Lecture 21: General Relativity

Readings: Section 24-2

Key Ideas:

<u>Postulates:</u>

Gravitational mass=inertial mass (aka Galileo was right)

Laws of physics are the same for *all* observers

<u>Consequences:</u>

Matter tells spacetime how to curve.

Curved spacetime tells matter how to move.

Clocks run more slowly in strong gravitational fields

<u>Tests of General Relativity</u>

Perihelion Precession of Mercury

Bending of light near the Sun/Galaxy Clusters

Gravitational Redshift

Gravity Waves

<u>Relevance</u>

General Relativity <u>must</u> be used for strong gravitational fields or for large accelerations

General Relativity is <u>not</u> a quantum theory and does not work on the smallest scales.

Newtonian Gravity

Matter tells gravitation how to exert a *Force*.
Forces tell matter how to *accelerate.*

A mass m is accelerated by the gravity of another mass M:

$$Force = \frac{GMm}{R^2}$$

$$Acceleration = \frac{Force}{m} = \frac{GMm/R^2}{m}$$

$$= \frac{GM}{R^2}$$

The acceleration due to gravity does not depend on the mass of the object being accelerated.

See nssdc.gsfc.nasa.gov/planetary/luna/Apollo_15_feather_drop.html for the video of an astronaut illustrating this point by dropping a feather and a hammer on the moon.

"I frame no hypothesis"

Newton could not explain what gravity was.

- He asserted that Gravity was an "action at a distance"
- He had no hypothesis for what "agent" communicates the gravitational force across empty space.

People assumed gravity worked as described, but didn't worry about why….

General Relativity

New way of looking at gravity. Maybe the motions of masses under gravity didn't have anything to do with the objects themselves.

Instead: Curved spacetime tells matter how to move.

Consequences:

- Photons affected by curved spacetime.
- Disagreement with the inverse square law (Newton's Law of Gravity)
- Matter tells spacetime how to curve.

How do objects move in curved spacetime?

In flat space, they move in straight lines

Straight line=shortest distance between two points

The Shortest Path…

On a flat surface:

- The shortest path between two points is a straight line.
- Parallel lines stay parallel forever

On a curved surface:

- The shortest path is a curved line
- Lines that start parallel can converge or diverge at some distance away.

A New Theory of Gravity

General Relativity may be summarized as:

Matter tells spacetime how to curve.

Curved spacetime tells matter how to move.

Replaces the Newtonian idea of a "force" with the curvature of spacetime as the agent of Gravity.

GR has withstood all experimental tests.

The Laws of Physics are the same for *all* observers

<u>Newton's First Law:</u>

Objects in motion will remain in motion in a straight line *unless* acted upon by an outside force.

<u>General Relativity</u>

Objects follow the shortest path in spacetime.

Final note: gravity same idea as acceleration (think roller coaster)

Tests of General Relativity

The Precessing Orbit of Mercury:

The major axis of Mercury's orbit precesses slowly by 574 arcseconds/century.

Einstein 1, Newton 0

<u>Newtonian Gravity:</u>

Predicts precession of 531 arcsec/century

~43 arcsec/century **smaller** than observed

<u>General Relativity</u>

Spacetime curvature changes as Mercury gets closer to the sun on its orbit

Gives the orbit a little twist

This adds an extra 43 arcsec/century!!

Bending of Starlight

Light travels on the *shortest* path through spacetime.

<u>Predication</u>

Gravity bends light passing a massive object

<u>Confirmed:</u>

1919 Solar Eclipse

Gravitational Lenses (1980s)

Einstein 2, Newton 0

Newtonian Gravity:

Photons are massless and should not be bent by gravity.

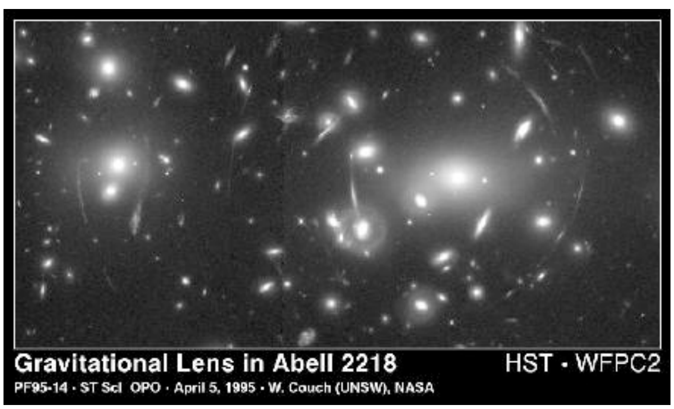
General Relativity:

Photons must also follow the shortest path in spacetime.

Gravitational Lens

Large clusters of galaxies have enough mass to "lens" the light of galaxies that lie behind them.

Example of Gravitational Lens



Gravitational Redshift

Gravitational field affects time.
Clocks in stronger gravitational fields run slow.
If true, predicts a gravitational redshift

Wavelength of light seen from strong gravitational fields is redshifted.
(Note: different from Doppler shift)

Gravitational Redshift Observed

Pound & Rebka (1960) -- Harvard Tower

Hafele & Keating (1971) – jetlagged clocks
Scout D rocket (1976) – clocks on rockets

Gravitational Waves

Newton thought the force of gravity was instantaneously transported through space.
But, remember, in special relativity, information travels at the speed of light.
Changes in gravity are transmitted at the speed of light.
Gravity waves
- Travel at the speed of light
- Carry energy away

Binary Pulsar

2 pulsars=rapidly rotating neutron stars sending out radio jets
Accurate timing
Strong gravitational field
Test of theory
See system losing energy
- Pulsars are getting closer together
- 75 millionths of a second/year different in period of pulses

Nobel Prize of Hulse & Taylor

Practical Relativity

Global Positioning System (GPS)
- 24 satellites in high Earth orbit
- 20,000 km altitude, 12^h period (14,000 km/h)
- Carry on-board atomic clocks

Relativistic effects on these clocks
- Special Relativity 7 microseconds/day *slower*
- General Relativity 45 microseconds/day *faster*

Combined correction 45-7=38 microseconds/day

Whither Newton?

Newton's laws are approximations of GR.
<u>Conditions:</u>
- Weak gravitational fields
- Speeds much slower than the speed of light

<u>Newton's Laws:</u>

Work accurately in the "everyday" world.
Are mathematically much simpler.

Status of General Relativity

It has passed every test we've thrown at it.
We will continue to test it, particularly in the strongest gravitational fields we can find.
Its effects must be included in binary pulsar calculations, collapses of stars to black holes, and in cosmology, among other applications.
Probably not the last word in gravity. We need a theory of quantum gravity.