Lecture 8. Gravity

Early Astronomy

- As far as we know, humans have always been interested in the motions of objects in the sky.
- Not only did early humans navigate by means of the sky, but the motions of objects in the sky predicted the changing of the seasons, etc.

http://static.tumblr.com/

Lecture 8. Gravity

Early Astronomy

- There were many early attempts both to describe and explain the motions of stars and planets in the sky.
- All were unsatisfactory, for one reason or another.

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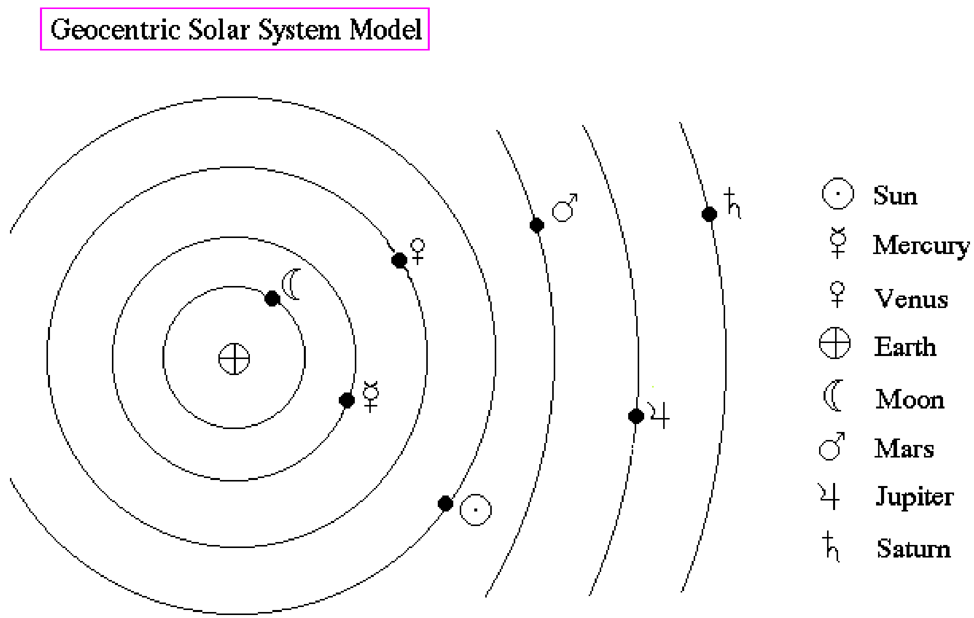
The Earth-Centered Universe

- A geocentric (Earth-centered) solar system is often credited to Ptolemy, an Alexandrian Greek, although the idea is very old.



http://abyss.uoregon.edu/~js/ast123/lectures/lec02.html

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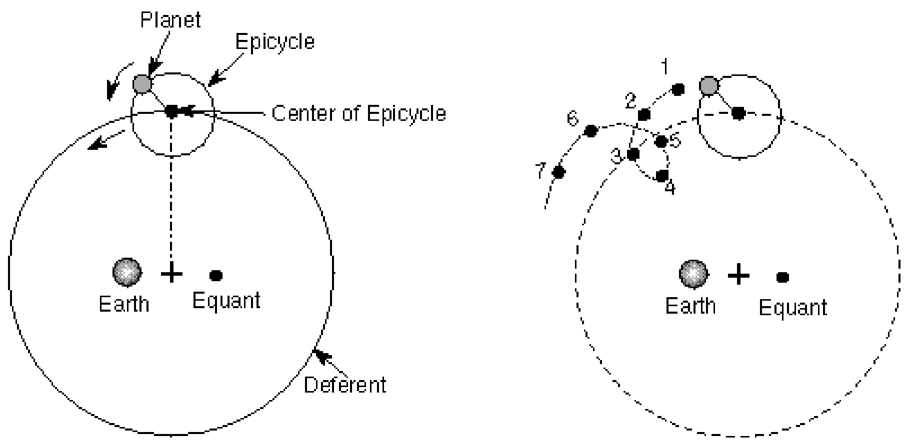
Ptolemy’s Solar System

- Ptolemy’s solar system could be made to fit the observational data pretty well, but only by becoming ***very*** complicated.



Center of epicycle moves counter-clockwise on deferent and epicycle moves counterclockwise. Epicycle speed is uniform with respect to equant. The combined motion is shown at right.

Deferent motion is in direction of point 1 to 7 but planet’s epicycle carries it on cycloid path (points 1 through 7) so that from points 3 through 5 the planet moves backward (retrograde).

