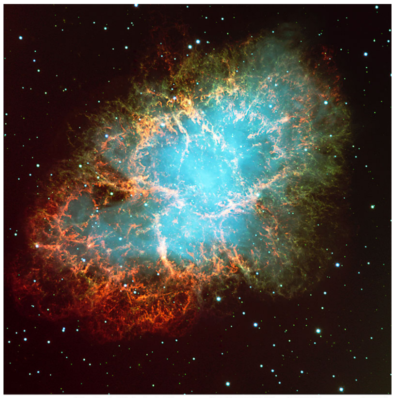
Life of a High-Mass Stars



The Crab Nebula in Taurus (VLT KUEYEN + FORS2)

ESO PR Photo 40f/99 (17 November 1999)

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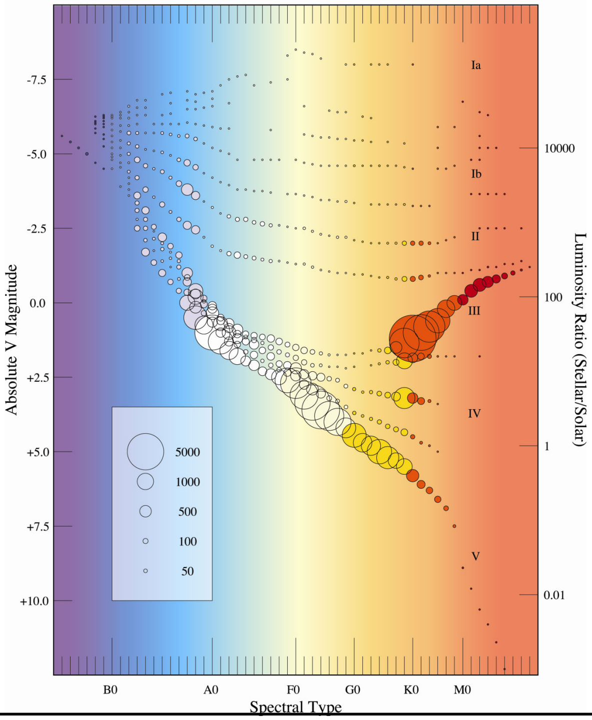


CNO Cycle

High mass stars can fuse four hydrogen nuclei into one helium nucleus by a series of nuclear reactions that use carbon, nitrogen, and oxygen as catalysts. This series is known as the CNO cycle. It requires higher temperatures and a large abundance of the catalysts. The sequence of reactions is:

$$^{12}C + {}^{1}H \rightarrow {}^{13}N + \gamma$$

$$^{13}N \rightarrow {}^{13}C + e^{+} + \nu$$

$$^{13}C + {}^{1}H \rightarrow {}^{14}N + \gamma$$

$$^{14}N + {}^{1}H \rightarrow {}^{15}O + \gamma$$

$$^{15}O \rightarrow {}^{15}N + e^{+} + \nu$$

$$^{15}N + {}^{1}H \rightarrow {}^{12}C + {}^{4}He$$

Energy Rates Diagram

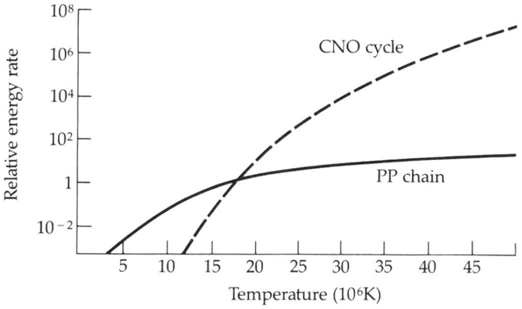


Figure 16–2 Energy-generation rates. The rates for the PP chain and CNO cycle are compared as a function of temperature for Population I stars. Note the crossover at about 18 million K.

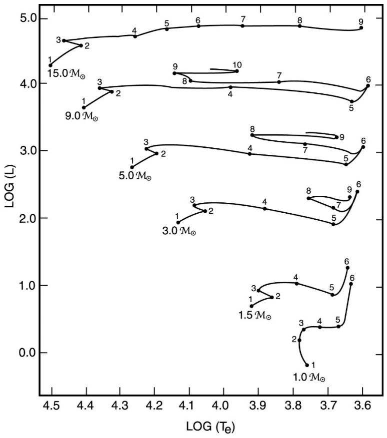
Astronomy & Astrophysics, Zeilik and Gregory

Evolutionary Tracks

Paths of high-mass stars on the HR Diagram are different from those of low-mass stars.

Once these stars leave the main sequence, they quickly grow in size to the supergiant regime (~100 $R_\odot$).

These extended stars, already extremely luminous, do not increase their intrinsic brightness.



