## Stars

Stellar Evolution Nucleosynthesis

Homework postponed now due Thursday 17 February

## Evolution of sun-like star



- As Hydrogen fuel is exhausted in the core, fusion occurs in a shell around the inert Helium core.
- The core contracts, its temperature increases, nuclear reaction rates increase (in the shell), and the Luminosity increases.

## Helium Flash

- The core continues to shrink and heat as the rest of the star expands and becomes more luminous.
  Ascends giant branch for a billion years
- At a critical temperature and density, helium fusion suddenly begins.
  - The Helium Flash
- The star evolves rapidly, finding a new equilibrium with He burning in the core and H burning in a shell surrounding the core.



Helium fusion tough—larger charge leads to greater repulsion. Worse, the fusion of two helium nuclei doesn't work; <sup>4</sup>He more stable than Beryllium (<sup>8</sup>Be). Need three <sup>4</sup>He nuclei to make carbon (<sup>12</sup>C). Only works because of resonant state of carbon predicted by Fred Hoyle.



Helium burning stars reside for a brief time on the **Horizontal Branch**.

## Life Track After Helium Flash



- Red giants shrink and become less luminous after helium fusion begins in the core.
- May lose some mass during the Helium Flash. How much probably depends on the composition and affects where along the horizontal branch a star falls.

## Life Track After Helium Flash



- Helium-burning stars are found in a *horizontal branch* on the H-R diagram.
- Low metallicity stars populate the Blue Horizontal Branch (BHB) while solar metallicity stars are redder.
  - sometimes part of "red clump"

## Double-Shell Burning AGB stars

- Helium also gets used up in the core. He continues to fuse into carbon in a shell around a growing, inert carbon core, and H fuses to He in a shell around the helium layer.
- The star expands again, ascending the

- Asymptotic Giant Branch (AGB stars)

- though brief, this phase can dominate the light of ~1 Gyr old populations.
- Equilibrium becomes hard to maintain—the fusion rate periodically spikes upward in a series of *thermal pulses*. (Mira variable stars.)
- With each spike, some of the outer layers may be lost to space stars may lose 50 70% of their mass during this phase.



- Double-shell burning ends with a pulse that ejects the H and He into space as a *planetary nebula*.
- The PN phase is brief (~10<sup>4</sup> years)
- The core left behind becomes a white dwarf.



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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. (The sun is massive enough to fuse some He with C to make oxygen, but most of the C and O will be trapped forever in the white dwarf).
- Degeneracy pressure supports the white dwarf against gravity.
- White dwarf spend eternity cooling off, eventually going dark entirely.

## Life Track of a Sun-Like Star







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

# Absolute magnitude —<del>></del>



<-- Temperature

## The evolution of high-mass stars



 $M > 8M_{Sun}$ 

#### These die more dramatically than low mass stars...

## 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)

#### —Etc:

more stages of nuclear burning as wellC, O, Ne, Mg, Si, all the way up to Fe (iron)



#### Supergiants

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## High mass stars synthesize the heavy elements



The heavier elements of which the planets are built were made in the nuclear furnace of high mass stars.

