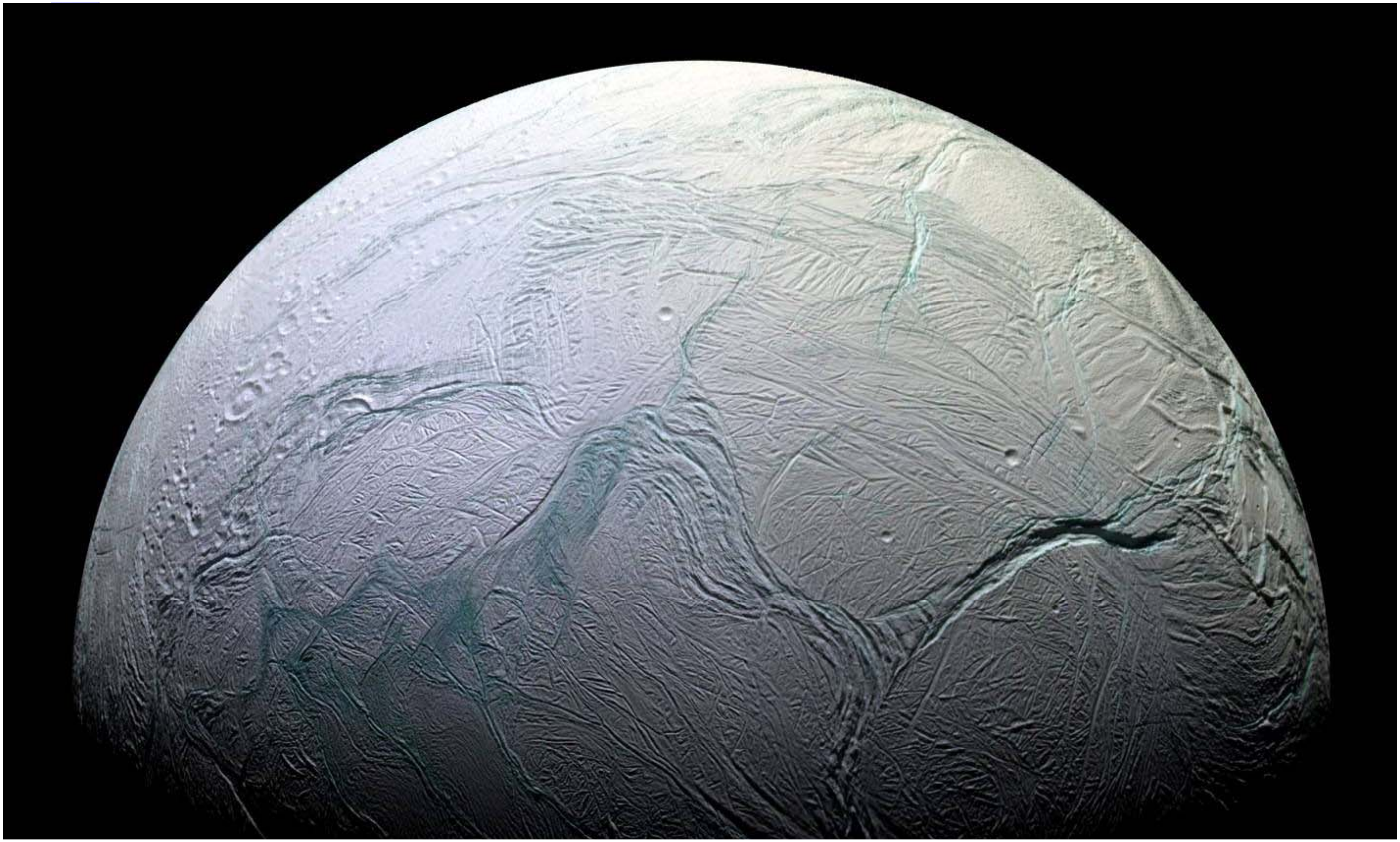
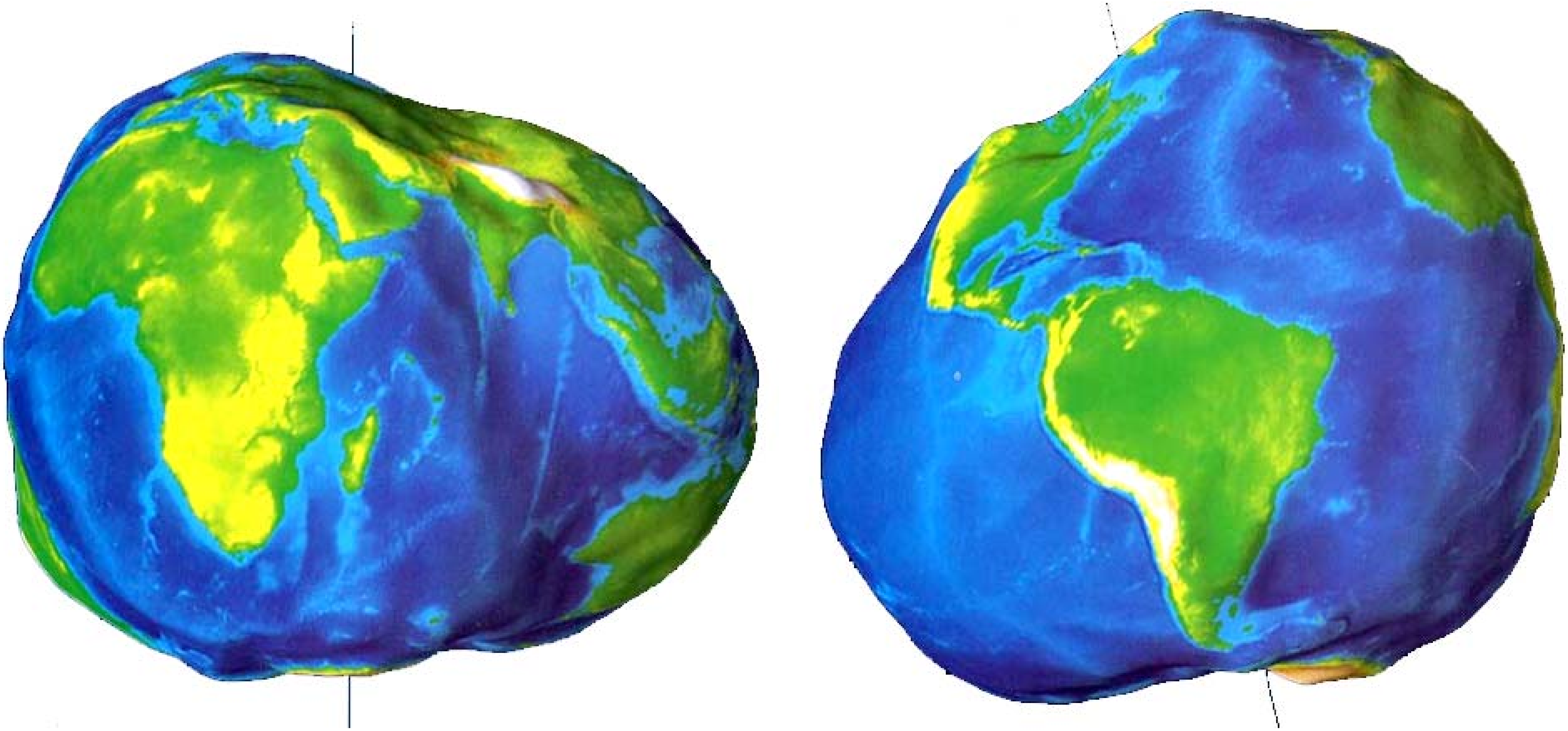
Announcements

- **D2L site up**
- **Homework 1 posted after class on website**
  - **http://www.lpl.arizona.edu/~shane/PTYS_206**
- **Look at the homework early!**
  - **You have a week to finish – not a week to start!**
  - **Due in class next Thursday**
- **TA is only Kevin Jones for now**
- **Priyanka will join us in ~3 weeks – please don't visit her until then.**
- **Office hours:** **Kevin – Tuesday 2-4pm, Gould-Simpson 511**
  Myself – Tue./Thur. 1.45-4pm, Kuiper 524



- **Observations**
  - **Craters, Trenches, Bright/white surface**
  - **Higher ground on the right, more craters on the left**

