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 fusion (giant)
 - Helium core fusion (horizontal branch)
 - Double-shell burning (supergiant)
- ... only they're more massive, so everything happens faster

BIG BANG MADE 75% H, 25% HE— STARS MAKE EVERYTHING ELSE.

| H | | | | Key | 5 | | | | | | | | | | | | | |
|---|--|---|----------------|--|-----------------------------|--------------------------------|-----------------------------|-----------------------------|-------------------------|---------------------------|---------------------------------|--------------------------|-----------------------------|----------------------------------|---|---|---------------------------|---------------------------------|
| Linu Be bayling bit in proportion to the abundance of each isotope on Earth. Bit Bit bit bit bit bit bit bit bit bit bit b | Hydrogen | | | Mg Element's symbol Magnesium Element's name 24.305 Atomic mass* | | | | | | | | | | Helium 4.003 | | | | |
| K Ca Sc Ti V Cr Min Fe Co Ni Cu Zn Ga Ge As Se Br Kr 9008 40.05 47.88 50.94 51.947 55.847 58.932 85.867 63.546 65.946 63.546 65.946 67.959 69.71 74.922 73.96 74.92 73.96 74.92 73.96 74.92 73.96 74.92 73.96 74.92 73.96 74.92 73.96 74.92 74.92 73.96 74.92 74.92 </th <th>Li Lithium 6.941 11 Na Sodium 22.990</th> <th>Be Beryllium 9.01218 12 Mg Magnesium 24.305</th> <th></th> <th colspan="11">*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. Boron 12.011 13 14 15 16 17 Aluminum 26.98 28.086 10 10 10 11 10 11 11 11 11 11 11 11 11</th> <th>F Fluorine 18.988 17 Cl Chlorine 35.453</th> <th>Ne Neon 20.179 18 Ar Argon 39.948</th> | Li Lithium 6.941 11 Na Sodium 22.990 | Be Beryllium 9.01218 12 Mg Magnesium 24.305 | | *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. Boron 12.011 13 14 15 16 17 Aluminum 26.98 28.086 10 10 10 11 10 11 11 11 11 11 11 11 11 | | | | | | | | | | | F Fluorine 18.988 17 Cl Chlorine 35.453 | Ne Neon 20.179 18 Ar Argon 39.948 | | |
| 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 Rb Str Y Zr Nb Mo Mo Tc Ru Ru Ru Pd Ag Cd In Sn Sb Sb <t< th=""><th>K Potassium</th><th>Ca Calcium</th><th>Sc Scandium</th><th>Ti Titanium</th><th>V Vanadium</th><th>Cr Chromium</th><th>Mn Manganese</th><th>Fe Iron</th><th>Co Cobalt</th><th>Ni Nickel</th><th>Cu Copper</th><th>Zn Zinc</th><th>Ga Gallium</th><th>Ge Germanium</th><th>As Arsenic</th><th>Se Selenium</th><th>Br Bromine</th><th>Kr Krypton</th></t<> | K Potassium | Ca Calcium | Sc Scandium | Ti Titanium | V Vanadium | Cr Chromium | Mn Manganese | Fe Iron | Co Cobalt | Ni Nickel | Cu Copper | Zn Zinc | Ga Gallium | Ge Germanium | As Arsenic | Se Selenium | Br Bromine | Kr Krypton |
| Rubidium 85.68 Strontum 87.62 Wittium 88.9059 Jicanian 91.224 Niobium 92.91 Molyodenum 95.94 Ruthenium (98) Ruthenium 101.07 Ruthenium 102.906 Ruthenium 102.906 Siver 107.868 Cadmium 114.41 Indium 114.42 Tin 114.42 Antimony 118.71 Tellurium 127.05 Iodian 126.905 Xenon 131.29 55 56 56 72 73 74 76 76 77 78 79 80 81 82 83 84 85 86 Cesium 132.91 137.34 74 75 76 77 77 78 79 80 81 82 83 84 85 86 Cesium 132.91 137.34 78 78 79 80 91 101 111 112 113 114 115 116 117 118 R R B0.95 106 107 108 109 110 111 112 113 114 115 116 117 118 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 50 | 51 | 52 | | 54 |
| 55 56 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 Cesim 132.91 137.34 137.34 137.34 137.34 1004 105 106 107 108 109.2 192.24 196.06 100 111 111 112 113 114 115 116 117 118 87 88 Fr Radium (23) 226.0254 83 84 85 86 Rn 87 Rg Rg Db Sg Bh Hs Mt Ds Rg Cn Uut Uut <th>Rubidium</th> <th>Strontium</th> <th>Yttrium</th> <th>Zirconium</th> <th>Niobium</th> <th>Molybdenum</th> <th>Technetium</th> <th>Ruthenium</th> <th>Rhodium</th> <th>Palladium</th> <th>Silver</th> <th>Cadmium</th> <th>Indium</th> <th>Tin</th> <th>Antimony</th> <th>Tellurium</th> <th></th> <th>Xenon</th> | Rubidium | Strontium | Yttrium | Zirconium | Niobium | Molybdenum | Technetium | Ruthenium | Rhodium | Palladium | Silver | Cadmium | Indium | Tin | Antimony | Tellurium | | Xenon |
| 87 Fr 88 Radium (283) 104 105 106 107 108 109 110 111 112 113 114 115 116 117 118 Francium (223) Radium (263) Db Sg Bh Hs Mt Ds Rg Cn Uut Uut Uup Uuh Uus Uus Uuo (223) 226.0254 (23) (26) (26) (277) (26) (277) (28) (281) (272) (285) (280) (280) (294) | 55 Cs Cesium | 56 Ba Barium | | 72 Hf Hafnium | 73 Ta Tantalum | 74 W Tungsten | 75 Re Rhenium | 76 Os Osmium | 77 Ir Iridium | 78 Pt Platinum | 79 Au Gold | 80 Hg Mercury | 81 Ti Thallium | 82 Pb Lead | 83 Bi Bismuth | 84 Po Polonium | 85 At Astatine | 86 Rn Radon |
| 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 Lat Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu Lanthanum 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 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 | 87 Fr Francium | 88 Ra Radium | | 104 Rf Rutherfordium | 105 Db Dubnium | 106 Sg Seaborgium | 107 Bh Bohrium | 108 HS Hassium | 109 Mt Meitnerium | 110 DS Darmstadtiun | 111 Rg Roentgenium | 112 Cn Copernicium | 113 Uut Ununtrium | 114 Uuq Ununquadium | 115 Uup Ununpentium | 116 Uuh Ununhexium | 117 Uus Ununseptium | 118 Uuo Ununoctium |
| La Lanthanum 138.906Ce Cerium 140.12Pr Prasedymium 140.908Pm Nod (145)Sm Pm (145)Eu Lu Europium 150.36Gd Europium (150.36Tb Tot Tot 151.96Dy Dy pysprosium 158.925Ho Fer Holmium 164.93Er Tm Thulium 164.93Yb Verbium 168.934Lu Lutetium 173.04Actinice Series89 Ac90 Th91 Pa92 U93 Np94 Pu95 Am96 Cm97 Bk98 Cf99 Es Fm101 Md102 No103 Lr | | | | | | | | | | | | | | | | | | |
| Actinide Series 99 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 | | | | La Lanthanum | Ce Cerium | Pr Praseodymium | Nd Neodymium | Pm Promethium | Sm Samarium | Eu Europium | Gd Gadolinium | Tb Terbium | Dy Dysprosium | Ho Holmium | Er Erbium | Tm Thulium | Yb Ytterbium | Lu Lutetium |
| Ac Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No Lr | | | | | | | | | | | | | | 174.901 | | | | |
| | | | | Ac | Th | Pa | U | Np | Pu | Am | Cm | Bk | Cf | Es | Fm | Md | No | Lr |

(247)

227.028

238.029

237.048

HELIUM FUSION CAN MAKE CARBON IN LOW-MASS STARS.

