Lecture 17: Evolution of Massive Stars and Type II Supernovae

Stars more massive than about 8 solar masses have a different evolution because their central temperatures and densities are high enough to allow nuclear burning even beyond Oxygen burning. They have a continuing supply of useful fuel, therefore, which allows them to carry on the following reactions (only the principal reactions are listed, not all the minor ones):

Carbon Burning: \( T \sim 900 \) million

\[ ^{12}\text{C} + ^{12}\text{C} \rightarrow ^{20}\text{Ne} + ^{4}\text{He} \]

\[ ^{12}\text{C} + ^{12}\text{C} \rightarrow ^{23}\text{Na} + ^{1}\text{H} \]

\[ ^{12}\text{C} + ^{12}\text{C} \rightarrow ^{24}\text{Mg} + \gamma \]

Neon Burning: \( T \sim 1.7 \) billion

(photosynthesis)

\[ \gamma + ^{20}\text{Ne} \rightarrow ^{16}\text{O} + ^{4}\text{He} \]

\[ ^{4}\text{He} + ^{20}\text{Ne} \rightarrow ^{24}\text{Mg} + \gamma \]

Oxygen Burning: \( T \sim 2.3 \) billion

\[ ^{16}\text{O} + ^{16}\text{O} \rightarrow ^{28}\text{Si} + ^{4}\text{He} \]

Silicon Burning: \( T \sim 4 \) billion

\[ \gamma + ^{28}\text{Si} \rightarrow ^{24}\text{Mg} + ^{4}\text{He} \]
The photodissociations create alpha particles (Helium-4 nuclei) which are the building blocks for putting together higher elements in ever more energy efficient arrangements. That is, those atoms that have the most binding energy per nucleon are favored. This is sometimes called the “e process” or equilibrium process which takes things to their most stable arrangement, energetically. The process is responsible for the “iron peak” in the distribution of the elements. Examples of the reactions that occur are as follows:

\[ ^4\text{He} + ^{28}\text{Si} \rightarrow ^{32}\text{S} + \gamma \]
\[ ^4\text{He} + ^{32}\text{S} \rightarrow ^{36}\text{Ar} + \gamma \]
\[ ^4\text{He} + ^{36}\text{Ar} \rightarrow ^{40}\text{Ca} + \gamma \]
and so on, until....... finally
\[ ^4\text{He} + ^{52}\text{Fe} \rightarrow ^{56}\text{Ni} + \gamma \]

That’s it for the e-process since atoms with more than 56 nucleons are not energetically favorable. They require energy to be created. Fortunately for them, an explosion is imminent! The end result is either 56-Fe or 56-Ni (which is radioactive and ultimately decays to 56-Fe) or 56-Co (also radioactively decays to 56-Fe). The table on the next page shows that the time scales for advanced nuclear burning are incredibly short!
Evolution stages for a 25 solar mass star:

<table>
<thead>
<tr>
<th>Process</th>
<th>Time Scale</th>
<th>Temperature</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-burning</td>
<td>7 million yrs</td>
<td>60 million K</td>
<td>50 gm/cc</td>
</tr>
<tr>
<td>He-burning</td>
<td>500,000 yrs</td>
<td>230 million K</td>
<td>700</td>
</tr>
<tr>
<td>C-burning</td>
<td>600 yrs</td>
<td>930 million K</td>
<td>200,000</td>
</tr>
<tr>
<td>Ne-burning</td>
<td>1 yr</td>
<td>1.7 billion K</td>
<td>4 million</td>
</tr>
<tr>
<td>O-burning</td>
<td>6 months</td>
<td>2.3 billion K</td>
<td>10 million</td>
</tr>
<tr>
<td>Si-burning</td>
<td>1 day</td>
<td>4.1 billion K</td>
<td>30 million</td>
</tr>
</tbody>
</table>
The “onion” model of a pre-supernova.

