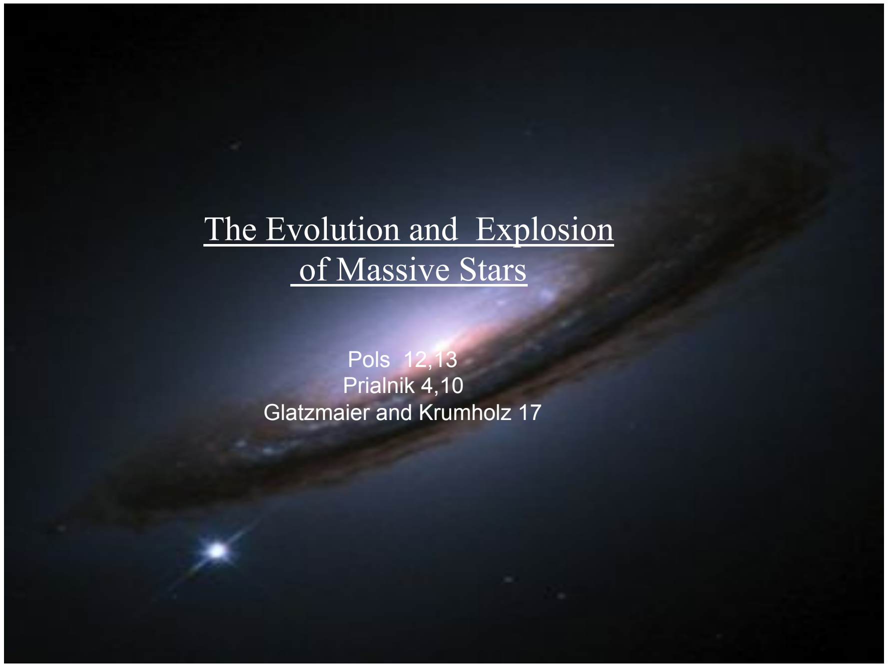


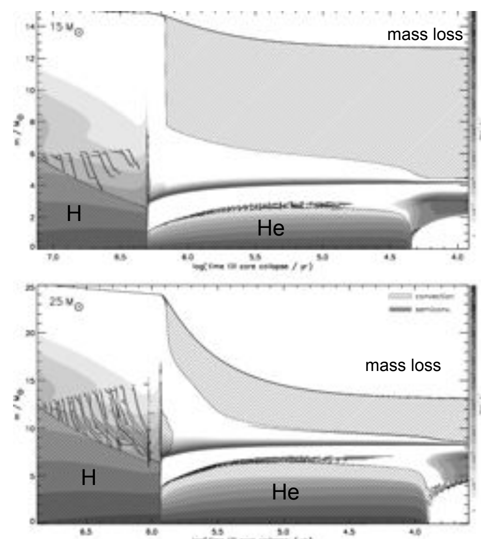
Overview of Evolution (150 > M > 8 Solar Masses)

- Above 8 solar masses, stars ignite carbon burning stably after helium depletion. They avoid becoming degenerate in their centers and go on to burn heavier fuels culminating in the production of an iron core
- Such massive stars have very high luminosities and short lives. They are all (presently) of Population I.
- During the red giant stage the very high luminosities of these stars (and their large radii) imply that the surface layers are very loosely bound. Extensive mass loss occurs
- For stars above about 35 solar masses the entire hydrogen envelope is lost during helium burning. The star becomes a Wolf-Rayet star and even then mass loss continues at a rapid pace.

Overview of Evolution (150 > M > 8 Solar Masses)

- On the main sequence such massive stars have convective cores and are powered by the CNO cycle. Their surfaces are not convective. After burning hydrogen they ignite helium burning non-degenerately (no “helium flash”)
- Evolution beyond helium burning is greatly accelerated by thermal neutrino losses, especially from electron-positron pair annihilation (TBD).
- The massive stars that keep part of their hydrogen envelope become Type II supernovae. Those that lose their envelope (either in binaries or single stars above 35 solar masses) become Type Ib or Ic supernovae

Convective history 15 $M_\odot$ and 25 $M_\odot$ stars



note: radiate surfaces and convective centers on the main sequence. Time axis is log time until death as a supernova.

Above about 35 solar masses, everything outside the helium core is lost. This makes a Wolf-Rayet star.

SUMMARY

Advanced Nuclear Burning Stages

(e.g., 20 solar masses)

Fuel	Main Product	Secondary Products	Temp (10^9 K)	Time (yr)
H	He	^{14}N	0.02	10^7
He	C,O	^{18}O,^{22}Ne s- process	0.2	10^6
C	Ne, Mg	Na	0.8	10^3
Ne	O, Mg	Al, P	1.5	3
O	Si, S	Cl, Ar K, Ca	2.0	0.8
Si	Fe	Ti, V, Cr Mn, Co, Ni	3.5	1 week

Massive stars are the ultimate "recyclers". They use the ashes of the previous stage as fuel for the next.

Why the big speed up? Pair Neutrino Losses

After helium burning the core contracts and the temperature rises. The most abundant fuel with the lowest charge is carbon (^{12}C). In order to get two carbons to fuse, a temperature of almost a billion K is required (actually 0.8 billion).

At such high temperatures, a new energy loss mechanism comes into play.

$$\text{Gamma rays } (\gamma) \rightleftarrows e^+ + e^-$$

$$\text{Very rarely though} \quad e^+ + e^- \rightarrow \nu_e + \bar{\nu}_e$$

For T ~ 10^9 K, kT = 86 keV

The average photon has energy 2.7 kT = 232 keV

$m_e c^2$ = 511 keV

Clayton (Chap 4) and Lang in Astrophysical Formulae give some approximations

$$(NDNR) \quad P_\pm \approx 4.9\times10^{18}\ T_9^3 \exp(\underbrace{-11.86/T_9}_{2m_ec^2/kT})\ \text{erg cm}^{-3}\ \text{s}^{-1} \qquad T_9 < 2$$

$$(NDR) \quad P_\pm \approx 4.6\times10^{15}\ T_9^9\ \text{erg cm}^{-3}\ \text{s}^{-1} \qquad T_9 > 3,\ \text{but not too bad at } T_9 > 2$$

(better is 3.3×10^{15})

Note origin of T^9 :

If $n_\pm$ is relativistic, $n_\pm \propto T^3$ (like radiation)

$$\sigma \propto \frac{E^2}{v} \propto \frac{(kT)^2}{v}$$

energy carried per reaction ~ kT

$$P_\pm \approx \underbrace{(T^6)}_{n_+n_-}\underbrace{(T^2)}_{\sigma v}\underbrace{(T)}_{E} = T^9$$

v cancels $1/v$ in σ

For $.8 < T_9 < 2 \quad 5\times10^7 \left(\frac{10^6\ \text{g cm}^{-3}}{\rho}\right) T_9^{14}$ is a fair approximation

CARBON BURNING

At a temperature $T \approx 8\times10^8$ K and a density $\rho \approx 10^5$ g cm^{-3}, carbon fusion provides energy at a rate that balances losses due to neutrinos.