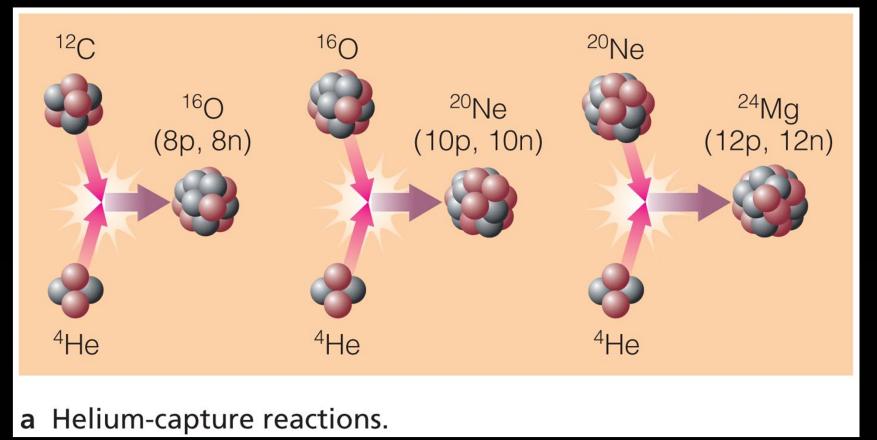
| | | | Key | | | | | | | | | | | | | | |
|--------------------------------------|--|--|-----------------------------------|---------------------------------------|--|--|---|---------------------------------------|---------------------------------------|------------------------------------|--|-------------------------------------|--------------------------------------|--|---|--|--|
| 1 H Hydrogen 1.00794 | | | 1 M Magno 24.3 | esium | — Elem — Elem | ic numbe ent's sym ent's nan ic mass* | lod | | | | | | | | | | 2 He Helium 4.003 |
| 3 Li Lithium 6.941 | 4 Be Beryllium 9.01218 | | weig | hted ave | ses are fra rage of a to the abu | tomic ma | isses of c | different is | 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 | 10 Ne Neon 20.179 |
| 11 Na Sodium 22.990 | 12 Mg Magnesium 24.305 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 13 Al Aluminum 26.98 31 | 14 Si Silicon 28.086 32 | 15 P Phosphorus 30.974 33 | 16 S Sulfur 32.06 34 | 17 Cl Chlorine 35.453 35 | 18 Ar Argon 39.948 36 |
| K Potassium | Ca Calcium 40.08 | Scandium | Ti Titanium | V Vanadium | Cr Chromium | Mn Manganese | Fe Iron | Co Cobalt | Ni Nickel | Cu Copper | Zn Zinc 65.39 | Gallium 69.72 | Ge Germanium | As Arsenic 74,922 | Selenium 78.96 | Br Bromine | Kr Krypton |
| 39.098 37 Rb | 38 Sr | Y Zr Nb Mo Tc Ru Rh P | | | | | | | 46 Pd | 63.546 47 Ag | 48 Cd | 49 In | 72.59 50 Sn | 51 Sb | 52 Te | 79.904 53 | 83.80 54 Xe |
| Rubidium 85.468 55 | Strontium 87.62 56 | Yttrium Zirconium Niobium Molybdenum Technetium Ruthenium Rhodium Palladium Silver Cadmium 88.9059 91.224 92.91 95.94 (98) 101.07 102.906 106.42 107.868 112.41 72 73 74 75 76 77 78 79 80 | | | | | | | Indium 114.82 81 | Tin 118.71 82 | Antimony 121.75 83 | Tellurium 127.60 84 | lodine 126.905 85 | Xenon 131.29 86 | | | |
| Cs Cesium 132.91 | Ba Barium 137.34 | | Hf Hafnium 178.49 | Ta Tantalum 180.95 | W Tungsten 183.85 | Re Rhenium 186.207 | Os Osmium 190.2 | Ir Iridium 192.22 | Pt Platinum 195.08 | Au Gold 196.967 | Hg Mercury 200.59 | Ti Thallium 204.383 | Pb Lead 207.2 | Bi Bismuth 208.98 | Po Polonium (209) | At Astatine (210) | Rn Radon (222) |
| 87 Fr Francium | 88 Ra Radium | | 104 Rf Rutherfordium | | 106 Sg Seaborgium | | 108 Hs Hassium | 109 Mt Meitnerium (268) | | 111 Rg Roentgenium | the second s | | | 115 Uup Ununpentium (288) | | | |
| (223) | 226.0254 | | (263) Lanthan | (262) iide Sei | (266) ries | (267) | (277) | (208) | (281) | (272) | (285) | (284) | (289) | (288) | (292) | (294) | (294) |
| | | | 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 | | | 199.29 | (145) | 100.00 | 101.00 | 101.20 | 100.020 | 102.00 | 104.30 | 101.20 | 100.004 | 110.04 | 114.001 |
| | | | 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) |

THE CNO CYCLE CAN CHANGE C INTO N AND O

| | | | Key | 1 | | | | | | | | | | | | | |
|--------------------------------------|-------------------------------------|---------------------------------------|---|--|--|--|---|--------------------------------------|--|-------------------------------------|---------------------------------------|--|--------------------------------------|--|--|---|-------------------------------------|
| 1 H Hydrogen 1.00794 | | 1 | M Magne | 12 — 19 — 305 — | Eleme | nic numbe lient's sym lient's nam nic mass* | nbol ne | | | | | | | | | | 2 He Helium 4.003 |
| 3 Li Lithium 6.941 | 4 Be Beryllium 9.01218 | | *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 | | | |
| 11 Na Sodium 22.990 | 12 Mg Magnesium 24.305 | | | portion | | | Ul each is | | T Latur. | | | 13 Al Aluminum 26.98 | 14 Si Silicon 28.086 | 15 P Phosphorus 30.974 | 32.06 | 17 CI Chlorine 35.453 | 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 Kr Krypton 83.80 |
| 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 I Iodine | 54 Xe Xenon |
| 85.468 55 Cs | 87.62 56 Ba | 88.9059 | 91.224 72 Hf | 92.91 73 Ta | 95.94 74 W | (98) 75 Re | 101.07 76 Os | 102.906 77 Ir | 106.42 78 Pt | 107.868 79 Au | 112.41 80 Hg | 114.82 81 Ti | 118.71 82 Pb | 121.75 83 Bi | 127.60 84 Po | 126.905 85 At | 131.29 86 Rn |
| Cesium 132.91 87 Fr | Barium 137.34 88 Ra | | Hafnium 178.49 104 Rf | Tantalum 180.95 105 Db | Tungsten 183.85 106 Sg | Rhenium 186.207 107 Bh | 0smium 190.2 108 HS | Iridium 192.22 109 Mt | Platinum 195.08 110 DS | Gold 196.967 111 Rg | Mercury 200.59 112 Cn | Thallium 204.383 113 Uut | Lead 207.2 114 Uuq | Bismuth 208.98 115 Uup | Polonium (209) 116 Uuh | Astatine (210) 117 Uus | Radon (222) 118 Uuo |
| Francium (223) | Radium 226.0254 | | Rutherfordium (263) | | Seaborgium (266) | | Hassium (277) | | A 100 100 100 100 100 100 100 100 100 10 | nRoentgenium (272) | | | | Ununpentium (288) | and the second | and the second se | |
| | | | Lanthanide Series 57 58 59 60 61 62 63 64 65 66 67 68 69 70 | | | | | | | | | | 71 | | | | |
| | | | La Lanthanum 138.906 | Ce | Pr | Nd | Promethium (145) | Samarium 150.36 | Eu Europium 151.96 | Gd Gadolinium 157.25 | Tb | Dysprosium 162.50 | Ho Holmium 164.93 | Er Erbium 167.26 | Tm Thulium 168.934 | Yb Ytterbium 173.04 | Lu Lutetium 174.967 |
| | | | Actinide | | | | | | | | | | | | | | |
| | | | 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) |
| | | L. | 227.020 | 202.000 | 201.000 | 200.020 | 201.040 | (244) | (240) | (247) | (241) | (201) | (202) | (201) | (200) | (200) | (200) |

BIGGER STARS, MORE GRAVITY, MORE PRESSURE, HOTTER, DENSER...

