Outline of today’s lecture

• Finish up lecture 16 (nucleosynthesis)

• Supernovae
  • 2 main classes: Type II and Type I
  • Their energetics and observable properties
  • Supernova remnants (pretty pictures!)

• Neutron Stars
  • Review of formation
  • Pulsars

The evolution and explosion of massive stars

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Like all true stars, massive stars are gravitationally confined thermonuclear reactors whose composition evolves as energy is lost to radiation and neutrinos. Unlike lower-mass stars ($M \leq 8 M_\odot$), however, no point is ever reached at which a massive star can be fully supported by electron degeneracy. Instead, the center evolves to ever higher temperatures, fusing ever heavier elements until a core of iron is produced. The collapse of this iron core to a neutron star releases an enormous amount of energy, a tiny fraction of which is sufficient to explode the star as a supernova. The authors examine our current understanding of the lives and deaths of massive stars, with special attention to the relevant nuclear and stellar physics. Emphasis is placed upon their post-helium-burning evolution. Current views regarding the supernova explosion mechanism are reviewed, and the hydrodynamics of supernova shock propagation and “fallback” is discussed. The calculated neutron star masses, supernova light curves, and spectra from these model stars are shown to be consistent with observations. During all phases, particular attention is paid to the nucleosynthesis of heavy elements. Such stars are capable of producing, with few exceptions, the isotopes between mass 16 and 88 as well as a large fraction of still heavier elements made by the $r$ and $p$ processes.
All heavy elements are formed through fusion processes in stars.

<table>
<thead>
<tr>
<th>Process</th>
<th>Location</th>
<th>Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Big bang</td>
<td>big bang</td>
<td>H, He, Li</td>
</tr>
<tr>
<td>Hydrogen burning</td>
<td>All MS stars</td>
<td>He</td>
</tr>
<tr>
<td>Helium burning</td>
<td>Post-MS stars M &gt; 0.5 M_\odot</td>
<td>C, O</td>
</tr>
<tr>
<td>C, O, Si burning</td>
<td>Post-MS stars M &gt; 8 M_\odot</td>
<td>Elements up to iron</td>
</tr>
<tr>
<td>s-process</td>
<td>AGB stars M &lt; 8 M_\odot</td>
<td>Heavy elements up to bismuth</td>
</tr>
<tr>
<td>r-process</td>
<td>Type II supernovae</td>
<td>Remaining heavy elements</td>
</tr>
</tbody>
</table>

The “s-process” occurs in AGB stars, during helium shell burning.

Heavy elements are formed by the addition of neutrons, one at a time, followed by beta decay (neutron decays into proton).

The “r-process” occurs during a Type II supernova explosion.

Heavy elements are formed by the rapid addition of neutrons to nuclei (relative to the beta decay timescale).

A nucleus can gain lots of neutrons quickly before undergoing beta decay.

Neutrons are produced in the following reactions:

- \( ^{22}\text{Ne} + ^{4}\text{He} \rightarrow ^{25}\text{Mg} + n \)
- \( ^{13}\text{C} + ^{4}\text{He} \rightarrow ^{16}\text{O} + n \)

\[
\begin{align*}
^{56}\text{Fe} + n & \rightarrow ^{57}\text{Fe} + \gamma \\
^{57}\text{Fe} + n & \rightarrow ^{58}\text{Fe} + \gamma \\
^{58}\text{Fe} + n & \rightarrow ^{59}\text{Fe} + \gamma \\
^{59}\text{Fe} & \rightarrow ^{59}\text{Co} + e^- + \gamma \\
^{59}\text{Co} + n & \rightarrow ^{60}\text{Co} + \gamma \\
^{60}\text{Co} & \rightarrow ^{60}\text{Ni} + e^- + \gamma \\
^{60}\text{Ni} + n & \rightarrow ^{61}\text{Ni} + \gamma \\
\end{align*}
\]

etc…... to lead & bismuth.
Optimal conditions for the r-process

To build up heavy elements using the r-process, you need lots of neutrons bombarding the nuclei --> very high neutron densities are required.

During the supernova explosion, temperatures and densities are sufficiently high for the r-process to proceed.

For example, at $T = 2.5 \times 10^9$ K, $n_n \sim 10^{27}$ cm$^{-3}$ or about a kilogram of neutrons per cubic cm.