A little bit of extra energy powers convection and keeps the core hot. Roughly, carbon $\rightarrow$ neon and magnesium but in greater detail, the chief reaction is the fusion of two ^{12}C nuclei to produce isotopes of neon, sodium and magnesium

$$^{12}\text{C} + {}^{12}\text{C} \rightarrow {}^{23}\text{Na} + p + 2.24\ \text{MeV}$$

$$^{12}\text{C} + {}^{12}\text{C} \rightarrow {}^{20}\text{Ne} + \alpha + 4.62\ \text{MeV} \qquad (\alpha \equiv {}^4\text{He})$$

$$^{12}\text{C} + {}^{12}\text{C} \rightarrow {}^{23}\text{Mg} + n - 2.63\ \text{MeV} \qquad \text{(rarely)}$$

CARBON BURNING

The neutrons, protons and alpha-particles (helium nuclei) react with other species that are there so that following the composition becomes complicated (but calculable)

$$^{23}\mathrm{Na} + \mathrm{p} \rightarrow {}^{24}\mathrm{Mg} + \gamma \qquad {}^{23}\mathrm{Na} + \alpha \rightarrow {}^{27}\mathrm{Al} + \gamma$$
$$^{20}\mathrm{Ne} + \alpha \rightarrow {}^{24}\mathrm{Mg} + \gamma \qquad {}^{23}\mathrm{Mg} + \mathrm{n} \rightarrow {}^{24}\mathrm{Mg} + \gamma$$
$$^{24}\mathrm{Mg} + \mathrm{n} \rightarrow {}^{25}\mathrm{Mg} + \gamma \qquad etc.$$

The net result is that $4 \times 10^{17}\ \Delta X_{12}$ erg g^{-1} are released and the most abundant isotopes of neon, sodium, magnesium and aluminum are created. Oxygen also survives with a slightly increased abundance. $\Delta X_{12} \approx 0.2$

Note the gradual decrease in energy yield from 5×10^{18} erg g^{-1} for hydrogen burning to about 5×10^{17} erg g^{-1} for helium burning to about 10^{17} erg g^{-1} for carbon burning.

Principle nucleosynthetic products:

$^{20,21}Ne$ (^{22}Ne was made in helium burning by alpha capture (*2) onto ^{14}N

^{23}Na

$^{(26),27}Al$ (^{26}Al is unstable and decays in about a million years. Gamma-rays from its decay have been detected coming from the interstellar medium.)

Some $^{28,29}Si$ and ^{31}P (these 3 isotopes are made more profusely in a process called neon burning that we are glossing over here)

Lifetime: $\tau_{12,12} = \left(\frac{1}{Y_{12}}\frac{dY_{12}}{dt}\right)^{-1} = \frac{1}{\rho Y_{12}\lambda_{12,12}} \qquad \left(\frac{dY_{12}}{dt} = -2Y_{12}^2\rho\lambda_{12,12}/2\right)$

At $T_9 = 0.8$, $\lambda_{12,12} = 7.9 \times 10^{-14}$ $Mole\, s^{-1} cm^3 g^{-1}$;Take $\rho = 2\times 10^5$ $g\ cm^{-3}$

$\tau_{12,12} = 120$ years $(X_{12} = 0.2)$ Varies with stellar mass and convection.

OXYGEN BURNING

- Similar to carbon burning; at T ~ 2.0 x 10^9K, ρ ~ 2 x 10^6 g cm^{-3}

$$^{16}\mathrm{O} + {}^{16}\mathrm{O} \rightarrow {}^{28}\mathrm{Si} + \alpha$$
$$^{16}\mathrm{O} + {}^{16}\mathrm{O} \rightarrow {}^{31}\mathrm{P} + \mathrm{p}$$
$$^{16}\mathrm{O} + {}^{16}\mathrm{O} \rightarrow {}^{31}\mathrm{S} + \mathrm{n}$$

and a host of secondary reactions

- The net result is

^{16}O, ^{20}Ne, ^{24}Mg $\rightarrow$ abundant isotopes of silicon, sulfur, chlorine, argon potassium and calcium. Most abundant ashes - ^{28}Si and ^{32}S

$$q_{nuc} \approx 5.0 \times 10^{17}\ \Delta X_{16}\ \ \mathrm{erg\ g^{-1}}$$
$$\varepsilon_{nuc} \propto T^{33}$$

Principle nucleosynthetic products:

^{28}Si, $^{32,33,34}S$, $^{36,38}Ar$, $^{40,42}Ca$ (about 90% by mass Si and S)

$^{35,37}Cl$ (the ^{37}Cl is initially made as radioactive ^{37}Ar)

$^{39,41}K$ (the ^{41}K is initially made as radioactive ^{41}Ca)

Lifetime: $\tau_{16,16} = \left(\frac{1}{Y_{16}}\frac{dY_{16}}{dt}\right)^{-1} = \frac{1}{\rho Y_{16}\lambda_{16,16}} \qquad \left(\frac{dY_{16}}{dt} = -2Y_{16}^2\rho\lambda_{16,16}/2\right)$

At $T_9 = 1.8$, $\lambda_{16,16} = 2.2 \times 10^{-13}$ $Mole\, s^{-1} cm^3 g^{-1}$;Take $\rho = 2\times 10^6$ $g\ cm^{-3}$

$\tau_{16,16} = 2$ years $(X_{16} = 0.6)$. Varies with stellar mass and convection.

At $T_9 = 2.0$, the lifetime is 20 days.

Note that the burning rate is very temperature sensitive T^{35}.

SILICON BURNING

- $T \approx 3.5 \times 10^9$ K, $\rho \approx 10^7$ g cm^{-3}.
- At the end of oxygen burning the lighest element is silicon.
- Nuclear reactions are complicated, but in the end

$$[Si, S, Cl, Ar, K, Ca] \rightarrow [Ti, V, Cr, Mn, Fe, Co, Ni]$$

- The most abundant nucleus produced is ^{56}Fe

$$q_{nuc} = 2 \times 10^{17} \text{ erg g}^{-1}$$

$$\epsilon_{nuc} \propto T^{47}$$

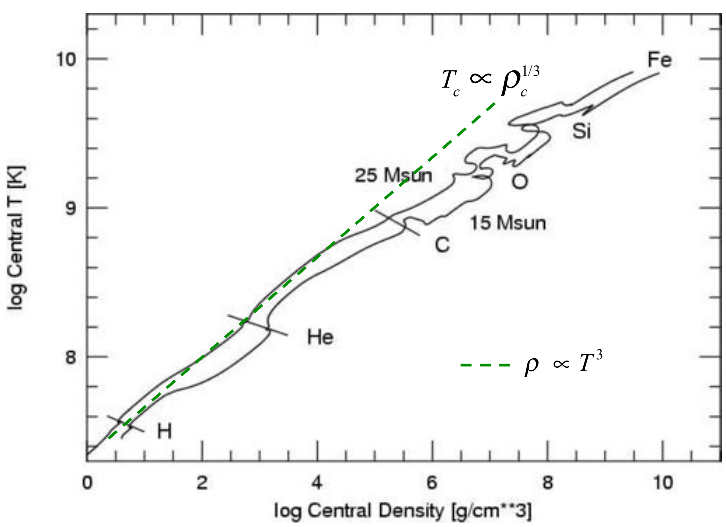
SUMMARY

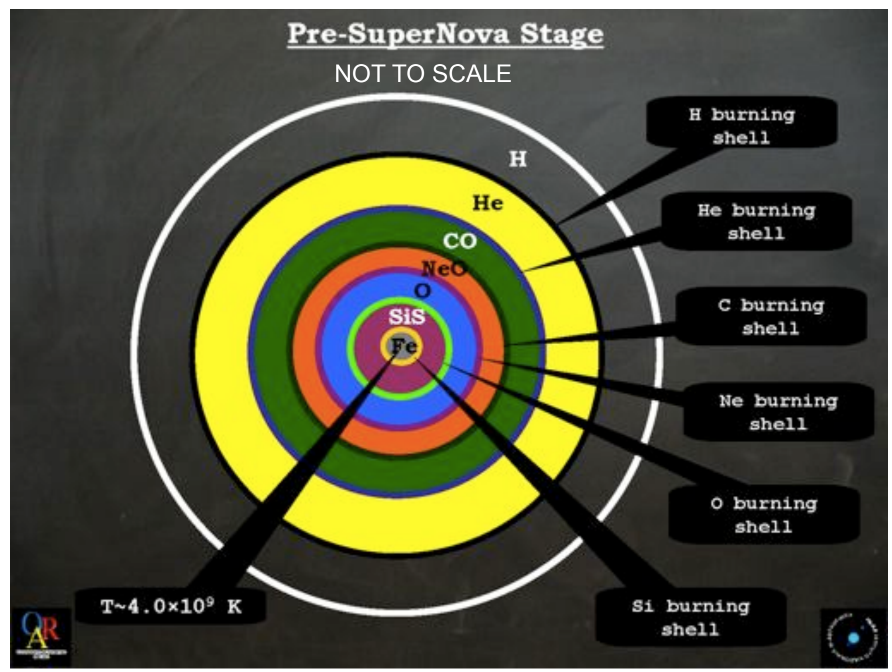
Advanced Nuclear Burning Stages

(e.g., 20 solar masses)

