Evolution of High Mass Stars



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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

Russel-Vogt Theorem: Stellar Mass determines Stellar Evolution



What are the life stages of a lowmass star?



Life Track of a Sun-Like Star



Life Stages

- 1. Protostar: gravitational contraction
- 2. Onset of Nuclear Reactions: gravity plus nukes
- 3. *Main Sequence*: ${}^{1}H \rightarrow {}^{4}He$ fusion (p-p chain) in core
- 4. End of M/S 10 billion yrs
- *Red Giant*: ¹H -->⁴ He fusion in shell around contracting core (leading to He Flash)
- 6. *He Main Sequence*: He fusion in core (horizontal branch)- 2 billion years
- 7. Double-shell (⁴He --> ${}^{12}C$; ¹H --> ${}^{4}He$) burning (red giant)
- 8. Ejection of H and He in a *Planetary Nebula* reveals hot (100,000K) stellar core
- 9. Leaving behind an inert *White Dwarf* (radiates store of thermal energy)

Earth's Fate



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

Earth's Fate



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

High Mass Stars



- L ∝ M³; Fuel ∝ M
 ⇒ Lifetime ∝ 1/M² (M/ M³)
 Massive stars live fast, die young (shorter lifetimes in all phases)
- 2. Higher $T \Rightarrow$ CNO Cycle on M/S
- 3. No core degeneracy (higher $T \Rightarrow$ higher P) means no helium flash
- 4. Higher $T \Rightarrow$ more nuclear burning stages (it is the high mass stars that make the elements heavier than C,N,O and even most of the C,N,O that goes into the ISM.
- 5. Massive stars will have very different evolutionary endpoints (remnants: neutron star or black hole vs white dwarf)

Life Tracks for Different Masses



- Models show that Sun required about 30 million years to go from protostar to main sequence
- Higher-mass stars form faster
- Lower-mass stars form more slowly

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)
- But continue with further stages:
 - Helium capture
 - Advanced nuclear stages to creation of Iron

How do high-mass stars make the elements necessary for life?



		Key															
H Hydrogen 1.00794		i i	12 Atomic number Mg Element's symbol Magnesium Element's name 24.305 Atomic mass* 5 6 7 8 9														He Helium 4.003
3 Lithium 6.941 11 Na Sodium 22.990	4 Beryllium 9.01218 12 Mg Magnesium 24.905		*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 Neon 20.179 18 Ar Argon 30.948	
19 K Potassium	20 Ca Calcium	21 Sc Scandium	21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Scandium Titanium Varadium Chromium Manganese Iron Cobalt Nickel Copper Zinc Gallium Germanium Arsenic Selenium Bromine														36 Fr Krypton
39.098 37 Rb Rubidium	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	45 Rh Rhodium	58.69 46 Pd Palladium	63.546 47 Ag Silver	48 Cd Cadmium	49 In Indium	72.59 50 Sn Tin 119.71	51 51 Antimony 121.75	78.96 52 Te Tellurium	79.904 53 Iodine	54 Xe Xenon 121 20
55 Cs Cesium 132,91	56 Ba Barium 137.34	00.3033	72 Hf Hafnium 178,49	73 Ta Tantalum 180.95	74 W Tungsten 183.85	(36) 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 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)				(0.0)		Transf
			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)	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	3												
			Actinide Series 89 90 91 92 93 94 95 96 97 98 99 100 101 102 1 Actinium Tho Pa U Np Pu Americium Cirium Bekelium Californium Fermium Medelevium Nobelium Lawr 227 028 232 038 231 036 238 029 237 048 (244) (247) (247) (251) (251) (252) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253) (253)													103 Lr Lawrencium (260)	

Big Bang made 75% H, 25% He – stars make everything else

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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 lodine 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 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 Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)
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			Lanthan	ide Ser	ies												
			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													

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-mass stars

			Key														
Hydrogen			1 M Magn 24.3	2 — Ig — esium- 305 —	- Atom Elem Elem Atom	ic numbe ent's sym ent's nam ic mass*							He Helium 4.003				
3 Lithium 6.941 11 Na Sodium 22.990	4 Beryllium 9.01218 12 Mg Magnesium 24.305		*Ator weig in pre	mic mass hted ave oportion	es are fra rage of at to the abu	actions be tomic ma undance	ecause th sses of c of each i	ney repre lifferent is sotope or	sent a sotopes— n Earth.	•		5 Boron 10.81 13 Aluminum 26.98	6 Carbon 12.011 14 Silicon 28.086	7 N Nitrogen 14.007 15 Phosphorus 30.974	8 Oxygen 15.999 16 S Sulfur 32.06	9 F Fluorine 18.988 17 CI Chlorine 35.453	10 Neon 20.179 18 Ar Argon 39.948
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 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
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Lanthanide Series