 Can squash together bigger, more repulsive things

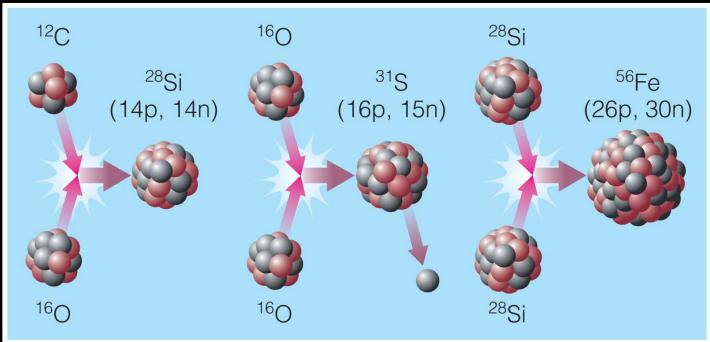


HELIUM CAPTURE BUILDS C INTO O, NE, MG ...

| | | Key | / | | | | | | | | | | | | | |
|-------------------------------------|---|--|--|--|--|---|---|---|---|--|---|---|--|---|---|---|
| | ı | N Magi | /lg | — Elem — Elem | ent's syn ent's nan | nbol ne | | | | | | | | | | 2 He Helium 4.003 |
| 4 Be Beryllium 9.01218 | | *Atomic masses are fractions because they represent a weighted average of atomic masses of different isotopes— in properties to the abundance of each isotope on Earth | | | | | | | | | | | | 10 Ne Neon 20.179 | | |
| Mg Magnesium 24.305 | | | | | | | | | | | AI Aluminum 26.98 | Silicon 28.086 | Phosphorus 30.974 | Sulfur 32.06 | CI Chlorine 35.453 | Ar Argon 39.948 |
| 20 Ca Calcium 40.08 | Scandiu | Im Titanium | 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 Gallium 69.72 | 32 Ge Germanium 72.59 | 33 As Arsenic 74.922 | 34 Se Selenium 78.96 | 35 Br Bromine 79.904 | 36 Kr Krypton 83.80 |
| 38 Sr Strontium | 39 Y Yttriun | 40 Zr Zirconium | 41 Nb | 42 Mo | 43 Tc | 44 Ru | 45 Rh Bhodium | 46 Pd Palladium | 47 Ag Silver | 48 Cd | 49 In | 50 Sn Tin | 51 Sb | 52 Te | 53 I | 54 Xe Xenon |
| 87.62 56 | | | 92.91 73 | 95.94 74 | (98) 75 | 101.07 76 | 102.906 77 | 106.42 78 | 107.868 79 | 112.41 80 | 114.82 81 | 118.71 82 | 121.75 83 | 127.60 84 | 126.905 85 | 131.29 86 |
| Ba Barium 137.34 | | Hf Hafnium 178.49 | Ta Tantalum 180.95 | W Tungsten 183.85 | Re Rhenium 186.207 | Os Osmium 190.2 | Ir Iridium 192.22 | Pt Platinum 195.08 | Au Gold 196.967 | Hg Mercury 200.59 | Ti Thallium 204.383 | Pb Lead 207.2 | Bi Bismuth 208.98 | Polonium (209) | At Astatine (210) | Rn Radon (222) |
| 88 Ra Radium | | 104 Rf Rutherfordium | 105 Db Dubnium | 106 Sg Seaborgium | 107 Bh Bohrium | 108 Hs Hassium | 109 Mt Meitnerium | 110 Ds Darmstadtiur | 111 Rg nRoentgenium | 112 Cn Copernicium | 113 Uut Ununtrium | 114 Uuq Ununquadium | 115 Uup Ununpentium | 116 Uuh Ununhexium | 117 Uus Ununseptium | 118 Uuo Ununoctium |
| 226.0254 | | (263) Lanthai | (262) nide Se | (266) ries | (267) | (277) | (268) | (281) | (272) | (285) | (284) | (289) | (288) | (292) | (294) | (294) |
| | | 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 | 71 Lu Lutetium |
| | | 138.906 Actinid | 140.12 e Series | 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 |
| | | 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) |
| | Be Beryllium 9.01218 12 Mg Magnesium 24.305 20 Ca Calcium 40.08 38 Sr Strontium 87.62 56 Ba Barium 137.34 88 Ra Radium | Be Beryllium 9.01218 12 Mg Magnesium 24.305 20 21 Ca Calcium 40.08 38 Sr Sr Strontium 87.62 56 Ba Barium 137.34 88 Ra Radium | 4 K Be *Atc Beryllium *Atc 9.01218 *atc 12 *Mg Mg *atc Ats *atc 20 21 22 Ca Sc Ti Calcium Scandium 44.956 Strontium Scandium 47.88 38 39 40 Sr Y Zr Strontium Y Zirconium 87 Y Zr Strontium 88.9059 91.224 56 72 Hf Barium 178.49 104 Ra Ra Atchridum 226.0254 Lanthanum 57 La Lanthanum | Be Beryllium 9.01218 *Atomic mass weighted ave in proportion 12 Mg Magnesium 24.305 *Atomic mass weighted ave in proportion 20 21 22 23 Ca Sc Calcium 44.956 Ti V 38 39 40 41 Sr Y Zr Nb Strontium 87.62 Y Zr Nb Strontium 87.62 Y Zr Nb Strontium 87.62 Y Zr Nb Strontium 87.62 Y Zr Nb Bai Barium 137.34 Tatalum 178.49 180.95 104 105 Ratium 126.0254 Lanthanum (263) Uubnium (263) Ce Strontium 138.906 Strote Strote Strote Strote Strote Strote Strote Strote Strote Strote Strote Barium 137.34 Strote Strote Strote Ratium 138.906 Strote Strote Strote Strote Strote Strote Strote Strote Strote Strote< | 4 12 Atom Mg Elem Magnesium Elem 9.01218 *Atomic masses are fraweighted average of a in proportion to the abuse of the abu | 4 12 Atomic number Mg Element's syn Magnesium Element's name 9.01218 *Atomic masses are fractions b weighted average of atomic mass weighted average of atomic mass Mg magnesium 24.305 20 20 21 22 23 24 25 Ca Sc Ti V Cr Mn 44.956 Titanium Vanadium Chromium Magnese 38 39 40 41 42 43 Sr Y Zr Nb Mo Tc Strontium Ra <td>4 12 Atomic number Element's symbol Mg Element's symbol Magnesium Element's name 9.01218 *Atomic masses are fractions because t weighted average of atomic masses of o in proportion to the abundance of each in 12 Mg Mgnesium *Atomic masses are fractions because t weighted average of atomic masses of o in proportion to the abundance of each in 20 21 22 23 24 25 26 Ca Sc Ti V Cr Mn Fe Calcium Scandium Titanium Varadium Chromium Magnesium 100 38 39 40 41 42 43 44 Sr Y Zr Nb Mo Tc Ru Strontium Yttrium Zroonium Niobium Molybdenum Technetium Ruthenium 137.34 88 Y Zr 73 74 75 76 Ba Translum Tantalum Tungsten Rhenium Osmium 10.02 137.34 104 105 106</td> <td>4 Atomic number Beryllium Element's symbol Mg Element's name 24.305 Atomic mass* *Atomic masses are fractions because they represented average of atomic masses of different is in proportion to the abundance of each isotope of each isotope of the abundance of each isotope of each isotope of the abundance of each isotope o</td> <td>4 Be Beryllium 9.01218 *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. 12 Magnesium 24.305 *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. 20 Cat Cata Calcium Vaandum Vaan</td> <td>4 Be Beryline 9.01218 12 </td> <td>4 Berylium Element's symbol Berylium </td> <td>4 4 6 6 5 8 8 8 9 4 5 8 8 9 12 23 24 25 26 27 28 29 30 31 12 12 12 12 23 24 25 26 27 28 29 30 31 13 13 13 13 13 13 13 14 10011 13 13 14 10011 13 13 14 10011 13 13 13 13 14</td> <td>Adomic number Adomic number Mg Element's symbol Element's name Element's symbol Adomic masses Adomic masses *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. 5 C Mg Mgmssim Z2 Z2 Z3 Z4 Z5 Z6 Z7 Z8 Z9 30 31 32 Mg Mgmssim V Z2 Z3 Z4 Z5 Z6 Z7 Z8 Z9 30 31 32 S8 S8.808 Z02 Z1 Ti V Cr Mn Fee Coal Nit Cup Zrn Galuin Germania 44.365 Tranulu Variadum Tornium Mo Tc Ru Rh Pd Ag Cd In Sistontum Bd Sistontum</td> <td>4 12 Atomic number Elements symbol Elements symbol Atomic masse 5 0 7 Be Baylion 201218 *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. \$</td> <td>Atomic number Mg Element's symbol Element's anset *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. \$</td> <td>Algorithm Algorithm <t< td=""></t<></td> | 4 12 Atomic number Element's symbol Mg Element's symbol Magnesium Element's name 9.01218 *Atomic masses are fractions because t weighted average of atomic masses of o in proportion to the abundance of each in 12 Mg Mgnesium *Atomic masses are fractions because t weighted average of atomic masses of o in proportion to the abundance of each in 20 21 22 23 24 25 26 Ca Sc Ti V Cr Mn Fe Calcium Scandium Titanium Varadium Chromium Magnesium 100 38 39 40 41 42 43 44 Sr Y Zr Nb Mo Tc Ru Strontium Yttrium Zroonium Niobium Molybdenum Technetium Ruthenium 137.34 88 Y Zr 73 74 75 76 Ba Translum Tantalum Tungsten Rhenium Osmium 10.02 137.34 104 105 106 | 4 Atomic number Beryllium Element's symbol Mg Element's name 24.305 Atomic mass* *Atomic masses are fractions because they represented average of atomic masses of different is in proportion to the abundance of each isotope of each isotope of the abundance of each isotope of each isotope of the abundance of each isotope o | 4 Be Beryllium 9.01218 *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. 12 Magnesium 24.305 *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. 20 Cat Cata Calcium Vaandum Vaan | 4 Be Beryline 9.01218 12 | 4 Berylium Element's symbol Berylium | 4 4 6 6 5 8 8 8 9 4 5 8 8 9 12 23 24 25 26 27 28 29 30 31 12 12 12 12 23 24 25 26 27 28 29 30 31 13 13 13 13 13 13 13 14 10011 13 13 14 10011 13 13 14 10011 13 13 13 13 14 | Adomic number Adomic number Mg Element's symbol Element's name Element's symbol Adomic masses Adomic masses *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. 5 C Mg Mgmssim Z2 Z2 Z3 Z4 Z5 Z6 Z7 Z8 Z9 30 31 32 Mg Mgmssim V Z2 Z3 Z4 Z5 Z6 Z7 Z8 Z9 30 31 32 S8 S8.808 Z02 Z1 Ti V Cr Mn Fee Coal Nit Cup Zrn Galuin Germania 44.365 Tranulu Variadum Tornium Mo Tc Ru Rh Pd Ag Cd In Sistontum Bd Sistontum | 4 12 Atomic number Elements symbol Elements symbol Atomic masse 5 0 7 Be Baylion 201218 *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. \$ | Atomic number Mg Element's symbol Element's anset *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. \$ | Algorithm Algorithm <t< td=""></t<> |