http://abyss.uoregon.edu/~js/ast123/lectures/lec02.html

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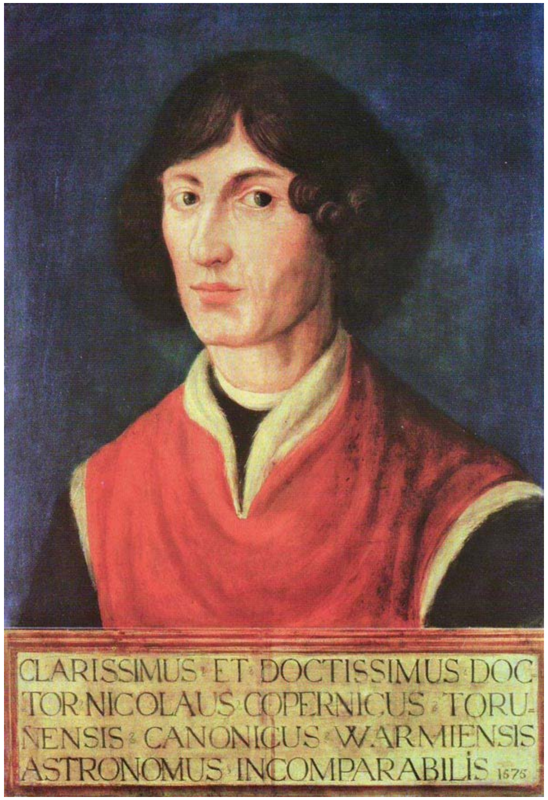
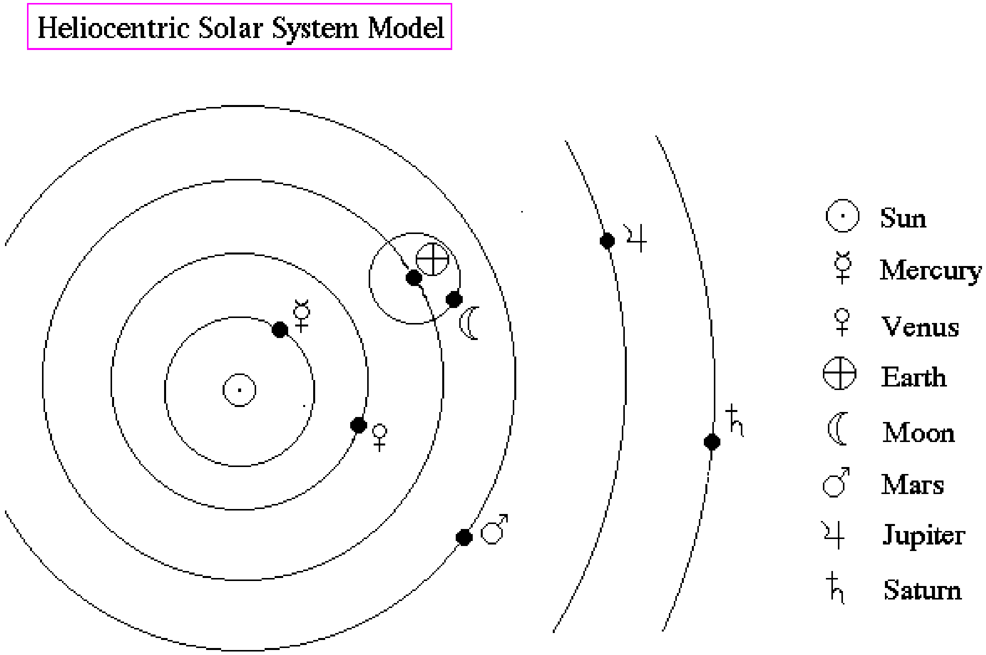
Copernicus' Solar System

- The Polish cleric Copernicus proposed a heliocentric (Sun centered) solar system in the 1500's.





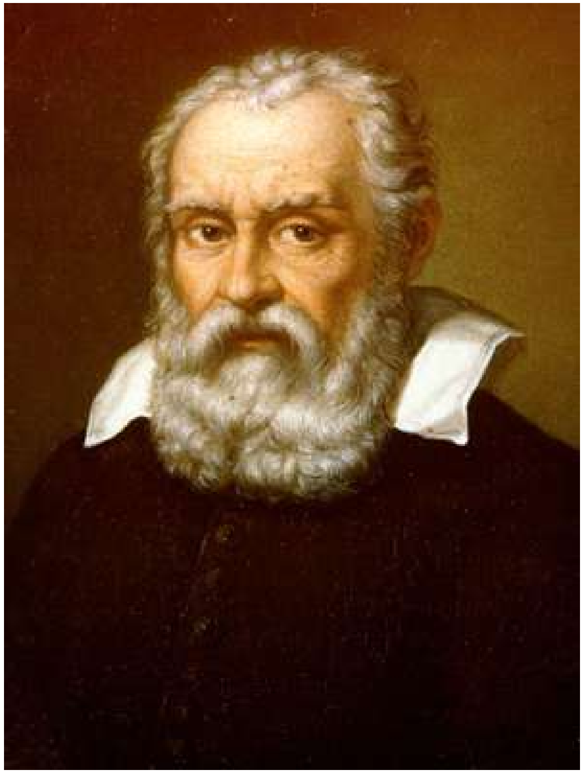
http://abyss.uoregon.edu/~js/ast123/lectures/lec02.html

Objections to Copernicus

- How could Earth be moving at enormous speeds when we don’t feel it?
  - (Copernicus didn’t know about *inertia*.)
- Why can’t we detect Earth’s motion against the background stars (stellar parallax)?