Orbits and Gravity



PTYS/ASTR 206 – The Golden Age of Planetary Exploration

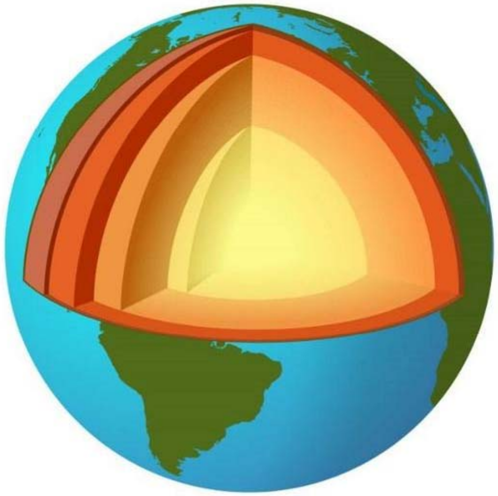
Shane Byrne – shane@lpl.arizona.edu

In this lecture…

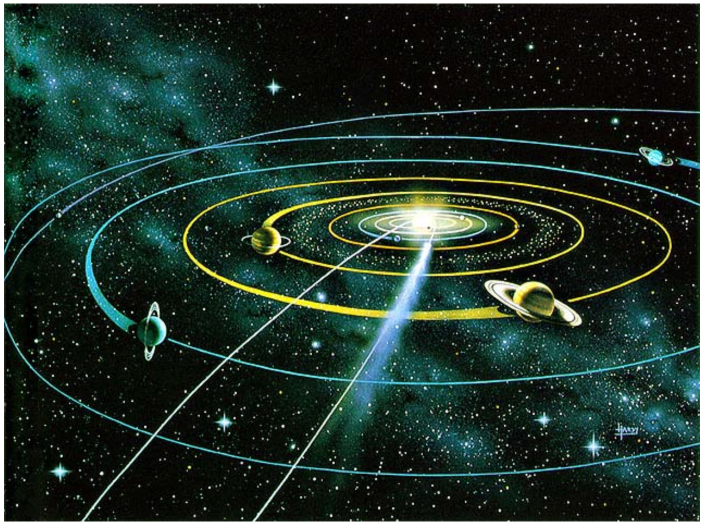
- Gravity
  - Newton and Galileo
- Planetary Shape
  - Flattening
  - The Geoid
- Tides
  - Fate of the Moon
- Orbits of planetary objects
  - Kepler’s laws

Where does gravity operate?

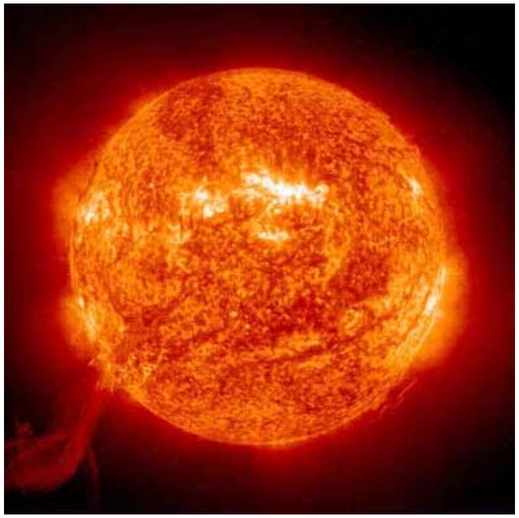
- Gravity is one of 4 physical forces in nature
  - Relatively unimportant on small scales
  - …but it dominates the universe at large scales



Holds planets together



Holds planets in their orbits



Provides pressure for fusion reactions in stars

Holds galaxies together

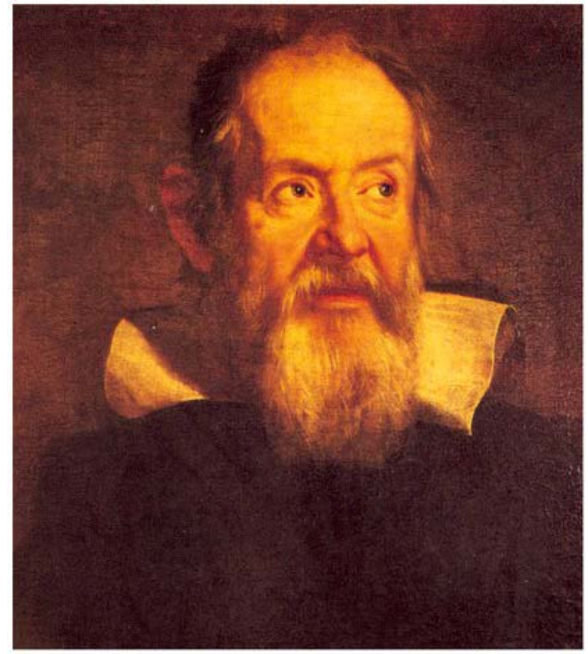
What’s gravity?

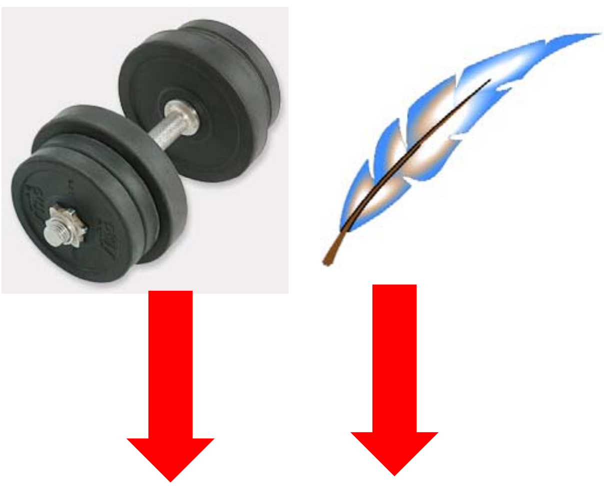
- **Objects that contain matter (they have mass) attract each other**
  - **This attractive force is called gravity, e.g.**
    - **Your body and the Earth**
    - **The Moon and the Earth**
    - **The Earth and the Sun**
    - **Your body with a comet billions of km away**
  - **The force of this attraction depends on three things**
    - **Mass of the first object**

    - **Mass of the second object**

    - **How far apart the objects are – e.g. distance between center of planet and objects on the surface**
  - **On Earth this force is the weight of the first object**

- **Galileo was first to systematically investigate gravity**
  - **Objects accelerate as they fall**
    - **i.e. the longer the drop the faster they hit the ground**
  - **All objects accelerate at the same rate**
    - **The famous leaning tower of Pisa experiment**
    - **Some doubt about whether this actually happened**

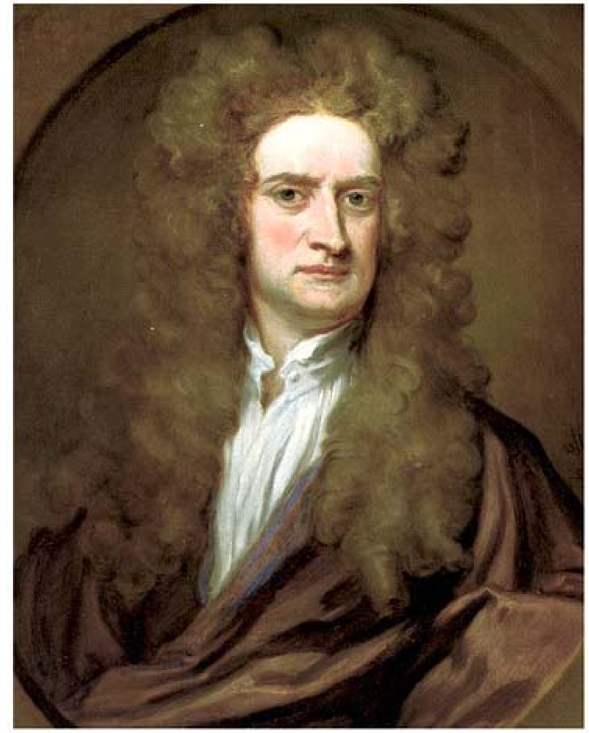




- **This acceleration is 9.8 m/s^2**
  - **0 m/s when you let it go**
  - **9.8 m/s after 1 seconds**
  - **2*9.8 m/s after 2 seconds etc…**

  - **This acceleration is not the same on other planets**
    - **e.g. it's 3.7 m/s^2 on Mars**

- **What gives?**
  - **Is gravity a force or an acceleration?**
  - **It's a force that produces an acceleration**
- **Isaac Newton developed modern mechanics – using three basic laws**
  - **With no forces operating an object doesn't change its momentum ($m_1 * v_1$)**
  - **A force (F) causes a change in momentum**
    - $F = M_1 * v_1 - M_1 * v_2 = M_1 * (v_1 - v_2) = M_1 * a_1$
  - **When one body exerts a force on another then there is an equal an opposite reaction**



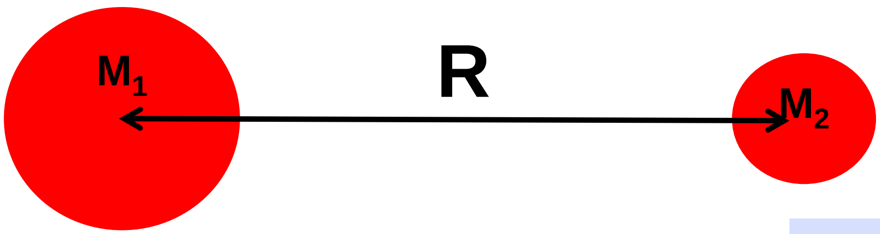
$$F = M_1 * a_1$$

$$F_{gravity} = M_1 * a_{gravity}$$

My $F_{gravity} = 80 \text{ kg} * 9.8 \text{m/s}^2$

784 Newtons (or ~175 lbs)

- Newton also figured out how to calculate the gravitational force between objects.
  - Mass of object 1 (M_1)
  - Mass of object 2 (M_2)
  - Distance between them (R)
- Objects behave like points at their centers of gravity



$$F_{gravity} = \frac{G * M_1 * M_2}{R^2}$$

'G' is a constant number
$6.67 * 10^{-11}$ m^3 kg^{-1} s^{-3}
The universal gravitational constant.

