TODAY

STARS

int :

- EVOLUTION OF HIGH MASS STARS
- NUCLEOSYNTHESIS
- SUPERNOVAE THE EXPLOSIVE DEATHS OF MASSIVE STARS



Another good job on exam!

- Class average was 71%
- Given the difficulty of the exam, this was an exceptional performance
 Between this and your previous exam, you are easily the best ASTR 100 class I've ever had
- Exams will be handed back in your sections

Extra credit (2 points)

- What is the final state of a star like our Sun?
- Be sure to include your name and section number
- You may consult your notes, but do not communicate with anyone else

Main sequence star ~10 billion years

subgiant/Red Giant
~1 billion years

Helium Flash

Horizontal Branch star ~100 million years

~

Asymptotic Giant ~10 million years

Planetary Nebula ~10 thousand years

White Dwarf eternity

Life story of a solar mass star

© 200

The evolution of high-mass stars



 $M > 8M_{Sun}$

Life video

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 well
- —C, O, Ne, Mg, Si, all the way up to Fe (iron)



Supergiants

High mass stars make the elements necessary for life



The oxygen and heavier elements in our bodies were made in the nuclear furnace of high mass stars.

Lithium B 6.941 (11 Na Sodium Ma	Be Beryllium 9.01218			000	- Elem Atom	ent's nan iic mass*	ibol ne					E	c	7	0		Helium 4.003
22.990	12 Mg lagnesium 24.305		*Ator weig in pre	mic mass hted ave oportion	ses are fra rage of a to the abi	actions b tomic ma undance	ecause tl sses of c of each i	ney repre different is sotope of	ssent a sotopes– n Earth.	-		5 Boron 10.81 13 Aluminum 26.98	6 C Carbon 12.011 14 Silicon 28.086	/ Nitrogen 14.007 15 P Phosphorus 30.974	8 Oxygen 15.999 16 Sulfur 32.06	9 Fluorine 18.988 17 Cl Chlorine 35.453	10 Neon 20.179 18 Ar Argon 39.948
19 K Potassium	20 Ca	21 Scandium	22 Ti Titanium	23 V Vanadium	24 Cr	25 Mn Manganese	26 Fe	27 Co	28 Ni Nickel	29 Cu Conner	30 Zn Zinc	31 Gallium	32 Ge Germanium	33 As Arsenic	34 Selenium	35 Br Bromine	36 Fr Krypton
39.098 37 Rb Rubidium S	40.08 38 Sr Strontium	44.956 39 Y Yttrium	47.88 40 Zr Zirconium	50.94 41 Nb Niobium	51.996 42 Mo Molybdenum	54.938 43 Tc Technetium	55.847 44 Ru Ruthenium	58.9332 45 Rh Rhodium	58.69 46 Pd Palladium	63.546 47 Ag Silver	65.39 48 Cd Cadmium	69.72 49 In Indium	72.59 50 Sn Tin	74.922 51 Sb Antimony	78.96 52 Te Tellurium	79.904 53 Iodine	83.80 54 Xe Xenon
85.468 55 Cesium 132.91	87.62 56 Ba Barium 137.34	88.9059	91.224 72 Hf Hafnium 178.49	92.91 73 Ta Tantalum 180.95	95.94 74 W Tungsten 183.85	(98) 75 Re Rhenium 186.207	101.07 76 Os 0smium 190.2	102.906 77 Ir Iridium 192.22	106.42 78 Pt Platinum 195.08	107.868 79 Au Gold 196.967	112.41 80 Hg Mercury 200.59	114.82 81 Ti Thallium 204.383	118.71 82 Pb Lead 207.2	121.75 83 Bi Bismuth 208.98	127.60 84 Po Polonium (209)	126.905 85 At Astatine (210)	131.29 86 Rn Radon (222)
87 Fr Francium (223) 2	88 Ra Radium 226.0254		104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (263)	107 Bh Bohrium (262)	108 Hs Hassium (265)	109 Mt Meitnerium (266)	110 Uun Ununnilium (269)	111 Uuu Unununium (272)	112 Uub Ununbium (277)						
			Lanthar	nide 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 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
			Actinide	Series	3												
			89 Ac Actinium 227.028	90 Th 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)

— stars make everything else.

