Isaac Newton and the Laws of Motion and Gravitation 2

ASTR 101 3/21/2018

- Center of Mass motion
- Oblate shape of planets due to rotation
- Tidal forces and tidal locking
- Discovery of Neptune

Center of Mass

- It is often said that the Moon goes around the Earth or the Earth revolve around the Sun.
- But that is not exactly correct. The gravitational attraction between two objects is mutual.
- Just as the Moon feels the gravitational pull from the Earth, Earth is subjected to the gravitational pull from the Moon.
 - So no reason the Earth stays in the middle and the Moon goes around it.
- What happens is that both Earth and the Moon go around their common center of mass.
- Center of mass is the average (or mean) location of all the mass in the system (single object or system made of few objects like the Earth and the Moon.)





The Earth and the Moon revolve around their mutual center of mass







- Center of mass is closer to the more massive object
- For example: the Earth is 82 time more massive than the Moon. (M_{c} = 7.35x10^{22 kg,} M_{\oplus} = 6x10²⁴ kg).
 - so the center of mass of the Earth-Moon system is 82 times closer to the Earth than the moon.
 - Center of mass of the Earth-Moon system is located within the Earth. To a good approximation it is like Moon moves around the Earth.
- The Sun is over 700 times more massive than the masses of all planets combined. Therefore the center of mass of the solar system is very close to the Sun.
 - For most purposes we can consider planets are moving around the Sun.



NH LORRI OPNAV CAMPAIGN 2 2015-01-25 02:01:00 UTC DISTANCE TO PLUTO: 202976224 km (PROPER MOTION)

Images taken by the New Horizons spacecraft in shows the dwarf planet Pluto and its largest moon, Charon, orbiting their common CoM. (orbital period ~6.4 days, images taken in January 2015, closest approach in July.)

www.nasa.gov/content/the-view-from-new-horizons-a-full-day-on-pluto-charon

- There are binary stars and planetary systems with companions having similar masses.
- When companions have comparable masses their center of mass is in the middle.

Oblate shape of the Earth

- In *Principia* Newton suggested that the Earth could not be perfectly round:
 - due to inertial forces resulting from rotation, the Earth had to bulge at the equator: Shape of an oblate spheroid



Without rotation gravity pulls matter towards the center from all directions



rotation creates an inertial outward force. It is largest near the equator

- Due to rotation, matter in the Earth moves in circular paths. Rotational velocity gets larger as the distance from the axis of rotation increases.
- As a result, inertia of matter tends to pull them outward. (just like a ball pull the string when it is in circular motion).
- It is zero at the poles and increases to a maximum at the equator.
- Resulting shape of this inertial "centrifugal force" and the Earth's gravity is an oblate spheroid.



• All rotating objects show such flattened shape.



- Earth:
 - Polar diameter: 12713 km
 - Equatorial diameter: 12756 km, flattening 0.3%
- Jupiter, and Saturn show much higher flattening due to their larger size and faster rotation.
 - Jupiter: flatting 6% (diameter $11d_{\oplus}$, rotational period ~10 hours)
 - Saturn: flattening 10% (diameter 9.5 d $_{\oplus}$ rotational period ~10.6 hours)



- Gravitational attraction between objects decrease with inverse square of the distance between them $(1/r^2)$.
- As a result when a large body (like Earth) is attracted to another (say Sun) it will experience a larger attractive force on the nearest side to the other than it will on the far side.
- This difference in the gravitational force across an object creates stress in the object called Tidal forces, which tries to stretch the object.
- Tidal forces could deform and tear apart objects

Roche Limit

planet

particles are at different distances are attracted differently by the planet

at the same time are attracted toward each other due to their mutual gravity

- The planet tries to tug the particles apart, while the particles themselves are trying to pull themselves together due to their own gravity.
- The distance to the particles from the planet determines which process dominates.
 - Far from the planet mutual gravity of the particles can pull them together, particles coalesce to form a larger object (a moon) under their own gravity
 - Close to the planet, the planet's tidal forces trying to rip them apart are stronger than the mutual gravitational forces trying to keep them together, and tear them apart.
- The borderline distance which separates the regions where an object (e.g. a moon) held together by its self-gravity can exist as a single object from the region where they get torn apart due to tidal forces is called the *Roche Limit*.

