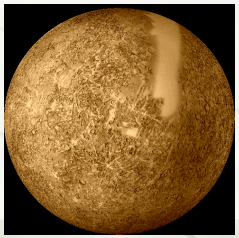
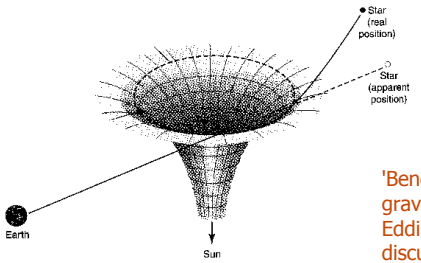
III: GR EFFECTS IN THE SOLAR SYSTEM

- Have already heard about bending of star light by the Sun (detected by Eddington).
- **Orbit of Mercury:**



Warping of space by Sun's gravity

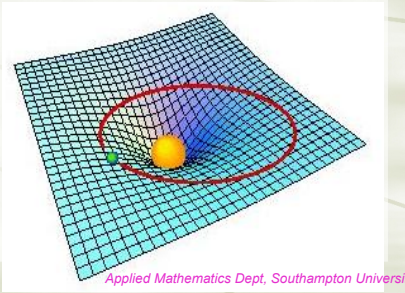


'Bending of light by gravity of sun- the Eddington test we discussed last time

- Light rays follow geodesics in warped space

How are orbits affected?

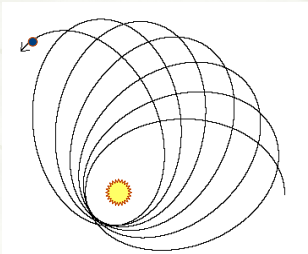
- Marble would follow straight line if weight were not there
- Marble's orbit becomes curved path because weight warps space



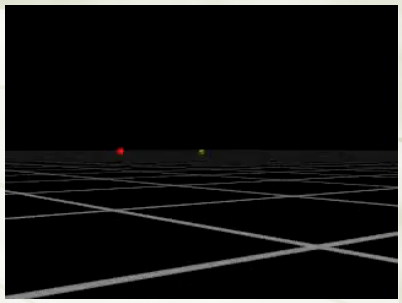
- Effect called "precession of perihelion".- Remember that under Newtonian physics, a two-body system consisting of a lone object orbiting a spherical mass would trace out an ellipse with the spherical mass at a focus but ...
  - Gravitational effect of other planets,
  - deformation of the Sun,
  - non-inertial nature of Earth's frame
- Produce a small effect - orbit twists by 5557 arc-seconds/century BUT
- the actual orbit twists by 5600 arc-seconds (1.56 degrees) per century
  - leaves 43 arc-seconds per century unexplained…
- Using GR, Einstein predicted (with no fiddling!) that Mercury should precess 43 arcseconds per century!

Precession of the perihelion

- Effect called “precession of perihelion”



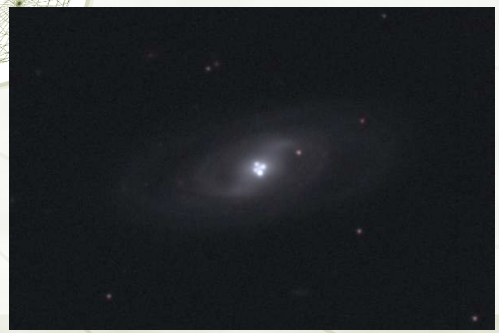
- Precession of the orbit of Mercury

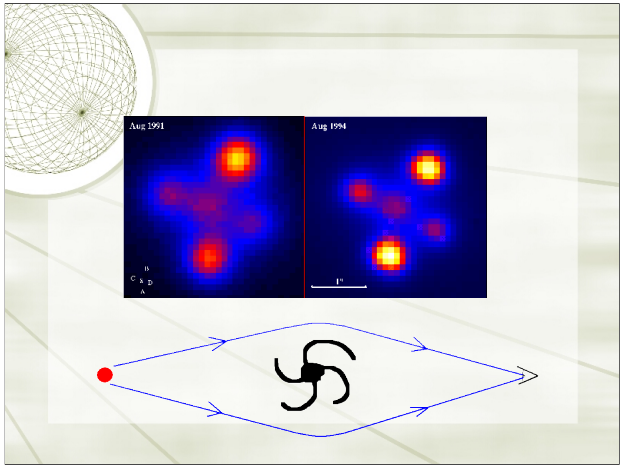


IV : THE BENDING OF LIGHT (GRAVITATIONAL LENSING)