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

$r$-Process Site #2: Merging neutron stars

Supernovae: Observations
SUPERNOVAE

- A supernova is the explosive death of a star. Unlike an ordinary nova, it does not repeat.

- Two types are easily distinguishable by their spectrum. Type II has hydrogen (H\textalpha). Type I does not.

- Very luminous. Luminosities range from a few times $10^{42}\ \text{erg s}^{-1}$ (relatively faint Type II; about 300 million $L_\text{sun}$) to $2 \times 10^{43}\ \text{erg s}^{-1}$ (Type Ia; 6 billion $L_\text{sun}$) - roughly as bright as a large galaxy.
  (Recently some rare supernovae have been discovered to be even brighter)

SPECTROSCOPICALLY

Type II SN has hydrogen (H\textalpha). Type I does not.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{supernova_spectroscopy.png}
\caption{Spectroscopic analysis of supernova types.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{supernova_diagram.png}
\caption{Diagram showing the lifecycle of stars leading to supernova creation.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{supernova_images.png}
\caption{Images of various supernovae.}
\end{figure}
Light Curve of Type IIp Supernovae

- The most common kind of supernova. Death of a massive star that still has its hydrogen envelope. The star is a red (usually) or blue (rarely) supergiant when it dies.

- There are three stages – shock breakout, the “plateau”, and the decline (or tail).

Theoretical light curve of a Type IIp supernova

- Breakout is the first time the supernova brightens. The shock wave erupts from the surface heating it to about 200,000 K for about 2000 s. It declines to 30,000 K after one day. Meanwhile the luminosity declines from about $10^{11}$ solar luminosities to about $10^9$ solar luminosities. This emission, in UV, has been seen in at least two supernovae less than one day after their explosion (Gezari et al 2008).

A sequence of ultraviolet images released in June 2008 shows shock break out. Just before the explosion, the host galaxy (top left) appears relatively quiet. Then a bright ultraviolet flash signals the onset of the supernova.

- As the hydrogen envelope expands and cools, it eventually reaches 5500 K where the hydrogen starts to recombine. This recombination moves into the expanding envelope as a wave over a period of about 3 months. The recombination reduces the opacity and lets out the energy deposited by the shock as it passed through the envelope. This is the plateau. The temperature stays pegged to 5500 K.
Still later the decay of radioactive nuclei produced in the supernova keeps it bright for years.

\[ ^{56}\text{Ni} + e^- \rightarrow ^{56}\text{Co} + \nu_e + \gamma \] (6.1 days)

\[ ^{59}\text{Co} + e^- \rightarrow ^{59}\text{Fe} + \nu_e + \gamma \] (77 days)

Together these reactions release 9.4 \times 10^{16} \text{ erg g}^{-1}. Thus 0.1 solar masses of \(^{56}\text{Ni}\) releases 2 \times 10^{49} \text{ erg}.

**Supernovae - General**

- In a Type II or Ibc supernova most of the energy comes out in the neutrino burst – 3 \times 10^{53} \text{ erg}. 300 times less is in the kinetic energy of the explosion – 10^{51} \text{ erg} – and 100 times less than that, 10^{49} \text{ erg}, is in the light. Bright as they are the electromagnetic radiation emitted by a supernova is a small part of its energy budget.

- The kinetic energy and total light output of SN II and SN I of all subtypes are comparable (though SN Ia are brighter), but a SN Ia emits no neutrino burst.

- The velocities of supernova ejecta typically range from 2000 to 20,000 km s\(^{-1}\). The highest velocities are seen early on. Type I supernovae expand faster than Type II.

**Type IIp Supernovae (cont’d)**

- The spectrum is dominated by the Balmer lines of hydrogen. On the plateau the spectrum is dominantly absorption lines, but at late time as the supernova becomes a nebula, one sees emission lines

- Radii inferred on the plateau are about 10^{15} \text{ cm} (100 \text{ AU}). The emission resembles a blackbody with T_{\text{eff}} approximately 5500 K.

- Type II supernovae always leave behind either a neutron star or a black hole. In many instances the neutron star is a “pulsar”.

**February 23, 1987 (+160,000 years)**

Brightest supernova in over 400 years.

