## [06] Life as a High-mass Star (2/13/18)

#### **Upcoming Items**

- 1. Homework #1 due now.
- 2. Read Ch. 18.1 for next class and do the self-study quizzes.
- 3. Read degeneracy.pdf in Files->derivations
- 4. Homework #2 due in two weeks.

### APOD 2/14/17: Rosette Nebula

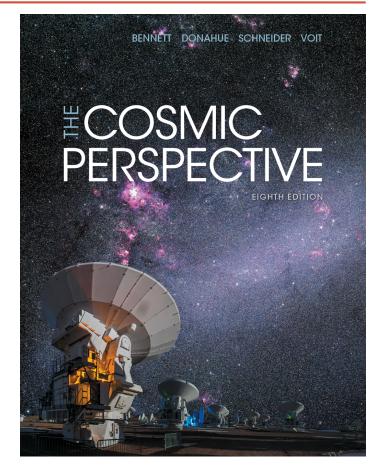


# LEARNING GOALS

For this class, you should be able to...

- ... sketch the approximate life track of a high-mass star on an H-R diagram;
- explain why a high-mass star is able to create a greater variety of elements than a low-mass star, keeping in mind that some elements may be formed after the star reaches the end of its life;

### Ch. 17.3–17.4



## Any astro questions?

## Life as a High-mass Star ( $M > 8 M_{\odot}$ )

- Most of the elements in the universe heavier than helium are formed in high-mass stars, because higher core temperatures permit more advanced fusion reactions.
  - Supernovae generate some to most of the remaining elements by fusion and fission. The remainder: neutron star mergers?
- Stages:
  - 1. Contraction of protostar to main sequence.
  - 2. <u>Main sequence</u>: H fuses to He in core, like low-mass star.
  - 3. <u>Red supergiant</u>: H fuses to He in shell around He core (no flash).
  - 4. <u>He core fusion</u>: He fuses to C in core, H fuses to He in shell.
  - 5. <u>Multiple shell fusion</u>: many elements fuse in shells.
  - 6. <u>Supernova</u> leaves *neutron star* or *black hole* behind.
- Things get complicated <u>if stars change mass</u> suddenly...

## Preview: Most Heavy Elements Are Created by Stars

- Recall: low-mass stars can only fuse elements up to He (why?).
- High-mass stars can make elements as heavy as iron in their cores, and their explosive deaths—supernovae! create a large fraction of the heavy elements on the periodic table.

But some elements may be made primarily in the inspirals and mergers of neutron stars with other neutron stars or black holes!

			Key														
1 <b>H</b> Hydrogen 1.00794		1	Magn	2 —   <b>g</b> — esium — 305 —	— Elem — Elem	ic numbe ent's sym ent's nan ic mass*	lod							7			2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.01218		weig	hted ave	ses are fra erage of a	tomic ma	sses of c	different is	sotopes–	_		5 <b>B</b> Boron 10.81	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 <b>F</b> Fluorine 18.988	10 <b>Ne</b> Neon 20.179
11 <b>Na</b> Sodium 22.990	12 Mg Magnesium 24.305		in proportion to the abundance of each isotope on Earth. 13 14 15 16 17 17 17 18 14 15 16 17 10 17 10 17 10 17 10 17 10 17 10 17 10 17 10 17 10 17 10 17 10 17 10 17 10 17 10 17 10 10 17 10 10 10 10 10 10 10 10 10 10														18 <b>Ar</b> Argon 39.948
19	20	21													34	35	36
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
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
33.050	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
Rb	Sr	Ŷ	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	Ĩ	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	Та	W	Re	Os	lr l	Pt	Au	Hg	Ti	Pb	Bi	Po	At	Rn
Cesium	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	Astatine	Radon
132.91 87	88		178.49	100.95	103.00	100.207	190.2	192.22	110	111	112	113	114	115	(209)	(210)	(222)
Fr	Ra		Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Uut	Uuq	Uup	Uuh	Uus	Uuo
Francium	Radium		Rutherfordium		Seaborgium	Bohrium	Hassium			nRoentgenium				Ununpentium			
(223)	226.0254		(263)	(262)	(266)	(267)	(277)	(268)	(281)	(272)	(285)	(284)	(289)	(288)	(292)	(294)	(294)
			Lanthan	ide Se	ries	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	90000 000 AUGUS													
			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
		L	Actinium	Thorium	Protactinium	Uranium	Neptunium	Plutonium	Americium	Curium	Berkelium	Californium	Einsteinium	100000000000000000000000000000000000000	Mendelevium	Nobelium	Lawrencium
			227.028	232.038	231.036	238.029	237.048	(244)	(243)	(247)	(247)	(251)	(252)	(257)	(258)	(259)	(260)

- Big Bang made 75% H, 25% He (and a tiny amount of Li, Be).
- Almost everything else comes from stars or mergers.

## Life Stages of High-mass Stars

- Late life stages of high-mass stars start out similar to those of low-mass stars...
  - Hydrogen core fusion (main sequence).
  - Hydrogen shell fusion (supergiant).
  - Helium core fusion (supergiant).

