Neutron Stars and Black Holes

Today’s Lecture:

**Neutron Stars** (Chapter 13, pages 312-323)
- General properties
- Pulsars
- Test beds of general relativity

**Black Holes** (Chapter 14, pages 324-343)
- What’s a black hole?
- Are there really black holes?
- Gamma-ray bursts
Type II Supernova: massive star

- Massive stars (> 10 M\(_{\text{sun}}\)) continue to burn fuel until iron (Fe) forms in the core. Fe is the most bound atomic nuclei. No more reactions in the Fe.
- The Fe core continues to grow.
- When the Fe core reaches 1.4M\(_{\text{sun}}\) the core collapses.

\[ p + e^- \rightarrow n + \nu \] The core is converted into neutrons

- The outer layers bounce off the core creating an explosion! (neutrinos also very important for driving the envelope away)
- A neutron star is formed.
Neutron Stars

• The core left over by a Type II supernova

• Held up from gravity by **neutron degeneracy pressure**

• First predicted in the 1930s, and confirmed with the discovery of pulsars in 1967 by Jocelyn Bell (her advisor got the Nobel Prize for the discovery).

• We think the maximum mass (like the Chandra limit for WDs) is 2-3$M_{\text{sun}}$ and 10 km radius. This is $10^{11}$ kg/cm$^3$!!!

• We now know about hundreds of neutron stars doing many exciting things (pulsing, surface explosions, highly magnetized).

• Neutron stars are important for testing **Einstein’s General Theory of Relativity** and testing our understanding of subatomic particles.
If one star is a white dwarf and the other star fills its Roche lobe (like a growing red giant), material can accrete onto the white dwarf.
Pulsars

• The first discovered neutron star was a pulsing radio source with a period of 1.3373011 seconds (1967)
• Initially thought to be extra terrestrial life
• Soon other sources were seen in all different directions, and it was realized that these are actually neutron stars
• The regular period is due to the spin of a neutron star emitting radio waves like a lighthouse.
• A pulsar was also discovered within the Crab Nebula, with a period of 0.033 sec. This confirmed pulsars are neutron stars!
• In 1982, a pulsar was found rotating around 642 times per second! A millisecond pulsar.
Albert Einstein’s
General Theory of Relativity (1916)

• A theory of gravity more general than Newton’s.
• Matter (and energy) **warp space and time**, causing paths of objects (including light) to curve.

Two early tests of general relativity:

1.) **Precession** of Mercury’s orbit. 43 seconds of arc per century!

2.) **Bending of starlight** in the vicinity of the Sun, seen during an eclipse (1919)
Binary Pulsars

• In 1974, a pulsar (17 times per sec) was found that was orbiting another neutron star (the other is not a pulsar)

• By measuring the shifts in the arrival time of pulses (like the Doppler effect) small changes in the orbits can be measured

• Joseph Taylor and Russell Hulse used these measurements to show that gravitational waves must be leaving the orbiting neutrons stars, removing energy and causing them to spiral together (got Nobel Prize for this).

• In 2003, the first double pulsar binary was found. Two neutron stars orbiting each other every 2.4 hours! Incredible laboratory for testing Einstein’s theory of general relativity.
• The relation between pressure and density in a NS is not yet know. The material is just too weird!

• No experiments can be done on Earth to help.

• By measuring the mass and radius, we can constrain which relations work best.

• Mass is easy (binaries), but radius is more difficult to study.
Spectral Line from NS surface explosions

• Absorption line is redshifted from coming out of the neutron star’s very strong gravitational field --> R ~ 12 km
Black Holes (BH)

- Neutron degeneracy pressure **cannot support** a neutron star having $M > 2-3M_{\text{sun}}$. So if more mass than this collapses (as may be the case for 20-100 $M_{\text{sun}}$ stars) it will form a **black hole**.

- **Gravity** is so strong that **nothing can escape**, not even light!

Consider Newton’s Law of Gravity:

$$F = \frac{G M_1 M_2}{d^2}$$

Halve $d$ --> quadruple $F$ --> escape velocity increases

(actually $V_{\text{escape}} \propto d^{-1/2}$)
Black hole conditions

• If matter is compressed so much that escape velocity equals the speed of light, then we have a black hole.

("escape velocity" is the minimum initial speed an object needs to escape to "infinity")

For a given $M$, a BH forms if

$$R_S = \frac{2GM}{c^2}$$

Schwarzschild radius, $R_S$

Example: for the Sun, $R_S = 3$ km

Since $R_S \propto M$, you should be able to use this to calculate the Schwarzschild radius of any mass object.