9

H Hydrogen 1.00794			Magr 24	12	Atom Elem Elem Atom	nic numbe nent's sym nent's nan nic mass*	er 1bol ne										He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.01218		*Ato weig	mic mass	ses are fra erage of a	actions b atomic ma	ecause t isses of c	hey repre different is	sent a sotopes-	-		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
11 Na Sodium 22.990	12 Mg Magnesium 24.305		in pr	oportion	to the ap	undance	oreach	isotope o	n Earth.			13 Al Aluminum 26.98	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.06	17 CI Chlorine 35.453	18 Ar Argon 39.948
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 7n	31 Ga	32 Ge	33 A s	34 Se	35 Br	36 Er
Potassium 39.098	Calcium 40.08	Scandium 44.956	Titanium 47.88	Vanadium 50.94	Chromium 51.996	Manganese 54.938	Iron 55.847	Cobalt 58.9332	Nickel 58.69	Copper 63.546	Zinc 65.39	Gallium 69.72	Germanium 72.59	Arsenic 74.922	Selenium 78.96	Bromine 79.904	Krypton 83.80
37 Bh	38 Sr	39 V	40 7r	41 Nb	42 Mo	43 Tc	44 Ru	45 Bh	46 Pd	47 A a	48 Cd	49 In	50 Sn	51 Sh	52 Te	53	54 Xo
Rubidium 85.468	Strontium 87.62	Yttrium 88.9059	Zirconium 91.224	Niobium 92.91	Molybdenum 95.94	Technetium (98)	Ruthenium 101.07	Rhodium 102.906	Palladium 106.42	Silver 107.868	Cadmium 112.41	Indium 114.82	Tin 118.71	Antimony 121.75	Tellurium 127.60	lodine 126.905	Xenon 131.29
55 Cs Cesium 132.91	56 Ba Barium 137.34		72 Hf Hatnium 178.49	73 Ta Tantalum 180.95	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os 0smium 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 Potonium (209)	85 At Astatine (210)	86 Rn Radon (222)
87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Uun	111 Uuu	112 Uub						
Francium (223)	Radium 226.0254		Rutherfordium (261)	Dubnium (262)	Seaborgium (263)	Bohrium (262)	Hassium (265)	Meitnerium (266)	Ununnilium (269)	Unununium (272)	Ununbium (277)						
			Lanthar	nide Sei	ries												
			57	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Th	66 DV	67 Ho	68 Fr	69 Tm	70 Vh	71
			La	00		nu		on	Lu	uu	10	Uy I	110	-		10	Lu

Actinide Series

[89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr
	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)

Helium fusion can make carbon in low-mass₁₀ stars.

H Hydrogen 1.00794			Key 1 Magn 24.	2 — Ig — sium — 305 —	Atom Elem Elem Atom	ic numbe ent's sym ent's nam ic mass*	er Ibol ne										Helium
3 Li Lithium 6.941	4 Be Beryllium 9.01218		*Ator weig	mic mass hted ave	ses are fra rage of a	actions be tomic ma	ecause ti sses of c	ney repre lifferent is	sent a sotopes-	-		5 B Boron 10.81	6 C Carbon 12.011	/ N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.988	10 Ne Neon 20.179
11 Na Sodium 22.990	12 Mg Magnesium 24.305		in pr	oportion	to the abi	undance	of each i	sotope or	n Earth.			13 Al Aluminum 26.98	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.06	17 CI Chlorine 35.453	18 Ar Argon 39.948
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	A s	Se	Br	Fr
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
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te		Xe
Rubidium	Strontium	Yttrium	Zirconium	Niobium	Molybdenum	Technetium	Ruthenium	Rhodium	Palladium	Silver	Cadmium	Indium	Tin	Antimony	Tellurium	lodine	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
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Ti	Pb	Bi	Po	At	Rn
Cesium	Barium		Hafnium	Tantalum	Tungsten	Rhenium	0smium	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 Fr Francium	88 Ra Radium 226 0254		104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (263)	107 Bh Bohrium (262)	108 Hs Hassium (265)	109 Mt Meitnerium (266)	110 Uun Ununnilium (269)	111 Uuu Unununium (272)	112 Uub Ununbium (277)						

