The Death of the Stars

Lecture 15

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**ALICE IN WONDERLAND**

Lewis Carroll

"There is no use trying," she said. "One can't believe impossible things."

"I daresay you haven't had much practice," said the queen. "When I was your age, I always did it for half-an-hour a day. Why, sometimes I've believed as many as six impossible things before breakfast."
# The Death of Stars

<table>
<thead>
<tr>
<th>Mass Range</th>
<th>Fate of Star</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{\text{star}} &lt; 1 , M_{\odot}$</td>
<td>Slow gravitational contraction</td>
</tr>
<tr>
<td></td>
<td>Brown dwarfs</td>
</tr>
<tr>
<td>$1 , M_{\odot}$ to $\sim 5 , M_{\odot}$</td>
<td>Mild core collapse</td>
</tr>
<tr>
<td></td>
<td>$\rho \sim 10^7 , \text{g/cm}^3$, $R \sim 7000 , \text{km}$</td>
</tr>
<tr>
<td></td>
<td>White Dwarfs</td>
</tr>
<tr>
<td>$\sim 5 , M_{\odot}$ to $15 , M_{\odot}$</td>
<td>Fast core collapse</td>
</tr>
<tr>
<td></td>
<td>$\rho \sim 3 \times 10^{14} , \text{g/cm}^3$, $R \sim 20 , \text{km}$</td>
</tr>
<tr>
<td></td>
<td>Neutron Stars</td>
</tr>
<tr>
<td>$M_{\text{star}} &gt; 15 , M_{\odot}$</td>
<td>Very fast core collapse</td>
</tr>
<tr>
<td></td>
<td>$\rho &gt; 10^{16} , \text{g/cm}^3$, $R \sim 4 , \text{km}$</td>
</tr>
<tr>
<td></td>
<td>Black holes</td>
</tr>
</tbody>
</table>

# Importance of Mass

- The fate of a star is linked to its mass when it nears the end of its life.
- This depends upon
  - Its initial mass
  - How much mass it loses along the way.
Stellar End-Products or what is left?

• White dwarfs
  – Light up planetary nebulae for a while
  – Eventually cool and fade away. They become too faint to see.
• Pulsars → cold Neutron Stars
  – A big nucleus in the sky
• Black Holes → ???

Stars explode!

• Mild Explosion → Planetary Nebula
  – Ejection of the outer layers of the red giant.
• Strong Explosion → Nova
  – Eruptions in a binary star system
• Catastrophic Explosion → Supernova
  – Blasting away of the outer parts of a star
Results of explosions

• Explosions put the processed stellar material back into the interstellar medium for the next generation of stars to use!

• In a Supernova, neutrons bombard nuclei and build up very heavy elements, e.g. Gold, Uranium, etc.

Solar-Mass Star End State

• Eventually He in core is exhausted
  – Core then must begin contracting again, raising its temperature
  – Ignites He shell burning around core
  – We now have twin layers of He and H shell burning – at ever increasing rates
  – Eventually, for solar mass stars, core stabilizes under electron degeneracy pressure
  – Envelope is ejected as a “planetary nebula”
  – Core remains as a “white dwarf”
White Dwarfs

• For $M_{\text{core}} < 1.4 M_{\text{sun}}$, the core is stable.
• A white dwarf forms.
  – Size of the earth but mass of the sun!

• As the star cools we might expect it to get smaller and smaller.
• It doesn’t!
What stops core collapse?

• **The Pauli Exclusion Principle:**
  – No two electrons can be at the same place at the same time with the same energy.

• Electrons can not move closer together because they have nowhere to go.

• The strong repulsion caused by the Exclusion Principle is called
  - *Electron Degeneracy Pressure*
Supernova!

• Massive stars reaching the end of their life can explode violently.

• The interior of the star contracts very rapidly, and the core bounce causes an explosion.

Core Collapse

• For $M_{\text{core}} > \text{few } M_{\text{sun}}$

• During the Red Giant phase, iron is produced in the core.

• Iron won’t “burn”, so the core contracts.
• The temperature rises to billions of degrees.
Core Collapse (cont’d)

• If the iron core becomes too dense, the electrons get high enough energy to penetrate atomic nuclei

• Proton and electrons combine into neutron and neutrinos in a process called “Neutron Drip”.

\[ p^+ + e^- \rightarrow n + \nu \]

Core Collapse (cont’d)

• The “disappearance” of the electrons
  \[ \Rightarrow \text{no more electron degeneracy pressure} \] (like knocking the legs out from underneath a table)

• The core collapses catastrophically.

• Neutrinos escape carrying away the energy.
Core Collapse (cont’d)

• The neutrons fall toward the center reaching speeds ~0.1-0.2 c.
• The collapse occurs over ~1 second.
• The Pauli Exclusion Principle for neutrons eventually takes effect

\[ \Rightarrow \] the falling matter stops instantly

Kaaabbooooommmmm!