BIGGER STARS, MORE GRAVITY, MORE PRESSURE, HOTTER, DENSER...

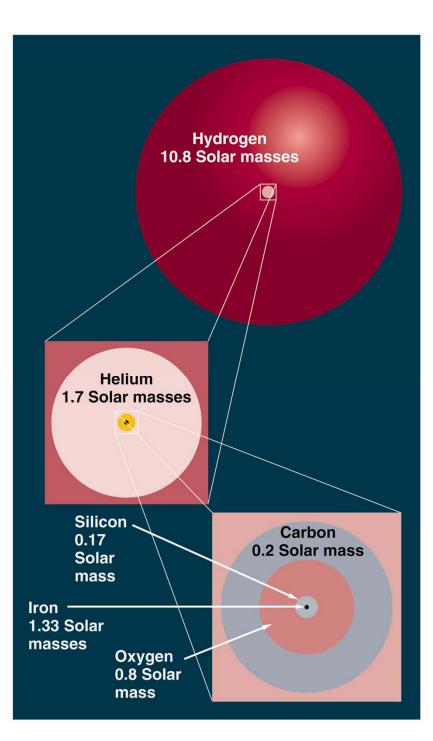
 Can squash together bigger, more repulsive things



b Other reactions. (Note: Fusion of two silicon nuclei first produces nickel-56, which decays rapidly to cobalt-56 and then to iron-56.)