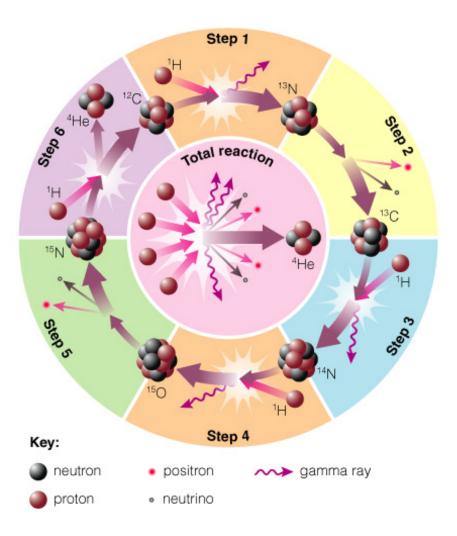
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19 K Potassium 39.098	20 <b>Ca</b> Calcium 40.08	21 <b>Sc</b> Scandium 44.956	22 <b>Ti</b> Titanium 47.88	23 V Vanadium 50.94	24 <b>Cr</b> Chromium 51.996	25 <b>Mn</b> Manganese 54.938	26 Fe Iron 55.847	27 <b>Co</b> Cobalt 58.9332	28 <b>Ni</b> Nickel 58.69	29 Cu Copper 63.546	30 <b>Zn</b> Zinc 65.39	31 Ga Gallium 69.72	32 Ge Germanium 72.59	33 <b>As</b> Arsenic 74.922	34 Se Selenium 78.96	35 <b>Br</b> Bromine 79.904	36 <b>Kr</b> Krypton 83.80
37 <b>Rb</b> Rubidium 85.468	38 <b>Sr</b> 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 <b>Ru</b> Ruthenium 101.07	45 <b>Rh</b> Rhodium 102.906	46 <b>Pd</b> Palladium 106.42	47 <b>Ag</b> 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 Te Tellurium 127.60	53 I lodine 126.905	54 <b>Xe</b> Xenon 131.29
55 <b>Cs</b> Cesium 132.91	56 <b>Ba</b> Barium 137.34		72 <b>Hf</b> Hafnium 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 <b>Ir</b> 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 <b>Bi</b> Bismuth 208.98	84 Po Polonium (209)	85 At Astatine (210)	86 <b>Rn</b> Radon (222)
87 <b>Fr</b> Francium (223)	88 <b>Ra</b> Radium 226.0254		104 <b>Rf</b> Rutherfordium (263)	105 <b>Db</b> Dubnium (262)	106 <b>Sg</b> Seaborgium (266)	107 <b>Bh</b> Bohrium (267)	108 <b>Hs</b> Hassium (277)	109 Mt Meitnerium (268)	110 Ds Darmstadtiur (281)	111 <b>Rg</b> mRoentgenium (272)	112 Cn Copernicium (285)	113 Uut Ununtrium (284)	114 Uuq Ununquadium (289)	115 Uup Ununpentium (288)	116 <b>Uuh</b> Ununhexium (292)	117 Uus Ununseptiun (294)	118 <b>Uuo</b> N Ununoctium (294)
	(223) 220.0234 (202) (202) (201) (211) (200) (201) (212) (203) (204) (203) (206) (203) (294) (294) (294)																
			57 La Lanthanum 138.906	58 <b>Ce</b> Cerium 140.12	59 <b>Pr</b> Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 <b>Sm</b> Samarium 150.36	63 Eu Europium 151.96	64 <b>Gd</b> Gadolinium 157.25	65 <b>Tb</b> 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
			Actinide	e Series													
			89 Ac Actinium 227.028	90 <b>Th</b> Thorium 232.038	91 Pa Protactinium 231.036	92 <b>U</b> Uranium 238.029	93 <b>Np</b> Neptunium 237.048	94 <b>Pu</b> Plutonium (244)	95 <b>Am</b> Americium (243)	96 <b>Cm</b> Curium (247)	97 <b>Bk</b> Berkelium (247)	98 <b>Cf</b> Californium (251)	99 <b>Es</b> Einsteinium (252)	100 <b>Fm</b> Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (260)

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

			Key														
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22.990	24.305											26.98	28.086	30.974	32.06	35.453	39.948
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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
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(220)	220.0234		Lanthan	<u>x===</u> /	N===1	(201)	(211)	(200)	(201)		(200)	(204)	(203)	(200)	(232)	(234)	(234)
			57 La Lanthanum	58 <b>Ce</b> Cerium	59 <b>Pr</b> Praseodymium	60 <b>Nd</b> Neodymium	61 <b>Pm</b> Promethium	62 <b>Sm</b> Samarium	63 <b>Eu</b> Europium	64 <b>Gd</b> Gadolinium	65 <b>Tb</b> Terbium	66 <b>Dy</b> Dysprosium	67 <b>Ho</b> Holmium	68 <b>Er</b> Erbium	69 <b>Tm</b> Thulium	70 <b>Yb</b> Ytterbium	71 Lu Lutetium
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		Actinide Series										00	00	100	101	100	100
			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	103 Lr Lawrencium
			227.028	232.038	231.036	238.029	237.048	(244)	(243)	(247)	(247)	(251)	(252)	(257)	(258)	(259)	(260)

• CNO cycle can change carbon to nitrogen and oxygen.

