**Supernovae, Neutron Stars, Pulsars, and Black Holes**

Massive stars (greater than 8 solar masses) can create core temperatures high enough to burn carbon and heavier elements, ending with iron in the core.

An iron core generates no energy.

The weight of the star compresses the iron core into degeneracy and increases its temperature to ~ 3 billion degrees.

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**Nucleosynthesis in a 20 solar-mass star**

<table>
<thead>
<tr>
<th>Fusion fuel</th>
<th>Product</th>
<th>Temperature (degrees K)</th>
<th>Burning period (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>Helium</td>
<td>10 million</td>
<td>10 million</td>
</tr>
<tr>
<td>Helium</td>
<td>Carbon</td>
<td>100 million</td>
<td>1 million</td>
</tr>
<tr>
<td>Carbon</td>
<td>Oxygen, neon, etc.</td>
<td>600 million</td>
<td>1,000 - 10,000</td>
</tr>
<tr>
<td>Neon, Oxygen</td>
<td>Magnesium, silicon, etc.</td>
<td>1 - 2 billion</td>
<td>1</td>
</tr>
<tr>
<td>Silicon</td>
<td>Iron, Nickel</td>
<td>3 billion</td>
<td>1 week</td>
</tr>
</tbody>
</table>

The iron nuclei are torn apart and protons and electrons are pushed together to make neutrons, creating a flood of neutrinos traveling at the speed of light.

The neutrons collapse into a sphere, 15 -20 km in diameter, supported by neutron degeneracy pressure.

The core collapse occurs in one second and the rebound of the infalling star material produces a great blastwave that carries away all the star material as a Type II SN.

99 per cent of the energy is carried away by neutrinos when the neutron core is formed.

The other 1 per cent becomes the blastwave of the Type II SN that is as bright as its host galaxy for a short time.

The blastwave is probably not spherical because the star is spinning as it collapses and will tend to collapse faster along the spin axis. Jets will form.

A spinning neutron “star” is left behind, the remnant of the core of the destroyed star.

Most of the heavier elements are made by the s-process, up to Bismuth (209), before the star explodes.

Heavier elements like Uranium cannot be made this way.

Uranium and the other heavy elements are made by the r-process (rapid). They are all created in the first few minutes of the Type II supernova blast.
**Differences between supernovae**

- **Type I supernovae** are the result of mass transfer of matter onto a white dwarf in a binary system. The white dwarf ignites when the critical temperature (600 million degrees) is reached and/or the Chandrasekhar mass limit is reached.

- There is no hydrogen in **Type I supernovae**.

- **Type II supernovae** are the result of the core collapse of a massive star. There is much hydrogen in **Type II supernovae**.

- **Type II supernovae** can form neutron stars.

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**Attributes of Neutron Stars**

Neutron stars are solid spheres consisting of a degenerate neutron superfluid with an iron nuclei surface crust a few kilometers thick.

They have a radius of about 8 - 10 kilometers with a mass 1 – 2 times that of our Sun.

They have a density roughly a billion times greater than the density of a white dwarf. A spoonful would weigh 100 million tons.

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Neutron stars probably have an atmosphere of hydrogen a few meters thick.

The surface has mountains, possibly as high as a half-meter, and hills and valleys as much as several centimeters. These heights are dictated by the intense gravitational field of the neutron star.

Neutron stars maintain their size as a result of degenerate neutron fluid pressure (the radius decreases with increasing mass).

Neutron stars generally rotate at a high speed and have a strong magnetic field.
Electromagnetic radiation is focused along the magnetic poles and radiate, like bipolar jets, from the poles (the red region in the previous figure).

The magnetic poles are at some angle with respect to the (vertical) rotation axis, referencing the figure.

As the neutron star rotates, the radiation jets swing around in circles, about the rotation axis.

If Earth happens to be in the path of the jet, we see a blip of radiation from the neutron star as the jet sweeps across Earth.

We have discovered a **pulsar**.

**Pulsars**
are rotating neutron stars with magnetic fields.

produce **synchrotron radiation** in beams along the magnetic poles. We will see them if the beam intersects the Earth.

have periods of rotation from 1.6 millisecond to 4 sec.

slow down and their magnetic fields diminish over time [ ~ 10 million years or so ].

Synchrotron radiation is non-thermal electromagnetic radiation caused by electrons with speeds near the speed of light interacting with a magnetic field.