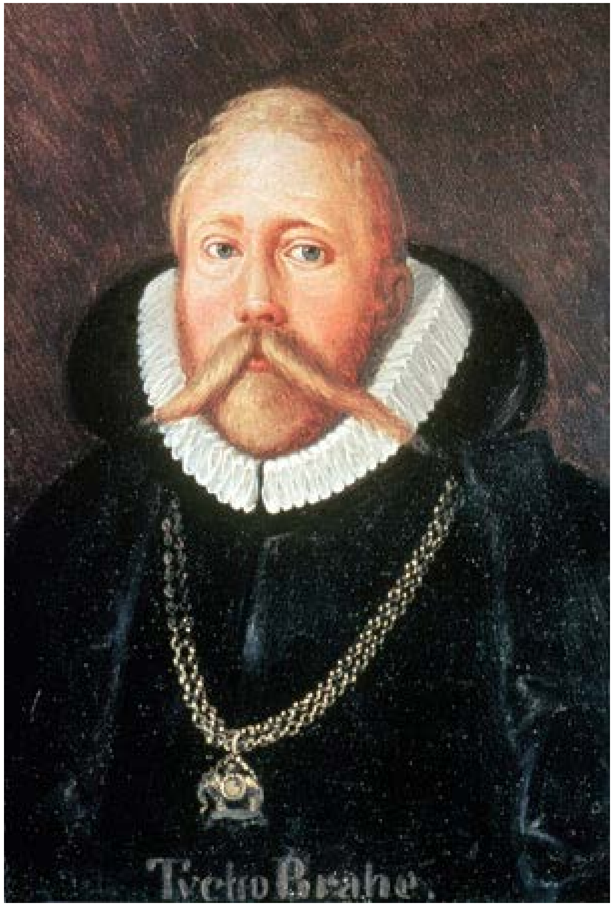
- Copernicus’ model did **not** fit the observational data very well.

Galileo & Copernicus



- Galileo became convinced that Copernicus was correct by observations of the Sun, Venus, and the moons of Jupiter using the newly-invented telescope.
- Perhaps Galileo was motivated to understand inertia by his desire to understand and defend Copernicus' ideas.

Tycho and Kepler



- In the late 1500's, a Danish nobleman named ***Tycho Brahe*** set out to make the ***most accurate measurements*** of planetary motions to date, in order to validate his own ideas of planetary motion.

Tycho and Kepler

- Tycho's data was successfully interpreted by the German mathematician and scientist ***Johannes Kepler*** in the early 1600's.

Kepler's Laws

The laws themselves are surprisingly simple and geometric:

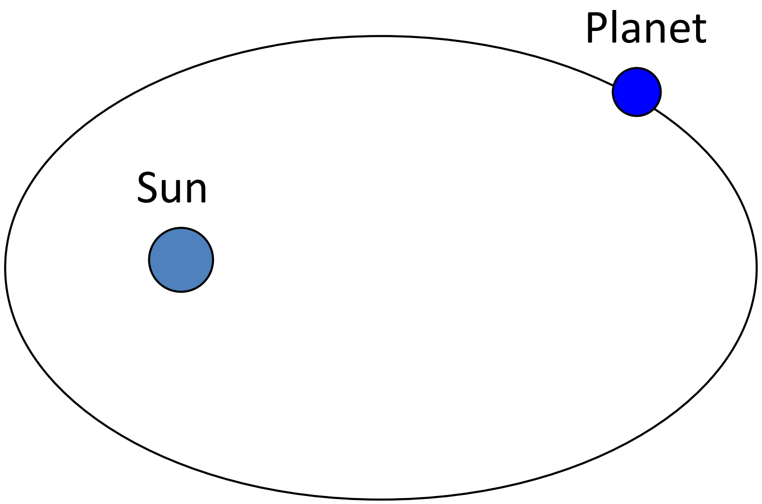
a) Planets move around the Sun in elliptical orbits with the Sun at one focus.

b) Planets sweep out equal areas in equal times as they orbit the Sun.

c) The mean radius of a planetary orbit (in particular, the semimajor axis of the ellipse) cubed is directly proportional to the period of the planetary orbit squared, with the same constant of proportionality for all of the planets.

Early Astronomy

- Kepler determined that the orbits of the planets were not perfect circles, but ***ellipses***, with the Sun at one focus.



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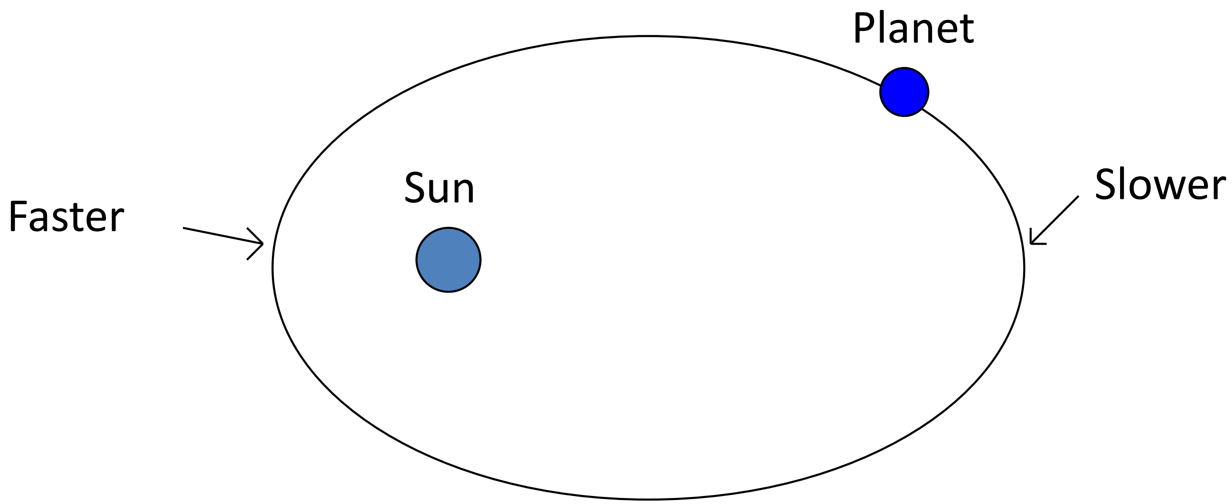
Kepler's Second Law

- Kepler determined that a planet moves faster when near the Sun, and slower when far from the Sun.