## Recall: CNO Cycle

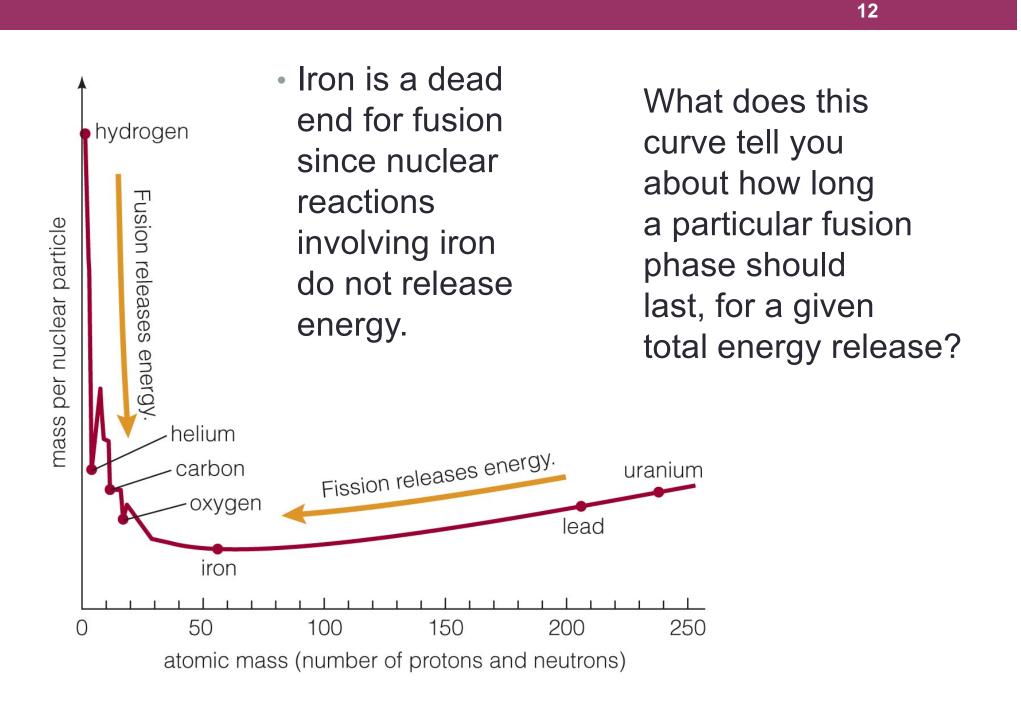


- Mid- to high-mass mainsequence stars fuse H to He at a higher rate using carbon, nitrogen, and oxygen as "catalysts."
- Greater core temperature enables hydrogen nuclei to overcome greater repulsion.

## Group Q: Nuclear Binding Energy

- You may know that nuclear fusion can't continue past iron, and you may also know that this is because iron has nearly the highest "binding energy" per nucleon of any nucleus Means energy needed per nucleon to fully disperse the nucleus
- But why?
- A hint: the electromagnetic force scales as 1/r<sup>2</sup>, where r is the distance between charges
- The strong force scales exponentially:  $\sim e^{-r/d}$ , where d~10<sup>-15</sup> m
- At ~10<sup>-15</sup> m (~size of proton or neutron), strong force is ~100x stronger than electromagnetic force
- Strong force binds nuclei together, and its strongest binding is when there are an equal number of protons and neutrons in the nucleus
- With this in mind, your two group questions are:

 Why should there be a maximum binding energy per nucleon?
For bigger nuclei, what do you expect to happen to the ratio of neutrons to protons in a nucleus?

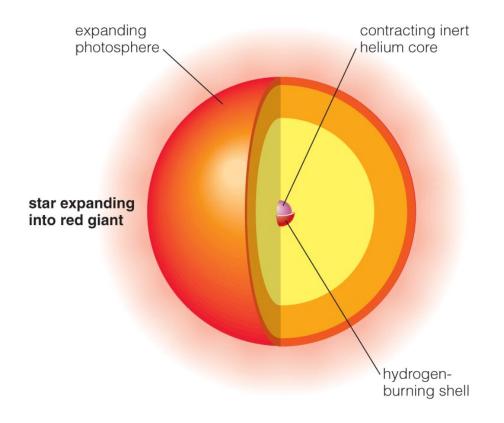


## Helium Flash for Low-Mass Stars

- We mentioned last time that there are some circumstances in which nuclear fusion can run away, in a burst
- This can occur for low-mass stars, when a helium shell is burning
- Why?
- Pressure gradients oppose gravity
- If the region is hot enough, it's thermal pressure; thus extra heat increases the pressure, and the region expands and therefore cools
- But at lower temperatures, it is quantum-mechanical degeneracy pressure (more in the next class) that matters; this is independent of the temperature
- Thus in that situation, an increased fusion rate does not increase the pressure much, and thus does not cause significant expansion and cooling

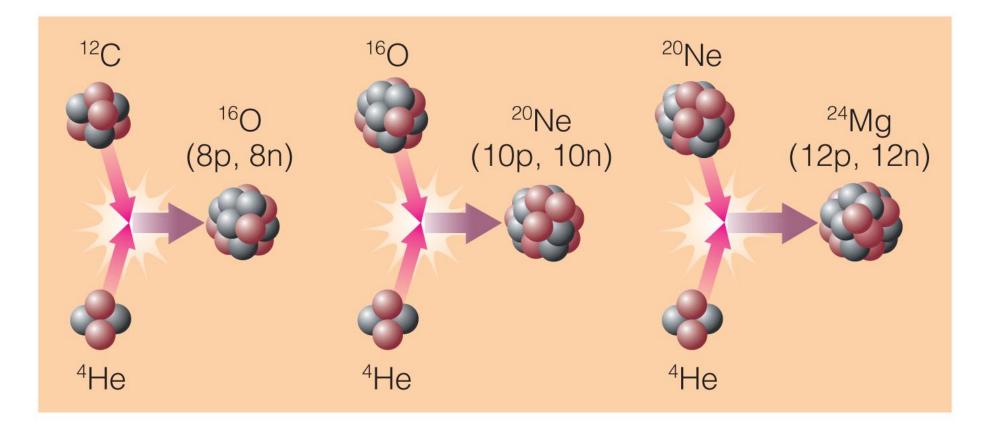
Recipe for runaway fusion, until hot enough for thermal pressure...