What's my $F_{gravity}$ with Earth?

M_1 = Me… 80 kg
M_2 = Earth… $5.97 * 10^{24}$ kg
R = Radius of Earth… 6371 km
R = Radius of Earth… $6.371*10^6$ m
…plug in the numbers…

784 Newtons

- **Reality check**
  - **Which is greater, the attraction between you and the Earth or you and the Sun?**

- **Reality check**
  - **Which is greater, the attraction between you and the Earth or you and the Sun?**
    - **The Earth – much closer…**

- **Reality check**
  - **Which is greater, the force on you from the Earth or force on the Earth from you?**

- **Reality check**
  - **Which is greater, the force on you from the Earth or force on the Earth from you?**
    - **They're the same – equal and opposite.**

- **It turns out that gravitational acceleration doesn't depend on how big your mass is**
  - **More mass makes it harder to accelerate**

…but…

  - **more mass also means a greater gravitational attraction**

- **Just like Galileo's falling object experiment**

$$F_{gravity} = \frac{G * M_1 * M_{EARTH}}{R^2}$$

$$F_{gravity} = M_1 * a_{gravity}$$

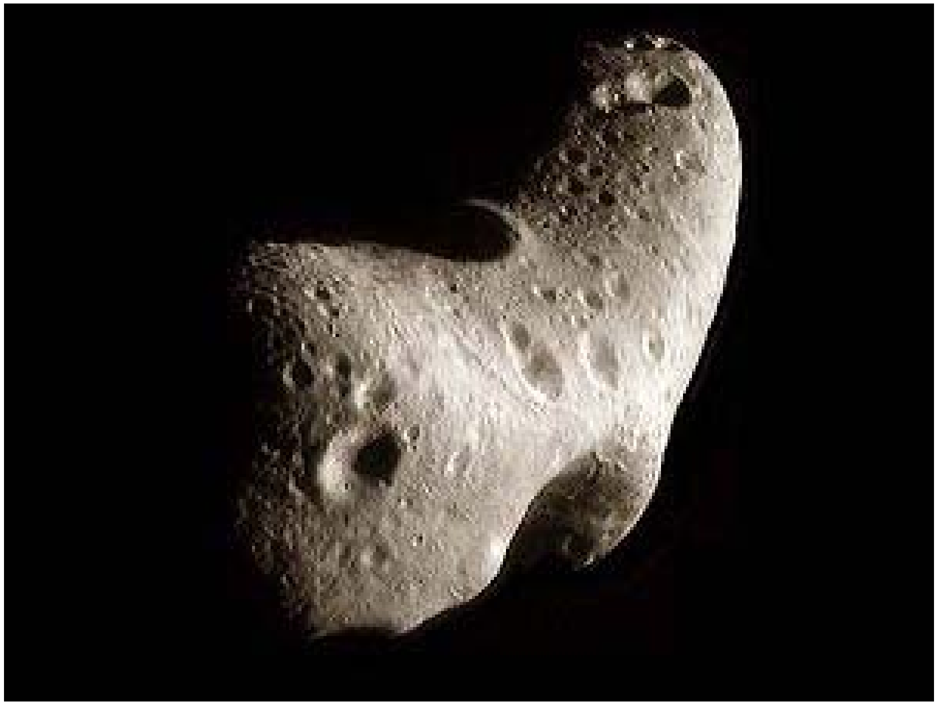
$$M_1 * a_{gravity} = \frac{G * M_1 * M_{EARTH}}{R^2}$$

$$a_{gravity} = \frac{G * M_{EARTH}}{R^2} = 9.8 \text{ m/s}^2$$

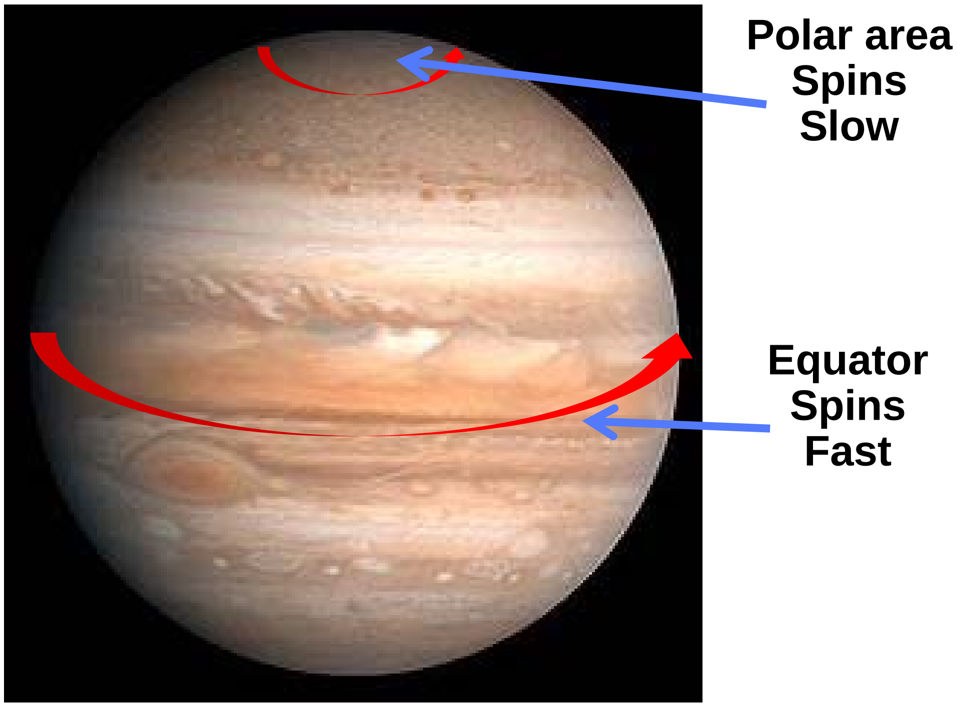
- **You can do this for any planet**

The shape of planets

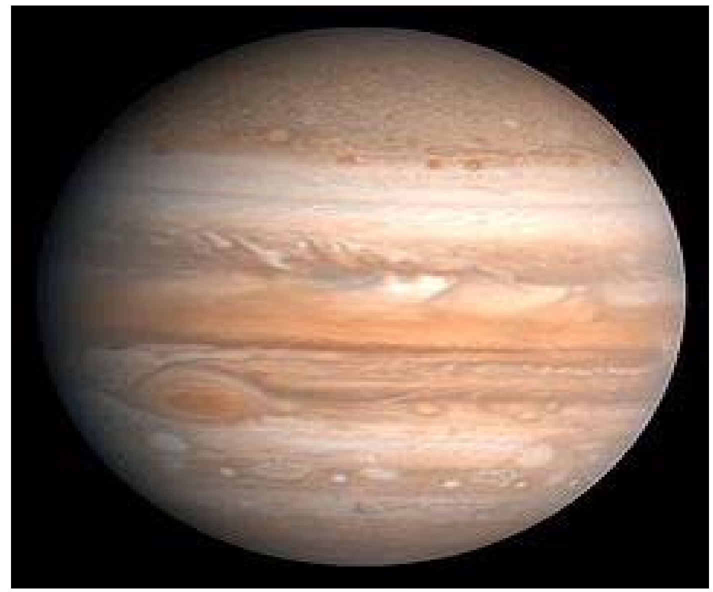
- Gravity has a strong influence on big bodies
  - Planets are round
  - Particles that formed them we're reorganized into a spherical shape
- …and a weak influence on the small ones.
  - Asteroids tend to be irregular
  - Particles that formed them remain stuck together in haphazard shape



- So gravity makes planets round…
  - That's not the end of the story
  - Planets are also spinning – creates a centrifugal force
  - All planets bulge at the equator
    - The faster the spin the bigger the bulge



What Jupiter currently looks like

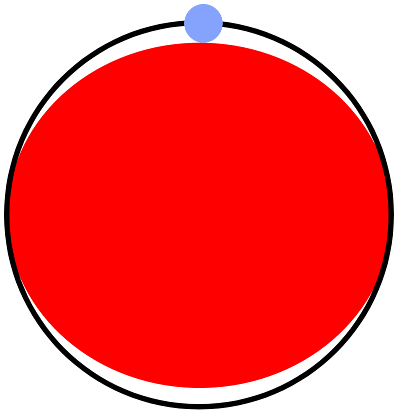


What Jupiter would look like if
We make it spin faster

- **We can figure out the expected shape by assuming a fluid planet**
  - **The 'Hydrostatic approximation'**

Planet	Equatorial Radius	Polar Radius
Earth	6378 km	6357 km
Mars	3396 km	3376 km
Jupiter	71,492 km	66,854 km

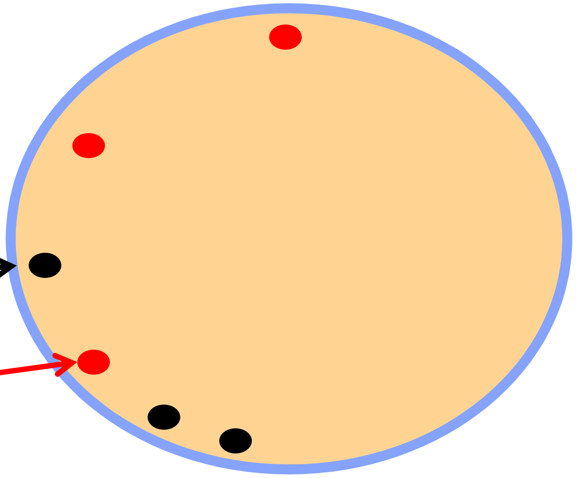
- **Combination of gravity and centrifugal forces**
  - **Planets mostly round**
  - **Slightly flattened**
  - **… but that's still not the whole story**



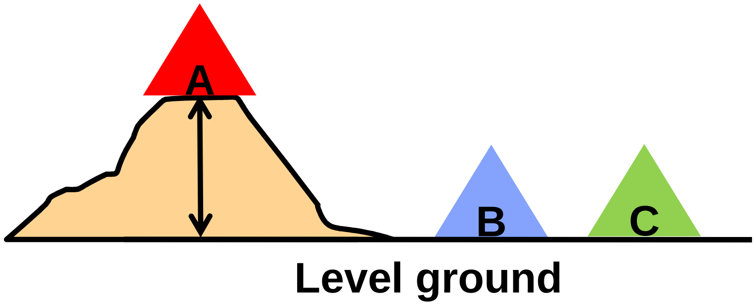
- **Jupiter rotates in only 10 hours**
  - **Very flattened**
  - **Difference in diameters is about the size of the Earth!**

- Earth looks a lot like this
  - But not quite….