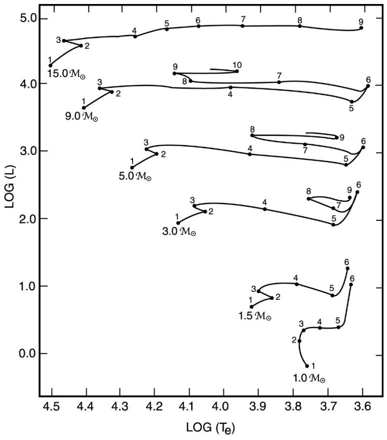
Adapted from Iben, *ARAA*, 5, 571, 1967

Evolutionary Tracks

The surface temperature decreases, and the stars quickly become **red supergiants**.

These supergiants move to the right (redward) while the inner core is not burning, and then move quickly back across the HR Diagram to the blue supergiant region when the core ignites.

The interior structure will have many shells of various reactions.



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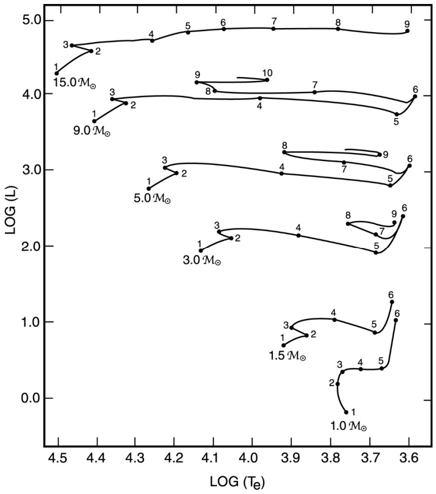
Evolutionary Tracks



Adapted from Iben, *ARAA*, 5, 571, 1967

Point	15.0 $M_\odot$	9.0 $M_\odot$	5.0 $M_\odot$
1	6.160×10^4	1.511×10^5	5.760×10^5
2	1.023×10^7	2.129×10^7	6.549×10^7
3	1.048×10^7	2.190×10^7	6.823×10^7
4	1.050×10^7	2.208×10^7	7.019×10^7
5	1.149×10^7	2.213×10^7	7.035×10^7
6	1.960×10^7	2.214×10^7	7.084×10^7
7	1.210×10^7	2.273×10^7	7.844×10^7
8	1.213×10^7	2.315×10^7	8.524×10^7
9	1.214×10^7	2.574×10^7	8.782×10^7
10		2.623×10^7	

3.0 $M_\odot$	1.5 $M_\odot$	1.0 $M_\odot$
2.510×10^6	1.821×10^7	5.016×10^7
2.273×10^8	1.567×10^9	8.060×10^9
2.394×10^8	1.652×10^9	9.705×10^9
2.478×10^8	2.036×10^9	1.024×10^{10}
2.488×10^8	2.105×10^9	1.045×10^{10}
2.531×10^8	2.263×10^9	1.088×10^{10}
2.887×10^8		
3.095×10^8		
3.262×10^8		

Triple-Alpha Cycle

The evolution of O and B stars is different from that of the low mass ones. The first major deviation occurs while the non-burning helium core is developing. Because the internal temperatures and pressures are so intense, He nuclei begin to fuse before the core becomes electron degenerate.

There is **no violent He flash** to disrupt the energy production. The burning of He primarily produces carbon and some oxygen, by the reactions:

$$^{4}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{8}\mathrm{Be}$$

$$^{8}\mathrm{Be} + {}^{4}\mathrm{He} \rightarrow {}^{12}\mathrm{C} + \gamma$$

$$^{12}\mathrm{C} + {}^{4}\mathrm{He} \rightarrow {}^{16}\mathrm{O} + \gamma$$

where ^{4}He is helium, ^{8}Be is beryllium, ^{12}C is carbon, ^{16}O is oxygen, and γ is a photon.

