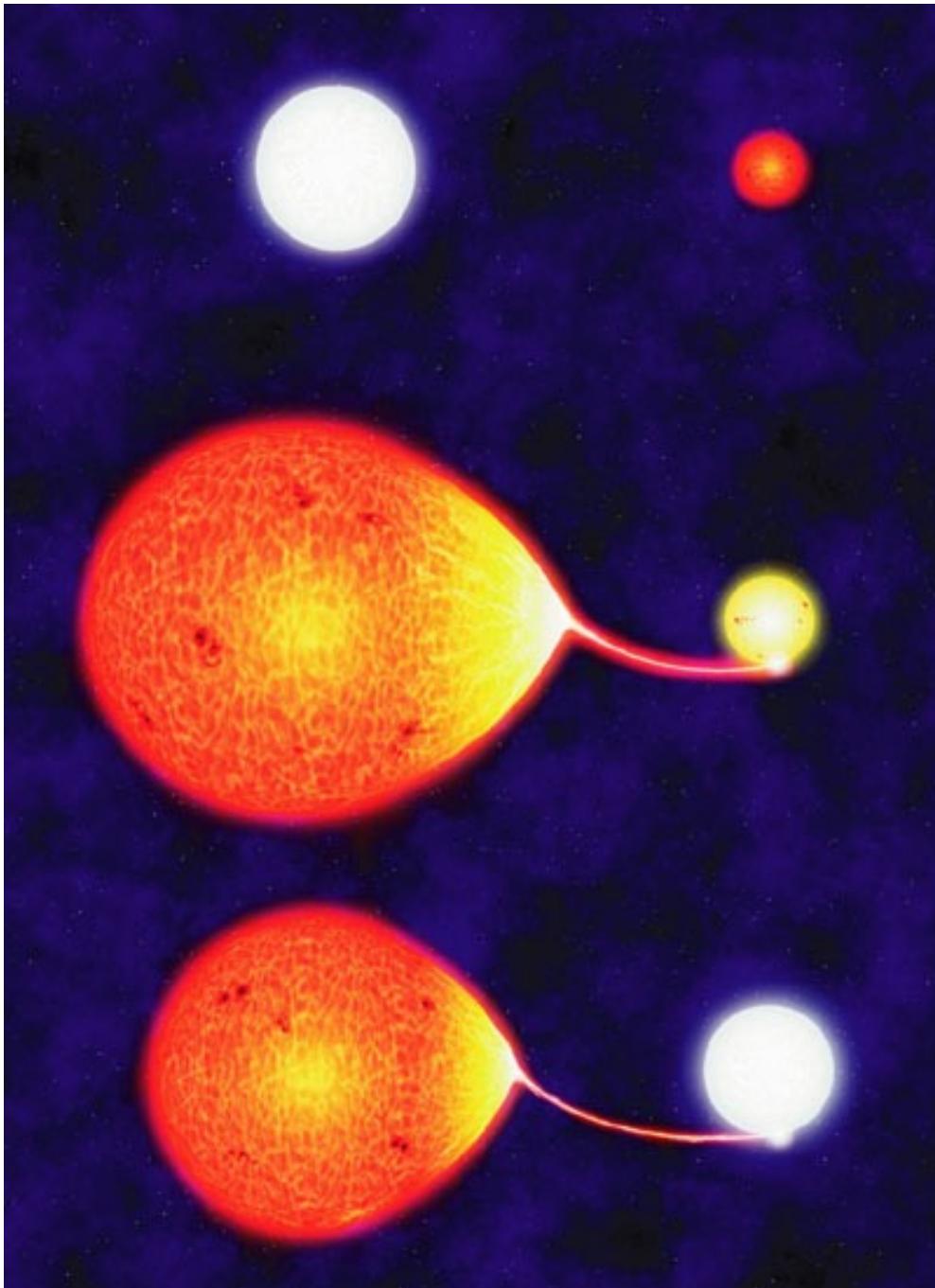


Mass Transfer

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.