ADVANCED NUCLEAR BURNING (M > 4 M $_{\odot}$) MAKES SI, S, CA, FE

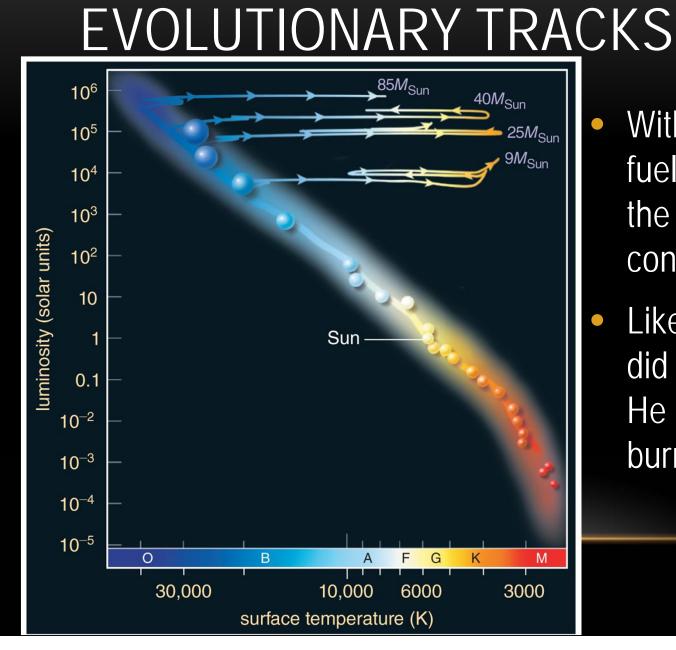
| | | | Key | | | | | | | | | | | | | | |
|---------------------------------------|--|---------------------------------------|---|---------------------------------------|--|--|---|---------------------------------------|---------------------------------------|---|---------------------------------------|---|--------------------------------------|---------------------------------------|--|--|-------------------------------------|
| 1 H Hydrogen 1.00794 | | | 13 Magne 24.3 | g | Elem Elem | ic numbe ent's sym ent's nan ic mass* | lod | | | | | | | - | | | 2 He Helium 4.003 |
| 3 Li Lithium 6.941 | 4 Be Beryllium 9.01218 | | *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 | | | |
| 11 Na Sodium 22.990 | 12 Mg Magnesium 24.305 | | in pro | oportion | to the abu | undance | of each i | sotope o | n Earth. | | | 13 Al Aluminum 26.98 | 14 Si Silicon 28.086 | 15 P Phosphoru 30.974 | 16 S Sulfur 32.06 | 17 Cl Chlorine 35.453 | 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 See Selenium 78.96 | 35 Br Bromine 79.904 | 36 Kr Krypton 83.80 |
| 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) |
| 87 Fr Francium (223) | 88 Ra Radium 226.0254 | 7 | 104 Rf Rutherfordium (263) | 105 Db Dubnium (262) | 106 Sg Seaborgium (266) | 107 Bh Bohrium (267) | 108 Hs Hassium (277) | 109 Mt Meitnerium (268) | 110 Ds Darmstadtiun (281) | 111 Rg Roentgenium (272) | 112 Cn Copernicium (285) | 113 Uut Ununtrium (284) | 114 Uuq Ununquadium (289) | 115 Uup Ununpentiun (288) | 116 Uuh Ununhexiun (292) | 117 Uus | 118 Uuo |
| (223) | 220.0204 | | _anthan | | | (201) | (217) | (200) | (201) | (212) | (200) | (204) | (203) | (200) | (232) | (234) | (234) |
| | | | 57 La Lanthanum 138.906 | 58 Ce Cerium 140.12 | 59 Pr Praseodymium I 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 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) |



WHEN ONE FUEL RUNS OUT

- A 15 M_☉ star in its Red Supergiant Phase
- Greater temperatures allow fusing of
 - Carbon
 - Neon
 - Oxygen
 - Silicon
- End up with Iron
 - Can't get energy out of iron fusion





With each successivefuel & shell burning,the star swells andcontracts

 Like lower mass stars did for H shell then He core and He shell burning

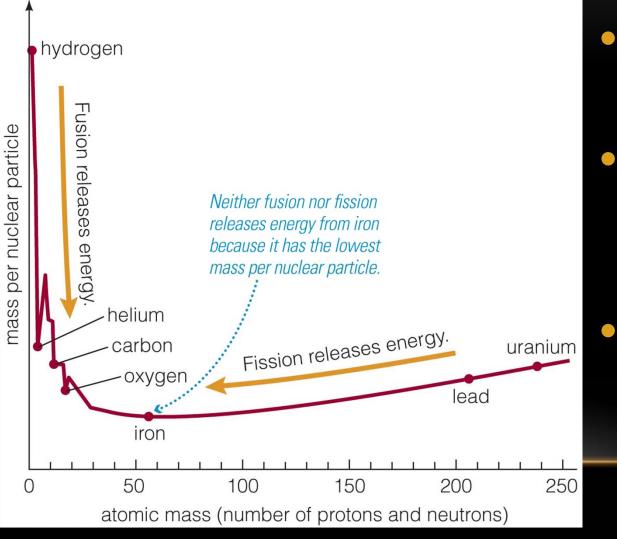
Fig.13.15

THE SLIPPERY SLOPE

- Each fuel lasts for a shorter time than the last
 - Higher temperatures, and less energy per fusion

| Fuel | Ash | Time | T (x10 ⁶ K) |
|------|-----------|--------------|------------------------|
| Η | He | 10 million y | 4 |
| Не | С | 1 million y | 100 |
| С | O, Ne, Mg | 1,000 y | 600 |
| Ne | O, Mg | Few years | 1,000 |
| 0 | Si, S | 1 year | 2,000 |
| Si | Fe | days | 3,000 |

IRON AND AVAILABLE ENERGY



- Iron is the most stable nucleus
- Can't get energy out by adding things
- Can't get energy out by breaking it up

Fig.13.18

IRON CORE?

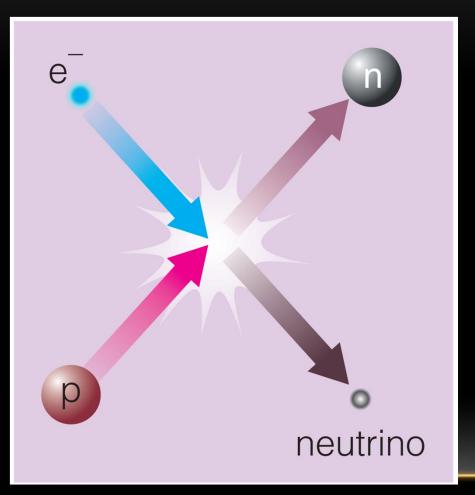


- Can't fuse Iron
- No more energy to supply upward pressure
- Still lots of gravitational pressure
 - More than a Chandrasekhar Limit worth of mass
- Core collapses into a neutron star
- Shockwave blows apart star

ENERGY AND NEUTRONS RELEASED IN A SUPERNOVA EXPLOSION ENABLE ELEMENTS HEAVIER THAN IRON TO FORM, INCLUDING AU AND U.

| | | | 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 Li Lithium 6.941 11 Na Sodium 22.990 | 4 Beryllium 9.01218 12 Mg Magnesium 24.305 | | *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. Al Aluminum 26.98 28.086 30.974 32.06 35.453 | | | | | | | | | | | 10 Neon 20.179 18 Ar Argon 39.948 | | | |
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| 87 Fr Francium (223) | 88 Ra Radium 226.0254 | | 178.49 104 Rf Rutherfordium (263) | 105 Db Dubnium (262) | 106 Sg Seaborgium (266) | 107 Bh Bohrium (267) | 108 Hs Hassium (277) | 192.22 109 Mt Meitnerium (268) | 110 Ds | 111 Rg nRoentgenium (272) | 112 Cn | 113 Ununtrium (284) | 114 Ununquadium (289) | 208.98 115 Uup Ununpentium (288) | (209) 116 Uuh Ununhexium (292) | (210) 117 Uus Ununseptiun (294) | (222) 118 Uuo Ununoctium (294) |
| (220) | 220.0204 | | Lanthan | ide Ser | ies | | | <u> </u> | | Vielden | | | | | | | |
| | | | 57 La Lanthanum 138.906 | 58 Ce Cerium 140.12 | 59 Pr Praseodymium I 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 |
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COLLAPSE?