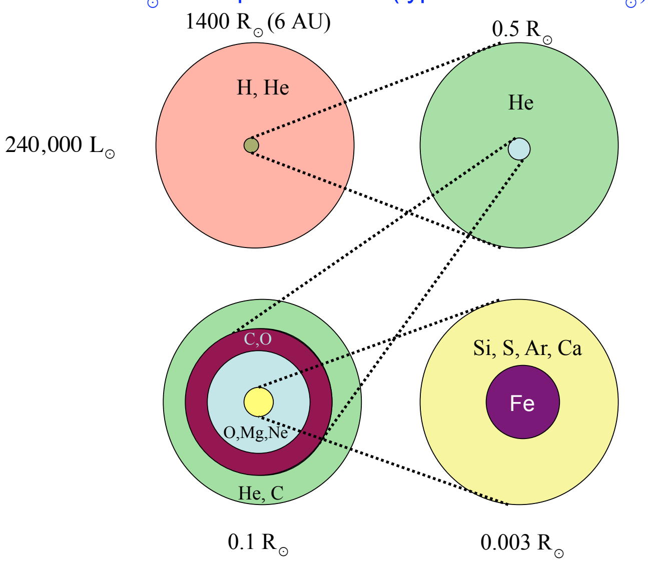
Fuel	Main Product	Secondary Products	Temp (10^9 K)	Time (yr)
H	He	^{14}N	0.04	10^7
He	C,O	^{18}O,^{22}Ne s- process	0.2	10^6
C	Ne, Mg	Na	0.8	10^3
Ne	O, Mg	Al, P	1.5	3
O	Si, S	Cl, Ar K, Ca	2.0	0.8
Si	Fe	Ti, V, Cr Mn, Co, Ni	3.5	1 week

After each burning stage the core contracts, heats up and ignites another fuel





25 $M_\odot$ Presupernova Star (typical for 9 - 130 $M_\odot$)



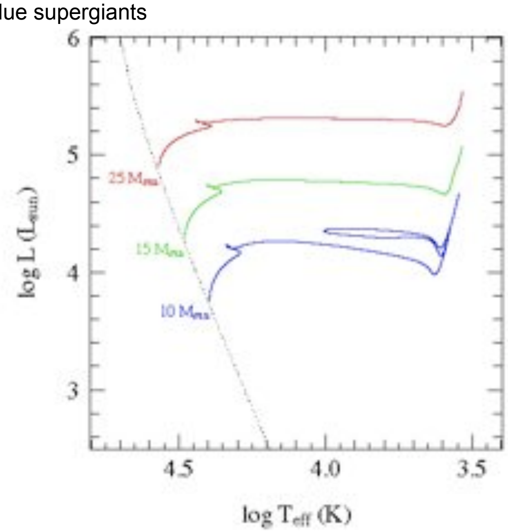
Actual – to scale

Neutrino emission dominates the energy budget after helium depletion in the center of the star…

Table 1 Burning stages in the evolution of a 20-$M_\odot$ star

Fuel	ρ_c (g cm^{-3})	T_c (10^9 K)	τ (yr)	L_{phot} (erg s^{-1})	L_ν (erg s^{-1})
Hydrogen	5.6(0)	0.040	1.0(7)	2.7(38)	—
Helium	9.4(2)	0.19	9.5(5)	5.3(38)	<1.0(36)
Carbon	2.7(5)	0.81	3.0(2)	4.3(38)	7.4(39)
Neon	4.0(6)	1.7	3.8(−1)	4.4(38)	1.2(43)
Oxygen	6.0(6)	2.1	5.0(−1)	4.4(38)	7.4(43)
Silicon	4.9(7)	3.7	2 days	4.4(38)	3.1(45)

In the HR diagram, massive stars evolve at nearly constant luminosity off the main sequence and eventually explode as red or blue supergiants



IRON CORE COLLAPSE

- Having exhausted silicon in the inner 1.3 to 2.0 solar masses of the star, the center of the star has no further nuclear energy resources
- It has become degenerate though, so it contracts and grows denser and hotter, looking for a new source of energy. None is found. Its mass also exceeds the Chandrasekhar mass so it must continue to contract.
- As the temperature exceeds about 10 x 10^9 K, the typical photons on the blackbody have energy ~ 2.3 MeV (2.7 kT). Photons further out on the tail have enough energy (~8 MeV) to begin to rip nucleons out of the nucleus (analogue to ionization). The process does not go to completion but about 10% helium by mass is "boiled" out of the iron and this process (photodisintegration) saps energy that might have held up the star. The collapse accelerates.

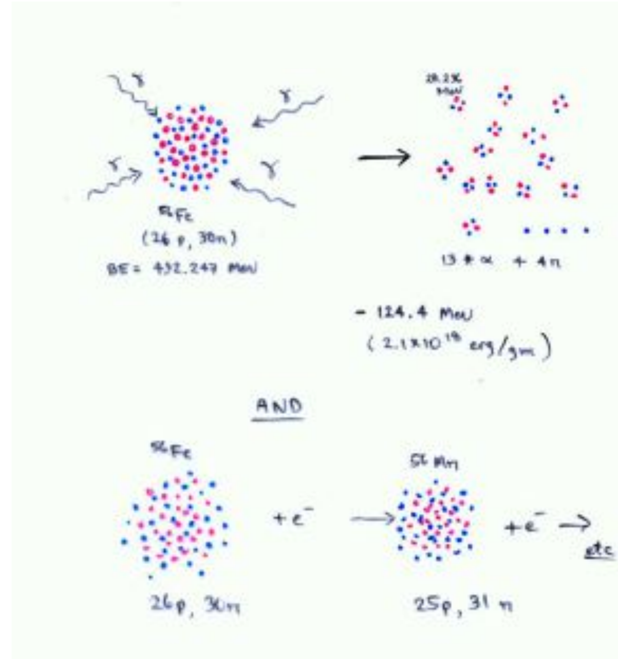
- As the density goes up above r~ 10^9 g cm^{-3}, the Fermi energy of the electrons is also becoming several MeV. Electrons begin to capture on nuclei like ^{56}Fe turning them into nuclei with a larger neutron-to-proton ratio

$$^{56}\text{Fe} + e^- \rightarrow \ ^{56}\text{Mn} + \nu_e \ (+e^-) \rightarrow \ ^{56}\text{Cr} + \nu_e \quad \text{etc.}$$

- Since these electrons were the chief source of pressure in the contracting core, their loss further accelerates the collapse.

- As the temperature and density continue to rise the emission of neutrinos by the pair process accelerates.

ALL OF THIS IS BAD NEWS FOR THE STABILITY OF THE STAR!



COLLAPSE AND BOUNCE

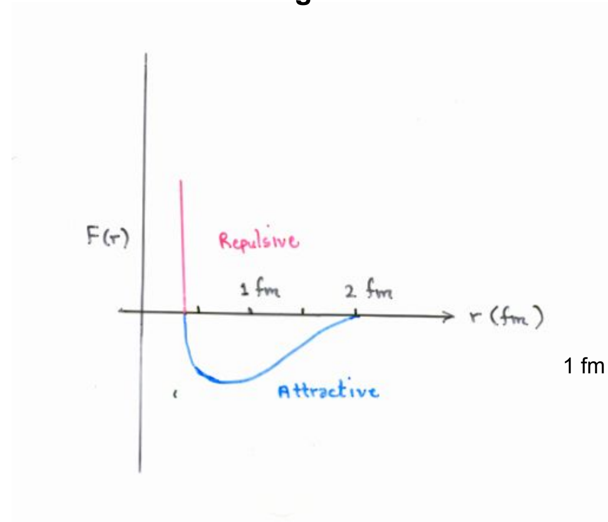
- As a result of these instabilities, the iron core is soon collapsing in almost free fall

- At a density of several times 10^{11} g cm^{-3}, the neutrinos start to be trapped. This provides some new pressure, but not enough to halt the collapse.