In the 30 Doradus H II region in the Large Magellanic Cloud.

Progenitor star was a previously catalogued blue supergiant Sk 202-69. Mass = 18 solar masses.
Type I Supernovae

- Type I supernovae lack hydrogen and thus have no plateau stage. The shock break out is also considerably fainter and shorter in wavelength (x-rays).

- The Type I supernova light curve is thus powered at all times by the decay of radioactive $^{56}\text{Ni}$ and $^{56}\text{Co}$.

- Type I supernovae are segregated into several classes: Type Ia, Ib, and Ic depending upon special features in their spectra (Si II, He I) and where they are found.

- Type Ib and Ic are caused by the death of a massive star, but one that has lost its envelope – most of the time to a binary companion. Type IIp and Ib/c are found in star-forming regions.

Type I Supernovae (cont’d)

- Type Ia supernovae are not found in star forming regions. They show no preference for spiral arms and can occur in elliptical galaxies where the star formation rate is very low.

- While the progenitor stars of about 10 Type II supernovae have been seen before they exploded (e.g. 1987A), no progenitor of a SN Ia has ever been identified. They must be faint.

- Type Ia supernovae are brighter than any other class. Type I supernovae in general are bright a shorter time than SN IIp (weeks rather than months).

- Neutron stars and black holes may be produced by Type Ib and Ic supernovae, but never by Type Ia.
Comparison of light curves

**Type IIp supernova**

**Type Ia supernova**

**Supernova**

(Death of a star)

<table>
<thead>
<tr>
<th>Type Ia</th>
<th>Type II</th>
</tr>
</thead>
<tbody>
<tr>
<td>• No hydrogen</td>
<td>• Hydrogen in spectrum</td>
</tr>
<tr>
<td>• Thermonuclear explosion of a white dwarf star</td>
<td>• M &gt; 8 solar masses</td>
</tr>
<tr>
<td>• No bound remnant</td>
<td>• Iron core collapses to a neutron star or black hole</td>
</tr>
<tr>
<td>• (\sim 10^{51}) erg kinetic energy</td>
<td>• (\sim 10^{51}) erg kinetic energy</td>
</tr>
<tr>
<td>• (v \sim 5,000 \text{ to } 30,000 \text{ km s}^{-1})</td>
<td>• (v \sim 2,000 \text{ to } 30,000 \text{ km s}^{-1})</td>
</tr>
<tr>
<td>• No neutrino burst</td>
<td>• Neutrino burst (\sim 3 \times 10^{53}) erg</td>
</tr>
<tr>
<td>(E_{\text{optical}} \sim 10^{49}) erg</td>
<td>(E_{\text{optical}} \sim 10^{49}) erg</td>
</tr>
<tr>
<td>(L_{\text{peak}} \sim 10^{43}) erg s(^{-1}) for 2 weeks</td>
<td>(L_{\text{peak}} \sim 3 \times 10^{42}) erg s(^{-1}) for about 3 months (varies from event to event)</td>
</tr>
<tr>
<td>Radioactive peak and tail ((^{56})Ni, (^{56})Co)</td>
<td>Radioactive tail ((^{56})Co)</td>
</tr>
<tr>
<td>1 every 200 yr in our Galaxy</td>
<td>2 every 100 yr in our Galaxy</td>
</tr>
<tr>
<td>Makes about 2/3 of the iron in the Galaxy</td>
<td>Makes about 1/3 iron and all the oxygen plus many other elements</td>
</tr>
</tbody>
</table>

There are also Type Ib and Ic supernovae that share many of the properties of Type II but have no hydrogen in their spectra.

**Supernovae - General**

- There have been 6 supernovae visible to the unaided eye in the last 1000 years. The last one before SN 1987A was Kepler’s supernova in 1604. This was about 2.5 kpc away and reached a magnitude of -2.5. The brightest supernova in history was SN 1006 which reached magnitude -8 to -10, as bright as a quarter moon.

- About two Type II supernovae are thought to occur in our galaxy every century and about one Type Ia every other century. Most have gone undetected.

