

## Chapter 17 Star Stuff



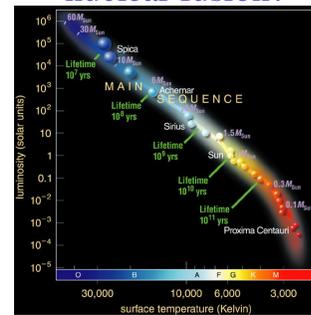
## Agenda

- Announce
  - Tutorial
  - Projects (Theme: Biographies? Fiction?)
- Ch. 17—Star Stuff
- GR Exercise

### 17.1 Lives in the Balance

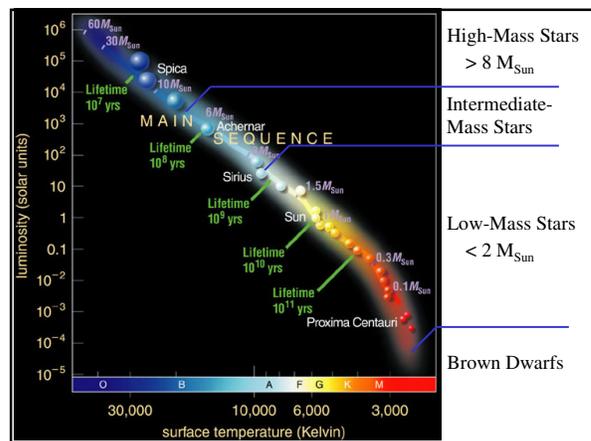
- Our goals for learning
- How does a star's mass affect nuclear fusion?

### How does a star's mass affect nuclear fusion?



### Stellar Mass and Fusion

- The mass of a main sequence star determines its core pressure and temperature
- Stars of higher mass have higher core temperature and more rapid fusion, making those stars both more luminous and shorter-lived
- Stars of lower mass have cooler cores and slower fusion rates, giving them smaller luminosities and longer lifetimes



## Star Clusters and Stellar Lives



- Our knowledge of the life stories of stars comes from comparing mathematical models of stars with observations
- Star clusters are particularly useful because they contain stars of different mass that were born about the same time

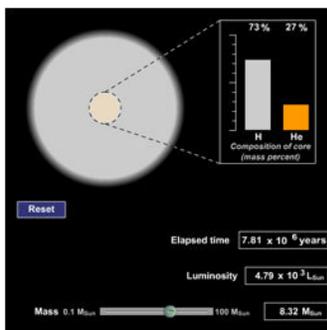
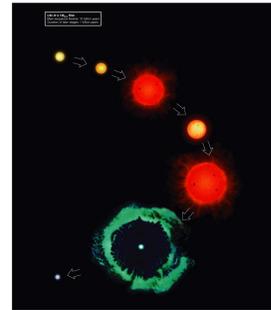
## What have we learned?

- How does a star's mass affect nuclear fusion?
  - A star's mass determines its core pressure and temperature and therefore determines its fusion rate
  - Higher mass stars have hotter cores, faster fusion rates, greater luminosities, and shorter lifetimes

## 17.2 Life as a Low-Mass Star

- Our goals for learning
- What are the life stages of a low-mass star?
- How does a low-mass star die?

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



A star remains on the main sequence as long as it can fuse hydrogen into helium in its core

## Thought Question

What happens when a star can no longer fuse hydrogen to helium in its core?

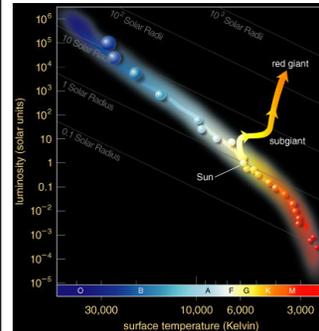
- Core cools off
- Core shrinks and heats up
- Core expands and heats up
- Helium fusion immediately begins

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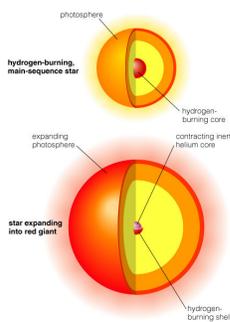
- A. Core cools off
- B. Core shrinks and heats up**
- C. Core expands and heats up
- D. Helium fusion immediately begins