- As the density nears 2.4 x 10^{14} g cm^{-3}, the density of the atomic nucleus, new forces come into play. First the attractive and then the strongly repulsive part of the strong force. The collapse in the central regions halts abruptly and rebounds.

- This rebounding inner core, about 0.7 solar masses, runs into the overlying collapse iron core at about 70,000 km/s. A "shock wave" forms.

Reminder: At short range the nuclear force is repulsive



1 fm = 10^{-13} cm

SHOCK PROPAGATION AND STALL

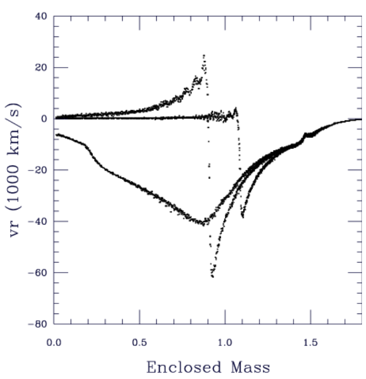
- In the center, temperatures rise above 10^{11}K. As the shock wave begins to move out material is halted and turned around, but it is heated to such high temperature that the iron is disintegrated to unbound neutrons and protons. This costs a lot of energy. All burning since the main sequence is undone

$$^{56}\text{Fe} + \gamma \rightarrow 26\,\text{p} + 30\,\text{n} - 10^{19}\ \text{erg g}^{-1}$$

- The shock weakens further because of neutrino cooling of the matter inside it. By the time it has passed through all the iron core, all outward velocity has been lost.

- As matter settles to super-nuclear density, most of the protons turn to neutrons. A giant nucleus with mass ~ 1.5 solar masses called a proto-neutron star is formed. All this took about 10 milliseconds.

DEATH OF THE SHOCK



Death of the shock in a star of 15 solar masses.

The shock is born near 0.7 solar masses. Initially the bounce gives it positive kinetic energy, but for each 0.1 solar masses it traverses and photodisintegrates about 10^{51} erg of energy is lost. Additional energy is lost to neutrinos as the shock moves to low densities, $\rho \approx 10^{11}$ gm cm^{-3}.

After about 10 ms the once powerful shock has stalled and become an accretion shock.

REBIRTH OF THE SHOCK

- The "prompt shock" has died, or more correctly become an "accretion shock". But now the proto-neutron star experiences its Kelvin-Helmholtz evolution as it contracts from R ~ 50 km to R ~ 10 km.

- During this phase the neutron star radiates away its binding energy, approximately ~3 x 10^{53} erg, as neutrinos (of all flavors). Brighter than the rest of the universe combined!!

- Most of these neutrinos escape without interaction but a few per cent deposit energy in the neutron star atmosphere (the region between the accretion shock and the neutrino "photosphere", or "neutrinosphere")

- The shock is re-energized by the hot radiation and pairs created beneath it and expands outwards again

INTERLUDE - NEUTRON STARS

Neutron stars are "stars" (actually giant nuclei) supported by *neutron* degeneracy pressure and the strong force.

Redoing the derivation of non-relativistic electron degeneracy pressure for neutrons, one gets the same answer except that the mass of the neutron substitutes for the mass of the electron

$$P_{\text{deg}}^{NR} \propto \frac{n^{5/3}}{m_e \text{ or } m_{\text{neut}}}$$

For neutrons

$$P_{\text{deg}}^{NR} = 1.7\times 10^{10}\ \rho^{5/3}\ \text{dyne cm}^{-2} \qquad (i.e.,\ \frac{P_{e,\text{deg}}}{1839\,Y_e^{5/3}})$$

The neutrons are more massive but move slower. The Fermi momentum, p_F, is the same but p = mv so v is 1839 times slower. The pressure goes as mv^2. The neutrons are never relativistic.

Complication: Cannot ignore the strong force here.

NEUTRON STARS

$$P_{n,\deg} \approx \frac{GM\rho}{2R}$$

if constant density

$$1.7 \times 10^{10}\ \rho^{2/3} = \frac{GM}{2R}$$

$$1.7 \times 10^{10} \left(\frac{3M}{4\pi R^3}\right)^{2/3} = \frac{GM}{2R}$$

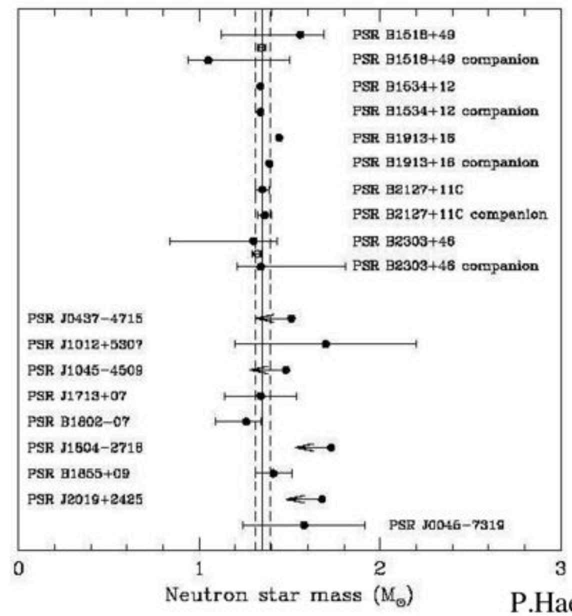
$$1.7 \times 10^{10} \left(\frac{3}{4\pi}\right)^{2/3} \frac{M^{2/3}}{M} \frac{2}{G} = R$$

$$R \approx 16\ \text{km} \left(\frac{M_\odot}{M}\right)^{1/3}$$

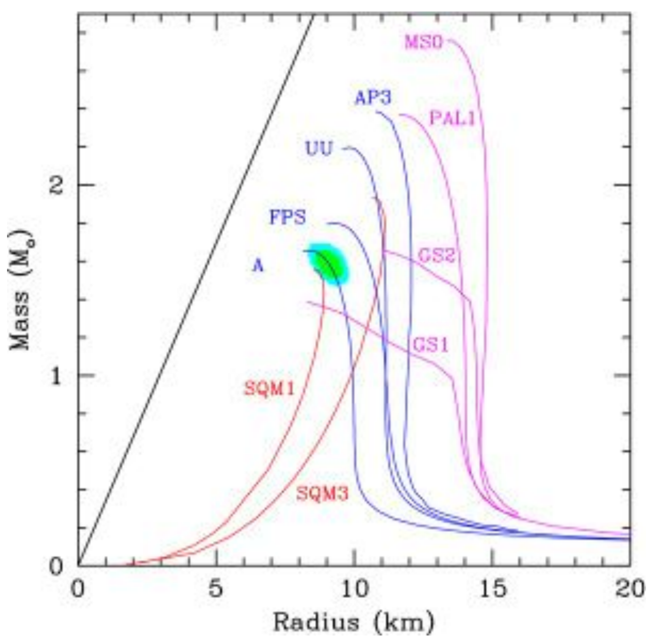
Actually

$R \approx 12$ km and $M \approx 1.4\ M_\odot$

Lattimer



P.Haensel, 2003



The heaviest neutron star detected yet (PSR J1614-2230) has a mass of 1.97 +- 0.04 solar masses. This rules out many of the “softer” equations of state.