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

TYPE II SUPERNOVA

- Type I is a white dwarf getting too much extra mass from a binary companion, then burning up all at once
 - See next chapter
- Type II are the core collapse of a massive star
 - All burned up
 - Collapses into a neutron star
 - Shock wave of this collapse blows apart rest of star

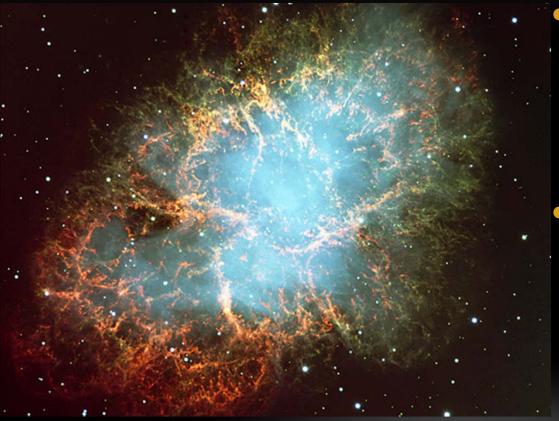
BRIGHT AS A GALAXY

 For a few weeks, a SN glows with billions of L_☉

 Compare stars (haze) in this galaxy with the SN

HST photo by High-Z SN Search Team A "nearby" SNIa in NGC 4526

SUPERNOVA REMNANTS



- All that stuff makes a nebula
 - Expands with time
 - Fades out
- This one is the remnant of the SN of 1054
 - We can measure its expansion over a few years

Crab Nebula photo by FORS team, 8.2m VLT

EXPANDING CRAB

- Comparison of 1973 and 2001 images
- Taken with the Kitt Peak 4m telescope

Animation by Adam Block, NOAO

OLDER REMNANTS

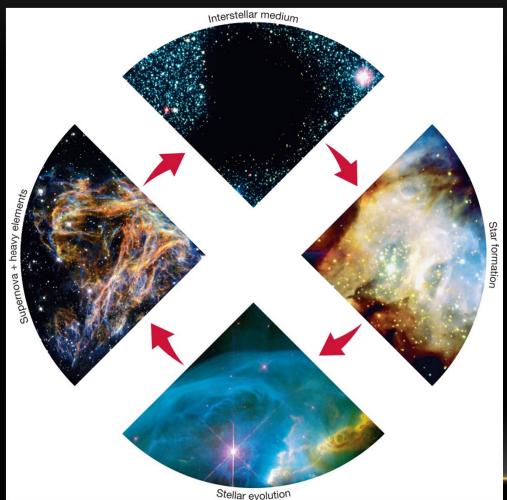


The ejecta expands, cools, fades out

- Stuff becomes just part of the ISM
- Will later condense to form new stars
 - Perhaps helped by a SN shock wave!
- All our heavy elements were formed in some long-ago SN
- This one is 11,000 years old

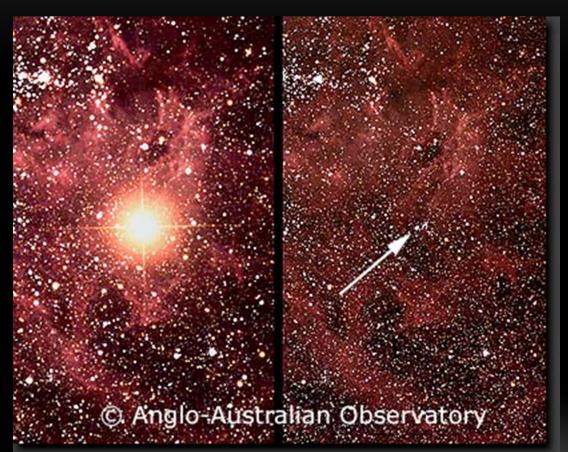
Vela SNR photo by David Malin, AAT

THE CYCLE OF STELLAR EVOLUTION



- Star formation is cyclical: stars form, evolve, and die.
- In dying, they send heavy elements into the interstellar medium.
- These elements then become parts of new stars.
- And so it goes.

SN1987A



- SNe get named by year, then sequentially by letter
- In Feb. 1987, a blue giant in the nearby Large Magellenic Cloud



Blue Giant SK -69 202

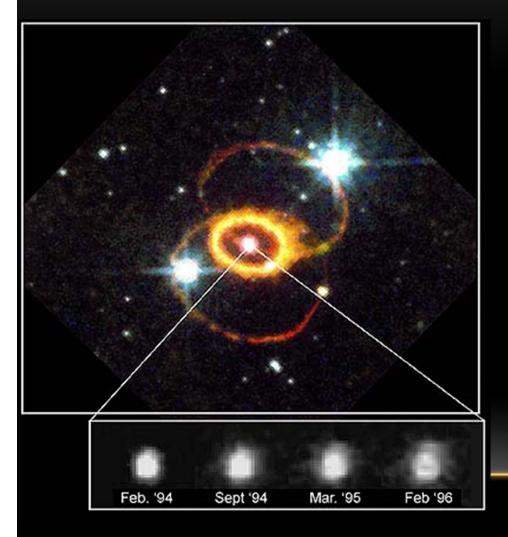
A VERY USEFUL SN

- Only 169,000 ly away
- Close enough we could get a good look
 - Identify the progenitor star for the only time
 - It is (oddly enough) a blue supergiant
 - SN light curve also dim and weird
- Observed only hours after it started
 - Usually it's days to weeks before someone notices

BLUE GIANT?

- SN1987A is an odd SN
- Could be because it was a Blue Giant star
 - Outer layers already blown off by stellar wind
 - Leaves hotter, more compact inner layers
- SK -69 202 was name of star
 - $L = 100,000 L_{\odot}$
 - $M = \sim 20 M_{\odot}$
 - B3 Supergiant, T= 16,000 K

WATCH THE ACTION

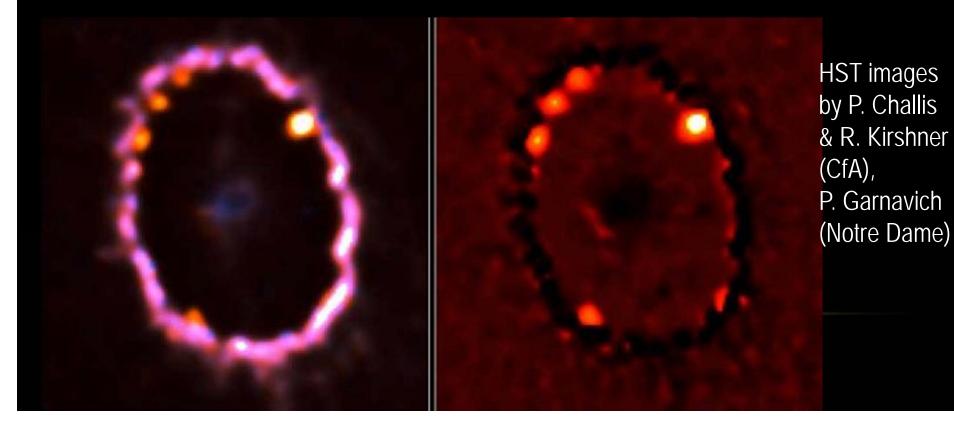


- We can see the fireball (lower)
- The shock wave crashing into previouslyejected stellar winds (above, the rings)

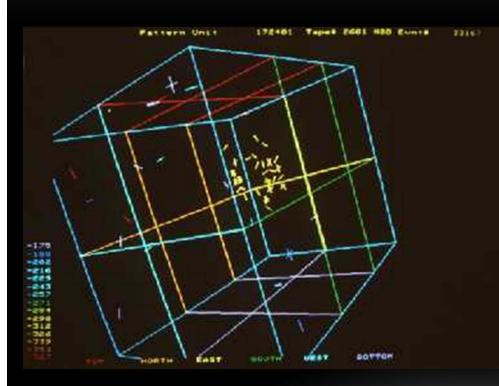
Photos by C. S. J. Pun (GSFC) & R. Kirshner (CfA) with HST

EXPANDING SHOCKS

- Right image in 1997, bright spots where the shock is hitting globs of matter
- Left image in 2000, shock catches up with whole shell

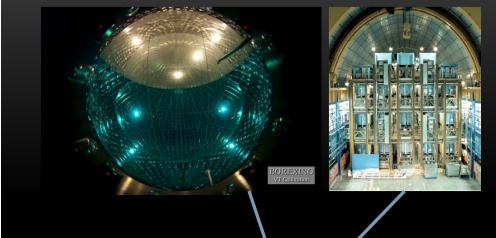


NEUTRINOS!