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Kepler's Laws

- Kepler's Laws provided a complete ***kinematical*** description of planetary motion (including the motion of planetary satellites, like the Moon) - but ***why*** did the planets move like that?

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The Apple & the Moon

- Isaac Newton realized that the motion of a falling apple and the motion of the Moon were both actually the ***same motion***, caused by the ***same force*** - the ***gravitational force***.

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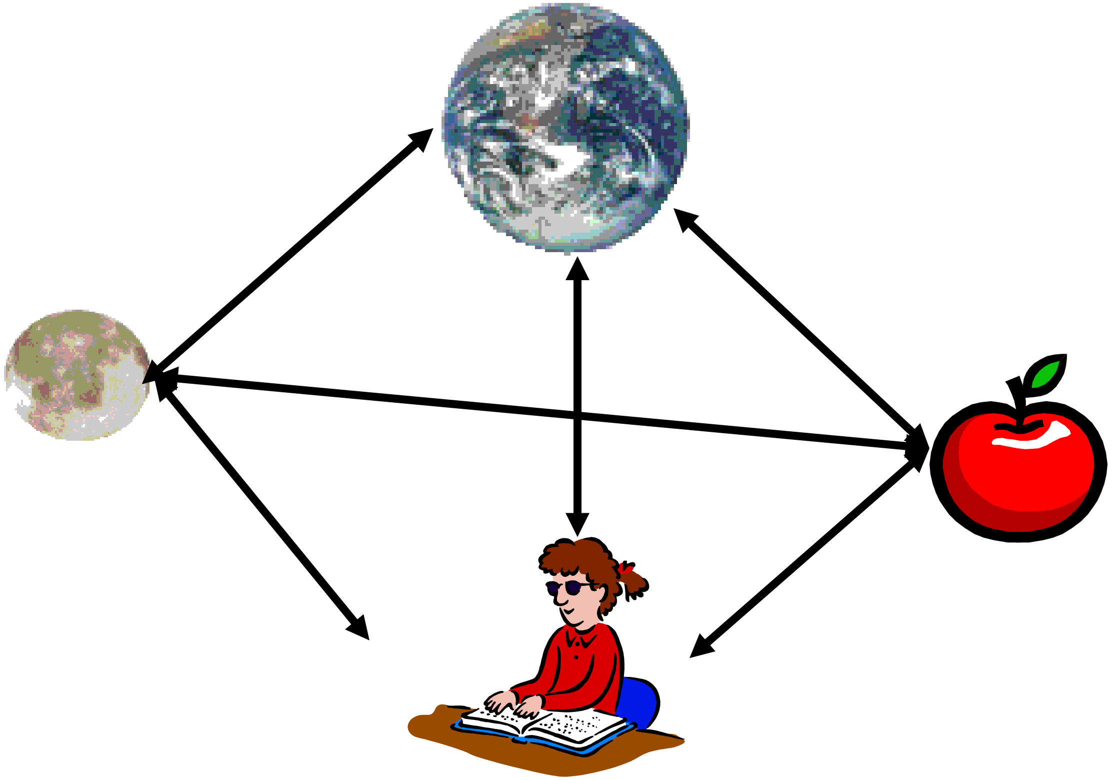
Universal Gravitation

- Newton's idea was that gravity was a ***universal*** force acting between ***any two objects***.



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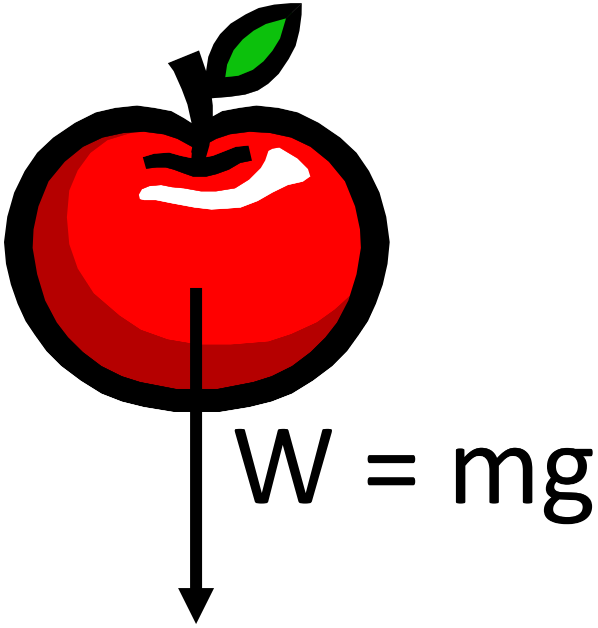
At the Earth's Surface

- Newton knew that the ***gravitational force*** on the apple equals the apple's ***weight, mg,*** where g = 9.8 m/s^2.



