Black Holes

Chapter Twenty-Four
Note from previous class…

• About Neutron Stars and Magnetic Field:
  While a neutron star is made predominantly of neutrons some protons and electrons exist-the Pulsar Magnetic Field is anchored to the neutron star by charged particles
The special theory of relativity changes our conceptions of space and time.

- This theory, published by Einstein in 1905, is based on the notion that there is no such thing as absolute space or time.
- Space and time are not wholly independent of each other, but are aspects of a single entity called spacetime.

Two basic principles: your description of physical reality is the same regardless of the constant velocity in which you move.

Regardless of your speed or direction of motion, you always measure the Speed of light to be the same.
The speed of light is the same to all observers, no matter how fast they are moving.

Incorrect Newtonian description: As seen by the astronaut in spaceship, the light is approaching her at \((3 \times 10^8 \text{ m/s}) + (1 \times 10^8 \text{ m/s}) = 4 \times 10^8 \text{ m/s}\).

Correct Einsteinian description: As seen by the astronaut in spaceship, the light is approaching her at \(3 \times 10^8 \text{ m/s}\).
Speed that you measure for ordinary objects

As seen by the outfielder, the ball is approaching her at \((30 \text{ m/s}) + (10 \text{ m/s}) = 40 \text{ m/s.}\)

It depends on the relative velocity
An observer will note a shortening of rulers that are moving with respect to the observer *along the its direction of motion*.
An observer will note a slowing of clocks with respect to the observer (example: muon life time $2.2 \times 10^{-6}$s and would never reach Earth but because they are moving with $v=0.999c$ their life time is $3.3 \times 10^{-5}$s and they reach Earth!)
• Another prediction of special theory of relativity is
• $E=mc^2$
• Mass can be converted in energy (this released energy is what makes the Sun shine)
• The special theory of relativity also predicts that NO spaceship can move at a speed of light (its ok to move 99.9999999% of the speed of light!)
General Theory of Relativity

• Including also gravity!

(a) The apple hits the floor of the compartment because the Earth’s gravity accelerates the apple downward.

(b) The apple hits the floor of the compartment because the compartment accelerates upward.

Equivalence Principle
Published by Einstein in 1915, this is a theory of gravity
A massive object causes space to curve and time to slow down
Gravity causes the same acceleration no matter the mass of the object!
Imagine a ball rolling along this surface: far from the well the surface is nearly flat and the ball moves in straight line
The curvature of the well has the same effect on a ball of any size (same gravity-
• These distortions of space and time are most noticeable in the vicinity of large masses or compact objects.

Gravity should bend light! This effect is not predicted by Newtonian mechanics because light has no mass! (this was shown by a total eclipse in 1919)
Precession of Mercury:

The theory of relativity predicts a number of phenomena, including the bending of light by gravity and the gravitational redshift, whose existence has been confirmed by observation and experiment.

As mercury moves along its elliptical orbits, the orbits themselves change orientation or precesses-most mercury’s precession is caused by gravity (as explained by Newtonian mechanics). But when all the gravitational pull of other planets were accounted for, still remained a one-sixth of a degree every century—explained by general relativity.
Gravitational Slowing down of time and gravitational red shift

Note: don’t confuse gravitational redshift with Doppler shift. Doppler effect: Redshift are caused by a light source moving away from the observer- Gravitational redshifts are caused by time flowing at different rates at different locations
The general theory of relativity also predicts the existence of gravitational waves, which are ripples in the overall geometry of space and time produced by moving masses.

Gravitational waves have been detected indirectly, and specialized antennas are under construction to make direct measurement of the gravitational waves from cosmic cataclysms (Russel Hulse and Joseph Taylor discovered that a binary system of neutron stars are losing energy as they spiral towards each other (loosing energy as they emit gravitational radiation)-1993 Nobel Prize.
The general theory of relativity predicts black holes

1. A supergiant star has relatively weak gravity, so emitted photons travel in essentially straight lines.
2. As the star collapses into a neutron star, the surface gravity becomes stronger and photons follow curved paths.
3. Continued collapse intensifies the surface gravity, and so photons follow paths more sharply curved.
4. When the star shrinks past a critical size, it becomes a black hole: Photons follow paths that curve back into the black hole so no light escapes.
If a stellar corpse has a mass greater than about 2 to 3 $M_\odot$, gravitational compression will overwhelm any and all forms of internal pressure. The stellar corpse will collapse to such a high density that its escape speed exceeds the speed of light.
Certain binary star systems probably contain black holes

- Black holes have been detected using indirect methods
- Some binary star systems contain a black hole
- In such a system, gases captured from the companion star by the black hole emit detectable X rays

It was not like the pulsating X-ray sources which emits regular X rays. Instead the X-ray emission from Cygnus X1 are highly variable. They flikers as short as one-hundredth of a second (size = c/ time ~ 3000 km across!) and the lines of HDE226868 shift back and forth as single line spectroscopic binary.
The mass probably is ~ 7 Msolar (too large to be a white dwarf or a neutron star).