Demorest et al, Nature,467, 1081, (2010)

NEUTRON STAR ALMOST A BLACK HOLE

The Schwarzschild radius for a 1.4 solar mass black hole is

$$R_S = \frac{2GM}{c^2}$$

or 4 km. Neutron stars are close to being black holes. Their escape speed is about 1/3 c and their binding energy is about 20% mc^2

The average density of a neutron star, $3M/4pR^3$, is ~ 10^{15} g cm^{-3}, greater than the density of an atomic nucleus

- During its roughly 3 second Kelvin-Helmholtz time, the luminosity of the neutron star in (all flavors of) neutrinos is L ~ 1 x 10^{53} erg s^{-1}. Contrast that to the luminosity of the Milky Way galaxy, about 10^{44} erg s^{-1}, or the luminosity of the entire observable universe.

L_{univ} ~ 3 x 10^{10} galaxies x 10^{43} erg s^{-1} per galaxy
~ 3 x 10^{53} erg s^{-1}

(very approximate)

The measured light density of the universe is 2 x 10^8 L_{sun} per cubic megaparsec – gives a similar number

The gravitational binding energy of the neutron star is enormous, a significant fraction even of its rest mass $Mc^2 = (1.4)(2\times10^{33})(3\times10^{10})^2 = 2.5 \times10^{54}$ erg

$$\Omega \approx \frac{3}{5}\frac{GM^2}{R} = 0.6\,\frac{(6.7\times10^{-8})(2.8\times10^{33})^2}{10^6}$$
$$= 3.1\times10^{53}\ \text{erg}$$

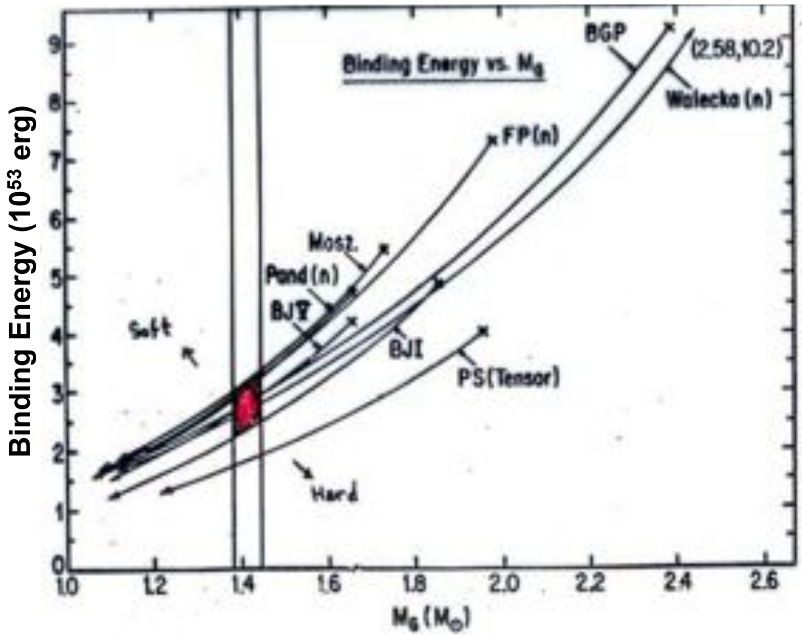
Actually 2 - 3 $\times$ 10^{53} erg when the realistic structure is used.

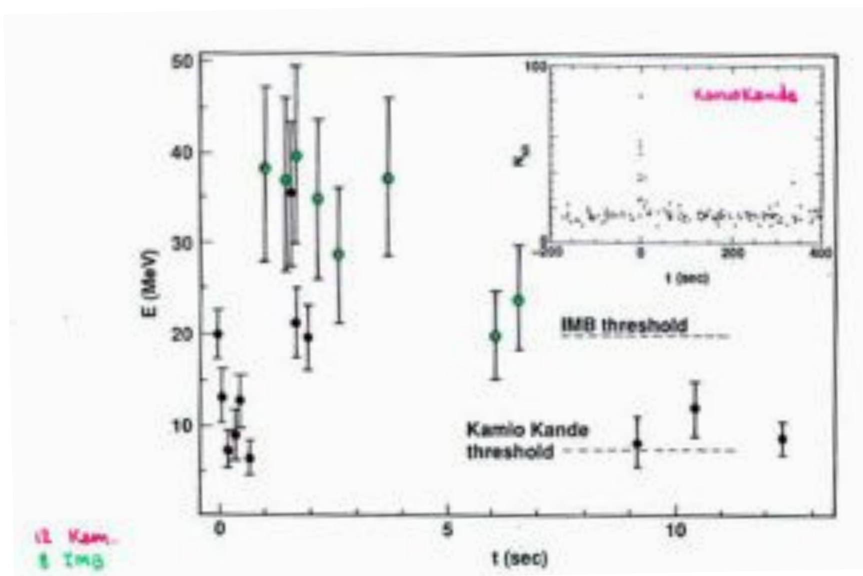
Where does all this energy go?
In the end the neutron star is supported by degeneracy and the strong force not heat. All the energy diffuses out as neutrinos. A neutrino mediated Kelvin Helmholtz stage

- These neutrinos are emitted equally in the 6 different flavors - $\nu_e, \bar{\nu}_e, \nu_\tau, \bar{\nu}_\tau, \nu_\mu, \bar{\nu}_\mu$ roughly like a blackbody

$$L_{\nu_e} \approx \frac{7}{8}(4\pi R^2 \sigma T_\nu^4)$$
$$\approx 10^{52}\ \text{erg s}^{-1}$$

which can be solved for the temperature, $T_\nu \approx 6\times10^{10}$ K, or energy about 5 MeV (1 MeV = 11.605 billion K).





NEUTRINO BURST SN 1987A
FEBRUARY 23, 1987

- Originated from SN 1987A in the Large Magellanic Cloud about 55 kpc from here – first signal from the supernova though the optical light was detected first (about 6 hr later) and the neutrino signal only discovered by processing data about a week later

- Detected in three locations – Kamiokande (Japan), IMB (Cleveland), and Baksan (USSR) – all in northern hemisphere. The neutrinos had come through the earth

- Observed at Kamiokande and IMB – 18 neutrino events from 8 to 40 MeV. Inferred neutrino temperature 5 Mev – or about 60 billion K

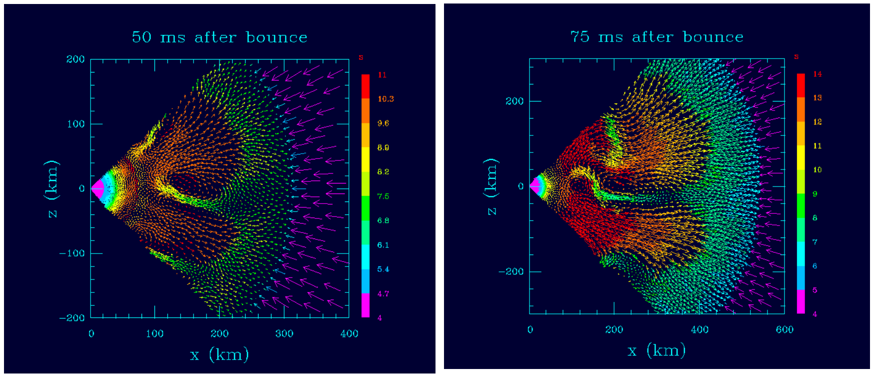
- Total energy inferred at the source about 2 to 5 x 10^{53} erg. Duration about 10 seconds with most emission occurring during the first 3 seconds

- Neutrino flux at the earth about 5 x 10^{10} neutrinos cm^{-2} s^{-1}.