			Key														
1 H Hydrogen 1.00794			1 Magn 24	2	Elem Elem Atom	ic numbe ent's sym ent's nan ic mass*	er ibol ne										Helium 4.003
Lithium 6.941 Na Sodium	4 Be Beryllium 9.01218 12 Mg Magnesium	*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.														10 Ne Neon 20.179 18 Ar Argon	
19 K	24.305 20 Ca	21 Sc	22 <b>Ti</b>	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 <b>Ni</b>	29 Cu	30 Zn	26.96 31 Ga	28.086 32 Ge	30.974 33 As	32.06 34 Se	35.453 35 Br	39.948 36 Fr
39.098	40.08	44.966	47.88	Vanadium 50.94	51.996	Manganese 54.938	55.847	58.9332	Nickel 58.69	63.546	2inc 65.39	69.72	72.59	Arsenic 74.922	78.96	79.904	Krypton 83.80
37 Bb	38 Gr	39 V	40 7r	41 Nb	42 Mo	43 Tc	44 Ru	45 Ph	46 Pd	47	48 Cd	49	50 Sn	51 Sh	52 Te	53	54 Xo
Rubidium	Strontium	Yttrium	Zirconium	Niobium	Molybdenum	Technetium	Ruthenium	Rhodium	Palladium	Silver	Cadmium	Indium	Tin	Antimony	Tellurium	lodine	Xenon
60.408	87.62	85.9059	91.224	92.91	30.94	(96)	101.0/	102.906	105.42	79	80	81	82	121.75	127.60	85	131.29
Cs	Ba		Hf	Та	w	Re	Os	Ir	Pt	Au	Hg	Ti	Pb	Bi	Po	At	Rn
Cesium 132.91	Barium 137.34		Hafnium 178.49	Tantalum 180.95	Tungsten 183.85	Rhenium 186.207	Osmium 190.2	Iridium 192.22	Platinum 195.08	Gold 196.967	Mercury 200.59	Thallium 204.383	Lead 207.2	Bismuth 208.98	Polonium (209)	Astatine (210)	Radon (222)
87	88		104	105	106	107	108	109	110	111	112	201000	Day 12	100.00	(easi)	(6.159	(eve)
Fr	Ra		Df	Dh	-												
	the second se		п	DD	Sg	Bh	Hs	Mt	Uun	Uuu	Uub						
(223)	Radium 226.0254		Rutherlordium (261)	Dubnium (262)	Seaborgium (263)	Bh Bohrium (262)	Hs Hassium (265)	Mt Meitnerium (266)	Ununnilium (269)	Unununium (272)	Ununbium (277)						
Francium (223)	Radium 226.0254		Ruthefordium (261)	Dubrium (262)	Seaborpium (263)	Bh Bohrium (262)	Hs Hassium (265)	Mt Meitnerium (266)	Ununnilium (269)	Uuu Unununium (272)	Ununbium (277)	66	67	69	80	70	74
Francium (223)	Radium 226.0254		Lanthan	Dubrium (262) nide Ser	Sg Seaborgium (263) ries 59 Pr	Bh Bohrium (262) 60 Nd	Hs Hassium (265) 61 Pm	Mt Meitnerium (266) 62 Sm	0un Urunnilium (269) 63 Eu	Uuu Uhununium (272) 64 Gd	0ub Ununbium (277) 65 Tb	66 <b>Dy</b>	67 <b>Ho</b>	68 Er	69 Tm	70 <b>Yb</b>	71 Lu
Francium (223)	Radium 226.0254		Lanthan 57 La Lanthanm	Dubrium (262) nide Ser 58 Ce Cerum	Sg Seaborgium (263) ries 59 Pr Przectymium	Bh Bohrium (262) 60 Nd Neodymium	Hs Hassium (265) 61 Pm Promethium	Mt Meitnerium (266) 62 Sm Samarium	63 Europium	64 Gdd Gddlinum	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium	71 Lu Lutetium
Francium (223)	Radium 226.0254		Authenordium (261) Lanthan 57 La Lanthanum 138.906	Dubrium (262) nide Ser 58 Ce Cerium 140.12	Sg Seaborgium (263) ries 59 Pr Prasedymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm 150.36	63 Europium 151.96	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy 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 Lu Lutetium 174.967
Francium (223)	Radium 226.0254		Autherlordium (261) Lanthan 57 La Lanthanum 138.906 Actinide	Db Dubrium (262) nide Ser 58 Ce Cerium 140.12 Series	Sg Seaborgium (263) ries 59 Pr Przecójmium 140.908	Bh Bohrium (262) 60 Nd Neodymium 144.24	Hs Hassium (265) 61 Pm Promethium (145)	Mt Meitnerium (266) 62 Sm Samarium 150.36	63 Europium 151.96	64 Gd Gatolinium 157.25	65 Tb Terbium 158.925	66 <b>Dy</b> Dysprosium 162.50	67 <b>Ho</b> Holmium 164.93	68 Er Erbium 167.26	69 <b>Tm</b> Thulium 168.934	70 <b>Yb</b> Ytterbium 173.04	71 Lu Lutetium 174.967
(223)	Radium 226.0254		Actinide	Db Dubrium (262) hide Ser 58 Ce Cerium 140.12 Series 90 Th	Sg Seaborgium (263) ries 59 Pr Praseodymium 140.908	Bh Bohrium (262) 60 Nd Neodymium 144.24 92	61 Pm Promethium (145) 93	Mt Meitnerium (266) 62 Sm Samarium 150.36	63 Eu Europium 151.96	64 Gd Gadolinium 157.25 96 Cm	65 <b>Tb</b> Terbium 158.925 97 <b>Bk</b>	66 Dy Dysprosium 162:50 98 Cf	67 <b>Ho</b> Holmium 164.93	68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
Francium (223)	Radium 226.0254		Ruherlordium (261) Lanthan 57 La Lanthanum 138.906 Actinide 89 Ac Actinium	Db Dubrium (262) nide Ser 58 Ce Cerium 140.12 e Series 90 Th Thorium	Sg Seaborgium (263) ries 59 Pr Praseodymium 140.908 3 91 Pa Protactinium	Bh Bohrium (262) 60 Nd Neodymium 144.24 92 U Uranium	Hs Hassium (265) 61 Pm Promethium (145) 93 Np Neptunium	Mt Meitnerium (266) 62 Sm Samarium 150.36 94 Pu Plutonium	63 Eu Europium 151.96 95 Am Americium	64 64 6d 6adolinium 157.25 96 Cm Curium	040 Ununbium (277) 65 <b>Tb</b> Terbium 158.925 97 <b>Bk</b> Berkelium	66 Dy Dysprosium 162.50 98 Cf Californium	67 Ho Holmium 164.93 99 Es Einsteinium	68 Er Erbium 167.26 100 Fm Fermium	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04 102 No Nobelium	71 Lu Lutetium 174.967 103 Lr Lawrencium