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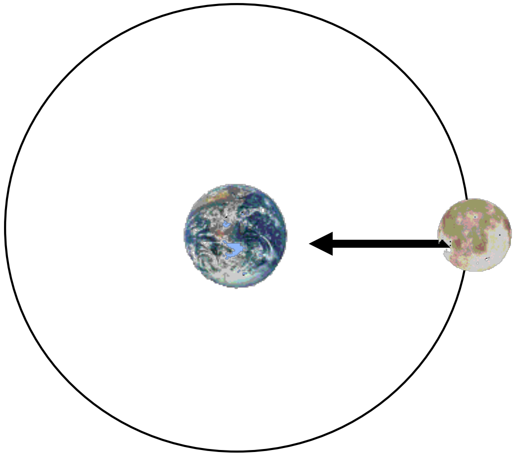
Weight of the Moon

- Newton reasoned that the centripetal force on the moon was also supplied by the Earth's gravitational force.



$$F_c \stackrel{?}{=} mg$$

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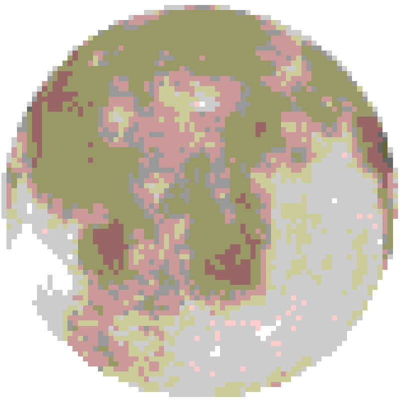
Weight of the Moon

- Newton's calculations showed that the centripetal force needed for the Moon's motion was about $1/3600^{th}$ of Mg, however, where M is the mass of the Moon.



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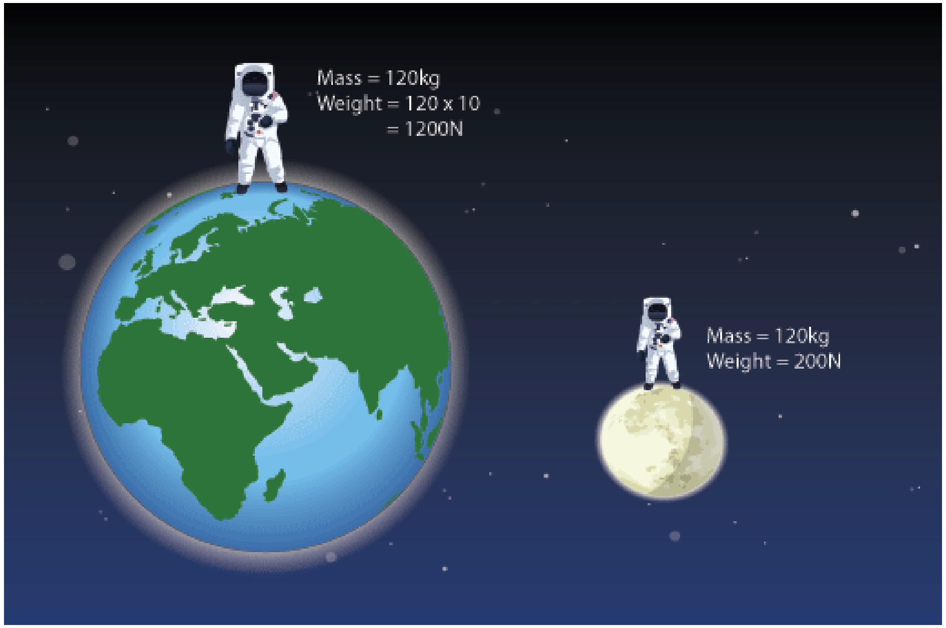
Weight of the Moon

- Newton knew, though, that the Moon was about ***60 times farther*** from the center of the Earth than the apple.
- And $60^2 = 3600$



http://www.bbc.co.uk/

Lecture 8. Gravity

Universal Gravitation

- From this, Newton reasoned that the strength of the gravitational force is ***not constant***, in fact, the magnitude of the force is ***inversely proportional to the square of the distance*** between the objects.
- Newton concluded that the gravitational force is:
  - ***Directly proportional*** to the ***masses*** of ***both*** objects.
  - ***Inversely proportional*** to the ***distance*** between the objects.

$$\vec{F}_{21} = -\frac{GM_1 m_2}{r^2}\hat{r}$$

where $G = 6.67\times10^{-11}$ N m^2/kg^2 is the universal gravitational constant

- Newton's Law of Universal Gravitation is often called an ***inverse square law***, since the force is inversely proportional to the square of the distance.