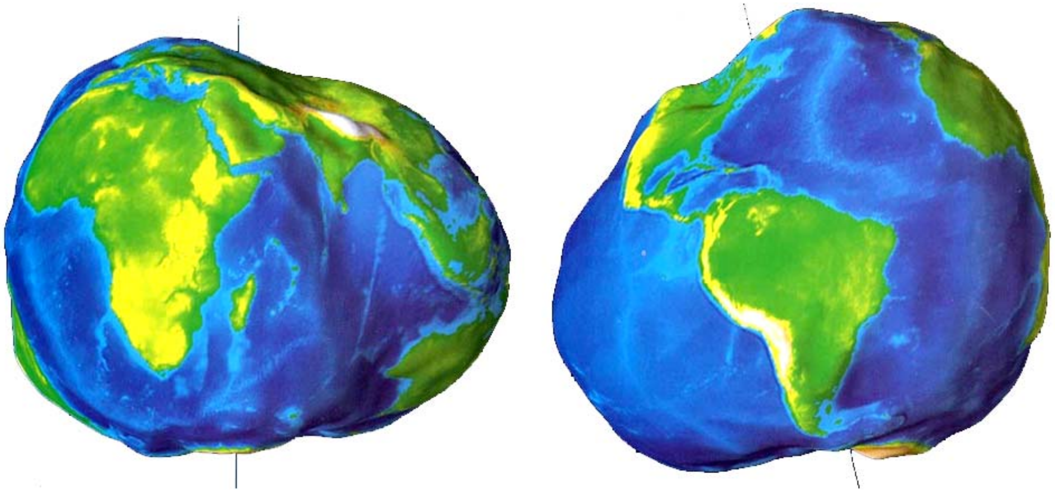
- Also variation underground
  - Mass excesses
    - Increases gravity
  - Mass deficits
    - Decreases gravity



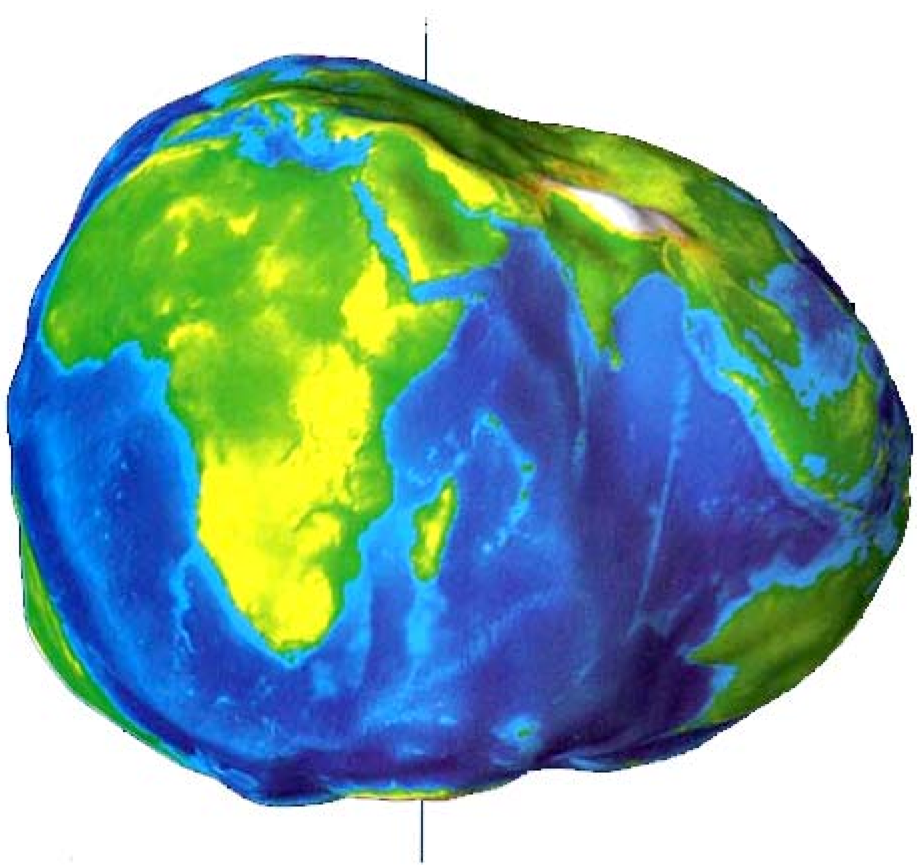
- What does flat mean?
  - Even a fluid planet (flat) has a curved surface
  - Flat means that the gravitational potential is the same

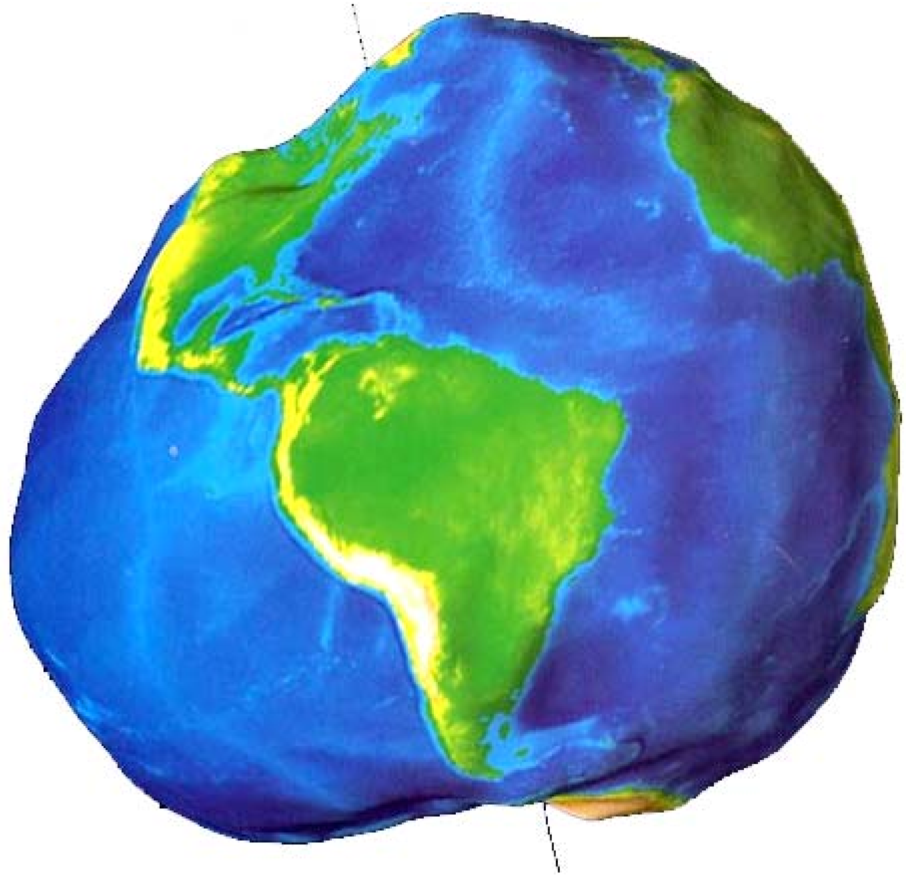


  - B & C here have the same potential, A has a higher potential
- Earth has lumps and bumps (mass deficits and excesses)
  - These lower and raise the equipotential surface
  - A "flat surface" on the Earth is pretty bumpy – called the Geoid



- **Geoid**
  - **Varies by about ±100m from the idealized ellipsoid**
  - **The view below is highly exaggerated**
  - **You can walk in and out of a ‘hollow’ in the geoid and it will have appeared flat**
  - **The geoid is the definition of what is flat**