This is also called the EVENT HORIZON of a black hole. Once you’re inside, there’s no way out.
Some properties of black holes

• **Far** from the event horizon, space-time is **normal**. If the Sun turned into a BH, the orbit of Earth would not be affected (BHs don’t suck!) Only close to the BH do amazing things happen.

• Matter inside the BH has collapsed to a mathematical point called a **singularity** (at least according to Einstein’s theory, we expect quantum effects will come into play here).

• A black hole has no hair
  -- the “no hair theorem”

A BH is completely described by 3 properties:

Mass, electric charge, and spin (angular momentum)
Photons (light) near a black hole

- **Light is trapped** inside a black hole due to the effects of general relativity: space-time is severely warped within the event horizon.

Other consequences:

- Light coming from a region close to (but outside) a BH is **bent** (if not radial) and **redshifted**.

- The **photon sphere**: Light can orbit a BH at a radius of $3GM/c^2$ (this is 1.5 times the Schwarzschild radius, $R_S$)
Tidal forces near a black hole

- Near a low-mass black hole, the differential (or tidal) forces can become huge!
- So you don’t want to get too close to a low-mass BH, or you’d be torn apart (spaghettification)
- It’s actually safer to go near a **massive BH** because the tidal forces near the event horizon are much **less**.
Suppose you (far from a BH) watch a friend fall toward a BH

1) You would see his clock slow down.
2) It would appear that he never falls in.
3) From his perspective, he does fall in!
4) If he escapes before crossing the event horizon, he will have aged less than you. This is a method for jumping into the future while aging little! (actual life span is unaffected)
5) Light signals from horizon are redshifted to zero energy: can’t see them!
Detecting a Black Hole

• Light doesn’t escape, so you can’t “see” a BH.

• We detect BHs by their gravitational influence.

• In some binary systems, we find an invisible companion and infer a minimum mass greater than 3 solar masses ---> probably a BH!

• These BHs are in accreting systems, so they are detected in the X-ray from their accretion disks.

• Cygnus X-1 was the first observed BH (1972). There are now about 20 known BHs with masses around 4-15 M$_{\text{sun}}$. Clear separation with measured NS masses.
Supermassive BHs

• In our galaxy we see many **stellar mass** black holes.

• Most galaxies are thought to have **supermassive** BHs at their center \( (10^8 - 10^{10} \, M_{\text{sun}}) \).

• Our Galaxy has a wimpier BH \( (\sim 4 \times 10^6 \, M_{\text{sun}}) \).

• Our black hole is confirmed from the orbits of nearby stars.

• Our black hole is also seen as a strong radio source.
Black Holes can evaporate!

• Black holes can **evaporate** due to a quantum process (Stephen Hawking)

• “Virtual pairs” are everywhere according to quantum physics.

• Close to the event horizon, one member of the pair can sometimes escape.

• The black hole loses mass progressively faster, ending with an explosion (mostly gamma-rays)

• Process is **negligible** except for mini-BHs (<$10^{15}$ g, roughly the mass of a big mountain).
What are Gamma-ray bursts (GRBs)?

NOT explosions of mini black holes!

• First detected in 1967 by the Vela satellites, designed to detect covert nuclear weapons tests by the USSR.

• Quickly realized they are from outer space: in 1973 they were declassified and published in Astrophysical Journal.

• Theorists went crazy! Thousands of papers written in next 20 years.

• Main problem: are they from our galaxy? The energetics totally different depending on distance.

• Because they were so short (~10 second or less) it was difficult to know their location, until 1991…
GRBs: Fantastic explosions!

• In 1991 new telescopes showed GRBs are isotropic on the sky, proving they are (usually) NOT from our galaxy

• Afterglows (optical) were seen from some GRBs. This allowed the host galaxies to be identified and distances to be measured.

• The luminosities of these things are HUGE: $10^{52}$ ergs/s. Equivalent to vaporizing a star into pure energy in a matter of 10 seconds.

• Also highly beamed and relativistic (indicating jets moving near the speed of light)

• Now we have the satellite Swift that can rotate quickly in the sky to do detailed studies of GRBs
Long and short GRBs

Further observations show that there are two classes:

• **Long gamma-ray bursts (> 2 sec):** Found in young, star forming regions. Some are clearly massive supernovae (hypernovae?) because spectra are seen.

• **Short gamma-ray bursts (< 2 sec):** Found in young and old regions. Thought to be two merging neutron stars or a neutron star plus a black hole.

In both classes, the “central engine” is the same: a **black hole rapidly accreting from a massive accretion disk**

The difference in times basically reflects the different reservoirs of mass available to accrete in each case.