## **Onset of Helium Fusion**



- Unlike low-mass stars (< 2 M<sub>☉</sub>), mid- and highmass stars do not start He fusion in a flash.
- Core temperature is hot enough that thermal pressure, not degeneracy pressure, supports it against gravity.

## Helium Capture

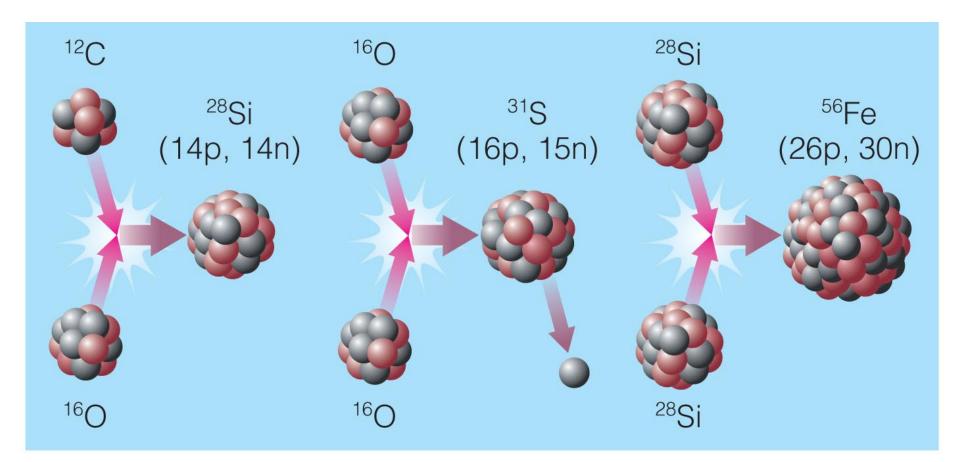


 High core temperatures allow helium to fuse with heavier elements.

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<b>K</b> Potassium	Ca Calcium	Scandium	Titanium	V Vanadium	Cr	Mn Manganese	Fe Iron	Co	Nickel	Cu Copper	Zn	Ga Gallium	Ge Germanium	As	Se Selenium	Br Bromine	Kr 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
Rubidium	Strontium	Yttrium	Zr Zirconium	Nb Niobium	Mo Molybdenum	Tc	Ruthenium	Rhodium	Pd Palladium	Ag	Cd	In Indium	Sn Tin	Sb Antimony	Tellurium	lodine	Xe Xenon
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Lanthanide Series													74				
							61	62	63	64	65	66	67	68	69	70	71
			57	58 Ce	59 Pr	60 Nd					100000	Dv	Ho	Er	Tm	Vh	1.0
			57 La Lanthanum	Ce Cerium	Pr	Nd Neodymium	Pm	Sm	Eu	Gd	Tb	Dy Dysprosium	Ho Holmium	Er Erbium	Tm Thulium	Yb Ytterbium	Lu
			La	Ce		Nd					100000	Dy Dysprosium 162.50	Ho Holmium 164.93	100000000000000000000000000000000000000	<b>Tm</b> Thulium 168.934	Yb Ytterbium 173.04	Lu Lutetium 174.967
			La Lanthanum	Cerium 140.12	Pr Praseodymium 140.908	Nd Neodymium	<b>Pm</b> Promethium	<b>Sm</b> Samarium	<b>Eu</b> Europium	<b>Gd</b> Gadolinium	<b>Tb</b> Terbium	Dysprosium	Holmium	Erbium	Thulium	Ytterbium	Lutetium
			La Lanthanum 138.906 Actinide	Ce Cerium 140.12 Series	Praseodymium 140.908	Nd Neodymium 144.24 92	Promethium (145) 93	Sm Samarium 150.36	Europium 151.96	Gd Gadolinium 157.25 96	<b>Tb</b> Terbium 158.925 97	Dysprosium 162.50 98	Holmium 164.93 99	Erbium 167.26 100	Thulium 168.934 101	Ytterbium 173.04 102	Lutetium 174.967 103
			La Lanthanum 138.906 Actinide	Ce Cerium 140.12 • Series 90 Th	Pr Praseodymium 140.908 91 Pa	Nd Neodymium 144.24 92 U	Promethium (145) 93 Np	Sm Samarium 150.36 94 Pu	<b>Eu</b> Europium 151.96 95 <b>Am</b>	Gd Gadolinium 157.25 96 Cm	<b>Tb</b> Terbium 158.925 97 <b>Bk</b>	98 Cf	Holmium 164.93 99 <b>ES</b>	Erbium 167.26 100 <b>Fm</b>	Thulium 168.934 101 <b>Md</b>	Ytterbium 173.04 102 <b>No</b>	Lutetium 174.967 103 <b>Lr</b>
			La Lanthanum 138.906 Actinide	Ce Cerium 140.12 Series	Praseodymium 140.908	Nd Neodymium 144.24 92	Promethium (145) 93	Sm Samarium 150.36	Europium 151.96	Gd Gadolinium 157.25 96	<b>Tb</b> Terbium 158.925 97	98 Cf	Holmium 164.93 99	Erbium 167.26 100	Thulium 168.934 101	Ytterbium 173.04 102	Lutetium 174.967 103

• Helium capture builds carbon into oxygen, neon, magnesium, and other elements.