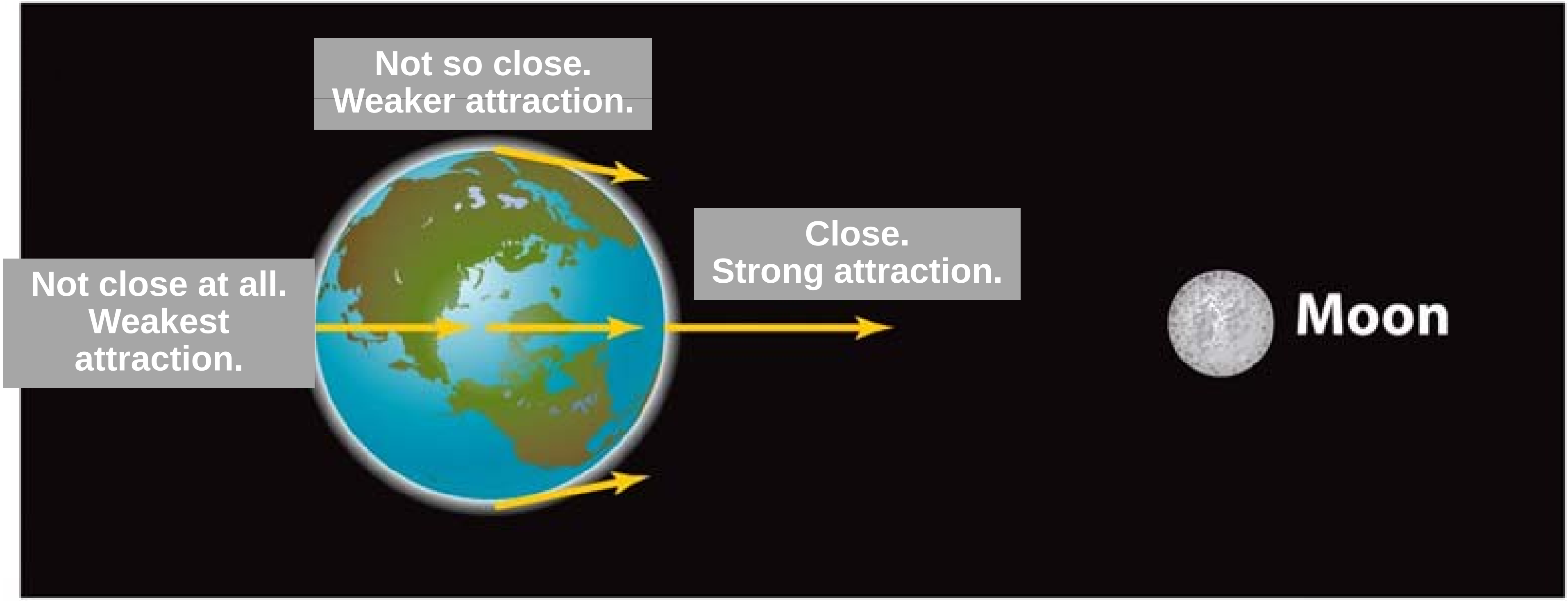




Tides

$$F_{gravity} = \frac{G * M_1 * M_{EARTH}}{R^2}$$

- We saw already that gravity depends on distance
  - When R is small (close) $F_{gravity}$ is big
  - This is what causes tides
- Tides on Earth are caused by the Sun and the Moon



- **Easier to think of this from the point of view of the center of the Earth**
  - **Which experiences the average amount of attraction**

- **Earth & Moon rotate around common center of gravity**
- **Each point experiences centrifugal and gravitational forces**
- **Forces at balanced at the center of the Earth**
  - **(but not at the surface)**
- **The tidal effect comes from the difference in these forces**

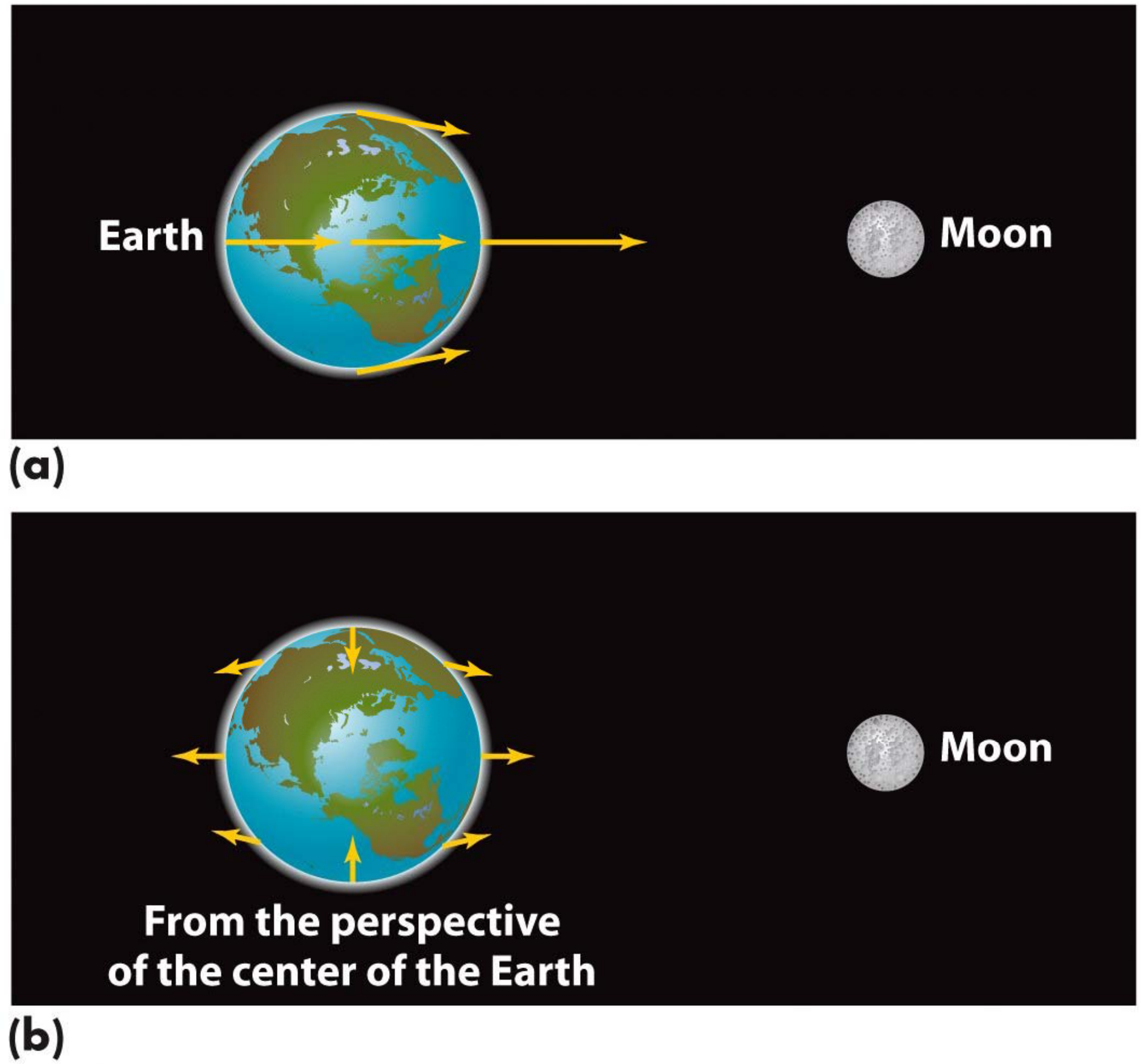
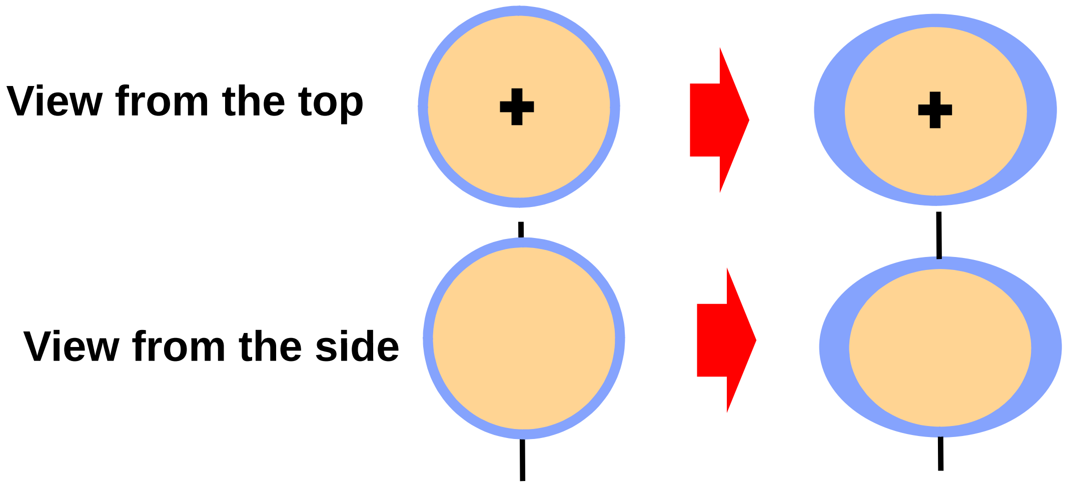


Figure 4-25
Universe, Eighth Edition

- **The tidal effect stretches out the planet**
  - **Not the same as flattening – stretch is in one direction only**
  - **Deforms the solid rocks**
  - **Pulls the liquid oceans even more**