### Life Track after Main Sequence

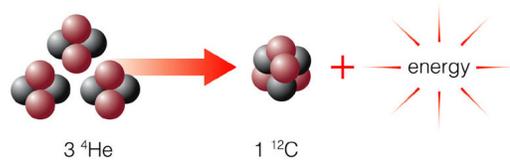


- Observations of star clusters show that a star becomes larger, redder, and more luminous after its time on the main sequence is over

### Broken Thermostat



- As the core contracts, H begins fusing to He in a shell around the core
- Luminosity increases because the core thermostat is broken—the increasing fusion rate in the shell does not stop the core from contracting



Helium fusion does not begin right away because it requires higher temperatures than hydrogen fusion—larger charge leads to greater repulsion

Fusion of two helium nuclei doesn't work, so helium fusion must combine three He nuclei to make carbon

### Thought Question

What happens in a low-mass star when core temperature rises enough for helium fusion to begin?

- A. Helium fusion slowly starts up
- B. Hydrogen fusion stops
- C. Helium fusion rises very sharply

*Hint: Degeneracy pressure is the main form of pressure in the inert helium core*

### Thought Question

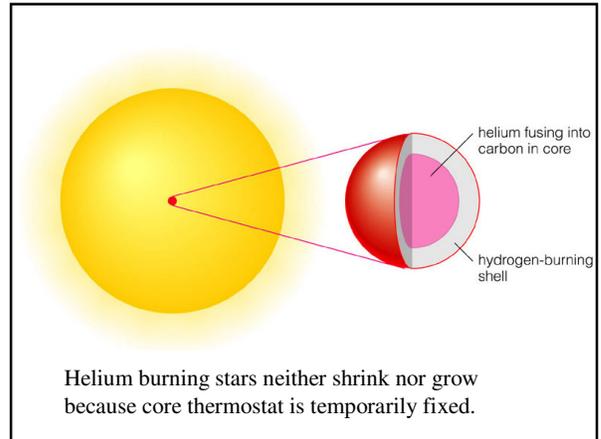
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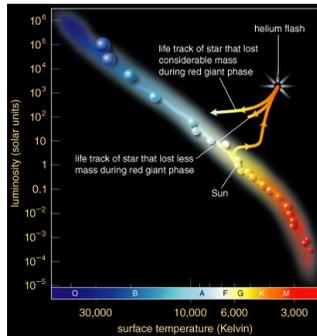
*Hint: Degeneracy pressure is the main form of pressure in the inert helium core*

## Helium Flash

- Thermostat is broken in low-mass red giant because degeneracy pressure supports core
- Core temperature rises rapidly when helium fusion begins
- Helium fusion rate skyrockets until thermal pressure takes over and expands core again

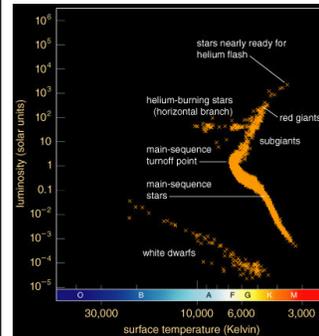


## Life Track after Helium Flash

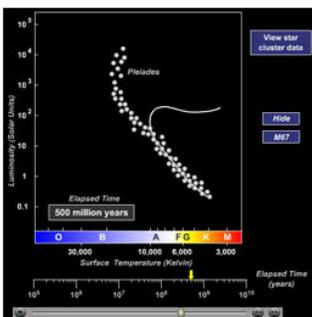


- Models show that a red giant should shrink and become less luminous after helium fusion begins in the core

## Life Track after Helium Flash

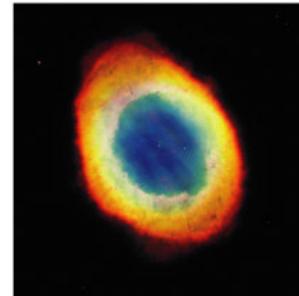


- Observations of star clusters agree with those models
- Helium-burning stars are found in a *horizontal branch* on the H-R diagram



Combining models of stars of similar age but different mass helps us to age-date star clusters

## How does a low-mass star die?



### Thought Question

What happens when the star's core runs out of helium?