Lanthanide Series

232.038

227.028

238.029

231.036

237.048

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
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	e Serie	s												
89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr
Actinium	Thorium	Protectinium	Hranium	Nentunium	Plutonium	Americium	Curium	Berkelium	Californium	Finsteinium	Fermium	Mendelewium	Nohelium	Lawrencium

(247)

(247)

(251)

(252)

(257)

(258)

(259)

(260)

Fusion can also produce heavier elements

(243)

(244)

Helium Capture



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

H Hydrogen 1.00794			Key N Magr 24.	12	Atom Elem Elem Atom	nic numbe nent's sym nent's nan nic mass*	er 1bol ne										He Helium 4.003
3 Lithium 6.941 11 Na Sodium 22 990	4 Be 9.01218 12 Mg Magnesium 24.305		*Ato weig in pr	mic mass hted ave oportion	ses are fra erage of a to the abi	actions b tomic ma undance	ecause t asses of o of each	hey repre different is isotope o	esent a sotopes– n Earth.	-		5 B Boron 10.81 13 Al Aluminum 26 gg	6 C Carbon 12.011 14 Silicon 28.096	7 N Nitrogen 14.007 15 P Phosphorus 30.974	8 Oxygen 15.999 16 Sulfur 32.06	9 F Fluorine 18.988 17 Cl Chlorine 35.453	10 Neon 20.179 18 Ar Argon 39.948
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mp	26 Fe	27 Co	28 Ni	29 Cu	30 7 n	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Fr
Potassium 39.098	Calcium 40.08	Scandium 44.956	Titanium 47.88	Vanadium 50.94	Chromium 51.996	Manganese 54.938	Iron 55.847	Cobalt 58.9332	Nickel 58.69	Copper 63.546	Zinc 65.39	Gallium 69.72	Germanium 72.59	Arsenic 74.922	Selenium 78.96	Bromine 79.904	Krypton 83.80
37 Rb Rubidium	38 Sr Strontium 87.62	39 Y Yttrium	40 Zr Zirconium 91 224	41 Nb Niobium 92 91	42 Mo Molybdenum 95.94	43 Tc Technetium	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 lodine 126 905	54 Xe Xenon 131 29
55 Cs Cesium	56 Ba Barium		72 Hf Hafnium 178.49	73 Ta Tantalum 180.95	74 W Tungsten 182.85	75 Re Rhenium	76 Os Osmium 190.2	77 Ir Iridium 102.22	78 Pt Platinum	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Ti Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium (200)	85 At Astatine	86 Rn Radon (222)
87 Fr Francium (223)	88 Ra Radium 226.0254		104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (263)	107 Bh Bohrium (262)	108 Hs Hassium (265)	109 Mt Meitnerium (266)	110 110 Ununnilium (269)	111 Uuu Unununium (272)	112 Ununbium (277)	204.303	207.2	200.30	(203)	(210)	(222)
			Lanthar	nide Se	ries												
			57 La	58 Ce	59 Pr Prasendumium	60 Nd	61 Pm Promethium	62 Sm Samarium	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho Holmium	68 Er	69 Tm	70 Yb	71 Lu

Actinide Series

89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr
 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)

Helium capture builds C into O, Ne, Mg ... 13



Evidence for helium capture:

Higher abundances of elements with even numbers of protons "alpha elements"

14

Advanced Nuclear Burning



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

	Key H Atomic number Key He 100791 Be Element's symbol Element's name 4 11 Be Atomic number Be Name Be Name Be Name Be Name Name Science Atomic masses 7 B 9 N Name Boon Name																
Hydrogen 1.00794			1 Magn 24.	2 — Ig — esium- 305 —	Atom Elem Elem Atom	ic numbe ent's sym ent's nan ic mass*	er 1bol ne										Helium 4.003
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	sent a sotopes-	-		5 B Boron 10.81	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O 0xygen 15.999	9 F Fluorine 18.988	Neon 20.179
11 Na Sodium 22.990	12 Mg Magnesium 24.305		in pr	oportion		undance	oreaction	solope of	r Earth.			13 Al Aluminun 26.98	14 Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.06	17 CI Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge Ass Se Br Fr 90.98 40.08 44.956 77.88 50.94 51.996 54.938 54.938 58.69 63.546 65.39 69.72 72.59 74.922 78.96 79.904 83.86 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 I Xe Rubidium Strontium 87.62 88.9059															36 Fr Krypton 83.80	
37 Rb Rubidium 85.468	Potassium 39.098 Calcium 44.956 Candium 44.956 Ttanium 47.88 Vanadium 50.94 Chromium 51.996 Manganese 54.938 Iron 54.938 Cobalt 58.932 Nickel 58.69 Copper 63.546 Zinc 65.39 Gallium 69.72 Germanium 72.59 Arsenic 74.922 Selenium 78.96 Bromine 79.904 Krypto 88.80 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 I Xe Rubidium 85.468 87.62 88.9059 91.224 92.91 95.94 (98) 101.07 102.906 106.42 107.868 81 82 83 84 85 86 55 56 72 73 74 75 76 77 78 79 80 81 82 83															54 Xe Xenon 131.29	
55 Cs Cesium 132.91	Rubidium 85.468 Strontium 87.62 Yttrium 88.9059 Zirconium 91.224 Niobium 92.91 Molybdenum 95.94 Technetium (98) Ruthenium 101.07 Rhodium 102.906 Silver 107.868 Cadmium 112.41 Indium 114.82 Tin 118.71 Antimony 121.75 Tellurium 127.60 Iodium 126.905 Xeno 131.2 55 56 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 Cs Ba Hf Ta W Ree Os Ir Pt Au Hg Ti Pb Bi Po At Astaine Rado 132.91 137.34 137.34 137.34 104 105 106 107 108 109 110 111 112 111 112 111 112 111 112 111 111 112 111 111 112 111 111 112 111 112 111 112 112 112 <td>86 Rn Radon (222)</td>															86 Rn Radon (222)	
87 Fr Francium (223)	0.5 0.0 1/2 1/3 1/4 1/5 1/6 1/7 1/8 1/9 0.0 0.1 0.2 0.3 84 85 86 Cesium Barium 137.34 Hf Ta W Re Os Ir Pt Au Hg Ti Pb Bi Po At Astaine Rado 132.91 137.34 137.34 178.49 180.95 186.207 190.2 190.2 195.08 196.967 200.59 201.59 208.98 207.2 208.98 207.2 208.98 (209) (210) (222) 87 88 Rf Db Sg Bh Hs Mt Uun Uun Uub Ununitium Uun Uun <td></td>																
			Lanthar	ide Sei	ies	60	61	62	63	64	65	66	67	68	69	70	71
		4	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	Lu Lutetium 174.967
			Actinide	Series										100	104	100	100
			Actinium 227.028	90 Th 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)	Md Mendelevium (258)	Nobelium (259)	Lr .awrencium (260)
Adva	ance	ed 1	read	ctic	ons	in	sta	rs n	nak	te e	len	nen	ts 1	ike	Si	, S,	Ca,
and H	Fe.														1	6	



Supergiants

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

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

Multiple-Shell Burning



- Advanced nuclear burning proceeds in a series of nested shells.
- Core of high mass (> 8M_{sun}) near the end of its life





Elements heavier than iron

If we can get to iron by fusion in stars, how do we get elements heavier than iron? A.A source of energy is required to get heavier elements

B. Fission of iron gives heavier elements

C. Fusion of iron releases energy and produces heavier elements

D. Heavier elements are produced by low mass stars

E.I don't know

Supernovae!