  - **Tidal bulge points towards the Moon**
  - **The Sun causes a smaller tidal bulge**

- **High tide when you're pointing toward the Moon (or Sun)**
  - **Rotation of the Earth means the 'high' and 'low' tides come and go**
- **Solar and lunar tides can…**
  - **Reinforce each other… Spring tide**
  - **Almost cancel each other… Neap tide**
- **(As usual) that's not the whole story…**

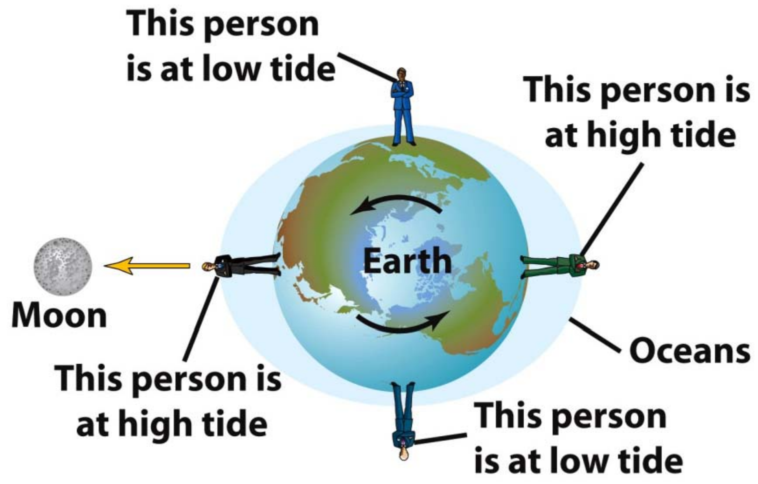


Figure 4-26a
Universe, Eighth Edition

Figure 4-26b
Universe, Eighth Edition

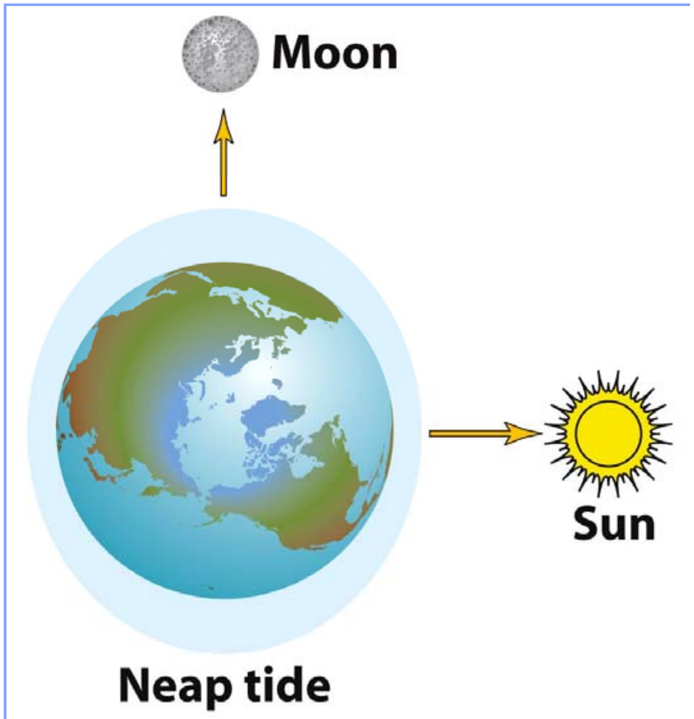
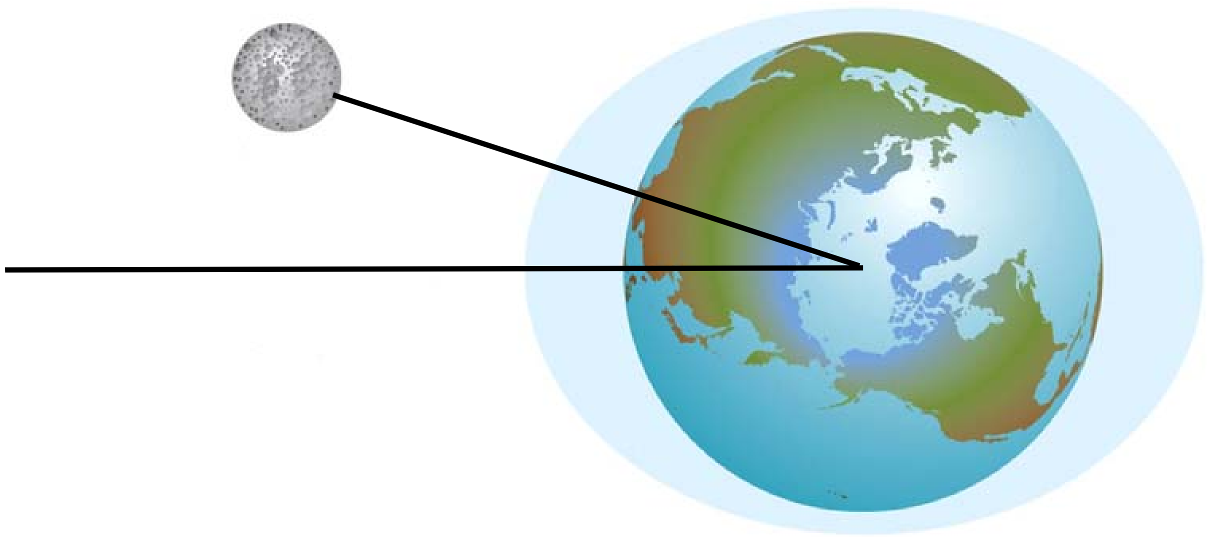
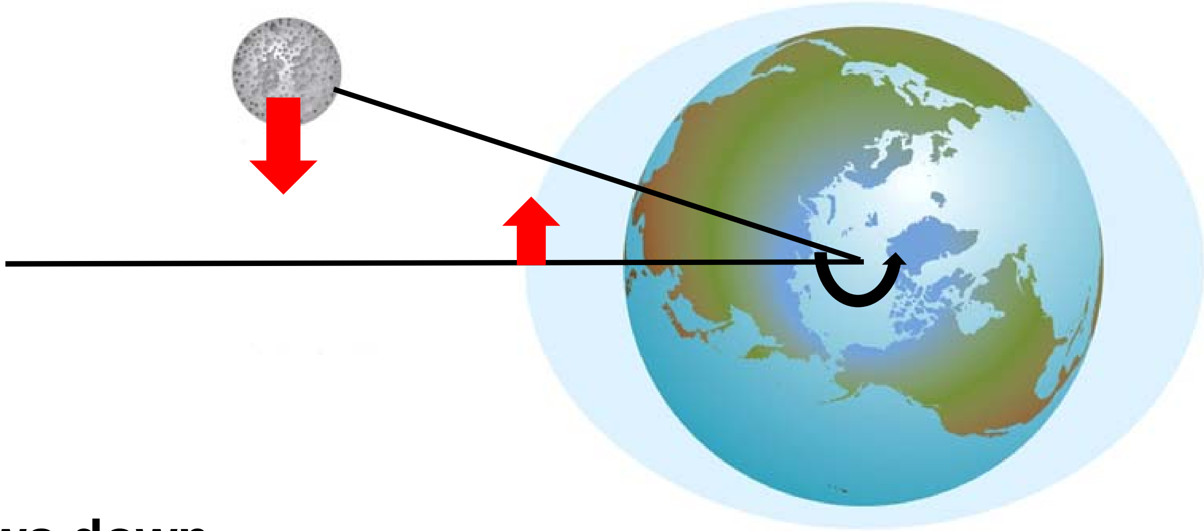


Figure 4-26c
Universe, Eighth Edition

- **Tidal bulge doesn't move exactly with the Moon**
  - **Earth is a big object**
  - **Rocks are stiff & hard to deform**
- **Earth rotates and carries the tidal bulge forward**
  - **The tidal bulge can't re-adjust fast enough to stay beneath the Moon**

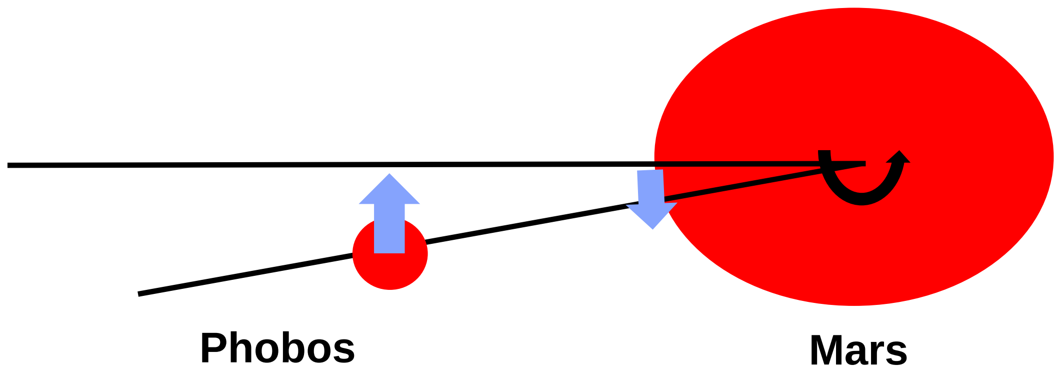


- **The Earth's bulge and the Moon can attract each other**



- **Earth's rotation slows down**
  - **~0.002 seconds/century**
- **Moon speeds up**
  - **And spirals away from the Earth**
  - **~1cm / year**