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

### Thought Question

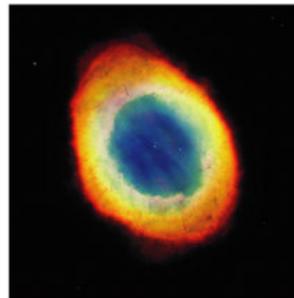
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### Double Shell Burning

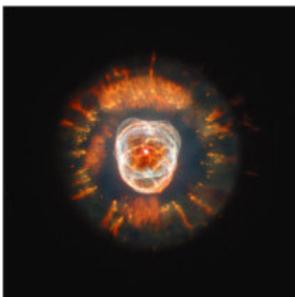
- After core helium fusion stops, He fuses into carbon in a shell around the carbon core, and H fuses to He in a shell around the helium layer
- This double-shell burning stage never reaches equilibrium—fusion rate periodically spikes upward in a series of *thermal pulses*
- With each spike, convection dredges carbon up from core and transports it to surface

### Planetary Nebulae



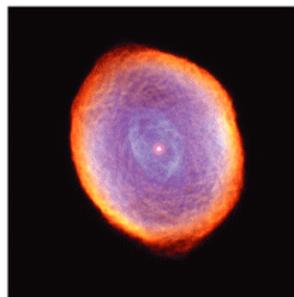
- Double-shell burning ends with a pulse that ejects the H and He into space as a *planetary nebula*
- The core left behind becomes a white dwarf

### Planetary Nebulae



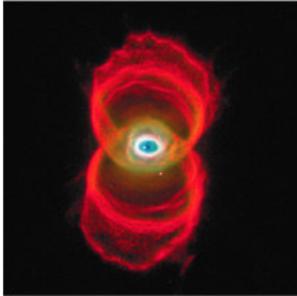
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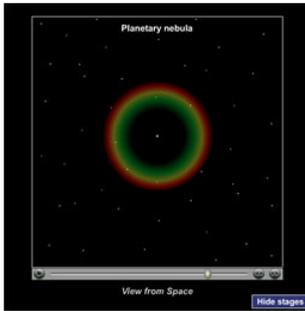
## Planetary Nebulae



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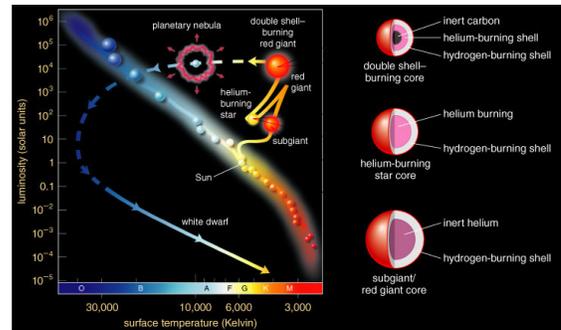
## End of Fusion

- Fusion progresses no further in a low-mass star because the core temperature never grows hot enough for fusion of heavier elements (some He fuses to C to make oxygen)
- Degeneracy pressure supports the white dwarf against gravity

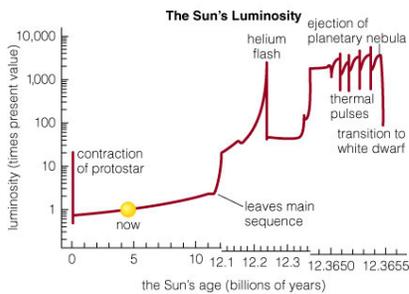


Life stages of a low-mass star like the Sun

## Life Track of a Sun-Like Star

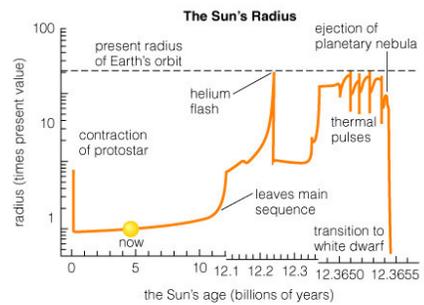


## Earth's Fate



- Sun's luminosity will rise to 1,000 times its current level—too hot for life on Earth

## Earth's Fate



- Sun's radius will grow to near current radius of Earth's orbit

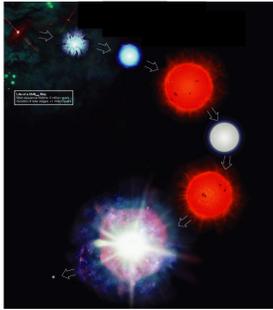
## What have we learned?