The Elements

22



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Iron is the ultimate ash.

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

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.**

Simulation, demo

			Key	'													
Hydrogen 1.00794			Magr 24.	12	— Atom — Elem — Elem — Atom	nic numb ent's syn ent's nan nic mass*	er nbol ne										Z He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.01218 12		*Ato weig in pr	mic mass hted ave oportion	ses are fra rage of a to the ab	actions b tomic ma undance	ecause t asses of o of each	hey repre different is isotope o	esent a sotopes- n Earth.	-		5 B Boron 10.81	6 C Carbon 12.011	7 N Nitrogen 14.007	8 Oxygen 15,999	9 F Fluorine 18.988 17	10 Neon 20.179 18
Na Sodium 22.990	Mg Aagnesium 24.305											Aluminun 26.98	Silicon 28.086	P Phosphorus 30.974	Sulfur 32.06	CI Chlorine 35.453	Ar Argon 39.948
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87 Fr Francium (223)	88 Ra Radium 226.0254		104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (263)	107 Bh Bohrium (262)	108 Hs Hassium (265)	109 Mt Meitnerium (266)	110 Uun Ununnilium (269)	111 Uuu Unununium (272)	112 Uub Ununbium (277)						
			Lanthar	nide Se	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 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
			Actinide	e Series													
			89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Energy and neutrons released in a supernova explosion enable elements heavier than iron to form, including Au and U. 25

1 H Hydrogen				١	1ad	e in	Ea	rly l	Jniv	vers	е						2 He Helium
3 Li Lithium 11 Na Sodium	4 Be Beryllium 12 Mg Magnesium					Ma	de i	n St	tars			5 Boron 13 Al	6 C Carbon 14 Si Silicon	7 Nitrogen 15 Phosphorus	8 O Oxygen 16 S Sulfur	9 F Fluorine 17 Cl Chlorine	10 Ne Neon 18 Ar Argon
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton
37 Rb Rubidium	38 Sr 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	Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Te I Yttrium Zirconium Niobium Niobium Molybdenum Technetium Ruthenium Rhodium Palladium Silver Cd In Sn Sb Te I 71 72 73 A A Re Os Ir Pt Ru Ru Ru Ru Ru Ru Ru Ru Silver Silver Silver Supervisition Rutimony Tellurium Iodine 71 72 73 Ru Re Os Ir Pt Ru Ru														
87 Fr Francium	88 Ra Radium	103 Lr swrencium	104 Rf 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
	1	R								1	Mad	e in	the	e lat	ora	itor	<u>.</u>
		/		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 Ac Actinium	90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 No Nobelium
								2	6								

Supernova Remnant



- Energy released by the collapse of the 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 in the Large Magellanic Cloud.
- Recent discoveries in other galaxies (video)





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



Not to scale!

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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 or black hole behind 35



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
- Planetary Nebula: leaves white dwarf behind ³⁶

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

White Dwarfs



• White dwarfs are the remaining cores of low mass dead stars.

• The mass of a star compressed into roughly the size of the Earth



Neutron Stars

Neutron stars are the remnants of massive stars that exploded as supernovae.

The mass of a star compressed to roughly the size of a city (~ 10 km).

Black Holes

A *black hole* is an object whose gravity is so powerful that not even light can escape it.

Some massive star supernovae can make a black hole if enough mass falls onto the core.

All mass compressed to a mathematical point.





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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