Energy Released

$$3\ {}^{4}\mathrm{He} \rightarrow {}^{12}\mathrm{C}$$

$$3\ m_{He} = 3 \times 4.002603 = 12.000781\ \mathrm{u}$$

$$1\ m_{C} = 12.000000\ \mathrm{u}$$

$$\Delta m = 0.000781\ \mathrm{u}$$

$$= 7.27\ \mathrm{MeV}$$

Carbon & Oxygen Burning

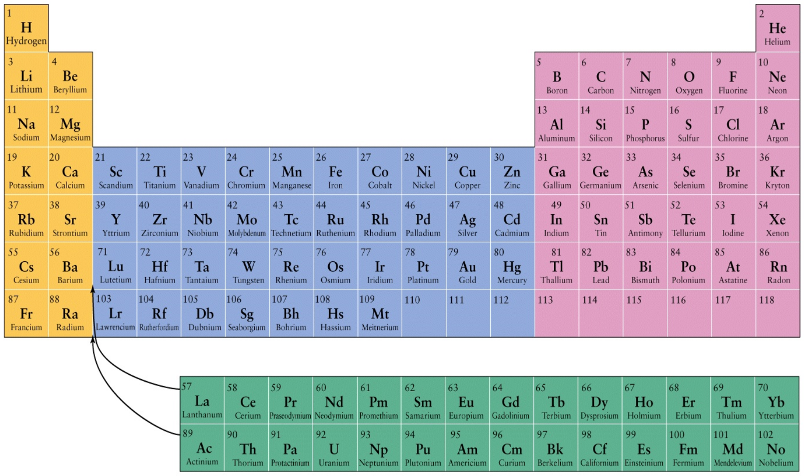
The late stages of evolution of stars more massive than about 8 solar masses is decidedly different from that of low mass stars.

As the He burning shell continues to add ash to the CO core, and as the core continues to contract, it eventually **ignites** carbon burning (before it becomes electron degenerate), generating a variety of by-products, such as O, Ne, Na, Mg, and Si.

$${}^{12}\mathrm{C} + {}^{12}\mathrm{C} \rightarrow {}^{16}\mathrm{O} + {}^{4}\mathrm{He} + {}^{4}\mathrm{He}$$

$${}^{16}\mathrm{O} + {}^{16}\mathrm{O} \rightarrow {}^{28}\mathrm{Si} + {}^{4}\mathrm{He}$$

Periodic Table



1 H Hydrogen																	2 He Helium
3 Li Lithium	4 Be Beryllium											5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
11 Na Sodium	12 Mg Magnesium											13 Al Aluminum	14 Si Silicon	15 P Phosphorus	16 S Sulfur	17 Cl Chlorine	18 Ar Argon
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	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 Kryton
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
55 Cs Cesium	56 Ba Barium	71 Lu Lutetium	72 Hf Hafnium	73 Ta Tantaium	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
87 Fr Francium	88 Ra Radium	103 Lr Lawrencium	104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110	111	112	113	114	115	116	117	118
				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

Elemental Abundances

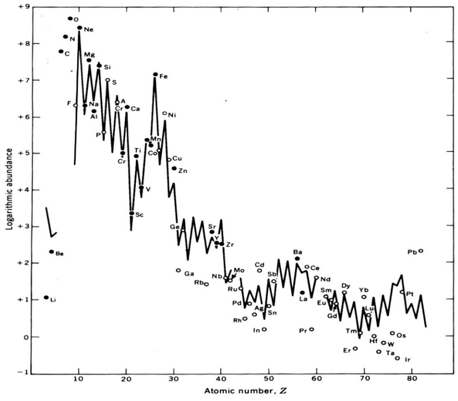


Fig. 1-22 The abundances of the elements in the solar system. The dots represent values obtained from the strengths of absorption lines in the spectrum of the sun, whereas the line represents the historic compilation of Suess and Urey, which was based mainly on chemical evidence from the earth and meteorites. Many of the estimates from both techniques have been improved since 1956, but the general features remain the same. It has been these abundance features which have inspired the nuclear physicists to seek the sets of thermonuclear circumstances that will reproduce this figure in a natural way.

Principles of Stellar Evolution and Nucleosynthesis, Clayton

Silicon Burning

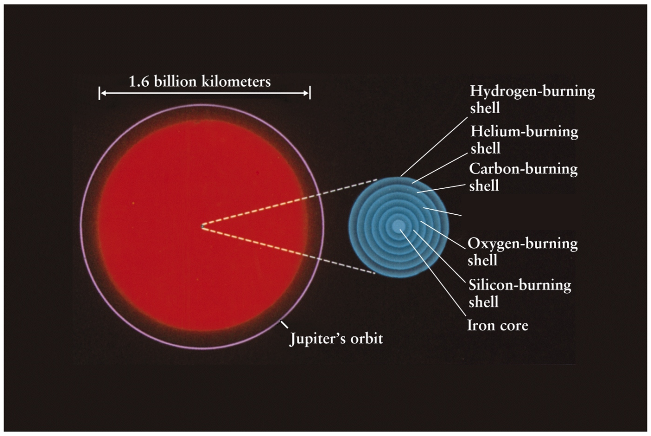
Assuming that each reaction sequence reaches equilibrium, an “onion-like” shell structure develops. Following C burning, the O in the resulting Ne-O core will ignite, producing a new core composition dominated by Si. Finally, at temperatures near 2.5 billion K, Si burning will begin