- What are the life stages of a low-mass star?
  - H fusion in core (main sequence)
  - H fusion in shell around contracting core (red giant)
  - He fusion in core (horizontal branch)
  - Double-shell burning (red giant)
- How does a low-mass star die?
  - Ejection of H and He in a planetary nebula leaves behind an inert white dwarf

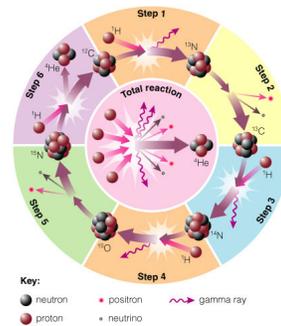
## 17.3 Life as a High-Mass Star

- 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?



## CNO Cycle

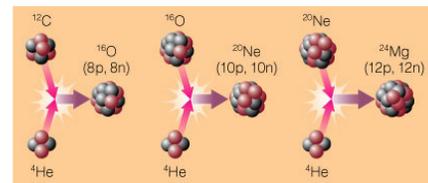


- High-mass main sequence stars fuse H to He at a higher rate using carbon, nitrogen, and oxygen as catalysts
- Greater core temperature enables H nuclei to overcome greater repulsion

## 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?



**Key**

- Atomic number
- Element's symbol
- Element's name
- 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.

H	He																
Li	Be																
B	C	N	O	F	Ne												
Na	Mg	Al	Si	P	S	Cl	Ar										
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac	Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub	Uut	Uuq	Uur	Uus	Uuq	Uur

**Lanthanide Series**

La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
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**Actinide Series**

Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr
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**Big Bang made 75% H, 25% He – stars make everything else**

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Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac	Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub	Uut	Uuq	Uur	Uus	Uuq	Uur

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**Helium fusion can make carbon in low-mass stars**

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Fr	Ra	Ac	Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub	Uut	Uuq	Uur	Uus	Uuq	Uur

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Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr
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**CNO cycle can change C into N and O**

## Helium Capture

• High core temperatures allow helium to fuse with heavier elements

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**Helium capture builds C into O, Ne, Mg, ...**