• Many of the neutrons BOUNCE and fly outward (like billiard balls).
• They sweep material up with them as they fly outward.
• And we have a very CATASTROPHIC explosion.
Veil SNR
Cassiopeia A Supernova Remnant

Composite x-ray, optical and infrared image

Neutron Star
A Supernova is born

- Enormous amount of energy are released over a very short time.
- The “star” brightens tremendously.
- During a supernova, a star may shine as brightly as an entire galaxy.
So what’s left?

- The core becomes a super dense object, either a
- Neutron Star: $M_{\text{core}} < \text{few } M_{\odot}$
- Black Hole: $M_{\text{core}} > \text{few } M_{\odot}$
- The rest of the star is blown away, becoming a Supernova Remnant.
Accretion onto a White Dwarf

Supernova Light Curves

![Graph showing Supernova Light Curves with Type I and Type II curves.](image)
Some amazing SN numbers

• For a supernova with $M_v = -19$.

• At 0.25 pc (0.8 lyr) from us it would appear as bright as the Sun.

• At 160 pc (520 lyr) from us it would appear as bright as a full moon.

How often do SN happen?

• The rate of Supernovae is
  
  $\sim 1$ SN / Galaxy / 50 years

• But there hasn’t been one seen in our galaxy in over 390 years!
Supernova Remnants (SNR)

• Residual material ejected by the explosion.
• Expanding at large velocities initially.
• Sweeps up material around the star.
• Very bright in the radio due to synchrotron radiation.
  – High energy electrons spiral around the magnetic fields of the SNR.
  – Emit lots of radio frequency photons.

Historical (Naked Eye) Supernovae

<table>
<thead>
<tr>
<th>Date (A.D.)</th>
<th>Constellation</th>
<th>Apparent Mag./Dist</th>
<th>Where Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1006</td>
<td>Lupus</td>
<td>-5 (&gt; Venus) 3 kpc</td>
<td>Many Places</td>
</tr>
<tr>
<td>1054</td>
<td>Taurus (Crab Nebula)</td>
<td>-5 (&gt; Venus) 2 kpc</td>
<td>China, SW America</td>
</tr>
<tr>
<td>1572</td>
<td>Cassiopeia (Tycho’s SN)</td>
<td>-4 (&lt; Venus) 5 kpc</td>
<td>Many Places</td>
</tr>
<tr>
<td>1604</td>
<td>Ophiucus (Kepler’s SN)</td>
<td>-2 (&gt; Sirius) 6 kpc</td>
<td>Many Places</td>
</tr>
<tr>
<td>1987</td>
<td>LMC</td>
<td>+3 (Avg. Star) 50 kpc</td>
<td>Southern Hemisphere</td>
</tr>
</tbody>
</table>
Neutron Stars

• Neutron Star:
  – Left over (stellar endpoint) from supernova
  – A sea of neutrons
  – A giant atomic nucleus in the sky!!
• Mass = 1.4 to \( \sim 3 \, M_{\text{sun}} \)
• Size \( \sim 10 \, \text{km} \)
• Density \( \sim 3 \times 10^{14} \, \text{g/cm}^3 \)
• Intense magnetic fields, rapidly rotating

Perspective on the density?

• Neutron Star density \( \sim 3 \times 10^{14} \, \text{g/cm}^3 \)
• Steel has a density of 7.7 g/cm\(^3\)

1 cm cube of a Neutron Star

\[ \downarrow \]

340 meter cube of steel!
The Discovery of Pulsars

• Jocelyn Bell - 1967
  – Graduate student at Cambridge, England
  – Discovered a pulsating radio signal coming from the sky!!
• LGMs? (Little Green Men)
• The object is a pulsar (pulsating star).
• Antony Hewish (her advisor) won a Nobel Prize.
Pulsar Radio Record from Arecibo.

Distribution of Pulsars.

Conservation of Angular Momentum

\[ \text{mass} \times \text{speed} \times \text{radius} = \text{CONSTANT} \]

As the radius of a star goes down, the speed must go up.
Neutron star rotation

• Neutron stars initially spin very rapidly.
• Conservation of angular momentum!
  – mass x velocity x radius = constant
• Rotation period of Sun = 25 days
• Shrinking the Sun to 10 km would give a rotation period of much less than 1 second!

Pulses from space

• A short pulse is detected at regular intervals.
The Millisecond Pulsar

1937 + 214
14 Nov 82
1412 MHz

9216 μsec

1 microsecond = 0.001 milliseconds
1 millisecond = 0.001 seconds
1 μsec = 1 microsecond

Pulsar Characteristics

- Rotating Neutron Star--T. Gold (Cornell)
- Period 1 sec
- Size 20 km
- Density \( \sim 3 \times 10^{14} \text{ g/cm}^3 \)
- Mass \( \sim 1 \) to \( 2 \text{ M}_{\text{sun}} \)
- Surface Temperature \( \sim 10^6 \text{ K} \)
- Surface Magnetic field \( \sim 10^{12} \) gauss
- Composition mostly neutrons
Binary Pulsar

The orbit precesses rapidly according to Einstein's General Theory of Relativity

General Relativity prediction \textit{CONFIRMED}. 