$$^{28}\mathrm{Si} + {}^{28}\mathrm{Si} \rightarrow {}^{56}\mathrm{Ni}$$

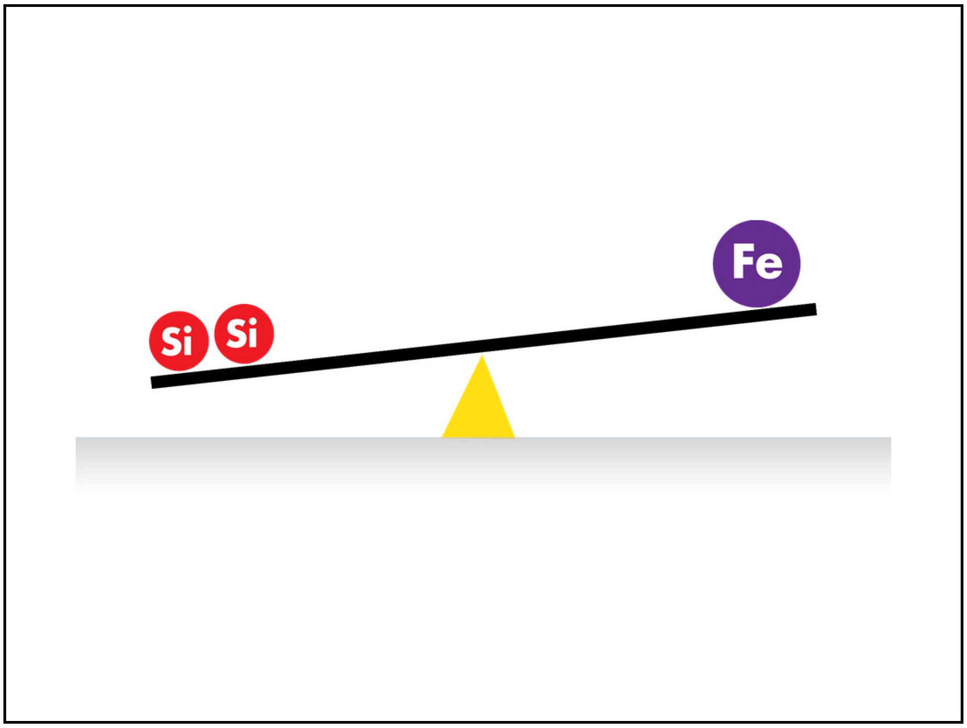
$$^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Fe} \text{ via decay}$$

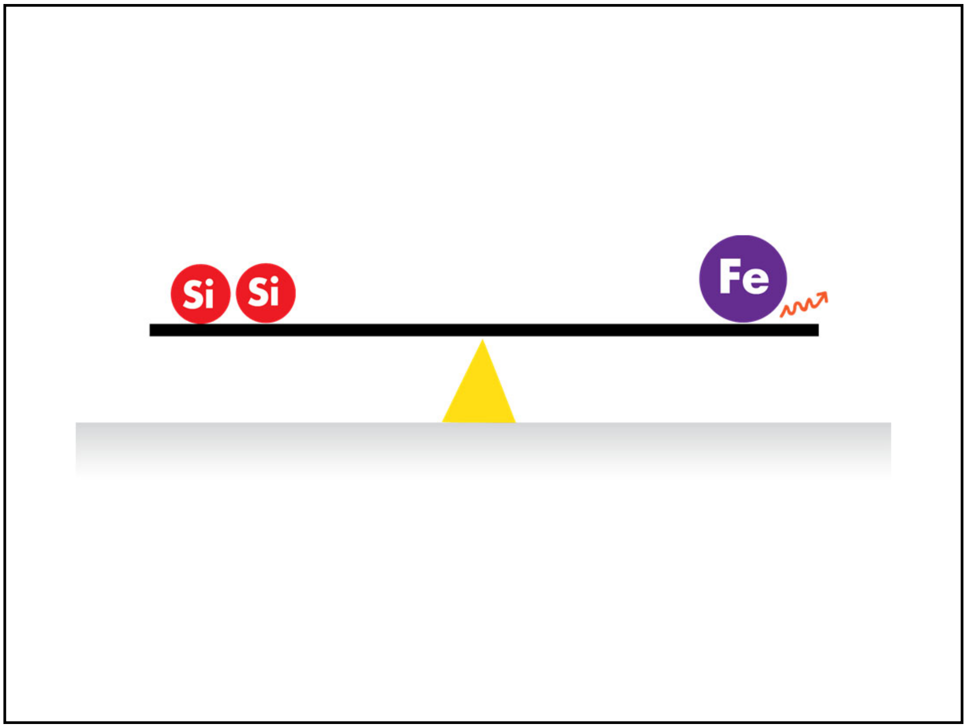
Si burning produces a host of nuclei centered near the Fe peak. Si burning produces an Fe core. Any further reactions that produce nuclei more massive than Fe are endothermic and cannot contribute to the luminosity of the star.