Roche Limit



Outside the limit material tends to coalesce, or stay together. , whereas Inside the Roche limit, orbiting material disperses and forms rings (like Saturn's rings)

(**Roche limits:** Earth 18,470 km, Jupiter 175,000km, Saturn 147,000km)

Roche limit

Tidal Forces



apod.nasa.gov/apod/ap040724.html

Comet Shoemaker-Levy torn into fragments by tidal forces before it collided with Jupiter. (Hubble space telescope photo taken on May 17, 1994)



a collision



Mars' moon Phobos is orbiting just 6,000 km above the surface of Mars. Grooves visible on Phobos could be an indication of early signs of the structural failure produced by tidal forces.

https://www.nasa.gov/feature/goddard/phobos-is-falling-apart

Roche limit

Rings: tidal forces prevented forming moons





Cassini spacecraft image of Saturn rings apod.nasa.gov/apod/ap040723.html

Rings are made of small particles (an illustration)

Saturn rings are made of small particles (from micrometers to meters in size), mostly ice particles. Since they are within the Roche limit, tidal forces prevent them coming together and forming large objects.

Ocean Tides



- Ocean tides are the phenomena of periodic rise and fall of the sea level. There are two high tides and two low tides every 24 h 50m.
- They are a result of the tidal forces of the Moon and the Sun on Earth.
- In Principia Newton explained what causing the tides.



Sun

Consider the effect of Sun's gravitation on the Earth and the ocean:

- The gravitational attraction to the Sun is stronger on the side closer to the sun (A).
- The gravitational attraction to the Sun is weaker on the side opposite to the sun (B).
 - The difference in gravitational attraction tries to pull Earth apart.
 - Solid earth cannot move, but ocean water can flow, thus rising ocean levels both toward and away from the Sun (high tides).
 - When water pileup under and opposite sides of the sun, water levels drop (low tide) in other areas (D,E).



Similar mechanism work with the Moon's gravitational pull on Earth:

- Moon's gravitational pull on Earth is weaker than that of the Sun.
- But the Moon is closer to the Earth than the Sun.
 - ⇒ difference in the Moon's gravitational attraction on opposite sides of the Earth is larger ⇒ Twice stronger tidal forces.
- Hence lunar tides are two times larger than solar tides.
 - High tides are experienced when the Moon is at the zenith or at the nadir.
 - Low tides occur when the moon is at the horizon (east or west)
 - Length of the lunar day is 24h 50m (That is the time for moon to come to same position in the sky again.)
 - High tides due to the Moon occur at a given location every 12h 25m. Same with low tides.





Overall tide is a combination of solar and lunar tides :

- When the Sun and the Moon line up combined lunar and solar tides reinforce each other causing largest tides called **Spring tides**
 - Happens on a full moon or new moon day



- When the Moon is at quarter phase, combined lunar and solar tides oppose each other, causing smaller tides called **Neap Tides**
 - Happens on a first quarter or last quarter moon

Tidal friction/acceleration in the Earth-Moon system



- Since tidal force by the Moon is stronger we expect the tidal bulge always point directly towards the moon.
 - But due to the rotation of the Earth and the friction between ocean floor and water, lunar tidal bulge sits slightly ahead of the Earth-Moon line.

Tidal friction/acceleration in the Earth-Moon system



- But due to the rotation of the Earth and the friction between ocean floor and water, lunar tidal bulge sits slightly ahead of the Earth-Moon line.
 - Tidal bulge closer to the Moon is pulled by Moon's gravity more than the tidal bulge on opposite side.
 - This creates a torque on earth, trying to turn it in opposite direction to its rotation.
 - That gradually slows down the rotation speed of Earth.
 - Length of the day increases by 1.4 millisecond per century
 - It is cumulative, a leap second is added to the day every few years.