75% H, 25% He is the starting point

— stars make everything else.

			Key														
H Hydrogen 1.00794			1 Magn 24.	2	Atom Elem Elem Atom	ic numbe ent's sym ent's nan ic mass*	er nbol ne										2 Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.01218		*Ator weig	mic mass hted ave	es are fra rage of a	actions b tomic ma	ecause t	hey repre different is	isent a sotopes-			5 B Boron 10.81	6 C Carbon 12.011	7 <b>N</b> Nitrogen 14.007	8 O Oxygen 15.999	9 <b>F</b> Fluorine 18.988	10 Neon 20.179
11 Na Sodium 22.990	12 Mg Magnesium 24.305		13 14 15 16 17   AI Si P S CI   Aluminum Silicon Phosphorus Sulfur Sulfur   24 22 23 24 26 27 29 20 20 21 22 23 24 25														
19 K Potassium 39.098	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 <b>Ni</b> 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 <b>Rb</b> Rubidium 85.468	38 Sr Strontium 87.62	39 <b>Y</b> Yttrium 88.9059	40 <b>Zr</b> 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 <b>Sb</b> Antimony 121.75	52 Te Tellurium 127.60	53   lodine 126.905	54 Xe Xenon 131.29
55 Cs Cesium 132.91	56 Ba Barium 137.34		72 Hf Hatnium 178.49	73 <b>Ta</b> Tantalum 180.95	74 W Tungsten 183.85	75 <b>Re</b> Rhenium 186.207	76 <b>Os</b> 0smium 190.2	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 <b>Ti</b> Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.98	84 Po Potonium (209)	85 At Astatine (210)	86 Rn Radon (222)
87 Fr Francium (223)	88 <b>Ra</b> Radium 226.0254		104 Rf Rutherlordium (261)	105 Db Dubrium (262)	106 <b>Sg</b> Seaborgium (263)	107 Bh Bohrium (262)	108 <b>Hs</b> Hassium (265)	109 Mt Meitnerium (266)	110 Uun Ununnilium (269)	111 Uuu Unununium (272)	112 Uub Ununbium (277)						
			Lanthar	ide Ser	ries												
			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 <b>Tb</b> Terbium 158,925	66 Dy Dysprosium 162.50	67 <b>Ho</b> Holmium 164.93	68 Er Erbium 167.26	69 Tm Thulium 168,934	70 <b>Yb</b> Ytterbium 173.04	71 Lu Lutetium 174.967
			Actinide	e Series													
			89 Ac Actinium 227 028	90 Th Thorium 232 038	91 Pa Protactinium 231 035	92 U Uranium 238.029	93 Np Neptunium 237 nds	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (260)

#### Helium fusion can make carbon in low-mass stars.

## Helium Capture



• High core temperatures allow helium to fuse with heavier elements.