57	58	59	60	61	62	63	64	65	66	67	68	69	70	7
La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	L
Lanthanum	Cerium	Praseodymium	Neodymium	Promethium	Samarium	Europium	Gadolinium	Terbium	Dysprosium	Holmium	Erbium	Thulium	Ytterbium	Lu
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	17
Actinide	e Series	s												
Actinide 89	e Series	s 91	92	93	94	95	96	97	98	99	100	101	102	1
Actinide ⁸⁹ Ac	90 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	
89 Actinide Actinium	90 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	Lawr

CNO cycle can change C into N and O

Helium Capture



• High core temperatures allow helium to fuse with heavier elements

	Кеу																
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11 Na Sodium 22.990	12 Mg Magnesium 24.305		in proportion to the abundance of each isotope on Earth. 13 14 15 16 17 AI Si P S CI Aluminum Silicon 28.086 30.974 32.06 35.453														18 Ar Argon 39.948
19 K	Ca	Sc	22 Ti	23 V	Cr	Mn	Ee 26		28 Ni	Cu 29	30 7n	Ga	Ge	33 As	Se	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	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
Rb	Sr	Y	Zr	Nb	Мо	Тс	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Те		Xe
Rubidium 85.468	Strontium 87.62	Yttrium BR 0050	Zirconium 01.224	Niobium 02.01	Molybdenum os. q./	Technetium (08)	Ruthenium	Rhodium 102 006	Palladium	Silver	Cadmium	11/ 82	118.71	Antimony 121.75	127.60	126 Q05	Xenon 131.20
55	56	00.3033	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	Ha	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						
Fr	Ra	_	Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub						
Francium (223)	Radium 226.0254		Hutherfordium (261)	(262)	(263)	Bohrium (262)	Hassium (265)	(266)	Ununnilium (269)	Unununium (272)	(277)						
(220)			Lanthan	ide Ser	ries	(101)	(200)	(000)	(200)	(0.2)	(2.1)	1					
			57	58 Co	59 Dr	60 Nd	61 Dm	62 Sm	63 Eu	64 Gd	65 Th	66 Dv	67	68 Er	69 Tm	70 Vh	71
			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
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			Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr
			Actinium 227.028	Thorium 232.038	Protactinium 231.036	Uranium 238.029	Neptunium 237.048	Plutonium (244)	Americium (243)	Curium (247)	Berkelium (247)	Californium (251)	Einsteinium (252)	Fermium (257)	Mendelevium (258)	Nobelium (259)	Lawrencium (260)

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

Advanced Nuclear Burning



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

		Кеу															
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Sodium 22.990 19	Aagnesium 24 305 20	21	22	23	24	25	26	30	Aluminun 26.98 31	Silicon 28.086 32	Phosphorus 30.974 33	Sultur 32.06 34	Chlorine 35.453 35	Argon 39.948 36			
K Potassium 39.098	Ca Calcium 40.08	Sc candium 44.956	Zi Zi <thzi< th=""> Zi Zi Zi<!--</th--><th>As Arsenic 74.922</th><th>Se Selenium 78.96</th><th>Br Bromine 79.904</th><th>Fr Krypton 83.80</th></thzi<>											As Arsenic 74.922	Se Selenium 78.96	Br Bromine 79.904	Fr Krypton 83.80
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87 Fr Francium (223)	137.34 88 Radium 226.0254	٦	178.49 104 Rf Rutherfordium (261)	105 Db Dubnium (262)	183.85 106 Sg Seaborgium (263)	107 Bh Bohrium (262)	190.2 108 Hassium (265)	192.22 109 Mt Meitnerium (266)	195.08 110 Ununnilium (269)	196.967 111 Unununium (272)	112 112 Ununbium (277)	204.383	201.2	208.98	(209)	(210)	(222)
(110)			Lanthan	ide Se	ries	(202)	(200)	(200)	(200)	(2, 2)	(211)	1					
			57 58 59 60 61 62 63 64 65 La Ce Pr Nd Pm Sm Eu Gd Tb 138.906 140.12 140.908 144.24 (145) 150.36 151.96 157.25 158.925											68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
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			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	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)			

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

Multiple Shell Burning



 Advanced nuclear burning proceeds in a series of nested shells





Evidence for helium capture:

Higher abundances of elements with even numbers of protons

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



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

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

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 $> 8M_{Sun}$ have short lives, eventually becoming hot enough to make iron, and end in supernova explosions
- Low-mass stars with $< 2M_{Sun}$ 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



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!



Not to scale!

High Mass Star Summary

- 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

What have we learned?

- What are the life stages of a high-mass star?
 - They are similar to the life stages of a lowmass 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

How are the lives of stars with close companions different?



Thought Question

The binary star Algol consists of a $3.7 \text{ M}_{\text{Sun}}$ main sequence star and a $0.8 \text{ M}_{\text{Sun}}$ 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