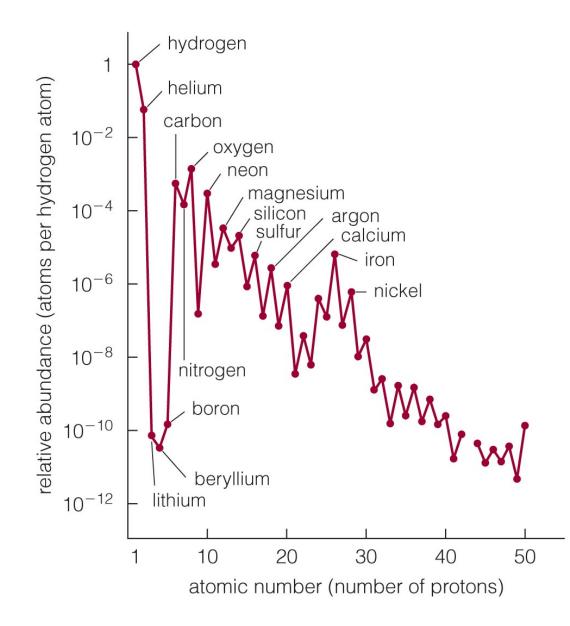
## **Advanced Nuclear Burning**



 Core temperatures in stars > 8 M<sub>☉</sub> allow fusion to elements as heavy as iron.

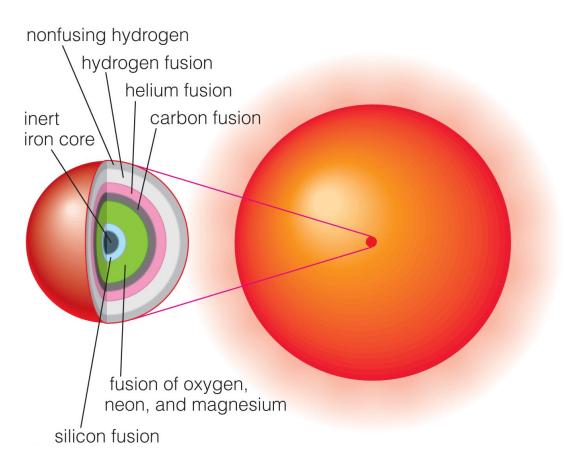
			Key														
1 <b>H</b> Hydrogen 1.00794		1	Magne		— Elem — Elem	iic numbe ent's sym ent's nan iic mass*	nbol ne										2 <b>He</b> Helium 4.003
3 Li Lithium	4 Be Beryllium		*Ator	nic mass	ses are fra	actions b		5 B Boron	6 C Carbon	Nitrogen	8 O Oxygen	9 F Fluorine	10 <b>Ne</b> Neon				
6.941	9.01218		-		rage of a					-		10.81	12.011	14.007	15.999	18.988	20.179
11	12		in pro	oportion	to the abi	undance	of each i	sotope o	n Earth.			13	14	15	16	17	18
Na	Mg							AI	Si	P	S	CI	Ar				
Sodium 22.990	Magnesium 24.305						Aluminum 26.98	Silicon 28.086	Phosphorus 30.974	Sulfur 32.06	Chlorine 35,453	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	As	Se	Br	Kr
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
39.090	40.06	44.930 39	47.00	41	42	43	44	45	46	47	48	49	50	51	52	53	54
Rb	Sr	Ŷ	Zr	Nb	Mo	Тс	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Те	Ĩ	Xe
Rubidium	Strontium	Yttrium	Zirconium	Niobium	Molybdenum		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 Cs	56 <b>Ba</b>		72 <b>Hf</b>	73 <b>Ta</b>	74 W	75 <b>Re</b>	76 Os	77	78 Pt	79 Au	80 Hg	81 <b>Ti</b>	82 Pb	83 Bi	84 <b>Po</b>	85 At	86 <b>Rn</b>
Cesium	Barium	—	Hafnium	Tantalum	Tungsten	Rhenium	Osmium	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	88		104	105	106	107	108	109	110	111	112	113	114	115	116	117	118
Fr	Ra		Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Uut	Uuq	Uup	Uuh	Uus	Uuo
Francium (223)	Radium 226.0254		Rutherfordium (263)	Dubnium (262)	Seaborgium (266)	Bohrium (267)	Hassium (277)	(268)	(281)	Roentgenium (272)	(285)	Ununtrium (284)	(289)	(288)	(292)	(294)	n Ununoctium (294)
	ZZ0.0234     (203)     (200)     (201)     (211)     (203)     (204)     (209)     (200)     (234)     (234)       Lanthanide Series																
			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 <b>Ho</b>	68 Er	69 Tm	70 Yb	71 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	Series	6												
			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
		L	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)
			221.020	202.000	201.000	200.020	201.040	(2-1-1)	(210)	(247)	(2.11)	(201)	(202)	(201)	(200)	(200)	(200)

 Advanced reactions in stars make elements like silicon, sulfur, calcium, and iron.