			Key														
1 H Hydrogen 1.00794			1 Magn 243	2	Elem Elem Atom	ic numbe ent's sym ent's nan ic mass*	er nbol ne										2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.01218		*Ator weig	nic mass	ses are fra rage of a	actions b tomic ma	ecause t isses of c	hey repre different is	isent a sotopes-			5 B Boron 10.81	6 Carbon 12.011	7 <b>N</b> Nitrogen 14.007	B Oxygen 15.999	9 F Fluorine 18.988	10 Neon 20.179
11 Na Sodium 22.990	12 Mg Magnesium 24.305		13 14 15 16 17   AI Si P S CI   Aluminum Silicon 28.060 30.974 32.453														18 Ar Argon 39.948
19 <b>K</b> Potassium 39.098	20 Ca Calcium 40.08	21 Sc Scandium 44.956	22 <b>Ti</b> Titanium 47.88	23 V Vanadium 50.94	24 Cr Chromium 51.996	25 Mn Mangarese 54.938	26 Fe Iron 55.847	27 Co Cobalt 58.9332	28 <b>Ni</b> 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 <b>Fr</b> Krypton 83.80
37 <b>Rb</b> Rubidium 85.468	38 <b>Sr</b> Strontium 87.62	39 Y Yttrium 88.9059	40 <b>Zr</b> Zirconium 91.224	41 <b>Nb</b> Niobium 92.91	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 <b>Rh</b> Rhodium 102.906	46 <b>Pd</b> Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112,41	49 In 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   lodine 126.905	54 Xe Xenon 131.29
55 <b>Cs</b> Cesium 132.91	56 <b>Ba</b> Barium 137.34		72 <b>Hf</b> Hatnium 178.49	73 <b>Ta</b> Tantalum 180.95	74 W Tungsten 183.85	75 <b>Re</b> Rhenium 186.207	76 <b>Os</b> 0smium 190.2	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercuty 200.59	81 <b>Ti</b> Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.98	84 Po Polonium (209)	85 At Astatine (210)	86 <b>Rn</b> Radon (222)
87 Fr Francium (223)	88 <b>Ra</b> Radium 226.0254		104 <b>Rf</b> Rutherlordium (261)	105 <b>Db</b> Dubrium (262)	106 Sg Seaborgium (263)	107 Bh Bohrium (262)	108 <b>Hs</b> Hassium (265)	109 Mt Meitnerium (266)	110 Uun Ununnilium (269)	111 Uuu Unununium (272)	112 Uub Ununbium (277)						
			Lanthan	ide Ser	ries												
			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 <b>Tb</b> Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93	68 Er Erbium 167.26	69 <b>Tm</b> Thulium 168.934	70 <b>Yb</b> Ytterbium 173.04	71 Lu Lutetium 174.967
			Actinide	Series													
			89 Ac Actinium 227.028	90 <b>Th</b> Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (260)

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



Evidence for helium capture: Higher abundances of elements with

"alpha elements"