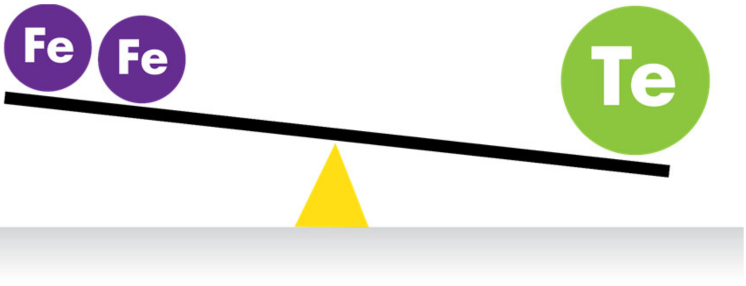
Interior Structure



Universe by Freedman, Geller, and Kaufmann

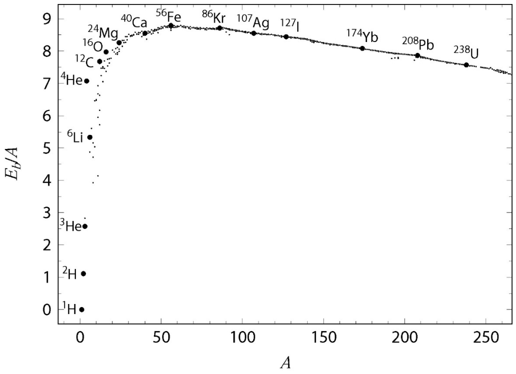

Si
Si
Fe


Si
Si
Fe



Binding Energy

Binding Energy is the energy released due to an accompanying loss in mass when nucleons are combined into atomic nuclei (i.e., **fusion**).



Modern Stellar Astrophysics, Ostlie and Carroll

Time Frames

Because C, O, and Si burning produce nuclei with masses progressively nearer the Fe peak of the binding energy curve, less and less energy is generated per gram of fuel. As a result, the time scale for each succeeding reaction sequence becomes shorter.

Evolutionary Stages for 25 $\mathcal{M}_{\odot}$ Star

STAGE	CORE (K)	DURATION
Hydrogen burning	40×10^6	7,000,000 yr
Helium burning	200×10^6	700,000 yr
Carbon burning	600×10^6	600 yr
Oxygen burning	$1{,}200 \times 10^6$	1 yr
Silicon burning	$2{,}700 \times 10^6$	1 day

The Dilemma

The star is quickly building an Fe core.

But the fusion of Fe will require – not release – energy.

What happens next?

First, the core does become electron degenerate.

Second, …

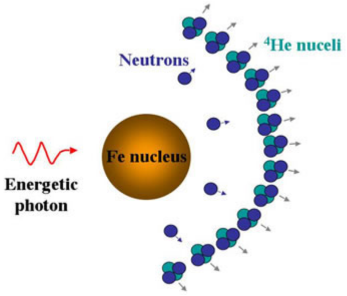
Photodisintegration

As the billion-degree temperatures continue to rise in the core, the photons soon possess enough energy to destroy heavy nuclei, a process known as photodisintegration.

Particularly important are the photodisintegration of Fe and He:

$^{56}\text{Fe} + \gamma \rightarrow 13\,^{4}\text{He} + 4\text{n}$

$^{4}\text{He} + \gamma \rightarrow 2\text{p}^{+} + 2\text{n}$



http://astronomy.swin.edu.au/cosmos/P/Photodisintegration

Photodisintegration

When the mass of the contracting Fe core has become large enough and the temperature sufficiently high, photodisintegration can, in a very short period of time, undo what the star has been trying to do its entire life – namely, produce elements more massive than H and He.

Of course, this process of stripping Fe down to individual protons and neutrons is highly **endothermic**.

Thermal energy is removed from the gas that would otherwise have resulted in the pressure necessary to support the core of the star.

Creation of Neutrinos

Under the extreme conditions that now exist in the core region (e.g., T ~ 8 billion K and $\rho \sim$ 10 billion g/cm^3 for a 20 solar mass star), the **electrons** that had assisted in supporting the star through pressure **collide with the protons** produced through photodisintegration. That reaction is

$$e^- + p^+ \rightarrow n + \nu$$

The amount of energy that escapes from the star by **neutrino** loss is enormous; during Si burning the **photon** luminosity of a 20 solar mass star is 4.4×10^{31} J/s [= 10,000 L_{sun}],

while the **neutrino** luminosity is 3.1×10^{38} J/s [= 10^{11} L_{sun}].