T in the disk ~ $10^6$ K; in the final 200 km above the hole the hot gases emit X-rays (the flickering is probably due to small hot spots of the inner edge of the accretion disk.)
Astronomers found 20 other black hole candidates like Cygnus X-1. All are compact X-ray sources orbiting ordinary stars in a spectroscopic binary system.
We have seen jets of hot Glowing material extending Several light-years from some Black holes Candidates Speeds of the jets ~ c (the idea that they form by Strong electric and magnetic Fields in the material around A rotating black hole.)
Formation of a black hole: by Type II supernova with $M > 3 \, M_\odot$.
by a white dwarf or a neutron star accretes enough matter
from its companion
two dead stars coalescing to form

*Formation of a black holes: calculations suggest that they are or extremely large or extremely small.*

Mass of a galaxy $\sim 10^{11} \, M_\odot$. 
Supermassive black holes exist at the centers of most galaxies

By measuring the doppler shifts of light
They were able to figure out that the Mass coming out from the star is ~ Hundreds of km/s and derived The central star mass ~ 1.2x10^9 Ms (and that it cannot be larger than our solar System) -> black hole

Jets extends 15,000pc from the center of the galaxy

These are detected by observing the motions of material around the black hole
• Black holes seem to fall in two very different groups:
  • 1. Supermassive black holes ($10^6$-$10^9$Ms)
  • 2. Stellar-mass black holes $\sim 10M_\odot$

• There are some evidence of **mid-mass black holes**
  (maybe a coalescence of many normal stars or direct merger of stellar mass black holes)

• Stephen Hawkins (Univ of Cambridge) suggested another type of black hole: *primordial black hole* (no evidence so far of that)
The entire mass of a black hole is concentrated in an infinitely dense singularity.

The singularity is surrounded by a surface called the event horizon, where the escape speed equals the speed of light.

More massive the BH larger is the event horizon.

Nothing—not even light—can escape from inside the event horizon.

If a dying star was not rotating
Before it collapses the black hole will
Not rotate
The distance from the center of the BH To the event horizon is Schwarzschild radius ($R_{sc}$) (its depend on the mass of the BH)
A nonrotating black hole has only a “center” and a “surface”

- Space and Time are all jumbled up at the center of the BH the singularity does not obey the laws of physics
- We are shielded from the random things that happen in the singularity by the Event Horizon
Just three numbers completely describe the structure of a black hole

- A black hole has only three physical properties: mass, electric charge, and angular momentum.
- A rotating black hole (one with angular momentum) has an ergoregion around the outside of the event horizon.
- In the ergoregion, space and time themselves are dragged along with the rotation of the black hole.

(a BH is unaffected by the information it destroys)

(not much of a charge…)
• BH with no B (only the disk around it with have a B). The collapsing star before settling inn to the event horizon will emit electromagnetic and gravitational waves

• When the matter is collapsing to form a BH that is rotating the matter does not compresses to a point but to a ring-shaped singularity

• If the BH is surrounded by a disk with a B the accretion disk might “brake” the BH rotation and make the disk speed up

(not much of a charge…)
(a) Looking directly toward the black hole from a distance of 1000 Schwarzschild radii: Note positions of stars 1, 2, and 3.

(b) Looking directly toward the black hole from a distance of 10 Schwarzschild radii: Light bending causes multiple images.
Falling into a black hole is an infinite voyage

Time slows near the BH due to gravity; gravitational redshift; The side closer to the BH will feel a much stronger gravitational force; the Sides are pulled together (straight line falling to the BH)
Could a black hole somehow be connected to another part of spacetime, or even some other universe? General relativity predicts that such connections, called wormholes, can exist for rotating black holes.
Black holes evaporate

1. Pairs of virtual particles spontaneously appear and annihilate everywhere in the universe.

2. If a pair appears just outside a black hole’s event horizon, tidal forces can pull the pair apart, preventing them from annihilating each other.

3. If one member of the pair crosses the event horizon, the other can escape into space, carrying energy away from the black hole.