even numbers

of protons

## Advanced Nuclear Burning



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

			Key														
H Hydrogen 1.00794			1 Magn 243	2	Elem Elem Atom	ic numbe ent's sym ent's nan ic mass*	er ibol ne										He Helium 4.003
3	Be											5 B	6 C	N	B	9 F	10 Ne
Lithium	Beryllium		*Ator	nic mass	ses are fra	actions b	ecause t	hey repre	esent a			Boron	Carbon	Nitrogen	Oxygen	Fluorine	Neon
6.941	9.01218		in on	nted ave	rage of all to the abi	10.81	12.011	14.007	15,999	18.988	20.179						
Na	Ma		AI SI P S C														18 Ar
Sodium	Agnesium	Aluminum Silicon Phosphorus Sulfur Chlorine														Argon	
22.990	24:305											26.98	28.085	30.974	32.05	35.453	39.948
19	20	21	22	23	24	25	26 50	27	28	29	30	31	32	33	34	35	36
Potassium	Calcium	Candium	Titanium	Vanadium	Chromium	Mangapese	Iron	Cobalt	Nickel	Conper	Zinc	Galium	Germanium	Arsenic	Selenium	Bromine	Krypton
39.098	40.08	44.966	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
Rb	Sr	Y	Zr	Nb	Mo	TC	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te		Xe
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
Cs	Ba		Hf	Та	W	Re	Os	Ir	Pt	Au	Hg	Ti	Pb	Bi	Po	At	Rn
Cesium 422.04	Barium		Hafnium 179.40	Tantalum 100.00	Tungsten 100 oc	Rhenium	Osmium 100.2	Iridium 403.32	Platinum	Gold	Mercury 200.50	Thallium	Lead	Bismuth	Polonium	Astatine	Radon
87	88		10.49	100.90	103.00	100.207	190.2	192.22	110	190.90/	112	204.303	CUI 2	200.90	(203)	(210)	(222)
Fr	Ra		Bf	Db	Sa	Bh	Hs	Mt	Uun	Uuu	Uub						
Francium	Radium		Rutherlordium	Dubrium	Seaborpium	Bohrium	Hassium	Meitnerium	Ununnilium	Unununium	Ununbium						
(223)	226.0254		(261)	(262)	(263)	(262)	(265)	(266)	(269)	(272)	(277)	1					
			Lanthan	ide Ser	ries												
			57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
			La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
		14	138 906	Cerium 140.12	Pt25800ymium 140 908	144.24	(145)	Samarium 150.35	Europium 151.96	Gadolinium 157.25	Terbium 158 925	Dysprosium 162.50	Holmium 164.93	Erbium 167.26	Thulium 168,934	Ytterbium 173.04	Lutetium 174.967
			a diata	Carl	110.500		(1459)	100.00	101.00	101.20	100.000	102.00	101.00	101.20	100.004	10.04	114,001
			Actinide	Series													
			89	90	91 Do	92	93	94	95	96	97	98	99	100	101	102	103
			Actinium	Thorium	Protactinium	Uranium	Necturium	Platonium	Americium	Curium	Berkelium	Californium	ES	Fermium	Mendelevium	Nobelium	Lawrencium
			227.028	232.038	231.036	238.029	237.048	(244)	(243)	(247)	(247)	(251)	(252)	(257)	(258)	(259)	(260)

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



Supergiants

can get a wiggle in evolutionary track as each fuel supply is exhausted.

Evolution very rapid massive stars live "only" millions of years

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## Multiple-Shell Burning



- Advanced nuclear burning proceeds in a series of nested shells.
- Core of high mass (> 8M<sub>sun</sub>) near the end of its life





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## Supernovae!





Iron is the ultimate ash.

With nothing left to support it, the core collapses and the outer parts explode, carrying elements into space.