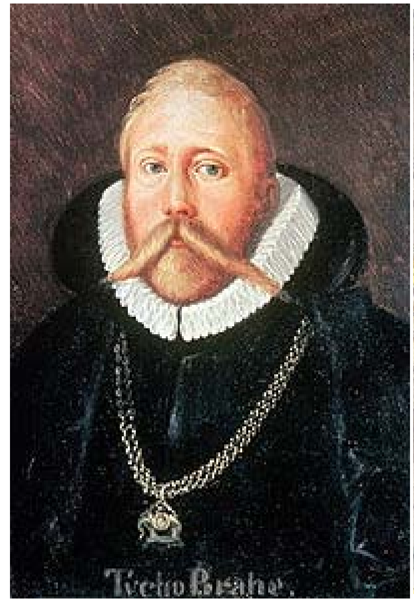
- Mars & Phobos
  - Opposite situation – Phobos orbits faster than Mars spins
  - Phobos is ahead of its tidal bulge
  - The tidal bulge can't re-adjust fast enough to stay beneath the Phobos

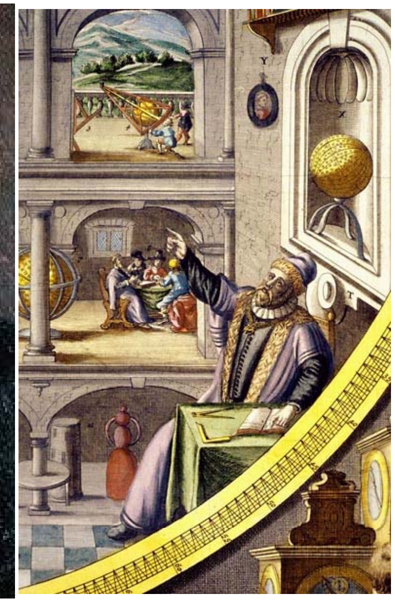


- Mars rotation speeds up
- Phobos slows down
  - And spirals towards Mars
  - Its days are numbered

Orbits

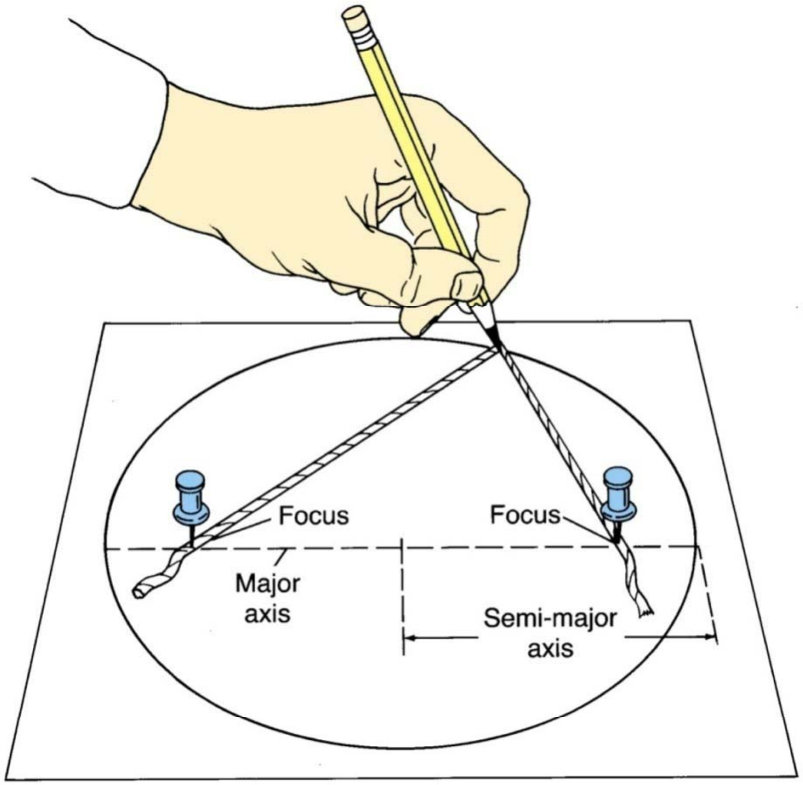
- **Observations by Tycho Brahe**
  - **Done without a telescope!**

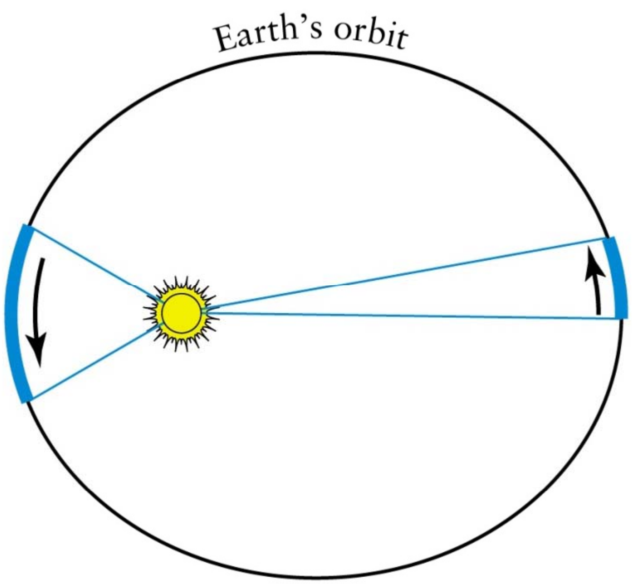




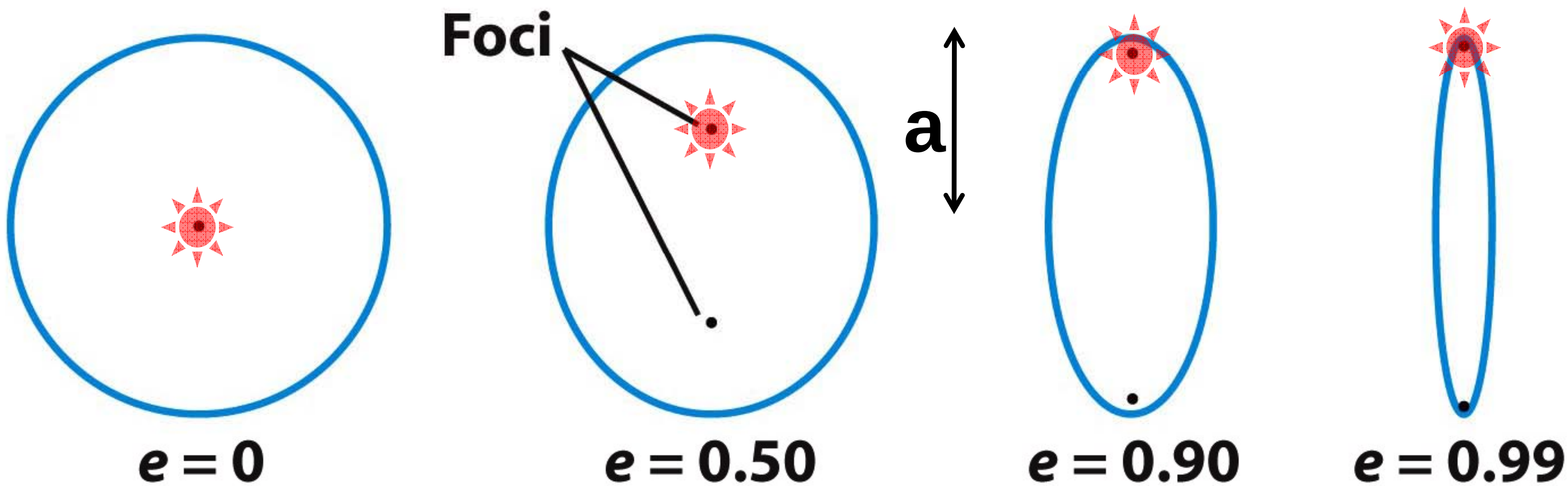
- **Kepler's 3 laws**
  - **Planetary orbits are ellipses**
  - **Planets move faster when closer to the sun**
  - **The period of a planet's orbit is related to its size**
    - **Big orbits take longer to complete**

- **Law 1: Orbits are ellipses**
  - **An ellipse has two foci**
  - **The further apart the foci are the more elongated the ellipse**
    - **With a circle the foci are both in the center and it's not elongated at all**
  - **The sun is at one of these foci**
  - **Means that planets are closer to the sun at some times that others**