Electrons moving this fast are called **relativistic electrons**.

Synchrotron radiation is observed at radio frequencies.

This pulsar shows about 5 pulses in five seconds, which means that the pulsar is completing one revolution on its axis every second.

Some pulsars rotate several hundred times each second.

**Pulsars from a rotating neutron star --- a pulsar**

**Neutron Stars in Binaries**
Neutron stars in binaries can acquire material from its companion, analogous to that of a white dwarf in its binary.

The material (mostly hydrogen) from the giant companion star falls through the Lagrange point into an accretion disk around the neutron star.

The accretion disk is very hot and radiates x-rays as well as intense visible light.
Hydrogen gas builds up on the neutron star's surface and ignites when the temperature reaches 10 million degrees.

The neutron star's gravity is extremely high, which makes the hydrogen gas surrounding the neutron star very dense.

The hydrogen fusion explosion is violent. This produces an intense x-ray flash or x-ray burst, thousands of times more luminous than the Sun.

The accretion process can repeat every few hours. We call this object an X-ray burster.

Some of the hydrogen gas falling into the rotating accretion disk is blown away at high speed by bipolar jets along the rotation axis of the accretion disk.

This has been observed.

Some pulsars have been found with hundreds of pulses per second (this means the time between pulses is in milliseconds).

Some of these millisecond pulsars have been found in globular clusters, which seems impossible. Why?

Globular clusters were created early in the universe (~ 10 billion years ago) and all of the stars are old.

Pulsars wind down in about 10 million years.

A likely possibility is that the pulsar is in a binary system with a companion star.

The companion expanded, filling its Roche Lobe, dumping hydrogen into a spinning accretion disk around the neutron star.

Matter fell from the accretion disk on to the neutron star and gave it a push to speed up its rotation.

This is a slow process. It takes about 100 million years to get a neutron star up to such speeds.

Betelguese, in the constellation Orion, is a red giant with mass of 15 – 20 $M_{\text{Sun}}$ and luminosity of about 12,000 $L_{\text{Sun}}$.

Its size is so large that the orbits of Mercury, Venus, Earth, and Mars could all fit inside of it.

Its distance from us is 427 ly (~130 pc)

It is in its final stage (~ 10,000 years).
During core collapse, $10^{46}$ J of neutrinos will radiate from the core at the speed of light and reach us 427 years later.

This is 1000 times more energy than our Sun will generate in 10 billion years.

The neutrinos will produce $\sim 4 \times 10^8$ recoils in the body of a 150 lb. person, well below a lethal dose, but may cause some damage to chromosomes.

The blast wave will take about an hour to reach the surface of Betelguese, traveling at 20,000 km/sec.

The initial flash will be at uv wavelengths and will have a luminosity $\sim 100$ billion times that of the Sun. This will last approximately one hour.

The ejecta of the supernova will expand and cool, and the total luminosity will first dim and then rise to a maximum after two weeks with a luminosity about 1 billion times that of the Sun.

The SN will look about as bright as a quarter moon for the next several months.

The surface temperature of the expanding SN will be $\sim 6000$ K. Most of the radiation will come from the radioactive decay of cobalt to iron; the light will decay exponentially.

A pulsar will likely form, and could emit gamma rays for thousands of years.

Supernova remnants

The glowing remains of an exploded star.

An exploding star produces a blastwave that carries away the star envelope and interacts with matter in nearby space.

The blastwave is very hot and radiates at many wavelengths.

The shockwave in front of the blastwave picks up particles (protons and electrons) and accelerates them to near light speeds, creating cosmic rays.

Supernova remnants and their shockwaves can last for many thousands of years.

The Crab nebula; the Type II Supernova remnant from a star that exploded in 1054 A.D. It is about 1800 pc from us and its size is now 2 pc across.
The Tycho supernova remnant from 1572 A.D. Distance is 2.3 kpc. A Type Ia SN

Kepler supernova remnant from 1604 Distance is about 4 kpc. Type Ia SN

Remnant from the 1987 Type II Supernova in the Large Magellanic Cloud (~50 kpc)

Cosmic rays (usually relativistic protons) come from elsewhere in the universe, enter our atmosphere, and collide with a nucleus of a nitrogen or oxygen atom. The result is a cascade of high energy particles that streak toward the Earth’s surface (and us).