- We see many more supernovae – hundreds each year – in other galaxies

- Supernovae have produced most of the elements heavier than nitrogen

<table>
<thead>
<tr>
<th>Year</th>
<th>Report</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>185 A.D.</td>
<td>Chinese Identification in doubt (Chin and Huang 1994)</td>
<td></td>
</tr>
<tr>
<td>386</td>
<td>Chinese unknown</td>
<td></td>
</tr>
<tr>
<td>393</td>
<td>Chinese unknown</td>
<td></td>
</tr>
<tr>
<td>1006</td>
<td>China, Japan, Korea, Arab lands, Europe Identified with radio SNR</td>
<td>Crab Nebula</td>
</tr>
<tr>
<td>1054</td>
<td>China, Japan</td>
<td>Crab Nebula</td>
</tr>
<tr>
<td>1181</td>
<td>China, Japan</td>
<td>Possible identification with radio SNR 3C58</td>
</tr>
<tr>
<td>1572</td>
<td>Europe (Tycho Brahe), China, Japan</td>
<td>Tycho's remnant</td>
</tr>
<tr>
<td>1604</td>
<td>Europe (Kepler), China, Japan, Korea</td>
<td>Kepler's remnant</td>
</tr>
</tbody>
</table>
**Historical Supernovae**

<table>
<thead>
<tr>
<th>Date (AD)</th>
<th>Apparent Visual Magnitude, V</th>
<th>Time Visible to Unaided Eye</th>
<th>Galactic Coordinates</th>
<th>Remnant Name</th>
<th>Distance (kpc)</th>
<th>Remnant Diameter (pc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>185</td>
<td>-8.0</td>
<td>20</td>
<td>G 315.4-02.3</td>
<td>RCW 86</td>
<td>3.0</td>
<td>35.0</td>
</tr>
<tr>
<td>385**</td>
<td>-4.5</td>
<td>3</td>
<td>G 112.0-00.3</td>
<td></td>
<td>≥ 5</td>
<td>≥ 6</td>
</tr>
<tr>
<td>393</td>
<td>0.0</td>
<td>8</td>
<td>G 346.5+00.1</td>
<td>CTB 37A</td>
<td>10.4</td>
<td>24.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>or G 346.7+00.3</td>
<td>CTB 37B</td>
<td>10.4</td>
<td>24.0</td>
</tr>
<tr>
<td>1006</td>
<td>-9.5</td>
<td>≥ 24</td>
<td>G 327.6+14.6</td>
<td>PKS 1459-41</td>
<td>1.0</td>
<td>8.8</td>
</tr>
<tr>
<td>1054</td>
<td>-5.0</td>
<td>22</td>
<td>G 184.6-05.8</td>
<td>Crab Nebula, 3C 144</td>
<td>2.0</td>
<td>2.9</td>
</tr>
<tr>
<td>1181</td>
<td>0.0</td>
<td>6</td>
<td>G 130.7+03.1</td>
<td>3C 58</td>
<td>2.6</td>
<td>5.3</td>
</tr>
<tr>
<td>1572</td>
<td>-4.0</td>
<td>16</td>
<td>G 120.1+01.4</td>
<td>Tycho, 3C 10</td>
<td>2.3</td>
<td>5.4</td>
</tr>
<tr>
<td>1694</td>
<td>-3.0</td>
<td>12</td>
<td>G 4.5+96.8</td>
<td>Kepler, 3C 358</td>
<td>4.4</td>
<td>3.8</td>
</tr>
</tbody>
</table>

1680 Cassiopeia-A

**Supernova Discovery History**

**Asiago Catalog (all supernova types)**

- Type Ia supernova used as standard candles to measure cosmological expansion

**Supernova Discovery Future**

*Rough predictions and promises…*

- PanStarrs
- Dark Energy Survey
- Joint Dark Energy Mission
- Large Synoptic Survey Telescope (LSST)

**The “First” Supernovae**

- Oldest recorded supernova, RCW 86, first documented by the Chinese in December, 185 A.D. (WISE telescope – infrared)
Supernova Remnants

Combination of IR data from the Spitzer telescope and x-ray data from the Chandra x-ray observatory shows the Tycho supernova remnant. Seen by the astronomer Tycho Brahe over 4 centuries ago (1572). Type Ia. In Cassiopeia. 2.3 kpc. Peak magnitude -4.

Remnant of Kepler’s supernova (1604). Also thought to be Type Ia. In Ophiuchus. 6 kpc. Magnitude -2.5. Chandra x-ray photograph.