When the electron degenerate, inert Fe/Ni core reaches the Chandrasekhar limit, it collapses on a dynamic time scale. This leads to a Type II (or Ib or Ic) SN.
What happens next is dictated by the physics of the core. Electron degeneracy pressure can no longer support the weight of the star above it and the core begins to collapse and heat. The following reactions occur throughout the core as it collapses and the temperature skyrockets, essentially undoing in an instant all the nuclear “cooking” that took millions of years to do!

\[
\gamma + ^{56}\text{Fe} \rightarrow ^{134}\text{He} + 4n
\]
\[
\gamma + ^{4}\text{He} \rightarrow 2p + 2n
\]
\[
p + e^- \rightarrow n + \nu_e
\]

With the last reaction, the electrons disappear entirely so the star’s source of support (electron degeneracy pressure) disappears and a rapid, catastrophic collapse of the core occurs until a new pressure source can be found to stabilize the star. That source is NEUTRON degeneracy pressure. The DeBroglie wavelength of the neutron is approximately the mass of the electron / mass of the neutron or about \(1/1840\) times the DeBroglie wavelength of the electron. There are about twice as many neutrons as there were electrons, so the radius of a neutron star is about \(2^{(1/3)}/1840 = 0.0007\) times the radius of a white dwarf. A typical white dwarf radius on the verge of collapse is about 6000 km so a neutron star radius is expected to be \(~5\) km. Detailed models and observations suggest \(~10\) km as the likely typical radii. Densities are \(~10^{14}\) gm/cc.
There is a maximum mass to a neutron star, analogous to the Chandrasekhar mass for white dwarfs. Its exact value depends on details of the neutron degeneracy equation of state, which is more complicated than the electron degeneracy equation of state because neutrons are not elementary particles, like electrons. So, the maximum mass of a neutron star is not certain but it is probably around 3.3 solar masses. This is more than a factor of two larger than the Chandrasekhar mass so the degenerate core should stabilize as a neutron star and not immediately collapse further to a black hole. It is likely that there is some overcompression of the neutron core during the collapse and a “bounce” occurs which actually ejects the rest of the star, although the details of this are not certain and may depend on the nature of the envelope and, therefore, the mass of the progenitor star.

In any event the total energy that must be dealt with is the gravitational binding energy of the neutron star, or roughly

\[ E = \frac{3}{5} \frac{GM^2}{R} \approx 2 \times 10^{53} \text{ ergs} \]

Note that this is about 100 times more energy than the Sun will radiate in its entire lifetime. On what timescale is this released into the star? Roughly the free fall time, which can be estimated as follows:
The free fall time can be estimated as one half of the orbital period for a test mass in an extremely eccentric orbit about the center of mass, starting from the surface. Using Kepler’s Third Law we have:

\[
t_{ff} = \frac{1}{2} P_{\text{orbital}} = \frac{1}{2} \left( \frac{4\pi^2}{GM} \right)^{\frac{1}{2}} R^{\frac{3}{2}} \approx 0.001 \text{sec}
\]

A lot of the energy goes into the production of the burst of neutrinos. About \(10^57\) neutrinos are formed in a millisecond. In Feb., 1987, two neutrino detectors on Earth, one in Ohio and one in Japan detected, simultaneously, a burst of neutrinos (20 of them!) arriving within a few seconds of each other. These may be attributed to SN 1987A and are solid evidence that the formation of a neutron star was responsible for the explosion of that star.
More recently

The progenitor was a blue supergiant in the LMC, in agreement with our notions of stellar evolution (well...pretty much....we had thought it would be a red supergiant, but that’s OK.)