Galaxy Cluster Abell 2218 **HST** • WFPC2
NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

"The Einstein Cross"





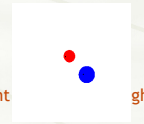
Smithsonian Castle

Smithsonian with black hole

E. Falco CASTLES survey, black hole of Saturn's mass in the middle of the mall

Gravitational micro-lensing

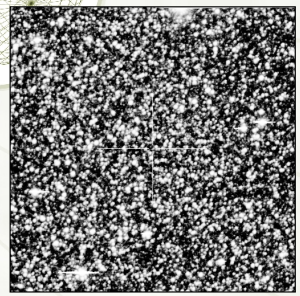
- Individual stars can also make a gravitational lens… **microlensing**.
- Suppose we…
  - Look at a distant star in our galaxy
  - Another massive (but dark) star passes in front…

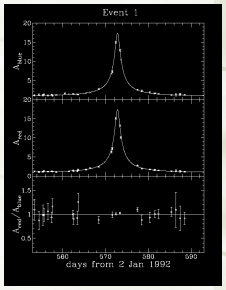


From web site of Ned Wright (UCLA)

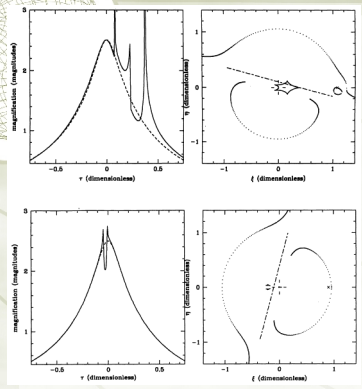
- Causes apparent ghtness of stellar image

Really hard to do!





MACHO Project



- Images for binary lenses with high mass ratio (i.e., a star and a planet, analogous to the Sun and Jupiter; Bolatto & Falco 1994)
- Planets have been found this way!

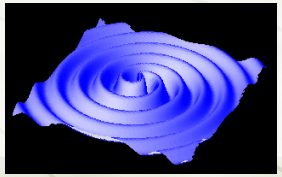
To Repeat: Einstein's Breakthrough Idea

- 4-dimensional space-time is "curved," not flat
  - Example: surface of sphere is curved 2D space; surface of football field is flat 2D space
- Free-falling objects move on geodesics through curved space-time
- The curvature (bending) of space-time is produced by matter and energy

- What is a geodesic?
  - The generalization of a straight line in flat space to curved space
  - It is the shortest path between two points on a surface; for instance, the path flown by an aircraft between cities on the globe
  - Unlike straight lines in flat space, geodesics that start as parallel can converge or diverge (or even cross)

GRAVITATIONAL WAVES-Another Prediction of GR and a Test

- Accelerating masses produce continual changes in space-time geometry
- Periodically-moving bodies (e.g. orbiting stars) create ripples in space-time curvature
- Ripples travel at speed of light through space-time (how do we know this if we've never found one?)
- These are called **gravitational waves**.



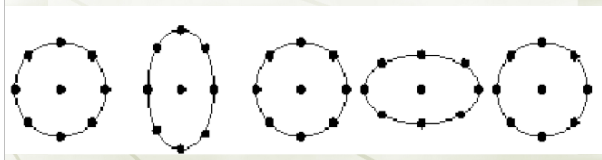
From LISA2 movie

Gravitational waves

- Features of gravitational waves…are radiated by objects whose motion involves *acceleration*, and are not perfectly spherically symmetric (like an expanding or contracting sphere) or cylindrically symmetric (like a spinning disk or sphere).
  - Usually extremely weak!
  - Only become strong when massive objects are orbiting close to each other.
  - Gravitational waves carry energy away from orbiting objects… this causes objects to spiral toward each other
  - The grand challenge – to compute the spiraling together of two black holes.
- How do we know that these waves exist?