- IMB in Cleveland.
 Kamiokande in Japan (predecessors to Super-K) both saw bursts of neutrinos from SN1987A
- Neutrinos get right out, ~3 h before the shock
- Produced by the formation of the neutron star

IMB SN1987A v event

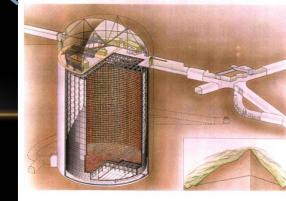


ALCERNATION OF THE OWNER OF THE OWNER OWNE

Antarctica

SNEWS http://snews.bnl.gov

- <u>Supernova Early Warning</u>
 <u>System</u>
 - Watch for coincidence from world's ν detectors
- Issue SN alarm, ~hours before light breaks out!

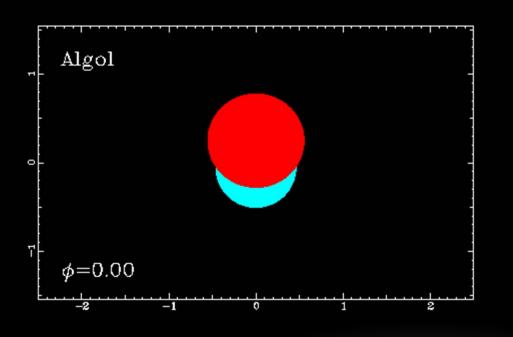


IPERKAMIOKANDE NOTITUTE FOR CODMIC TAY RESEARCH UNVERSITY OF

STARS IN CLOSE BINARIES

- When stars orbit very close to each other, what changes about how they age?
- For example, we looked at Algol as an example of an eclipsing binary
 - Algol consists of a 3.7 M_{Sun} main-sequence star and a 0.8 M_{Sun} subgiant star.

ALGOL

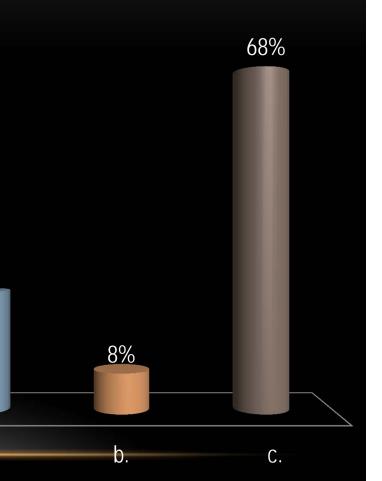


- The stars are a 3.5 R_☉
 K2 star and a 3R_☉ B8
 star
 - Primary eclipse is when you can't see much of the hot B8
- Note tidal distortion of larger star!

Animation by Larry Molnar

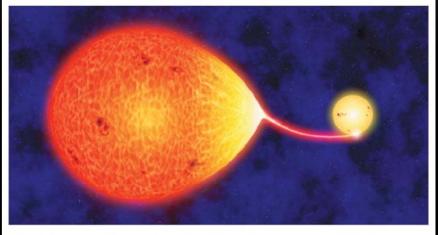
THE BINARY STAR ALGOL HAS A 3.7 SOLAR MASS MAIN SEQUENCE STAR AND A 0.8 SOLAR MASS RED GIANT. HOW COULD THAT BE?

- a. In this system the lower mass star must have evolved faster than the higher mass one.
- b. The red giant might be made of some different elements, so it evolved faster.
- C. The lower mass star *used to be* a more massive main sequence star, but when it became a giant some of its mass went onto the other star.

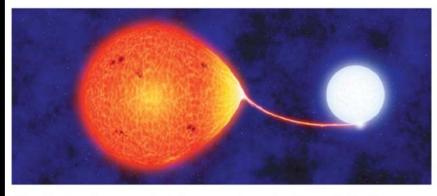




Algol shortly after its birth. The higher-mass star (left) evolved more quickly than its lower-mass companion (right).



Algol at onset of mass transfer. When the more massive star expanded into a red giant, it began losing some of its mass to its normal, hydrogen core fusion companion.



Algol today. As a result of the mass transfer, the red giant has shrunk to a subgiant, and the normal star on the right is now the more massive of the two stars.

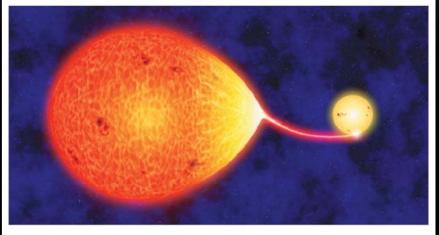
THE ALGOL PARADOX

- Algol's two stars are close enough that matter can flow from the subgiant onto the main-sequence star.
- We see evidence of this happening because that hot spot where it hits the other star shows up in spectra and eclipse data

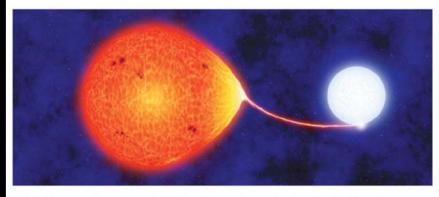
Fig.13.24



Algol shortly after its birth. The higher-mass star (left) evolved more quickly than its lower-mass companion (right).



Algol at onset of mass transfer. When the more massive star expanded into a red giant, it began losing some of its mass to its normal, hydrogen core fusion companion.



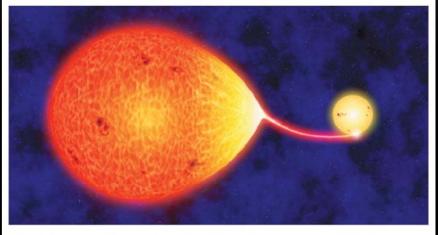
Algol today. As a result of the mass transfer, the red giant has shrunk to a subgiant, and the normal star on the right is now the more massive of the two stars.

THE ALGOL PARADOX

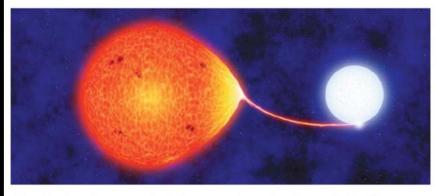
- The star that is now a subgiant was originally more massive.
- As it reached the end of its life and started to grow, it began to transfer mass to its companion (*mass exchange*).



Algol shortly after its birth. The higher-mass star (left) evolved more quickly than its lower-mass companion (right).



Algol at onset of mass transfer. When the more massive star expanded into a red giant, it began losing some of its mass to its normal, hydrogen core fusion companion.



Algol today. As a result of the mass transfer, the red giant has shrunk to a subgiant, and the normal star on the right is now the more massive of the two stars.

THE ALGOL PARADOX

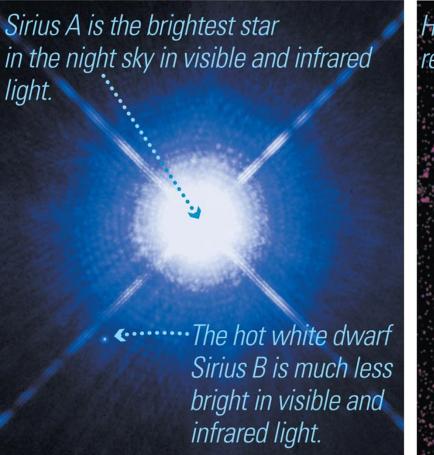
• Now the companion star is more massive.