- Arrival time at same time as the light (within 6 hours) after traveling for 160,000 years put limits on the mass of the neutrino. The neutrinos had to travel very close to the speed of light

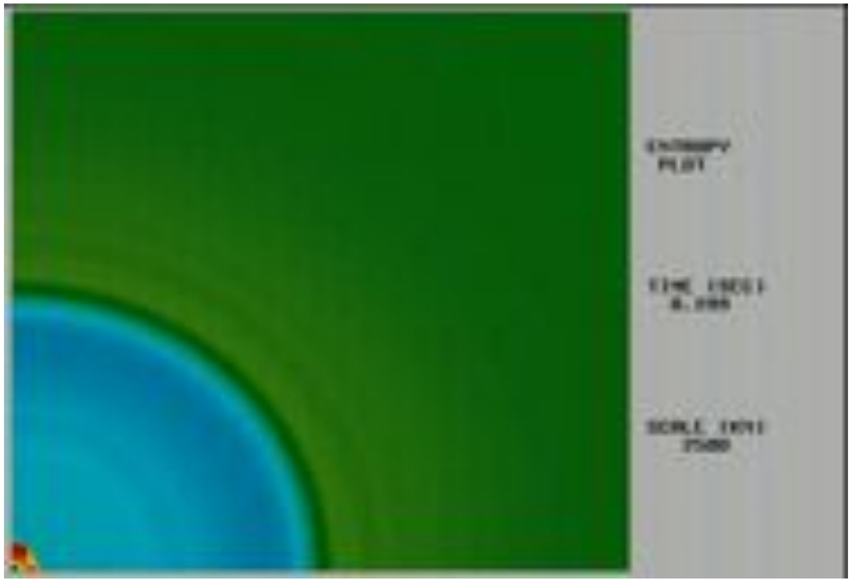
- Properties of the burst in overall good agreement with the theory.

BACK TO THE SHOCK

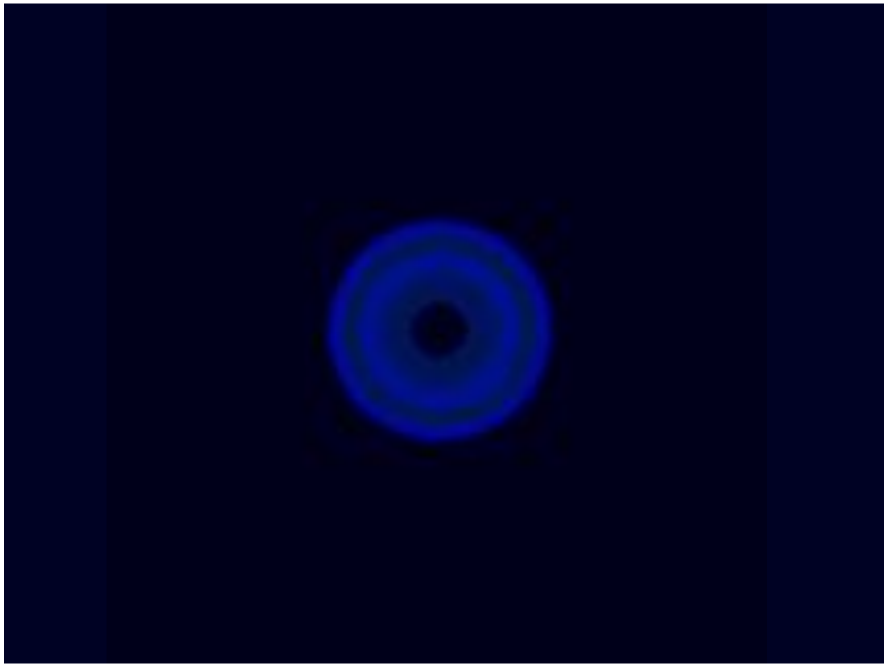


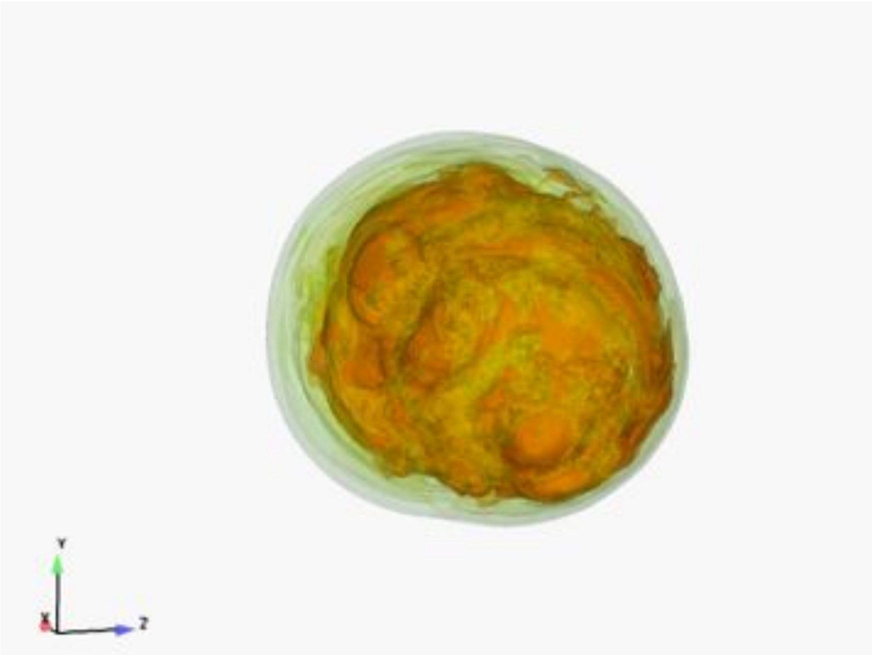
Herant and Woosley, 1995. 15 solar mass star.
successful explosion.
(see also Herant, Benz, & Colgate (1992), *ApJ*, **395**, 642)

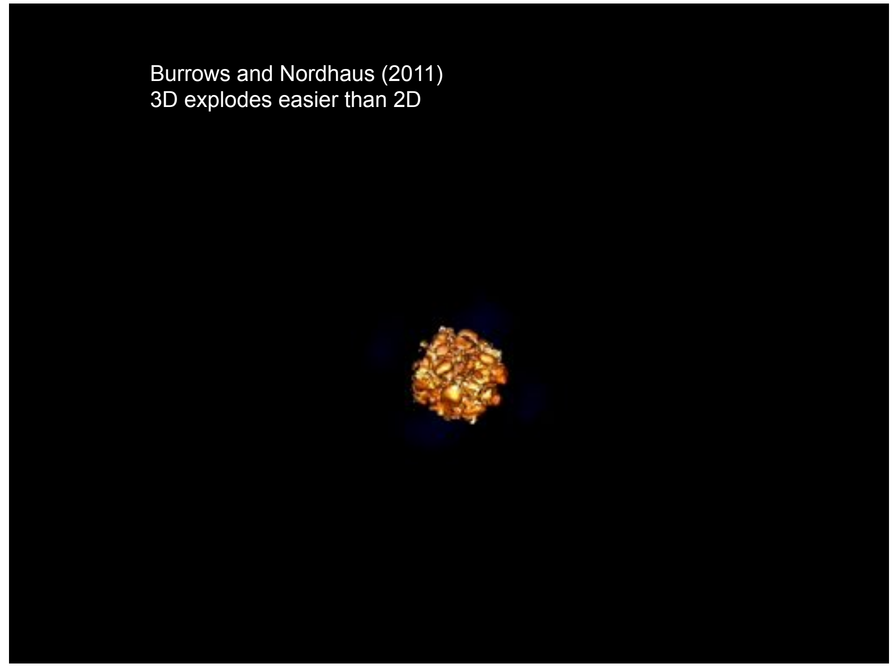
15 Solar masses – explodes with an energy of order 10^{51} erg.