## Advanced Nuclear Burning

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

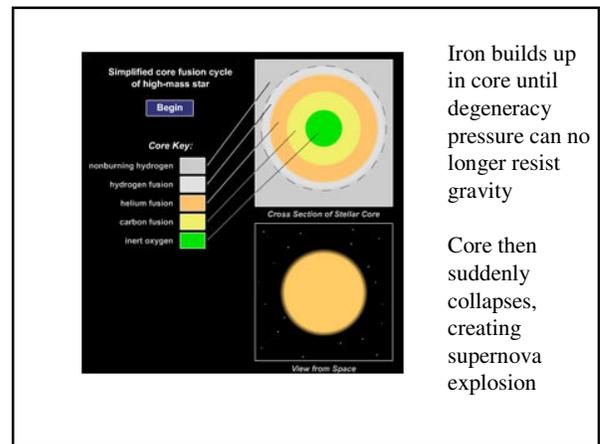
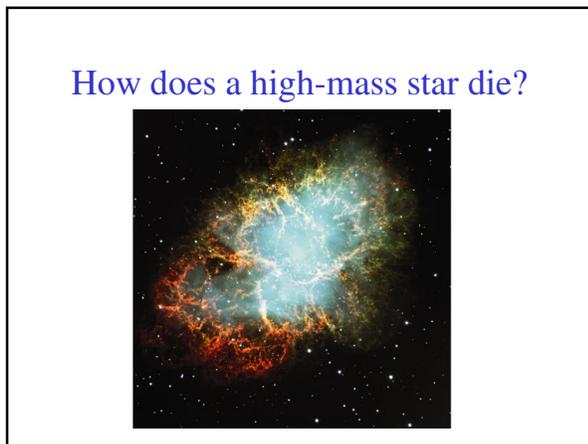
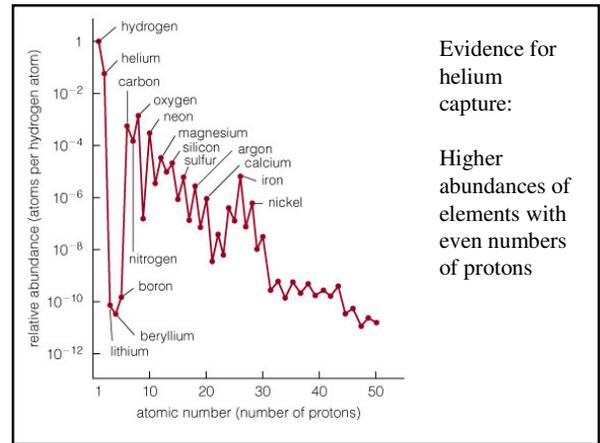
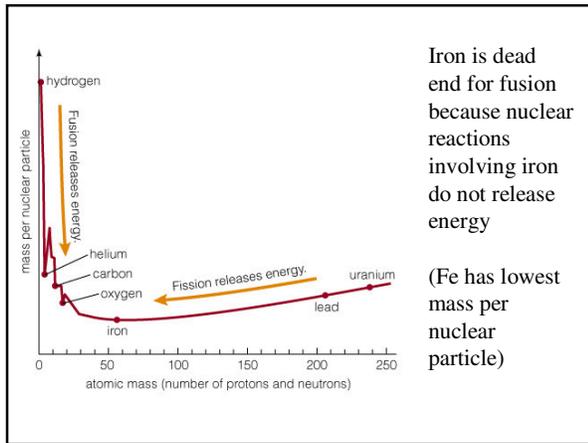
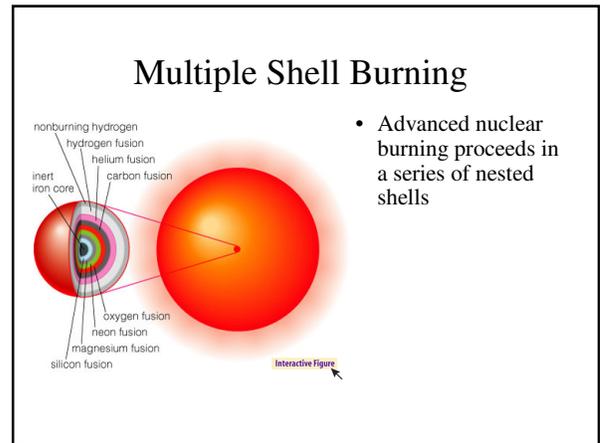
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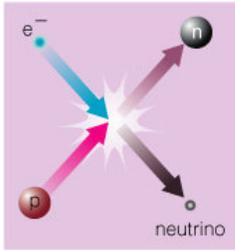
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1	2																	3	4											5	6	7	8	9	10									
Hydrogen	Helium																	Lithium	Beryllium											Boron	Carbon	Nitrogen	Oxygen	Fluorine	Neon									
1.008	4.0026																	6.941	9.0122											10.811	12.011	14.006	15.999	18.998	20.180									
																		Na	Mg											Al	Si	P	S	Cl	Ar									
																		19	20											21	22	23	24	25	26									
																		Sodium	Magnesium											Aluminum	Silicon	Phosphorus	Sulfur	Chlorine	Argon									
																		22.990	24.305											26.982	28.086	30.974	32.06	35.45	39.948									
																		K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr									
																		19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36									
																		Potassium	Calcium	Scandium	Titanium	Vanadium	Chromium	Manganese	Iron	Cobalt	Nickel	Copper	Zinc	Gallium	Germanium	Arsenic	Selenium	Bromine	Krypton									
																		39.098	40.078	44.956	47.88	50.942	51.996	54.938	55.845	58.933	58.933	63.546	65.38	69.723	72.630	74.922	78.96	79.904	83.80									
																		Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe									
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																		Rubidium	Strontium	Yttrium	Zirconium	Niobium	Molybdenum	Technetium	Ruthenium	Rhodium	Palladium	Silver	Cadmium	Indium	Tin	Antimony	Tellurium	Iodine	Xenon									
																		85.468	87.62	88.906	91.224	92.906	95.94	98	101.07	102.905	106.36	107.868	112.411	114.818	117.305	120.904	127.603	126.905	131.29									
																		Cs	Ba											Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
																		55	56											72	73	74	75	76	77	78	79	80	81	82	83	84	85	86
																		Cesium	Barium											Hafnium	Tantalum	Tungsten	Rhenium	Osmium	Iridium	Platinum	Gold	Mercury	Thallium	Lead	Bismuth	Polonium	Astatine	Radon
																		132.905	137.327											178.49	180.948	183.84	186.207	187.755	195.084	196.967	200.59	204.38	208.98	209	210	210	222	
																		Fr	Ra											Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub						
																		87	88											104	105	106	107	108	109	110	111	112						
																		Francium	Radium											Rutherfordium	Dubnium	Seaborgium	Berkelium	Hassium	Moscovium	Ununennium	Unbinilium	Untrium						
																		223	226											261	262	263	264	265	266	267	268	269	270	271	272	273	274	276
																		Lanthanide Series																										
																		57	58	59	60	61	62	63	64	65	66	67	68	69	70	71												
																		Lanthanum	Cerium	Praseodymium	Neodymium	Promethium	Samarium	Europium	Gadolinium	Terbium	Dysprosium	Ho	Er	Tm	Yb	Lu												
																		138.905	140.12	140.908	144.24	144.913	150.36	151.964	157.25	158.925	162.50	163.503	167.259	168.934	173.045	174.967												
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																		89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106									
																		Actinium	Thorium	Protactinium	Uranium	Nephtalium	Plutonium	Americanium	Curium	Berkelium	Californium	Einsteinium	Fermium	Mendelevium	Nobelium	Lr												
																		227	232	231	238	237	244	244	247	247	251	252	257	258	259	262	261	262	263									

