Lecture 6: Einstein’s Gravity

Newtonian Gravity

- Newtonian Gravity exhibits two key features that will be important for us:
  - Action at a distance
    - If $m_1$ ejects some matter, $m_2$ feels change in force instantaneously
    - Inconsistent with relativity
  - The Equivalence Principle
    - The inertial mass of an object is equivalent to its gravitational mass
  \[
  \Rightarrow \text{ All objects undergo universal acceleration in a gravitational field} \quad (a_2 \text{ does not depend on } m_2)
  \]

The Equivalence Principle and the Bending of Light

- An observer in a closed elevator cannot tell the difference between inertial motion and free-fall in a gravitational field
- Einstein used this to argue that the path of light is bent in a gravitational field

- Suppose a light is shined in our elevator at the instant it is dropped and allowed to fall
- The elevator observer believes he/she is in inertial motion
  - The elevator observer must see the light travel in a straight line
  \[\rightarrow\] The building observer sees the light move downward along with the elevator
  \[\rightarrow\] The path of light is bent by gravity!
Gravitational Redshift and Time Dilation

- Now **one observer** shines a light from the bottom just as the elevator is released
  - Wavelength of light remains constant to elevator observer
  - The wavelength seen by an **observer higher up** must decrease
  - Light propagating in a gravitational field is Doppler shifted (that is, its wavelength and frequency shift)
    - Wavelength is shorter in strong gravitational fields (**blueshifted**)
    - Wavelength is longer in weak gravitational fields (**redshifted**)

- Now place an atomic clock in a strong gravitational field, say one based on oscillations of Cesium atoms
  - We observe it from a region of weak gravitational field and measure a longer period for the Cesium radiation
    → We think the clock is running slower
  - In general, clocks in strong gravitational fields tick faster than clocks in weak gravitational fields

Equivalence Principle and Curved Paths

- A free-falling reference frame is indistinguishable from an inertial reference frame
- Gravity makes observers follow curved paths instead of straight ones
  - ...but an inertial observer always believes they are moving in a straight line

⇒ **The effect of gravity is to change what it means for a path to be straight**
Gravity and Curved Spacetime

- Einstein gravity: matter (actually energy-momentum) curves space-time!
  - All observers follow *geodesic paths*, that is paths of 'shortest distance'
    - Roughly, 'distance' between 2 events is time elapsed on a clock that passes through both
  - Straight line paths are bent when spacetime is curved by gravity

- Difficult to visualize curved spacetime
- Often use *Penrose diagrams* which are a type of spacetime diagram like we saw in lecture 1
  - Light moves on diagonal lines
  - Distances scaled so points that are 'infinitely far away' can fit on the page

Black Holes

- First nontrivial solution of Einstein’s equations found by Karl Schwarzschild in 1916
- Solution displays a *singularity* and an *event horizon*
  - If a rocket ship passes the event horizon it cannot escape the singularity
  - Not even light that passes the event horizon can escape the singularity
- The Schwarzschild solution describes a *black hole*
- Gravity curves spacetime so strongly that light cannot escape from behind the event horizon
- Many puzzles regarding the physics of black holes...more next lecture
Gravitational Waves

- In Newton’s theory, changes in gravitational force communicated instantaneously
  - This was ‘action at a distance’
  - Inconsistent with relativity
- In Einstein’s theory, a moving body will generate ‘ripples’ in spacetime
  - Gravitational waves that move at speed of light

- Changes in gravitational force are communicated through these waves (similar to the role of electromagnetic waves in electromagnetism)
- Gravitational waves distort space as they propagate
  - Periodically stretch space in some directions and contract it in others
- Indirectly detected through the energy loss of binary star systems
  - Direct detection experiments underway with large interferometers
    - LIGO, VIRGO, etc

Towards Quantum Gravity?

- Surely we know how to quantize gravity now, right?
  - Gravitational wave has a ‘smallest piece’, the graviton
  - Gravity is a quantum force with the graviton as a force carrier
  - No different from the other forces of the Standard Model, right?

...if only life were that easy...

Next time: Why is Quantum Gravity so hard?!?