Kepler’s supernova remnant in the optical (HST yellow), IR (Spitzer red), and x-ray (Chandra, blue and green). Blue and yellow are shocked gas, green is hot gas, red is dust.

Cassiopeia A (aka Cas A) is the remnant of an optically faint supernova (about m = 6) perhaps observed by John Flamsteed in 1680. It is 3.4 kpc away and 10 ly in diameter. This is a color coded x-ray photo by the Chandra X-Ray Astronomy Observatory taken in 1999. Red is about 20 million K; blue about 30 million K. Spectroscopy shows prominent lines of Fe, Si, O, S. Fe knots are found near the left outer boundary despite having been synthesized near the center. Brightest knots are Si, S.
SN 1054 (The Crab)

- Well observed by Chinese astronomers
- Bright enough to be seen in daylight for 23 days. Bright enough to cast a shadow.
- Visible in the night sky for 653 days
- 6300 ly distant
- May also have been seen by Anasazi and Irish. No conclusive European sightings (“Dark Ages”). Maybe records were lost.

Pulsars and Neutron Stars
A neutron star is the remnant core of a high-mass star.

Recall that a NS is formed from the collapsed core of a high-mass star.

A NS is essentially a giant ball of neutrons supported by **neutron degeneracy pressure**.

**Neutron stars were discovered by their radio emission.**

1967: Jocelyn Bell discovered radio pulses having a precise period (graph below), but she didn’t know where they came from.

By 1968, these mysterious sources were found in the middle of two supernova remnants, suggesting a link to neutron stars.

These objects are called **pulsars**.

**PULSARS**

- Are rotating magnetic neutron stars with their rotational and magnetic axes not aligned. $B \sim 10^{12}$ Gauss (average sun $\sim 100$ Gauss; sunspot $\sim 1000$ Gauss; Earth $\sim 1$ Gauss)

- Over 1000 now known. Periods range from about 1 ms to over 5 seconds. Accurate clocks (16 decimal places). Gradually slowing down. Concentrated towards Galactic disk.

- Evidence for high “peculiar” velocities of typically several hundred km s$^{-1}$. May get “kicked” in the explosion. Many leave the galaxy.

- Some evidence they turn off after $\sim 10^7$ years due to magnetic field decay and spin down.
The Crab Nebula contains a pulsar.

A pulsar is found at the center of the Crab Nebula, which is a supernova remnant.

Emission from the pulsar has been observed at regular intervals (0.033 sec apart).

Pulsars are extremely precise clocks.

The interval between pulses of the Crab pulsar is actually 0.0335028583 sec.

SYNCHROTRON RADIATION
Listen to pulsars:


PULSARS (continued)

- Occasionally experience abrupt changes in period due to “starquakes”

- Emit pulsed radiation at all wavelengths. Not blackbody emitters.

- Spin down times for solitary neutron stars in supernova remnants are thousands of years consistent with the ages of the remnants in which they are found

- Most rapid rotators are in mass-exchanging binaries – probably spun up.

- Sometimes in binaries with other pulsars, white dwarfs or black holes - and even a planet

http://www.astro.psu.edu/users/alex/pulsar_planets_text.html

Planets around pulsars?!

1992: Two planets were detected orbiting a pulsar by measuring tiny variations in the pulse period.

Four pulsar planets have been confirmed so far.

How could they have formed?

3 planets orbiting a pulsar

Artist’s drawing of planets around PSR B1257+12
### The Pulsar B 1257+12 Planetary System

<table>
<thead>
<tr>
<th>Companion</th>
<th>Mass (Earths)</th>
<th>Semimajor Axis (AU)</th>
<th>Orbital Period (d)</th>
<th>Eccentricity</th>
<th>Radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>.02+-.002</td>
<td>.19</td>
<td>25</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>4.3+-.2</td>
<td>.36</td>
<td>66</td>
<td>0.0186</td>
<td>-</td>
</tr>
<tr>
<td>C</td>
<td>3.9+-.2</td>
<td>.46</td>
<td>98</td>
<td>0.0252</td>
<td>-</td>
</tr>
<tr>
<td>D</td>
<td>.0004</td>
<td>2.6</td>
<td>1250</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>


Note that the iron core that collapsed had ~20% more mass.