Tidal friction/acceleration



- The gravity of the tidal bulge pulls the Moon ahead, increasing the moon's speed
- Which increases its distance.
 - The Moon recedes from the Earth 4 cm a year.

Slowing down of the Earth



- The Earth was rotating faster in the past and the Moon was closer.
 - Evidence from fossilized coral and mineral sediments
 - Daily and annual coral growth patterns suggest that
 - 350 million years ago a year was about 385 days (a day was 23 hours)
 - 620 million years ago a year was about 400 days (a day was 22 hours)

www.scientificamerican.com/article/earth-rotation-summer-solstice

Discovery of Uranus and Neptune



Replica of the 7 inch reflector telescope used by Herschel to discover Uranus



Uranus Distance to Sun: 2.9×10^9 km (19.2 AU) Orbital period: 84.1 years Rotational period: 17.24 hours Mass: 8.68 \text{1025 kg}, (14.5 M_{\overline{\phi}}) Diameter: 51100 (4 d_{\overline{\phi}}) Temperature: 55K (-218°C)}}

- Five planets ("wandering stars") were known since antiquity.
- Planet Uranus was discovered in 1781 by William Herschel, a professional musician and an amateur astronomer.
 - On March 13, 1781 while he was looking for double stars with his telescope in the constellation Gemini, he saw a star appeared like a fuzzy disk rather than a point.
 - He initially thought it was a comet. But subsequent observation by him and others indicated that it was a planet, located beyond Saturn and not known until then. It was named Uranus.
 - Hershel became a prominent astronomer later, built larger telescopes, and made many discoveries.



- Distance to Sun: 30.1 AU Orbital period: 164.9 years
- After the discovery of Uranus, it was noticed that its position in the sky did not follow the orbit estimated with Newton's laws.
- It was deviating about 1 arc second per year from the predicted orbit.
 - It could be something wrong with Newton's laws of motion and gravitation.
 - or it could be some unknown massive object pulling it away from its orbit around the Sun.
- Two mathematicians, British John Adams and French Urbain Le Verrier thought it was the gravitational pull of an unknown planet causing the deviation of Uranus orbit.
 - They independently predicted the position of such an object that would account for observed deviations of Uranus' position.
- Neptune was first observed on 1846 Sept 23, very close to the predicted location by two German astronomers, Johan Galle and Heinrich d'Arrest.
- It was a major triumph of the Newton's laws of motion and gravitation.

- Gravitation not only described the motions of planets orbiting the Sun, they enabled making predictions and calculate things they had not previously thought were possible.
- This was a spectacular achievement, something no one had ever done before.
- In summary, Newton's laws of motion and universal gravitation provided a comprehensive, quantitative framework to explain the motions of all objects, on the Earth and in the universe.
- This set the framework for physical science which remains with us to today.
- And so it is not surprising that Newton is regarded as one of the great intellectual giants of all time.

"I do not know what I may appear to the world, but to myself I seem to have been only like a boy playing on the sea-shore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me" -Isaac Newton

Review Questions

- What is the center of mass? If both stars of a binary system has similar masses where would be its center of mass located?
- Does the sun move due to gravitational pull by planets?
- What is the greater force, gravitational pull by the Moon on Earth or the gravitational pull by the Earth on the Moon?
- What keeps the moon falling into the Earth due to earths gravitational pull on the moon
- What causes tides?
- Why does the Moon causes grater tides than the Sun even though the Sun's gravitational pull is greater on Earth than the gravitational pull by the Moon?
- What are spring tides and neap tides. What is the phase of the Moon when they occur?
- What is the reason for the Oblate spheroid shape of Saturn?
- Is Sun the only object influence the motion of a planet in the solar system?
- According to Kepler laws path of a planet is an eclipse with the Sun at one of the foci. From what you learned in this section is that exactly true statement?
- What made the astronomers think that the planet Neptune must exist ?