			Key														
1 H Hydrogen 1.00794		12 Atomic number   Mg Element's symbol   Magnesium Element's name   24.305 Atomic mass*														2 He Helium 4.003	
3 Lithium 6.941	4 Be Beryllium 9.01218		*Ator weig	mic mas	ses are fra rage of a	actions b tomic ma	ecause the second secon	hey repre different is	isent a sotopes-	_		5 B Boron 10.81	6 C Carbon 12.011	7 N Nitrogen 14.007	0 Oxygen 15,999	9 F Fluorine 18.988	10 Ne Neon 20.179
11 Na Sodium 22.990	12 Mg Jagnesium 24.305		in proportion to the abundance of each isotope on Earth.   13 14 15 16 17   AI AI Si P S CI   Aluminum Silicon Phosphorus Sulfur Chlorine   26.98 28.066 30.974 32.06 35.453														18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.08	21 Sc candium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.94	24 Cr Chromium 51.996	25 Mn Mangarese 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 <b>Rb</b> Rubidium 85.468	38 Sr 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 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	48 Cd Cadmium 112.41	49 In Indium 114.82	49 50 In Sn Indium Tin 114.82 118.71	51 <b>Sb</b> Antimony 121.75	52 <b>Te</b> Tellurium 127.60	53   lodine 126.905	54 Xe Xenon 131.29
55 <b>Cs</b> Cesium 132.91	56 Ba Barium 137.34		72 Hf Hatnium 178.49	73 <b>Ta</b> Tantalum 180.95	74 W Tungsten 183.85	75 <b>Re</b> Rhenium 186.207	76 Os Osmium 190.2	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold	80 Hg Mercury 200.59	81 <b>Ti</b> Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.98	84 Po Polonium (209)	85 At Astatine (210)	86 <b>Rn</b> Radon (222)
87 Fr Francium (223)	88 <b>Ra</b> Radium 226.0254	٦	104 Rf Rutherlordium (261)	105 <b>Db</b> Dubnium (262)	106 Sg Seaborgium (263)	107 Bh Bohrium (262)	108 <b>Hs</b> Hassium (265)	109 Mt Meitnerium (266)	110 Uun Ununnilium (269)	111 Uuuu Unununium (272)	112 Uub Ununbium (277)						
			Lanthan	ide Se	ries	20	64	60	60	64	0E	20	67	20	20	70	74
		57     58     59     60     61     62     63     64     65     66     66       La     Ce     Pr     Nd     Pm     Sm     Eu     Gd     Tb     Dy     H       138.906     140.12     140.908     144.24     (145)     150.36     151.96     157.25     158.925     162.50     16									Ho Holmium 164.93	Erbium 167.26	Tm Thulium 168.934	Yb Ytterbium 173.04	Lu Lutetium 174.967		
			Actinide	Series													
		89     90     91     92     93     94     95     96     97     98     99     100     101     102       Ac     Th     Pa     U     Np     Pu     Am     Cm     Bk     Cf     Es     Fm     Md     No       Actinium     Thorium     232.038     231.036     238.029     237.048     (243)     (243)     (247)     (247)     (251)     (252)     (257)     (258)     (259)     (259)											103 Lr Lawrencium (260)				

Energy and neutrons released in a supernova explosion enable elements heavier than iron to form, including Au and U.

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1 H Hydrogen	Made in Early Universe															2 He Helium	
3 Li Lithium	4 Be Beryllium					Ma		5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon				
11 Na Sodium	12 Mg Magnesium					1 Ia	13 Aluminum	14 Silicon	15 P Phosphorus	16 Sulfur	17 Cl Chlorine	18 Ar Argon					
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton						
37 <b>Rb</b> Rubidium	38 <b>Sr</b> Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53   Iodine	54 Xe Xenon
55 Cs Cesium	56 Ba Barium	71 Lu Lutetium	72 Hf Hafnium	73 Ta Tantalum	7 W Tungsten	Re Rhenium	Osmium	upe Iridium	Pt Platinum	Vae Au Gold	80 Hg Mercury	81 TI Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
87 Fr Francium	88 Ra Radium	103 Lr wrencium	104 <b>Rf</b> Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110 Ds Darmstadtium	111	112	113	114	115	116	117	118
		N									Mad	le in	the	e lat	ora	tor	у
		/		57 La Lanthanum	58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium
	89   90   91   92   93   94   95   96   97   98   99   100     Ac   Th   Pa   U   Np   Pu   Am   Cm   Bk   Cf   Es   Fr     Actinium   Thorium   Protectinium   Uranium   Np   Pu   Am   Cm   Bk   Cf   Es   Fr													100 Fm Fermium	101 Md Mendelevium	102 No Nobelium	

## Mass is destiny



## 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.
- Low-mass stars have long lives, never become hot enough to fuse beyond carbon nuclei, and end as white dwarfs.



#### 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

Not to scale!

## Dead Stars leave corpses

- White dwarfs
  - remnant core of low mass star
  - supported by electron degeneracy pressure
- Neutron stars
  - remnant core of high mass star
  - supported by neutron degeneracy pressure
- Black Holes
  - remnant of some massive stars
  - gravity's ultimate victory

## Supernova types

- SN Type II hydrogen in spectrum
  - core collapse supernova
    - explosion of massive star when too much iron accumulates in the core
  - Primarily produces Oxygen and alpha elements
    - builds metals on short time scale
- SN Type Ia lacks hydrogen in spectrum
  - white dwarf supernova
    - explosion of white dwarfs that exceeds the Chandrasekhar limit (1.4 M<sub>o</sub>)
  - Primarily produces iron peak elements
    - builds metals on long time scale