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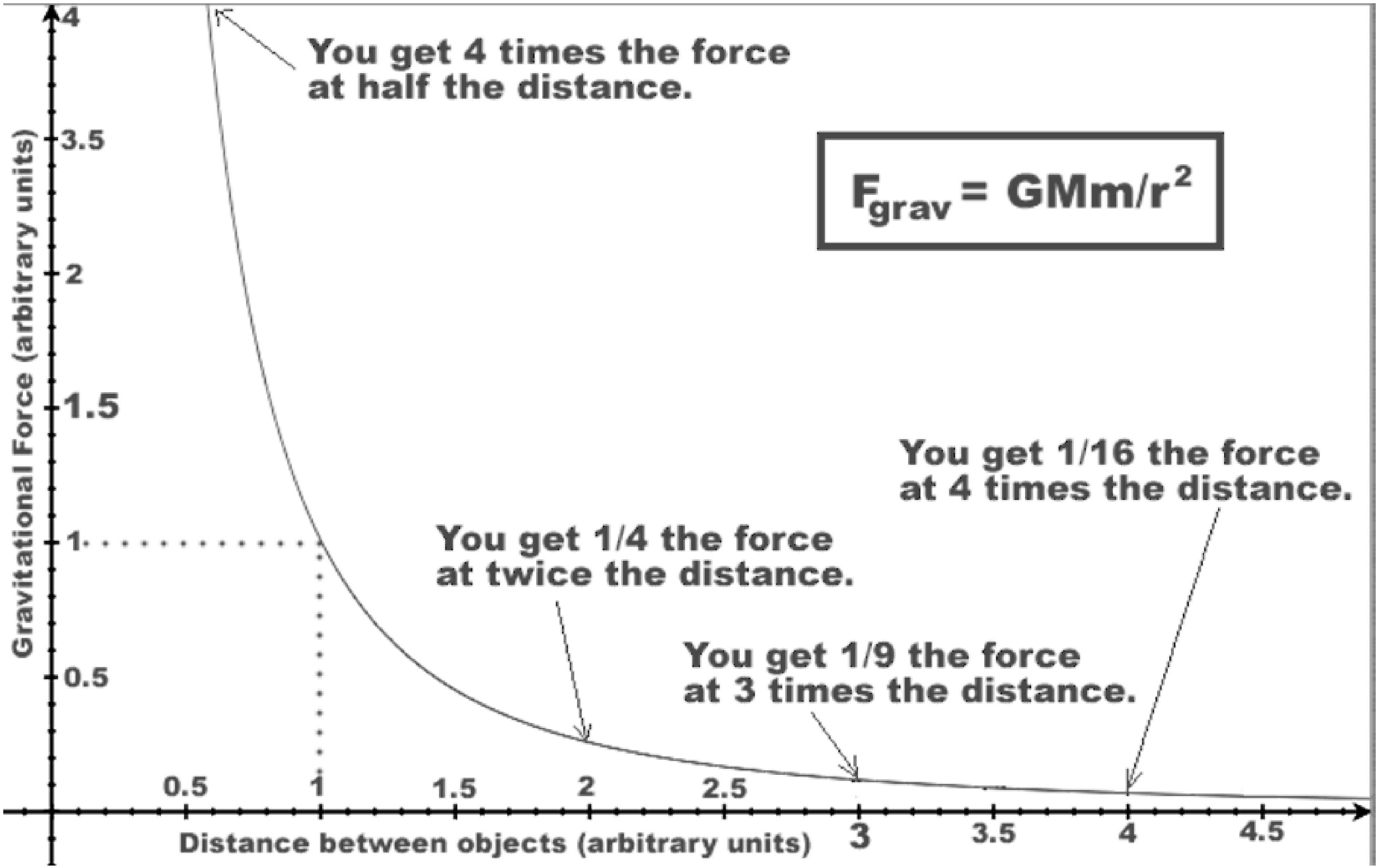

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Experimental Evidence

- The Law of Universal Gravitation allowed extremely accurate predictions of planetary orbits.
- Cavendish measured gravitational forces between human-scale objects before 1800. His experiments were later simplified and improved by von Jolly.
- In Newton's time, there was much discussion about HOW gravity worked - how does the Sun, for instance, reach across empty space, with no actual contact at all, to exert a force on the Earth?
- This spooky notion was called "action at a distance."

Lecture 8. Gravity

The Gravitational Field

- During the 19th century, the notion of the "***field***" entered physics (via Michael Faraday).
- Objects with mass create an ***invisible disturbance in the space around them*** that is felt by other massive objects - this is a ***gravitational field***.
- So, since the Sun is very massive, it creates an intense gravitational field around it, and the ***Earth responds to the field***. No more "action at a distance."

Lecture 8. Gravity

Gravitational Field Strength

- To measure the strength of the gravitational field at any point, measure the gravitational force, F, exerted on any "test mass", m.
- ***Gravitational Field Strength, g = F/m***
- Near the surface of the Earth, $g = F/m = 9.8\ N/kg = 9.8\ m/s^2$.
- In general, $\boldsymbol{g = GM/r^2}$, where M is the mass of the object creating the field, r is the distance from the object's center, and $G = 6.67 \times 10^{-11}\ Nm^2/kg^2$.

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Gravitational Force

- If g is the strength of the gravitational field at some point, then the gravitational force on an object of mass m at that point is $F_{grav} = mg$.
- If g is the gravitational field strength at some point (in N/kg), then the free fall acceleration at that point is also g (in m/s^2).

Gravitational Field Inside a Planet

- If you are located a distance r from the center of a planet:
  - all of the planet's mass inside a sphere of radius r pulls you *toward the center* of the planet.
  - All of the planet's mass outside a sphere of radius r exerts ***no*** net gravitational force on you.

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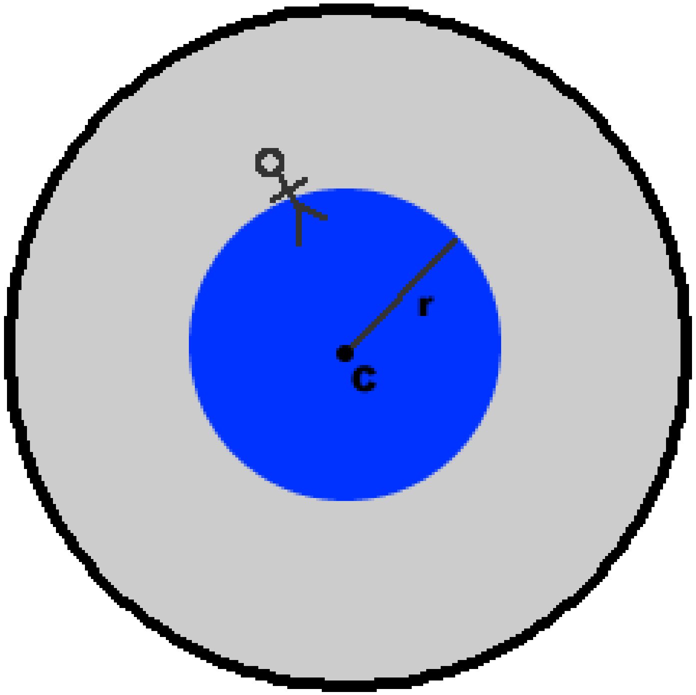
Gravitational Field Inside a Planet

- The blue-shaded part of the planet pulls you toward point C.
- The grey-shaded part of the planet does not pull you at all.