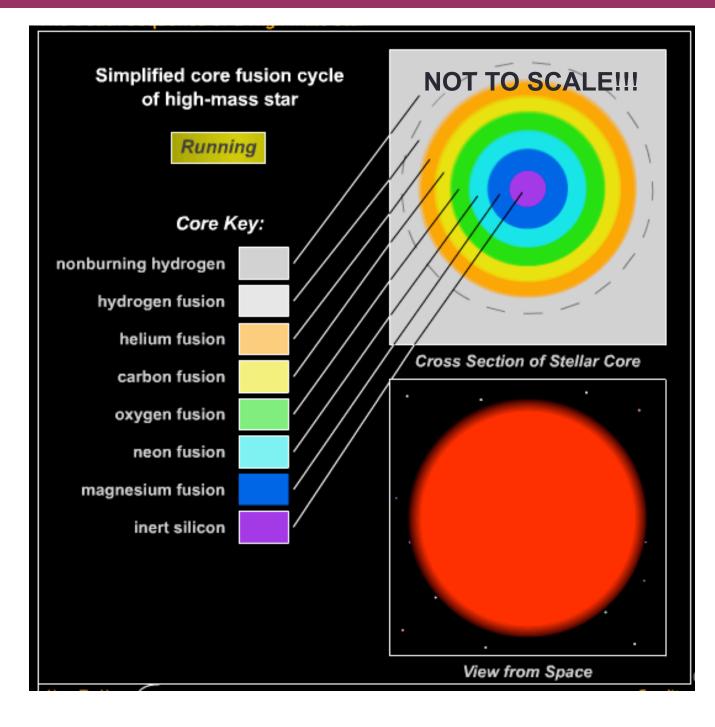


 Evidence for He capture: higher abundances of elements with even numbers of protons.

## **Multiple Shell Burning**



 Advanced nuclear burning proceeds in a series of nested shells.



- Iron builds up in core until degeneracy pressure can no longer resist gravity.
- The core then suddenly collapses, creating a supernova explosion.

	nonary stages of a 23-		
Stage	Core temperature (K)	Core density (kg/m <sup>3</sup> )	Duration of stage
Hydrogen fusion	4 × 10 <sup>7</sup>	5 × 10 <sup>3</sup>	$7 imes 10^6$ years
Helium fusion	$2 \times 10^8$	7 × 10⁵	$7 imes 10^5$ years
Carbon fusion	6 × 10 <sup>8</sup>	2 × 10 <sup>8</sup>	600 years
Neon fusion	1.2 × 10 <sup>9</sup>	4 × 10 <sup>9</sup>	1 year
Oxygen fusion	1.5 × 10 <sup>9</sup>	10 <sup>10</sup>	6 months
Silicon fusion	<b>2.7</b> × 10 <sup>9</sup>	3 × 10 <sup>10</sup>	1 day
Core collapse	5.4 × 10 <sup>9</sup>	3 × 10 <sup>12</sup>	<sup>1</sup> / <sub>4</sub> second
Core bounce	<b>2.3</b> × 10 <sup>10</sup>	4 × 10 <sup>15</sup>	milliseconds
Explosive (supernova)	about 10 <sup>9</sup>	varies	10 seconds

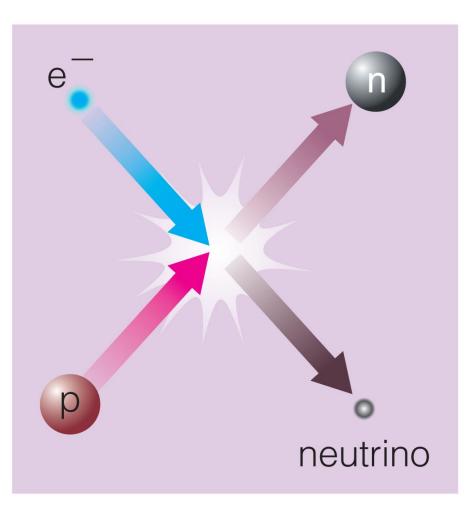
Based on calculations by Stanford Woosley (University of California, Santa Cruz) and Thomas Weaver (Lawrence Livermore National Laboratory).

Table 20-1 Evolutionary Stages of a 25-M<sub>o</sub> Star

## Supernova Simulation



## Supernova Explosion

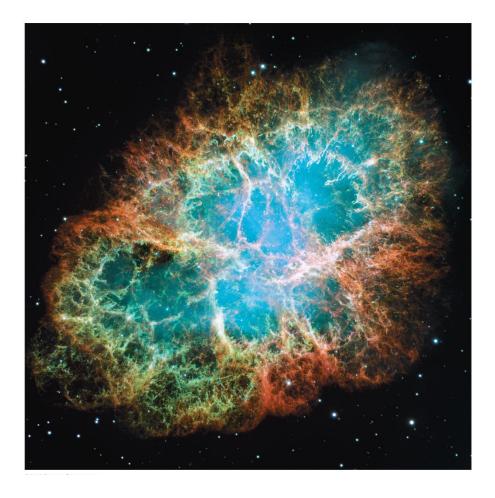


- Core degeneracy pressure goes away because electrons combine with protons, making neutrons and neutrinos.
- Neutrons collapse to the center, forming a neutron star.