Another confirmation of the theory comes from the discover in 1967 by Jocelyn Bell and Anthony Hewish of radio pulsars. Radio pulses are detected with frequencies of microseconds to seconds. We now understand this as the rotation frequency of a magnetized neutron star.
You can calculate the maximum spin rate of an object as the orbital period of a test particle in a circular orbit at the radius of the object. If something were to spin faster than that, then the centrifugal force would be greater than gravity and the test particle would spiral out. Starting, again with Kepler’s Third Law, we can see that maximum rotation rate, just like free fall time, depends on the mean density of the object to the -1/2 power:

\[ P^2 = \frac{4\pi^2}{GM} R^3 = \frac{4\pi^2}{G} \frac{3}{4\pi \bar{\rho}} = \frac{3\pi}{G\bar{\rho}} \quad \text{or,} \quad P \propto \bar{\rho}^{-\frac{1}{2}} \]

Since the Earth has a circular orbit (nearly enough for our purposes here!) we can use its orbital period to determine the scale and find:

\[ \frac{P_{\text{pulsar}}}{P_{\text{Earth}}} = \left( \frac{\bar{\rho}_{\text{pulsar}}}{\bar{\rho}_{\text{Earth}}} \right)^{\frac{1}{2}} \approx 10^{-3} \text{ sec} \]

Note that in this derivation the average density appropriate to the Earth’s orbit is obtained by taking the mass of the Sun and the volume of a sphere of radius 1 AU.
Pulsars are born spinning at close to this “critical” rate and slow down over time as they lose mass and angular momentum and their magnetic field drags against the surrounding matter. An optical pulsar was found in the Crab nebula, which formed about 1000 years ago and its rate of decrease of rotation has been measured. However, sometimes there are “glitches” in the rotation rates of pulsars due, apparently, to “star quakes” on their essentially solid crusts. The physics of neutron stars is incredibly interesting and complex!
Supernova Classification Scheme:

The Core Collapse SN (Types Ib, Ic, and II) can all be understood in terms of the collapse of an iron/nickel core to form a neutron star and the “bounce” that ejects the rest of the star. If the star still has a H-rich envelope it appears as a Type II SN. If it has lost its H-rich envelope in prior episodes of mass loss, then it will appear as a type Ib or Ic SN, depending on whether it has also lost its Helium-rich shell. So, the physics of these is all the same, it is just differences in the overlying layers that makes them appear different. These kinds of SNe are rather heterogeneous and not so useful as “standard candles” for cosmological studies. What about the Type Ia’s which are VERY HOMOGENEOUS in their behavior?
Type Ia Supernovae:

These have a very uniform light curve (most anyway) that reaches a reliable maximum brightness and fades away in predictable fashion (a standard light curve”, once one accounts for time dilation effects in very distant ones! ...Time really does slow down when you are moving fast!)

The uniformity and lack of H in the spectrum suggests the following model for Type Ia SNe: a white dwarf near the Chandrasekhar limit is pushed over the limit by accretion of matter from a companion star. The composition of the star is C/O or O/Ne and, in either case, this is “combustible” matter (unlike an Fe/Ni core). Hence, instead of collapsing to a neutron star, it ignites and blows itself apart -- a “standard bomb” as they are sometimes called!
The decay of the supernova light curve is powered by the radioactive decay of Nickel-56 (1/2 life of 6 days) and Cobalt-56 (1/2 life of 78 days) and shows a decay time scale consistent with this. The debris of these kinds of supernovae is very iron rich and accounts for the “iron peak” elements.

Another “product” of SN explosions is the “runaway star” -- the former companion whose orbital motion is transferred to straight line motion when its companion disappears.

SN Ia are used by cosmologists to determine distances to very distant galaxies, based on the assumption that the basic physics of the Chandrasekhar mass limit being hit in a C/O or O/Ne white dwarf is the same throughout the Universe. The study of these objects led to the discovery that they are fainter in the distant Universe than around here, if one assumes that the Universe has been expanding at a constant or steadily decreasing rate with time. The favored interpretation is that, in fact, the Type Ia SNe in the distant Universe are not intrinsically fainter and are not extinguished by intergalactic dust, but they are simply further away than the steady expansion or deceleration models of the Universe would predict. This is taken as evidence that the expansion of the Universe is actually ACCELERATING, evidence for the “dark energy” or cosmological constant that acts in the opposite direction to gravity and is a property of space itself.