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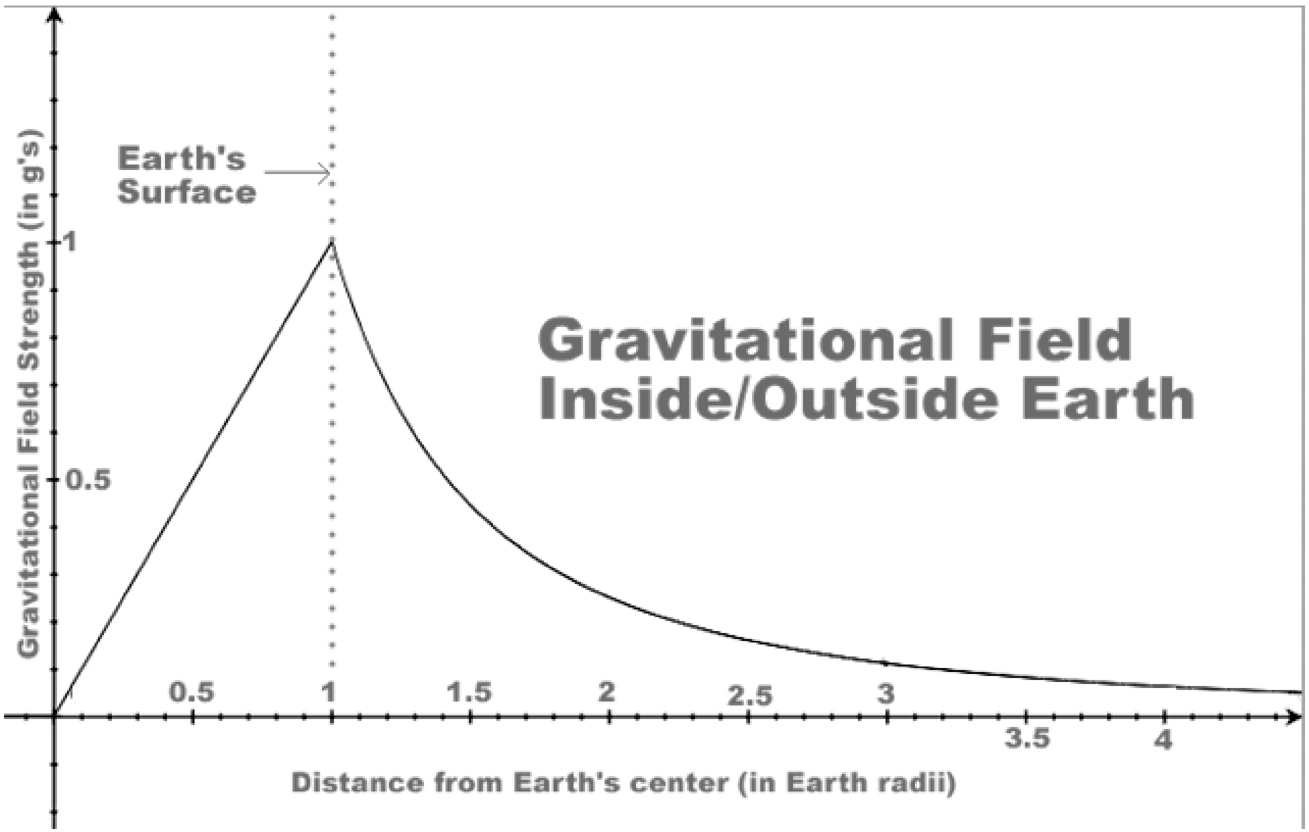
Gravitational Field Inside a Planet

- Half way to the center of the planet, g has one-half of its surface value.
- At the center of the planet, g = 0 N/kg.