Core Collapse

Due to (a) the photodisintegration of Fe and (b) electron capture by protons and heavy nuclei,

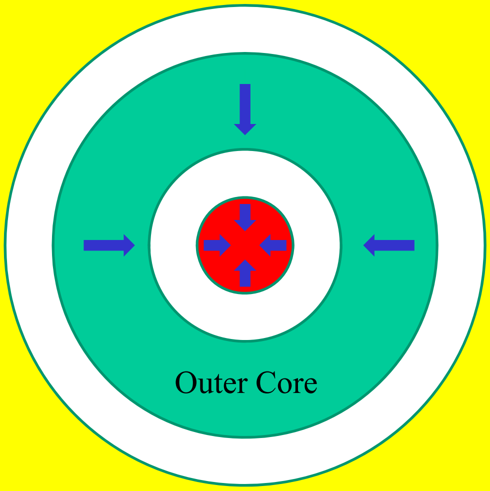
most of the core's support in the form of electron degeneracy pressure is suddenly gone

and the core begins to collapse extremely rapidly.

Core Collapse

At the radius where the velocity exceeds the local sound speed, the inner core decouples from the now outer core, which is nearly in free-fall.

During the collapse, speeds can reach almost 70,000 km/s (0.25 c), and within about one second a volume the size of the Earth has been compressed to a diameter of 100 km!



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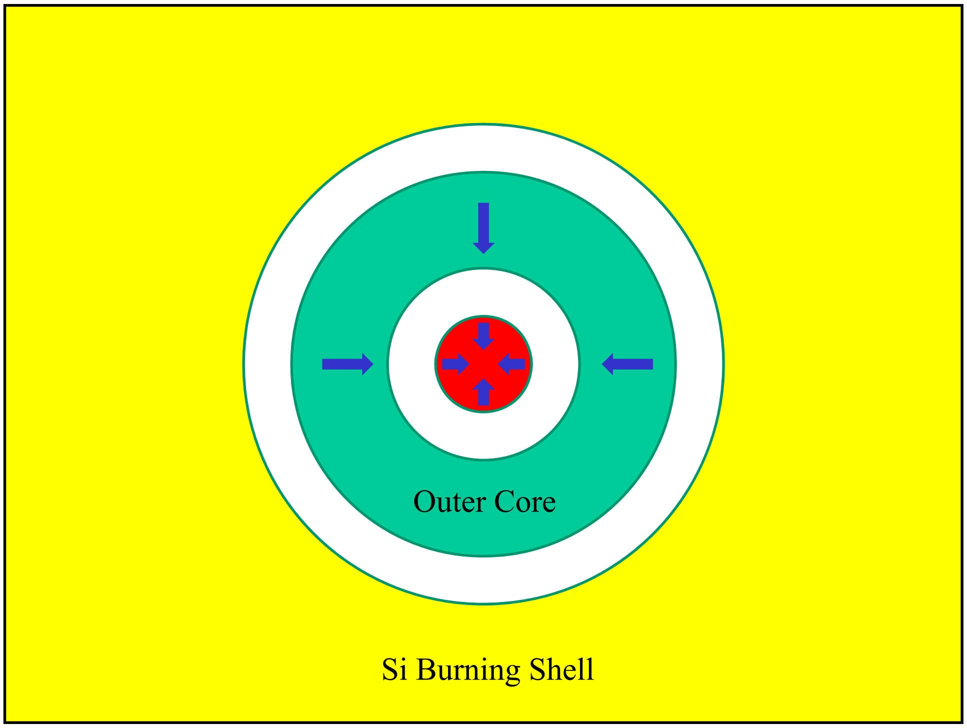
Core collapse	$5{,}400 \times 10^6$	0.25 seconds

Suspended Shells

Since mechanical information will only propagate through the star at the speed of sound and because the core collapse proceeds so quickly, there is not enough time for the outer layers to immediately learn about what has happened in the core.

The outer layers, including the O, C, and He shells, as well as the outer envelope, are left in the precarious position of being almost suspended above the catastrophically collapsing core.