 We'll see more ways mass exchange messes with things in the next chapter

Fig.13.24

WHITE DWARFS

Fig.14.1



However, Sirius A is relatively dim in ultraviolet and X rays while Sirius B outshines Sirius A in ultraviolet and X rays.

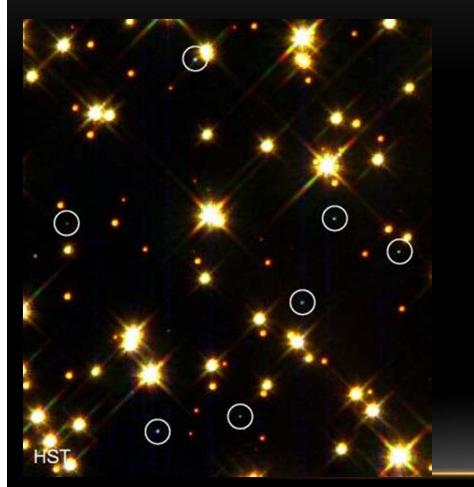
a Sirius as seen in infrared light b Sirius as seen by the Chandra by the Hubble Space Telescope. X-Ray Telescope.

WHITE DWARFS

| Earth |
|--------------------|
| White dwarf |
| Surface of the Sun |

- 0.02-1.5 M_{\odot} left in core
- 15,000 K surface temperature
- Very dense
 - 10⁶ g/cm³
- About Earth sized
- "Degenerate" as compact as normal matter can get
- Cool off slowly over a long time

DEGENERATE?

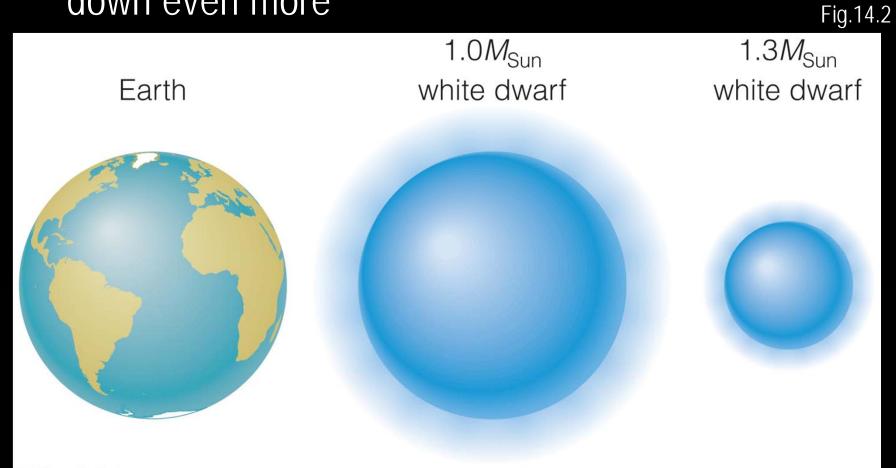


- All the protons, electrons, and neutrons are packed as close as quantum mechanics allows
- This provides the pressure to balance the gravity and keeps it from collapsing further
- Gravity for a white dwarf of over 1.4 M_☉ is too strong for this even
 - Electrons would have to be moving more than the speed of light
 - "Chandrasekar Limit"
 - Will collapse into a neutron star

A small section of globular cluster M4 -White Dwarfs all over! by H. Richer

MASS VS. RADIUS

 Pile more mass on, more gravity crushes things down even more

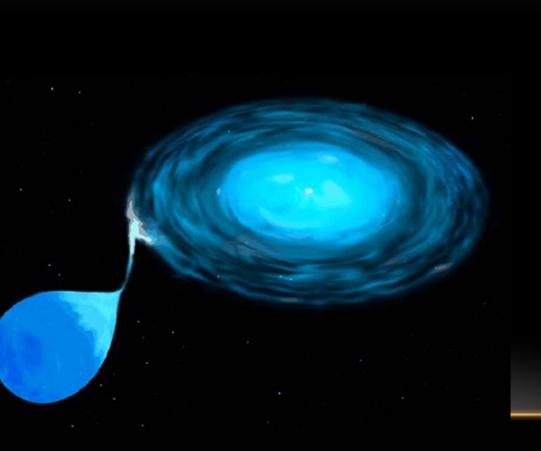


WHITE DWARFS IN CLOSE BINARIES



- What if one star in a binary system burns out and leaves a white dwarf before the other?
- When the 2nd star becomes a red giant, mass transfer happens if they're close enough

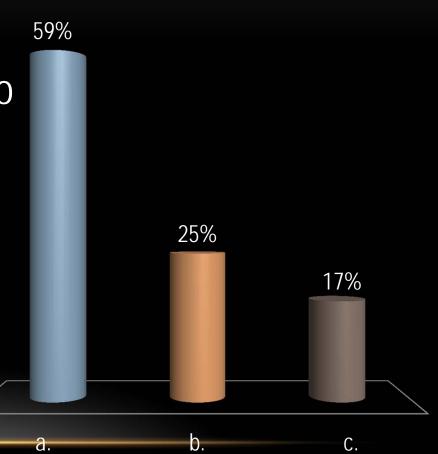
ACCRETION DISKS



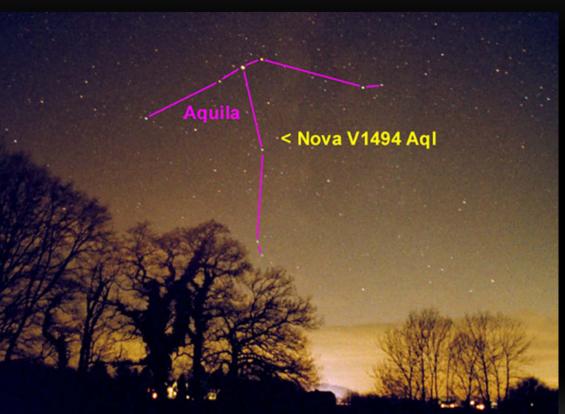
- Stuff spirals into the WD in an "accretion disk"
 - Because of friction in the disk
- Fresh star-stuff builds up on the surface of the WD

WHAT WOULD GAS IN THE DISK DO IF THERE WERE NO FRICTION?

- a. It would orbit indefinitely.
- b. It would eventually fall into the star.
- c. It would blow away.



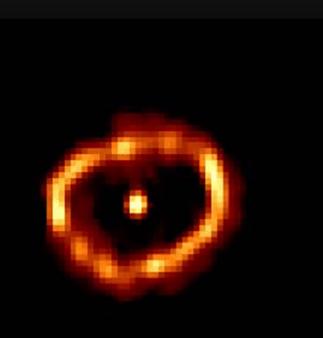
NOVA!



- A "new star"
- Really, just an old star suddenly burning 70,000x brighter
- Novae are mostly the stuff piling onto a white dwarf all undergoing fusion at once
- Will recur semi-regularly as long as the mass keeps coming
 - Supernovae are different

A nova on 12/1/99 by Till Credner

MORE CLUES



Nova Cygni 1992 seen by HST in 1995 by F. Paresce, R. Jedrzejewski

- Spectral analysis confirms this model
- We also see material flying off

Nova Velorum 1999 By Gordon Garradd WHAT HAPPENS TO A WHITE DWARF WHEN IT ACCRETES ENOUGH MATTER TO REACH THE $1.4M_{SUN}$ LIMIT?

- a. It explodes.
 - b. It collapses into a neutron star.
- c. It gradually begins fusing carbon in its core.