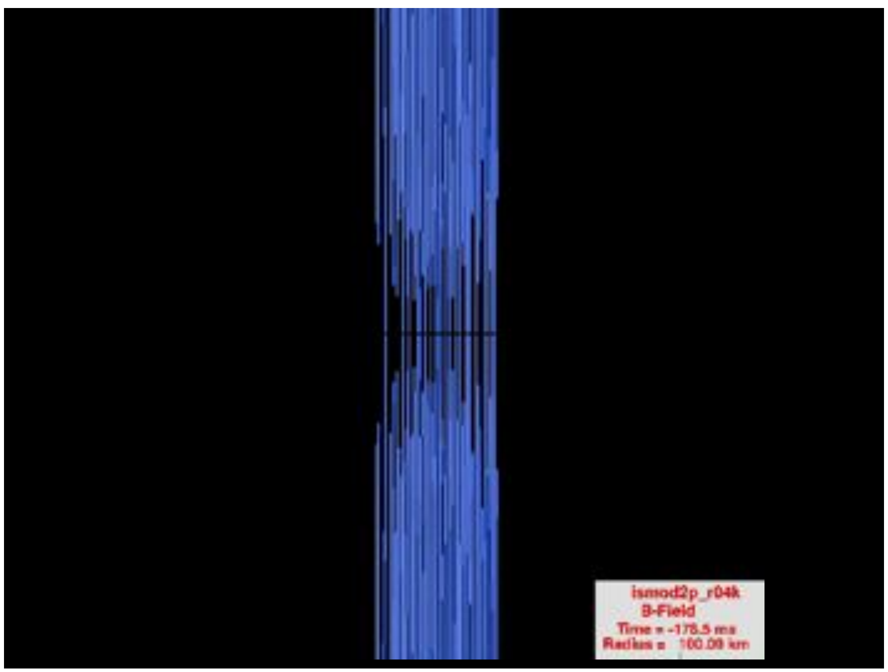


At 408 ms, KE = 4.2 x 10^{50} erg, stored internal energy is 3.8 x 10^{50} erg, and the total explosion energy is still growing at 4.4 x $1o^{51}$ erg s^{-1}.









Explosion

- As a result of the energy deposited by neutrinos (and rotation and magnetic fields?), a shock wave moves out through the star ejecting everything external to the neutron star. In some cases – quite massive stars – the ejection may be inefficient, and matter may fall back forming a black hole. In some cases the outgoing shock may never form. When successful about 10^{51}erg is deposited in the ejecta giving them a speed of 1000’s of km/s.

- All of the elements present outside the compact remnant are ejected, contributing to Galactic nucleosynthesis. Additonal elements are created in the explosion itself. One important species, ^{56}Ni, is created in the deepest layers to be ejected. This will later be important to the light curve as it decays to iron.

- The first optical indication that a supernova has happened is when the shock wave erupts from the surface.

Explosive Nucleosynthesis

Explosive nucleosynthesis

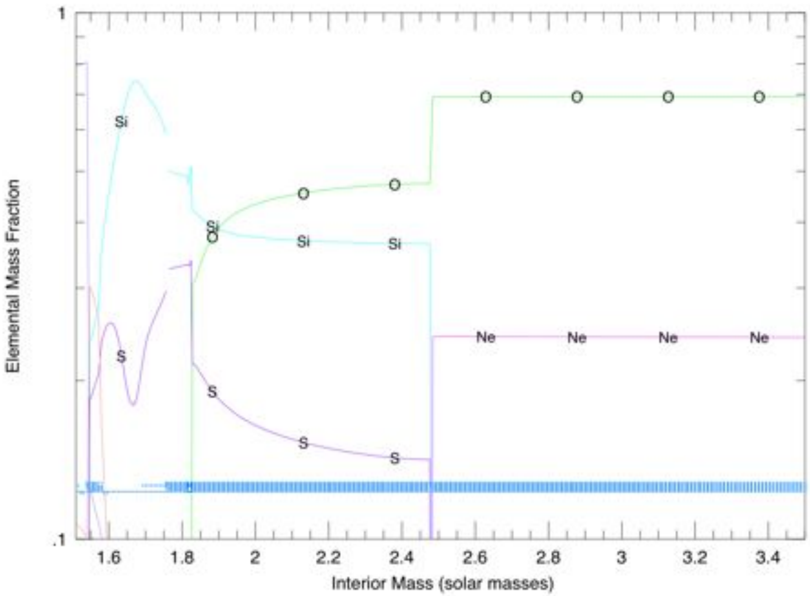
$$\tau_{nuc} \leq \tau_{HD} = \frac{446}{\sqrt{\rho}} \text{ sec } \sim 1 \text{ sec}$$

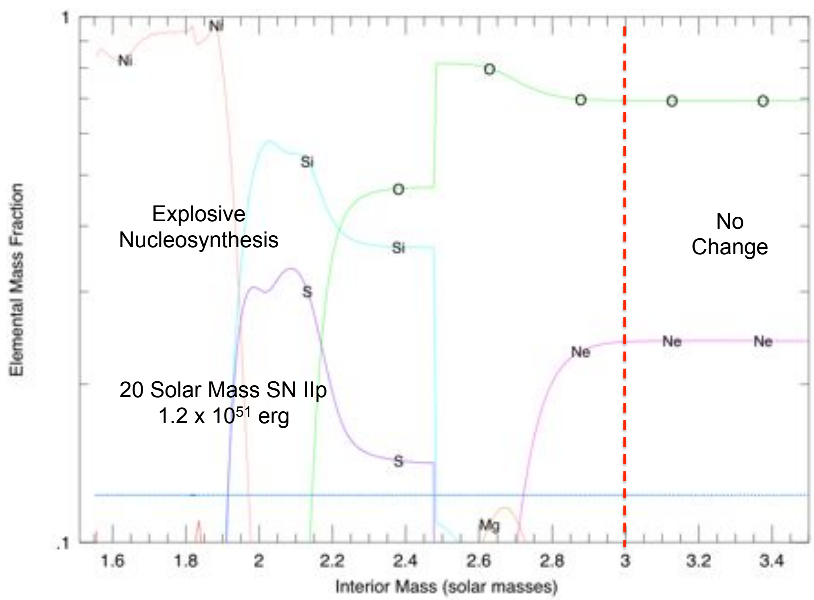
τ_{nuc} is very temperature sensitive - proportional to the inverse of the reaction rates hence

$$\frac{1}{T^n} \quad \text{with n} \gg 1$$

Explosive Nucleosynthesis

- As the shock wave propagates through the inner layers of the supernova, matter is abruptly raised to a higher temperature. Since nuclear reactions occur at rates that are very sensitive to the temperature, this causes an increase in the burning. New elements are created in seconds that it might otherwise have taken weeks and months to synthesize.
- Material heated to above 5 billion K is turned into "iron" (where the nuclear binding energy is maximal). Because there is no time for weak interactions, however, the nucleus produced has equal numbers of neutrons and protons, just like the fuel that burned. ^{56}Ni (Z = N = 28) is produced copiously
- Beyond the carbon burning shell, material is pused off without much explosive processing



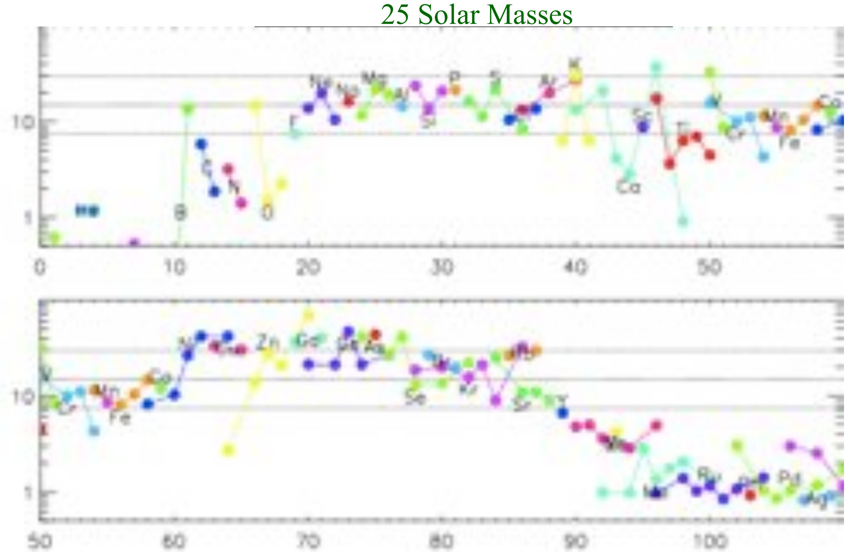


EXPLOSIVE NUCLEOSYNTHESIS

Fuel	Main Products	Secondary Products	Temperature (10^9 K)	Time (sec)
Si, O	^{56}Ni	Iron Group	> 4	0.1
O	Si, S	Ar, Ca, Cl, K	3 - 4	1