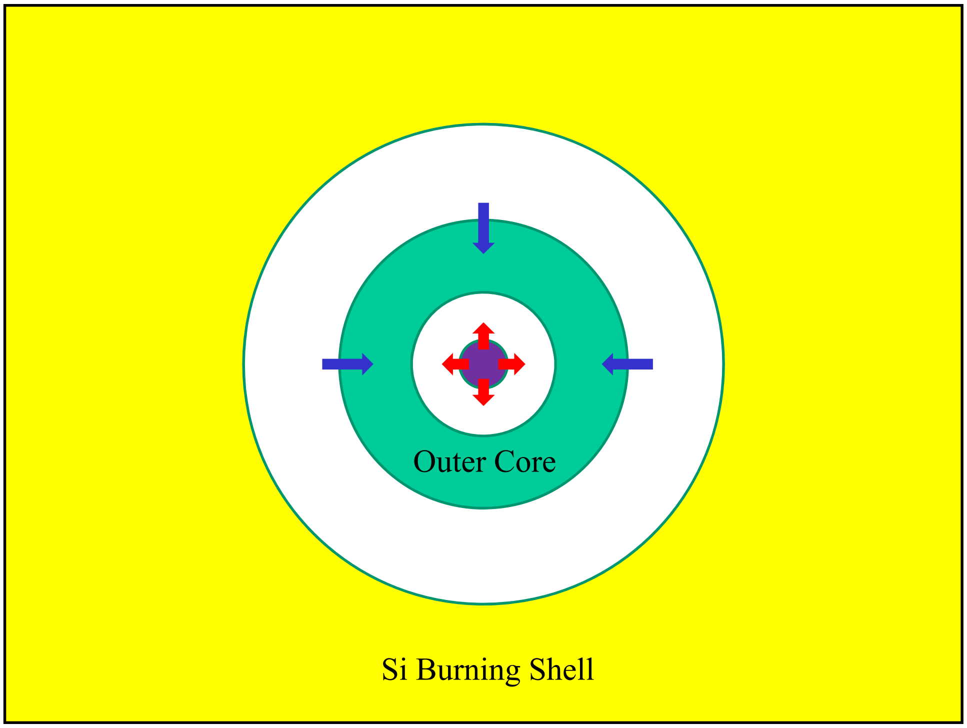


Neutron Degeneracy

The collapse of the inner core continues until the density there exceeds about 8 x 10^{14} g/cm^3, roughly three times the density of an atomic nucleus.

At that point, the nuclear material that now makes up the inner core stiffens because the **Strong Force** (usually attractive) suddenly becomes repulsive. This is a consequence of the Pauli Exclusion Principle applied to neutrons, e.g., **neutron degeneracy**.

The result is that the extremely-dense and "hard" inner core rebounds somewhat, sending ***pressure waves*** outward into the in-falling material from the outer core. When the velocity of the pressure waves reach the sound speed, they build into a shock wave.



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Core collapse	$5{,}400 \times 10^6$	0.25 seconds
Core bounce	$23{,}000 \times 10^6$	milliseconds

Shock Wave – Could be Fast

As the shock wave encounters the in-falling outer Fe core, the high temperatures that result cause further photodisintegration, robbing the shock of much of its energy. For every 0.1 solar mass of Fe that is broken down into protons and neutrons, the shock loses 1.7×10^{44} J.

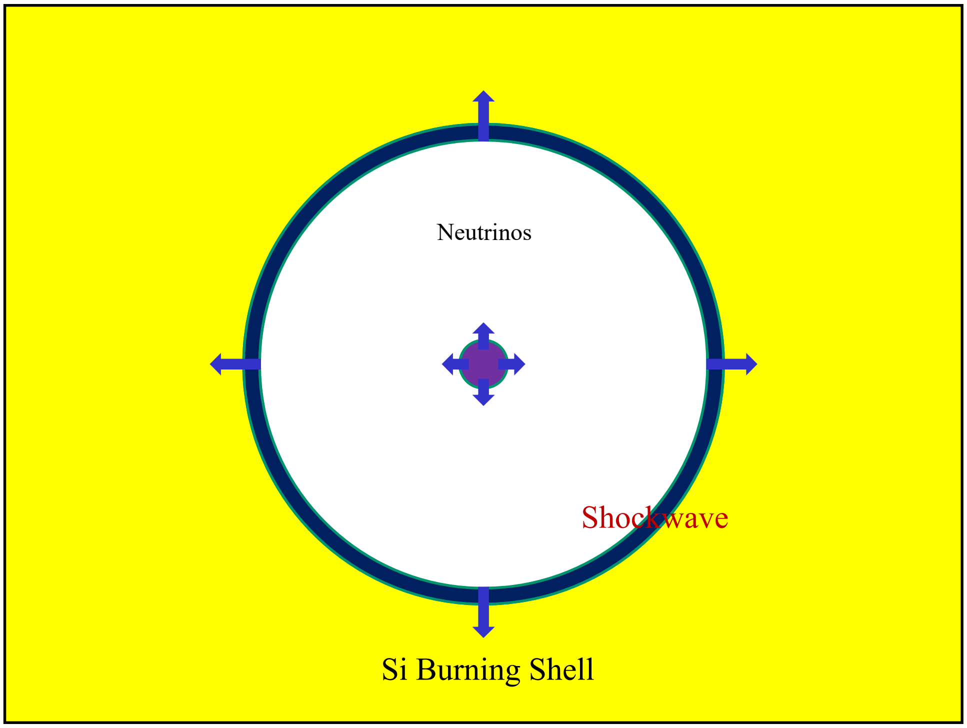
If the remainder of the Fe core is not too massive (the entire initial Fe core should not exceed about 1.2 solar masses), the shock will fight its way through the rest of the outer core and collide with the remainder of the nuclear-processed material and the outer envelope.