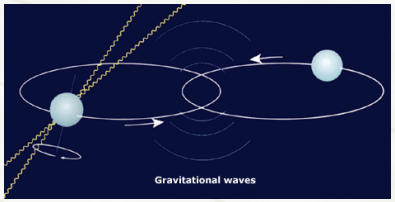
Gravitational Waves

- The waves are 'quadripolar'-motion of a test particle as the wave goes by
- The effect is extremely small- the motion $h=\Delta x/x=$ due the wave is expected to be $<10^{-21}$



The binary pulsar (PSR1913+16)

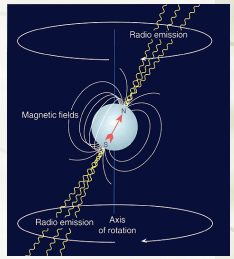
- Russell Hulse & Joseph Taylor (1974)
  - Discovered remarkable double star system
  - Nobel prize in 1993



From Nobel Prize website

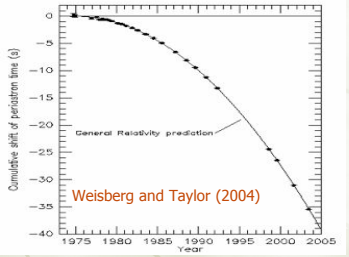
Hulse-Taylor system

- Two neutron stars orbiting each other
- One neutron star is a pulsar -
  - Neutron star is spinning on its axis (period of 59ms)
  - Emits pulse of radio towards Earth with each revolution
  - Acts as a very accurate clock!
- Strong gravity- good place to test GR
  - Orbit precesses by 4 degree per year!
  - Orbit is shrinking due to gravitational waves

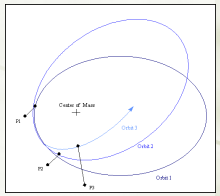


Precise test of certain aspects of GR

- When pulsar is approaching Earth, pulse frequency increases (Doppler shift); when pulsar is receding, pulse frequency decreases -- orbit of pulsar can therefore be "mapped"
- Orbit is observed to be precessing (same physics as for Mercury) and shrinking (loss of energy due to gravitational waves) at exactly the rate predicted by Einstein's theory



Weisberg and Taylor (2004)



Direct detection of gravitational waves

- How do you search for gravitational waves?
- Look for tidal forces as gravitational wave passes: local compression or expansion of space
- Pioneered by Joseph Weber (UMD Professor)
  - Estimated wave frequency (10000Hz)
  - Looked for "ringing" in a metal bar caused by passage of gravitational wave
  - Insufficient technology in the 1970's for detection

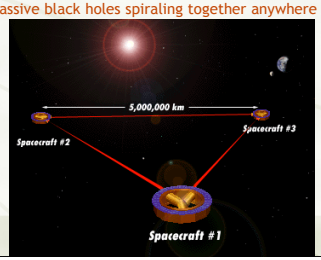
AIP archives

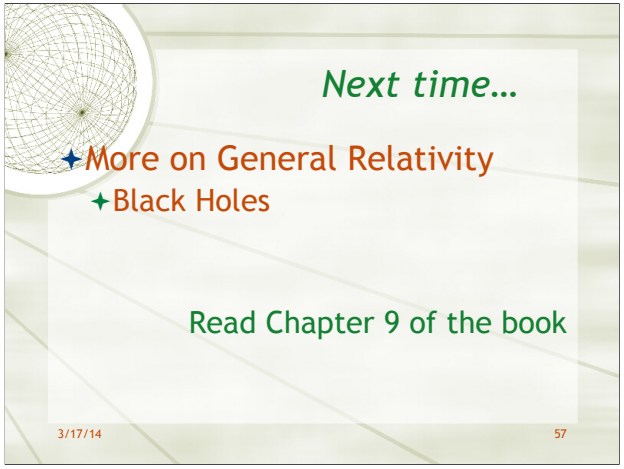
Modern experiments : LIGO

- Laser Interferometer Gravitational Wave Observatory
- Two L-shaped 4km components: Hanford, Washington, & Livington, Louisiana
- Recently became operational!
- Can detect gravitational waves with frequencies of about 10-1000Hz.
- VERY sensitive… need to account for
  - Earthquakes and Geological movement
  - Traffic and people!
- What will it detect?
  - Stellar mass black holes spiraling together
  - Neutron stars spiraling together

LISA

- Laser Interferometer Space Antenna
- Space-based version of LIGO (planned launch date >>2020, used to be 2011)
- Sensitive to lower-frequency waves (0.0001 – 0.1Hz)
- Will be able to see
  - Normal binary stars in the Galaxy
  - Stars spiraling into large black holes in the nearby Universe.
  - Massive black holes spiraling together anywhere in the universe!




Next time…
More on General Relativity
Black Holes
Read Chapter 9 of the book
3/17/14
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