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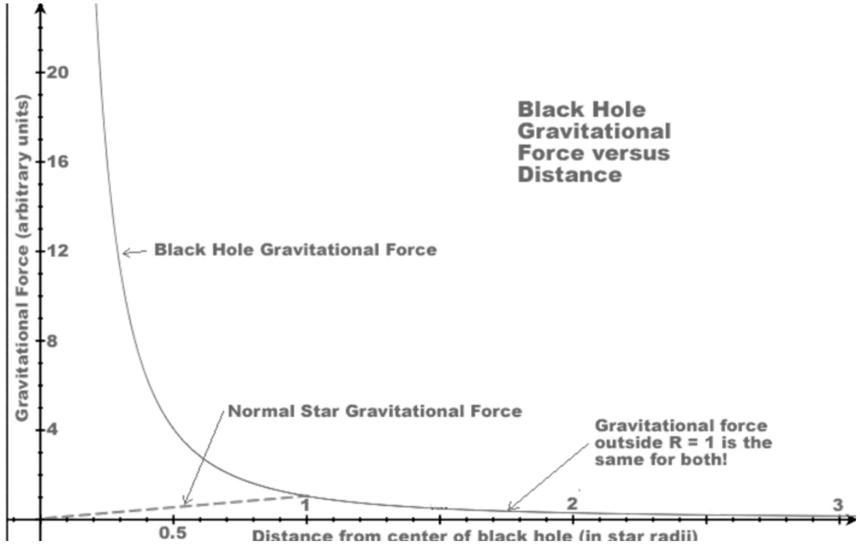
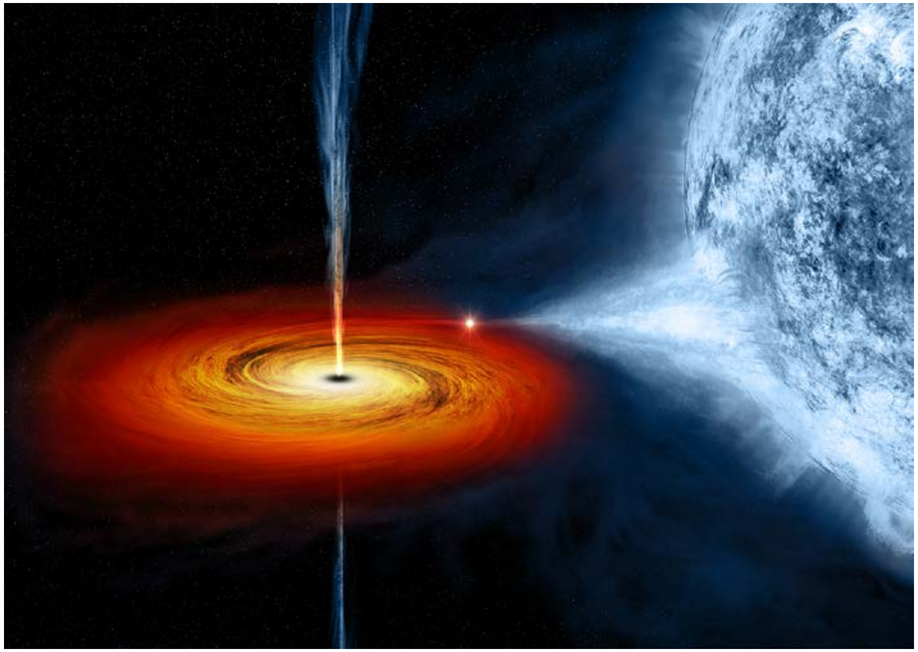
Black Holes

- When a very massive star gets old and runs out of fusionable material, gravitational forces may cause it to collapse to a mathematical point - a singularity. All normal matter is crushed out of existence. This is a black hole.





http://www.nasa.gov/

Black Hole Gravitational Force

- The black hole's gravity is the same as the original star's at distances greater than the star's original radius.
- Black hole's don't magically "suck things in."
- The black hole's gravity is intense because you can get really, really close to it!

Earth's Tides

- There are 2 high tides and 2 low tides per day.
- The tides follow the Moon.

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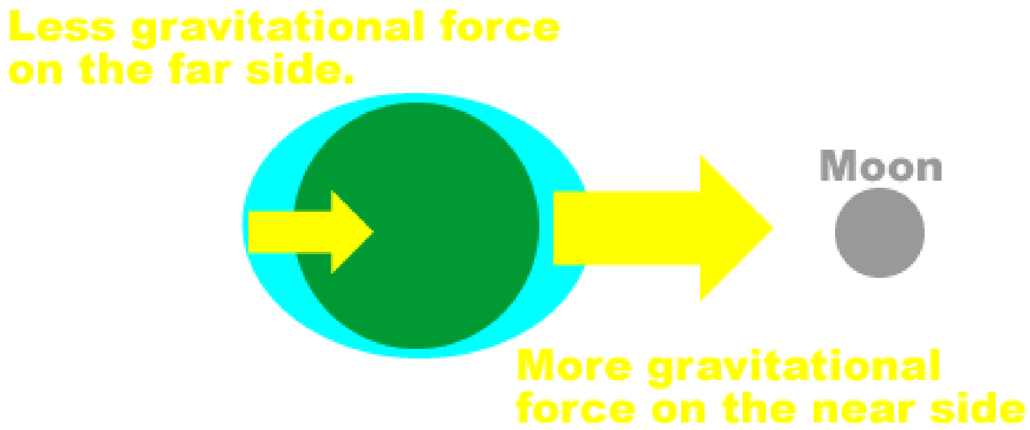
Why Two Tides?

- Tides are caused by the stretching of a planet.
- Stretching is caused by a difference in forces on the two sides of an object.
- Since gravitational force depends on distance, there is more gravitational force on the side of Earth closest to the Moon and less gravitational force on the side of Earth farther from the Moon.



$$F_{Grav} = G\frac{Mm}{r^2}$$

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Lecture 8. Gravity

Why the Moon?

- The Sun's gravitational pull on Earth is much larger than the Moon's gravitational pull on Earth. So why do the tides follow the Moon and not the Sun?
- Since the Sun is much farther from Earth than the Moon, the difference in distance across Earth is much less significant for the Sun than the Moon, therefore the difference in gravitational force on the two sides of Earth is less for the Sun than for the Moon (even though the Sun's force on Earth is more).
- The Sun does have a small effect on Earth's tides, but the major effect is due to the Moon.

http://principia-scientific.org/images/moon_earth_and_sun.jpg