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



## 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

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- Element's name
- 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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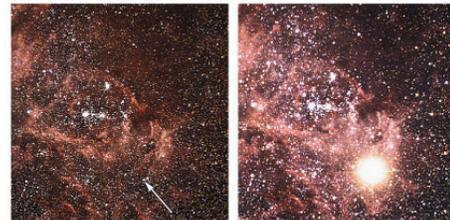
Energy and neutrons released in supernova explosion enable elements heavier than iron to form, including Au and U

## Supernova Remnant



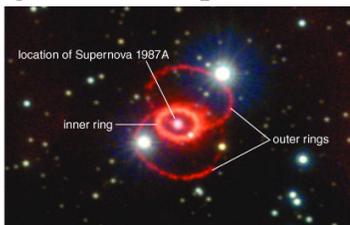
- Energy released by collapse of core drives outer layers into space
- The Crab Nebula is the remnant of the supernova seen in A.D. 1054

## Supernova 1987A



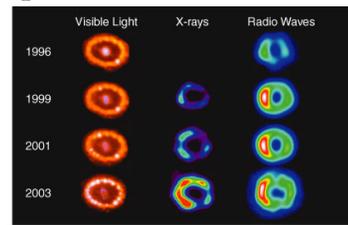
- The closest supernova in the last four centuries was seen in 1987

## 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 are showing the inner ring light up as debris crashes into it

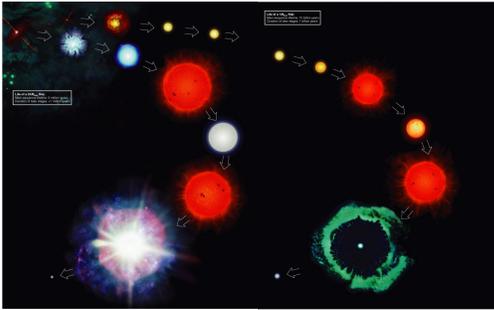
## What have we learned?