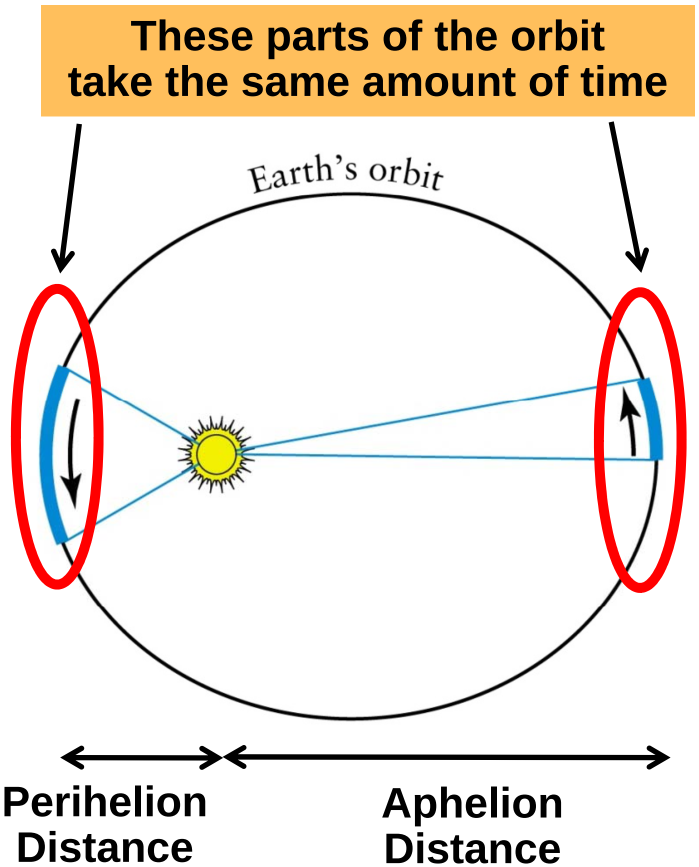
- **We describe how elongated the orbit is by the eccentricity (e).**
  - **Earth eccentricity is 0.017 – practically a circle!**
- **We describe the size of the orbit with the semi-major axis (a).**
  - **Half the long-axis of the ellipse**



Ellipses with different eccentricities

Figure 4-10b
Universe, Eighth Edition

- **Law 2: Objects move fastest when at closest to the sun**
  - **Perihelion distance = a*(1-e)**
  - **Aphelion distance = a*(1+e)**



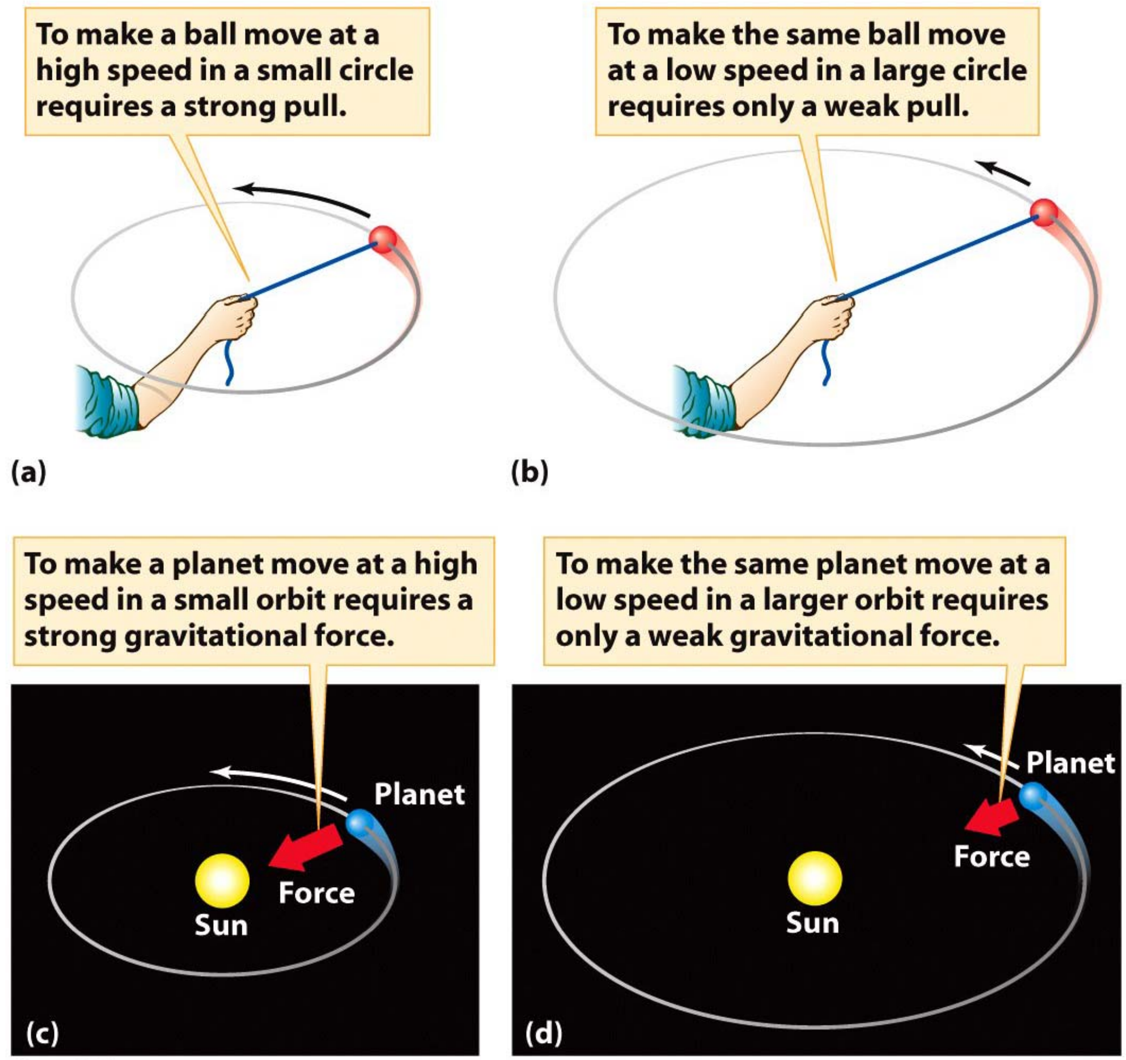


Figure 4-19
Universe, Eighth Edition

- **Law 3: The relation between semi-major axis and period**
  - **Back in Kepler's day the periods of planets were easy to measure**
  - **This law allowed them to be converted into semi-major axis**

$$p^2 = k_{sun} * a^3$$

  - **p is the period (usually seconds)**
  - **a is the semi-major axis (usually meters)**
  - **k_{sun} depends on the mass of the Sun.**
  - **…but we can make this easier**
    - **Use years for p**
    - **Use AU for a**
    - **Then k_{sun} is just one - i.e. you can ignore it**

$$p^2 = a^3$$

In years (p) — **In AU** (a)

  - **Careful, this works for things orbiting the Sun**
    Not other objects

Table 4-3 A Demonstration of Kepler's Third Law ($P^2 = a^3$)

Planet	Sidereal period P (years)	Semimajor axis a (AU)	P^2	a^3
Mercury	0.24	0.39	0.06	0.06
Venus	0.61	0.72	0.37	0.37
Earth	1.00	1.00	1.00	1.00
Mars	1.88	1.52	3.53	3.51
Jupiter	11.86	5.20	140.7	140.6
Saturn	29.46	9.55	867.9	871.0
Uranus	84.10	19.19	7,072	7,067
Neptune	164.86	30.07	27,180	27,190

Kepler's third law states that $P^2 = a^3$ for each of the planets. The last two columns of this table demonstrate that this relationship holds true to a very high level of accuracy.

Table 4-3
Universe, Eighth Edition

- **How about an example?**
  - **An asteroid takes 2 years to orbit the Sun.**
  - **What is its semimajor axis?**
    - **We know** $p^2 = a^3$
    - **So:** $2^2 = a^3$
    - **Use your calculator to figure this out:** $4 = a^3$ **So:** $4^{1/3} = a$
    - **The semi-major axis, a, turns out to be 1.59 AU**
- **And another?**
  - **Io orbits Jupiter every 1.77 days at a distance of 5.9 Jupiter Radii**
  - **For reasons we'll talk about later in the course Europa takes twice as long.**
  - **What's the size of Europa's orbit in Jupiter radii?**
    - **We know that, for things orbiting Jupiter:** $p^2 = k_{Jupiter} * a^3$
    - **Putting in the Io values of 1.77 for 'p' and 5.9 for 'a', gives** $k_{Jupiter} = 0.01525$
    - **Using that with Europa's period of 3.54 days:** $3.54^2 = 0.01525 * a^3$
    - **Then 'a' for Europa comes out to 9.4 Jupiter Radii**

- **And another example…**
  - **Io orbits Jupiter every 1.77 days at a distance of 5.9 Jupiter Radii**
  - **For reasons we'll talk about later in the course Europa takes twice as long.**
  - **What's the size of Europa's orbit in Jupiter radii?**
    - **We know that, for things orbiting Jupiter:** $p^2 = k_{Jupiter} * a^3$
    - **Putting in the Io values of 1.77 for 'p' and 5.9 for 'a', gives $k_{Jupiter} = 0.01525$**
    - **Using that with Europa's period of 3.54 days:** $3.54^2 = 0.01525 * a^3$
    - **Then 'a' for Europa comes out to 9.4 Jupiter Radii**
  - **Here we used units of Jupiter radii and days for length and time.**
  - **$K_{jupiter}$ depends on the mass of Jupiter, not the Sun**

In this lecture…

- Gravity
  - Newton and Galileo
- Planetary Shape
  - Flattening
  - The Geoid
- Tides
  - Fate of the Moon
- Orbits of planetary objects
  - Kepler's laws

Next: Light and Heat from Planets and Stars

- Reading
  - Chapter 4 to revise this lecture
  - Chapter 5 for next Tuesday