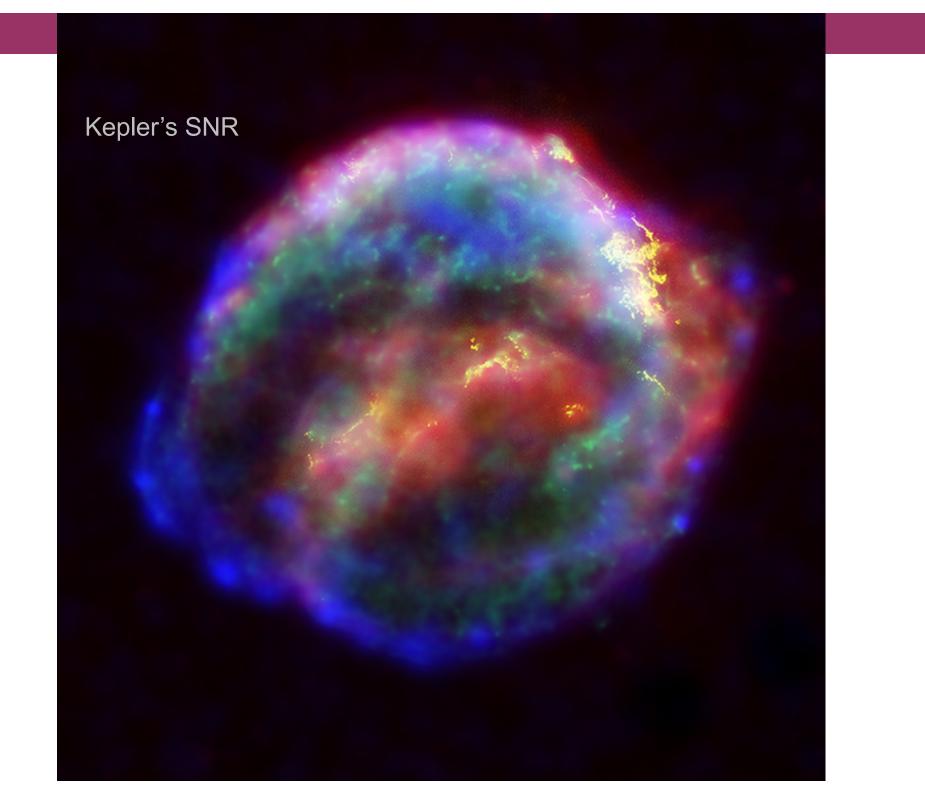
			Key														
1 <b>H</b> Hydrogen 1.00794		1	M Magne		Elem Elem	nic numbe lent's sym lent's nan nic mass*	nbol ne										2 <b>He</b> Helium 4.003
3 Li Lithium 6.941	4 <b>Be</b> Beryllium 9.01218		weig	hted ave	ses are fra rage of a	tomic ma	asses of c	different is	sotopes-	-1		5 <b>B</b> Boron 10.81	6 <b>C</b> Carbon 12.011	7 Nitrogen 14.007	8 <b>O</b> Oxygen 15.999	9 <b>F</b> Fluorine 18.988	10 <b>Ne</b> Neon 20.179
11 <b>Na</b> Sodium 22.990	12 Mg Magnesium 24.305		in proportion to the abundance of each isotope on Earth.														18 <b>Ar</b> Argon 39.948
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 <b>Ti</b> Titanium	23 V Vanadium	24 Cr Chromium	25 <b>Mn</b> Manganese	26 <b>Fe</b> Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 <b>Zn</b> Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 See Selenium	35 <b>Br</b> Bromine	36 <b>Kr</b> Krypton
39.098 37 <b>Rb</b> Rubidium	40.08 38 <b>Sr</b> Strontium	44.956 39 <b>Y</b> Yttrium	47.88 40 <b>Zr</b> Zirconium		51.996 42 Mo Molybdenum		55.847 44 <b>Ru</b> Ruthenium	58.9332 45 <b>Rh</b> Rhodium	58.69 46 <b>Pd</b> Palladium	63.546 47 <b>Ag</b> Silver	65.39 48 <b>Cd</b> Cadmium	69.72 49 In Indium	72.59 50 <b>Sn</b> Tin	74.922 51 <b>Sb</b> Antimony	78.96 52 <b>Te</b> Tellurium	79.904 53 Iodine	83.80 54 <b>Xe</b> Xenon
85.468 55 <b>Cs</b> Cesium	87.62 56 <b>Ba</b> Barium	88.9059	91.224 72 <b>Hf</b> Hafnium	92.91 73 <b>Ta</b> Tantalum	95.94 74 <b>W</b> Tungsten	(98) 75 <b>Re</b> Rhenium	101.07 76 <b>Os</b> 0smium	102.906 77 <b>Ir</b> Iridium	106.42 78 <b>Pt</b> Platinum	107.868 79 <b>Au</b> Gold	112.41 80 Hg Mercury	114.82 81 <b>Ti</b> Thallium	118.71 82 <b>Pb</b> Lead	121.75 83 <b>Bi</b> Bismuth	127.60 84 <b>Po</b> Polonium	126.905 85 <b>At</b> Astatine	131.29 86 <b>Rn</b> Radon
132.91 87 <b>Fr</b>	137.34 88 <b>Ra</b>		178.49 104 <b>Rf</b>	180.95 105 <b>Db</b>	183.85 106 <b>Sg</b>	186.207 107 <b>Bh</b>	190.2 108 <b>HS</b>	192.22 109 <b>Mt</b>	195.08 110 <b>DS</b>	196.967 111 <b>Rg</b>	200.59 112 <b>Cn</b>	204.383 113 <b>Uut</b>	207.2 114 <b>Uuq</b>	208.98 115 <b>Uup</b>	(209) 116 <b>Uuh</b>	(210) 117 <b>Uus</b>	(222) 118 <b>Uuo</b>
Francium (223)	Radium 226.0254		Rutherfordium (263)	Dubnium (262)	Seaborgium (266)	Bohrium (267)	Hassium (277)	Meitnerium (268)	Darmstadtiur (281)	nRoentgenium (272)	Coperniciun (285)	n Ununtrium (284)	Ununquadium (289)	Ununpentium (288)	Ununhexium (292)	Ununseptiun (294)	Ununoctium (294)
			Lanthan	ide Se	ries												
			57 La Lanthanum 138.906	58 <b>Ce</b> Cerium 140.12	59 <b>Pr</b> Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 <b>Sm</b> Samarium 150.36	63 <b>Eu</b> Europium 151.96	64 <b>Gd</b> Gadolinium 157.25	65 <b>Tb</b> Terbium 158.925	66 <b>Dy</b> 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 <b>Lu</b> Lutetium 174.967
			Actinide	e Series	3												
			89 Ac Actinium 227.028	90 <b>Th</b> Thorium 232.038	91 Pa Protactinium 231.036	92 <b>U</b> Uranium 238.029	93 <b>Np</b> Neptunium 237.048	94 <b>Pu</b> Plutonium (244)	95 <b>Am</b> Americium (243)	96 <b>Cm</b> Curium (247)	97 <b>Bk</b> Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 <b>Fm</b> Fermium (257)	101 Md Mendelevium (258)	102 <b>No</b> Nobelium (259)	103 <b>Lr</b> Lawrencium (260)