- 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?
  - Iron core collapses, leading to a supernova

## 17.4 The Roles of Mass and Mass Exchange

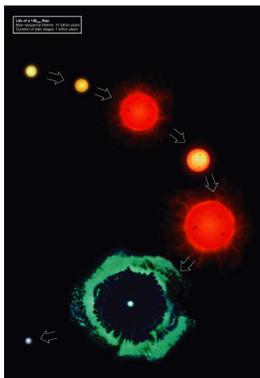
- Our goals for learning
- How does a star's mass determine its life story?
- How are the lives of stars with close companions different?

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



## Role of Mass

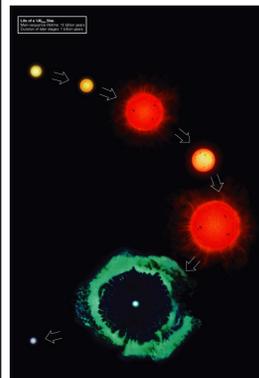
- A star's mass determines its entire life story because it determines its core temperature
- High-mass stars with  $>8M_{\text{Sun}}$  have short lives, eventually becoming hot enough to make iron, and end in supernova explosions
- Low-mass stars with  $<2M_{\text{Sun}}$  have long lives, never become 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



*Not to scale!*

### Low-Mass Star Summary

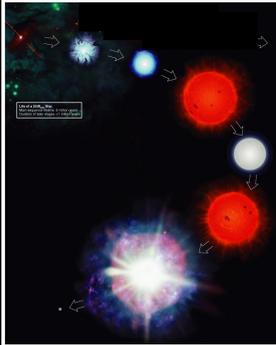
1. Main Sequence: H fuses to He in core
2. Red Giant: H fuses to He in shell around He core
3. Helium Core Burning: He fuses to C in core while H fuses to He in shell
4. Double Shell Burning: H and He both fuse in shells
5. Planetary Nebula leaves white dwarf behind



*Not to scale!*

### 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

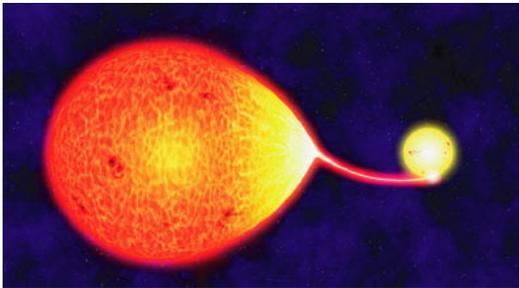


*Not to scale!*

**Life Stages of High-Mass Star**

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: He fuses to C in core while H fuses to He in shell
4. Multiple Shell Burning: Many elements fuse in shells
5. Supernova leaves neutron star behind

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

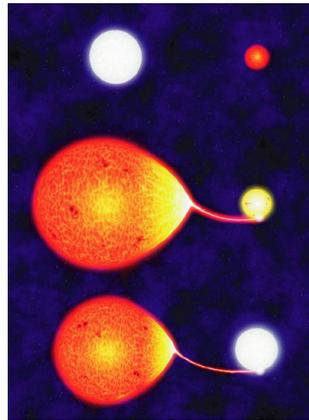


*Thought Question*

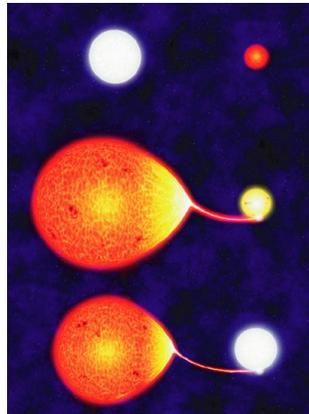
The binary star Algol consists of a  $3.7 M_{\text{Sun}}$  main sequence star and a  $0.8 M_{\text{Sun}}$  subgiant star.

What's strange about this pairing?

How did it come about?



Stars in Algol are close enough that matter can flow from subgiant onto main-sequence star



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

**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