A single 25 solar mass supernova ejects 3 solar masses of oxygen, enough for several million Earths

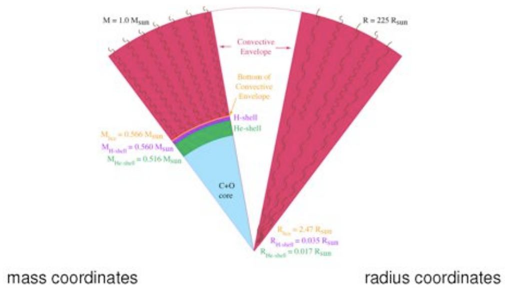
25 Solar Masses

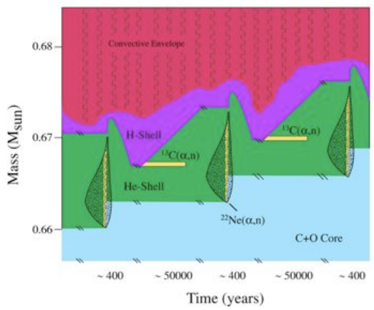


A 25 solar mass supernova ejects:

1.1 million	Earth masses of			oxygen *
160,000	"	"	"	carbon *
26,000	"	"	"	nitrogen *
6,200	"	"	"	sodium
76,000	"	"	"	magnesium
100,000	"	"	"	silicon
1,000	"	"	"	phosphorus *
35,000	"	"	"	sulfur
244	"	"	"	chlorine
107	"	"	"	potassium
3,500	"	"	"	calcium *
51,000	"	"	"	iron
0.01	"	"	"	silver
0.006	"	"	"	gold

plus about 70 other elements





The "s-process"

During helium burning in a star of about 1.5 to 8 solar masses

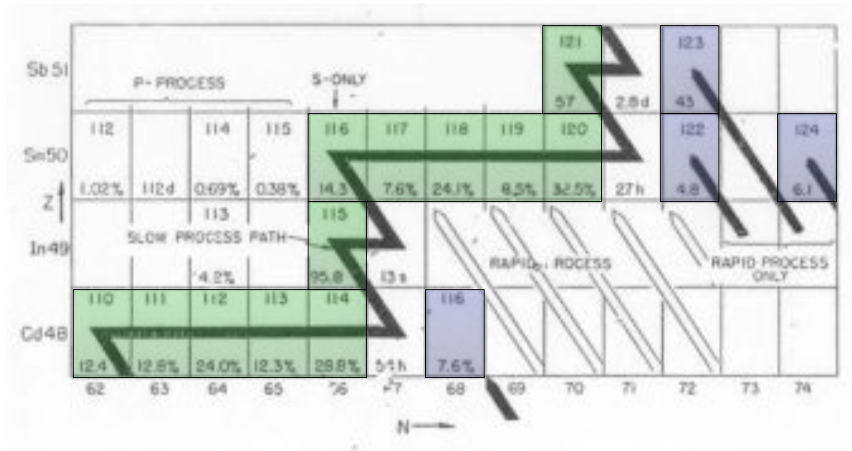
$^{22}Ne + ^{4}He \longrightarrow ^{25}Mg + n$

$^{13}C + ^{4}He \longrightarrow ^{16}O + n$

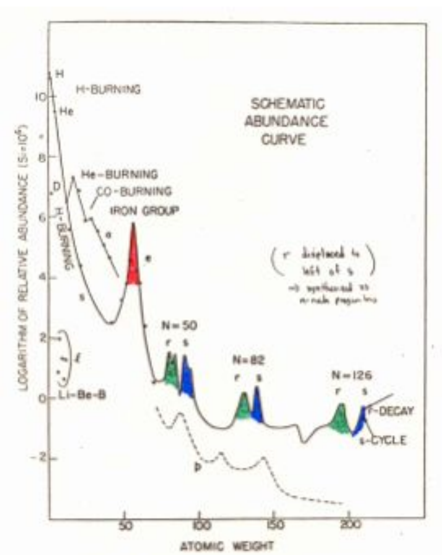
$^{56}Fe + n \longrightarrow ^{57}Fe + \gamma$
$^{57}Fe + n \longrightarrow ^{58}Fe + \gamma$
$^{58}Fe + n \longrightarrow ^{59}Fe + \gamma$
$^{59}Fe \longrightarrow ^{59}Co + e^{-} + \nu$
$^{59}Co + n \longrightarrow ^{60}Co + \gamma$
$^{60}Co \longrightarrow ^{60}Ni + e^{-} + \nu$
$^{60}Ni + n \longrightarrow ^{61}Ni + \gamma$

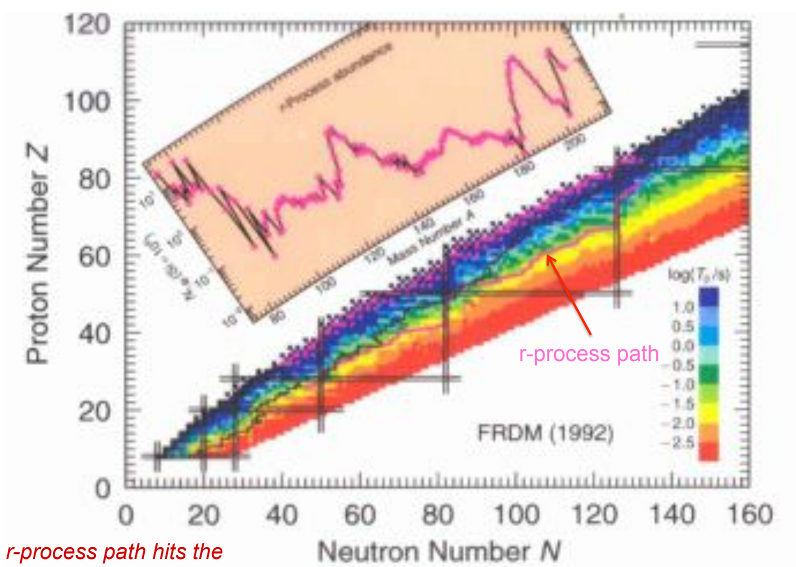
etc….. to lead

The *r*-Process



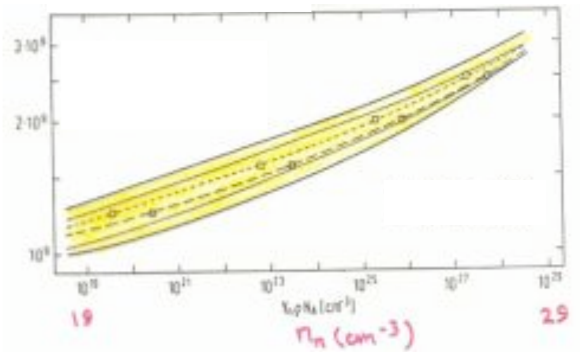
The r-Process





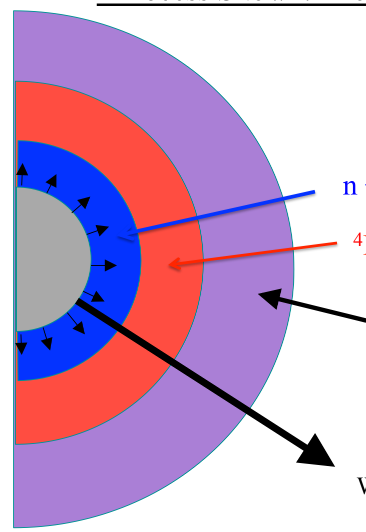
The r-process path hits the closed neutron shells for a smaller value of A (i.e., a lower Z)

Optimal conditions for the r-process



For example, at T_9=2.5, $n_n \sim 10^{27}$ cm^{-3} or about a kilogram of neutrons per cubic cm.

r-Process Site #1: The Neutrino-powered Wind



Woosley et al. (1994), *ApJ*, **433**, 229