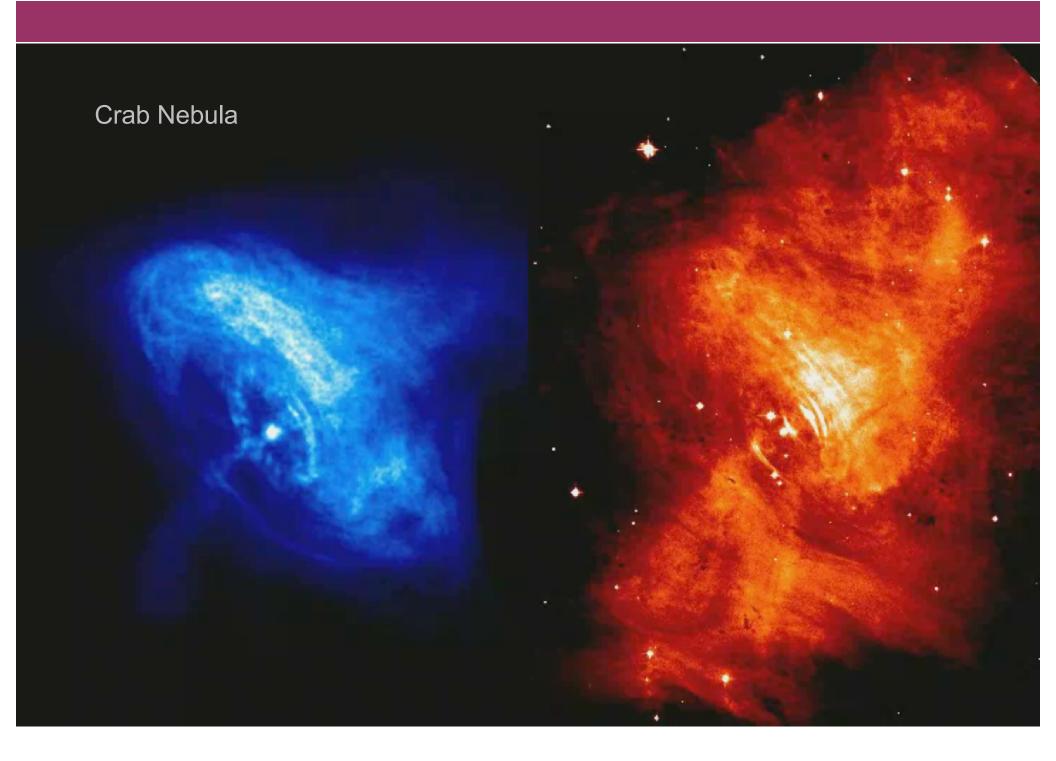
 Energy and neutrons released in supernova explosion enable elements heavier than iron to form, including gold and uranium.
But again, many of those elements formed in NS-NS inspiral...

## Supernova Remnant



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





## Supernova 1987A



**Before.** The arrow points to the star observed to explode in 1987.

After. The supernova actually appeared as a bright point of light. It appears larger than a point in this photograph only because of overexposure.

• The closest supernova in the last four centuries was seen in 1987.