Chapter 14: Neutron Stars and Black Holes

**Neutron Stars**
- Form from a 8-20 $M_{\odot}$ star
- Leftover 1.4-3 $M_{\odot}$ core after supernova
- Neutron Stars consist entirely of neutrons (no protons)

**Neutron Stars**
- About the size of a large city (5-10 miles), Several times the mass of the Sun
- So they are incredibly dense!
- One teaspoon of a neutron star would weigh 100 million tons!

• Held up by **degeneracy pressure**: the neutrons don’t like to be squished close together!

**What’s holding it up?**
White dwarfs and neutron stars are held up by degeneracy pressure

**Pulsars: Stellar Beacons**
- Spinning neutron stars
- Strong magnetic field emits a beam of **radio waves** along the magnetic poles
- These are not aligned with the axis of rotation.
- So the beam of radio waves sweeps through the sky as the Neutron Star spins.

**The Lighthouse Model of Pulsars**
A pulsar is a rotating neutron star.
A pulsar’s beam is like a lighthouse

If the beam shines on Earth, then we see a Pulse of energy (radio waves)
A massive star dies in a Supernova explosion. Most of the star is blasted into space.

The core that remains can be a neutron star. However...

**Neutron stars can not exist with masses \( M > 3 \, M_{\text{sun}} \)**

If the core has more than 3 solar masses...

It will collapse completely to single point –

\[ \Rightarrow \text{A black hole!} \]

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A White Dwarf gets too heavy it will collapse... into a Neutron Star (this triggers a second type of Supernova explosion)

White dwarfs cannot be more massive than 1.4 \( M_{\text{sun}} \)

Similarly, Neutron stars cannot be larger than about 3 \( M_{\text{sun}} \)

They will collapse completely and turn into a black hole!

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Escape Velocity

**Escape Velocity** \( (v_{\text{esc}}) \) is the speed required to escape gravity's pull.

On Earth \( v_{\text{esc}} = 11.6 \, \text{km/s} \).

If you launch a spaceship at \( v = 11.6 \, \text{km/s} \) or faster, it will escape the Earth

\[ \text{But } v_{\text{esc}} \text{ depends on the mass of the planet or star...} \]

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Why Are Black Holes Black?

On planets with more gravity than Earth, \( V_{\text{esc}} \) would be larger.

On a small body like an asteroid, \( V_{\text{esc}} \) would be so small you could jump into space.

A **Black Hole** is so massive that \( V_{\text{esc}} = \text{the speed of light.} \)

Not even light can escape it, so it gives off no light.
Black Holes & Relativity

- Einstein’s theory of General Relativity says space is curved by mass
- So a star like the Sun should bend space, and light traveling past it will get thrown off course
- This was confirmed during a solar eclipse in 1919

Light Can be Bent by Gravity

![Diagram showing light bending around a star and a black hole]

Event Horizon

- Nothing can get out once it’s inside the event horizon
- We have no way of finding out what’s happening inside!

The Schwarzschild Radius

- If \( V_{\text{escape}} > c \), then nothing can leave the star, not light, not matter.
- We can calculate the radius of such a star:
  \[
  R_s = \frac{2GM}{c^2}
  \]
- If something is compressed smaller than \( R_s \) it will turn into a black hole!

Black Holes: Don’t Jump Into One!

- If you fall into a Black Hole, you will have a big problem:
  - Your feet will be pulled with more gravity than your head.
  - You would experience “tidal forces” pushing & pulling
  - Time is also distorted near a black hole

<table>
<thead>
<tr>
<th>Table 11-1</th>
<th>The Schwarzschild Radius</th>
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</thead>
<tbody>
<tr>
<td>Mass ((M_*))</td>
<td>( R_s )</td>
</tr>
<tr>
<td>Star 10</td>
<td>30 km</td>
</tr>
<tr>
<td>Star 3</td>
<td>9 km</td>
</tr>
<tr>
<td>Star 2</td>
<td>6 km</td>
</tr>
<tr>
<td>Sun 1</td>
<td>3 km</td>
</tr>
<tr>
<td>Earth 0.000003</td>
<td>0.9 cm</td>
</tr>
</tbody>
</table>
How do we know they’re real?

• Black holes:
  – Kepler’s Laws, Newton’s Laws
  – Accretion disks
• Pulsars:
  – Observe radio jets
  – Strong magnetic fields

Evidence for Black Holes

• No light can escape a black hole, so black holes can not be observed directly.
  However, if a black hole is part of a binary star system, we can measure its mass.
  If its mass > 3 $M_{\odot}$ then it’s a black hole!

Evidence for Black Holes

• Cygnus X-1 is a source of X rays
• It is a binary star system, with an O type supergiant & a compact object

  The mass of the compact object is more than 20 $M_{\odot}$
  This is too massive to be a white dwarf or neutron star.
  This object must be a black hole.

Evidence for Black Holes: X-rays

Matter falling into a black hole may form an accretion disk. As more matter falls on the disk, it heats up and emits X-rays. If X-rays are emitted outside the event horizon we can see them.

Cygnus X-1: A black hole

Artists’ drawings of accretion disks

Supermassive Black Holes

• Stellar black holes come from the collapse of a star.
• They have masses of several $M_{\odot}$
• Bigger mass = bigger BH!
• This happens in the center of most galaxies.

A supermassive black hole devours a star, releasing X-rays

Life Cycles of Stars

• Low-mass stars: Fade out, stay on Main Sequence
• Sun-like stars: White dwarf & planetary nebula
• High-mass stars: Supernova -> SN remnant & dense core
  – Core < 1.4 $M_{\odot}$ = W.D.
  – 1.4 $M_{\odot}$ < Core < 3 $M_{\odot}$ = Neutron Star
  – Core > 3 $M_{\odot}$ = Black Hole
Stellar Evolution Lecture-Tutorial: Page 121

- Work with a partner or two
- Read directions and answer all questions carefully. Take time to understand it now!
- Come to a consensus answer you all agree on before moving on to the next question.
- If you get stuck, ask another group for help.
- If you get really stuck, raise your hand and I will come around.

The Milky Way

Milky Way Composite Photo

- Bulge in the center
- Dark strip in the middle, from dust

“Milky Way”: A band of light and a Galaxy

The band of light we see is really 100 billion stars

Milky Way probably looks like Andromeda.

Milky Way

Before the 1920’s, astronomers used a “grindstone model” for the galaxy
Tried to estimate our location in the galaxy by counting stars in different directions

Because some stars are blocked by dust, the true shape of this group of stars was unclear.
Finding the Center

- Harlow Shapley studied globular clusters.
- He theorized that they must orbit the true center of the galaxy.

Finding the Center

Shapely plotted the locations of the globular star clusters. He found that they are not centered on the Sun... but are centered on a point about 25,000 light years from the Solar System.

The Milky Way

Size: The Milky Way is roughly 100,000 light years across, and about 1,000 light years thick.

Stars: The Milky Way is comprised of over 100 billion stars!

Almost everything visible with the naked eye is inside the Milky Way.

Parts of Our Galaxy

- Disk: The Sun Resides in the Disk
- Nuclear Bulge: The dense central region
- Halo: Spherical region surrounding the disk where the globular clusters live.
Milky Way Scales Lecture Tutorial: Page 123

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