Once the shock forms above the surface of the inner core, the time required to penetrate the outer core is only 20 milliseconds. This process is known as a ***prompt* hydrodynamic explosion**.

Shock Wave – Could be Slow

If the initial Fe core is too large, the shock stalls, becoming nearly stationary, with in-falling material accreting onto it. In this case the shock becomes an accretion shock, akin to the situation during protostellar collapse. Below the shock, a **neutrinosphere** develops from the processes of photodisintegration and electron capture.

Since the overlying material is now so dense that even neutrinos cannot easily penetrate it, some of the neutrino energy (~5%) is deposited in the matter just behind the shock. This additional energy heats the material and allows the shock to resume its march toward the surface. The temporary stalling of the shock front is called a ***delayed* explosion mechanism**.



Neutrino Escape

There is a tremendous production of neutrinos, the majority of which escape into space with a total energy on the order of the binding energy of a neutron star, ~3 x 10^{47} J.

This represents 100 times more energy than the Sun will produce over its entire main-sequence lifetime!

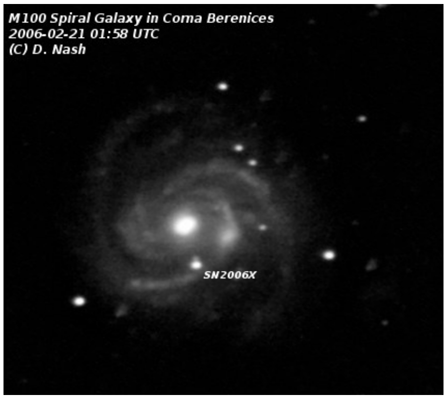
Shock Wave Completion

Meanwhile, the shock wave is still working its way toward the surface, driving the envelope in front of it. The total kinetic energy in the expanding material is on the order of ~1% of the energy liberated in neutrinos.

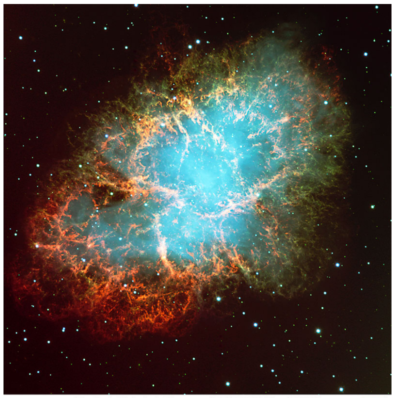
Finally, when the material becomes transparent at a radius of about 10^{10} km, a tremendous optical display results, releasing ~10^{42} J of energy in the form of photons, with **a peak luminosity of nearly roughly 10^{11} $L_{\odot}$, which is comparable to that of an entire galaxy**.

This is a **Supernova**.

Supernovae

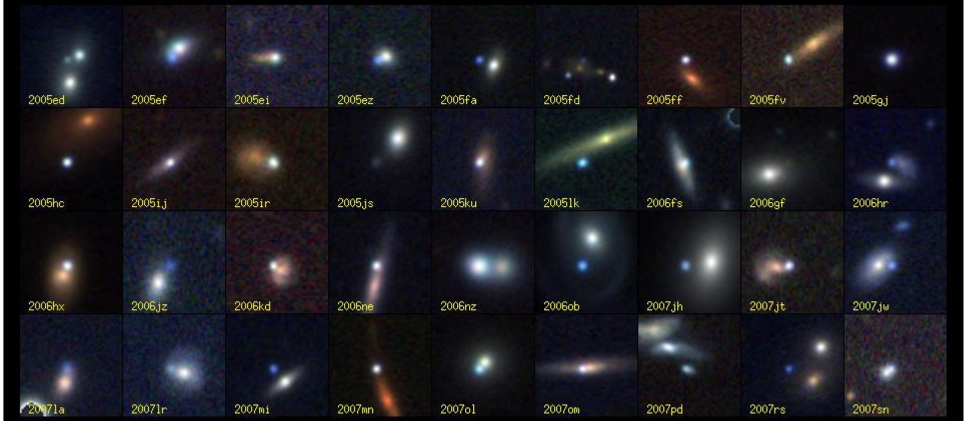


Death of a High-Mass Stars



The Crab Nebula in Taurus (VLT KUEYEN + FORS2)

ESO PR Photo 40f/99 (17 November 1999)



Final Product

If the initial mass of the star on the main sequence is not too large (< 25 solar masses), the remnant inner core will stabilize and become a **neutron star**, supported by degenerate neutron pressure.

However, if the initial stellar mass is much larger, even the pressure of neutron degeneracy cannot support the remnant against the pull of gravity. The final collapse will produce a **black hole**.