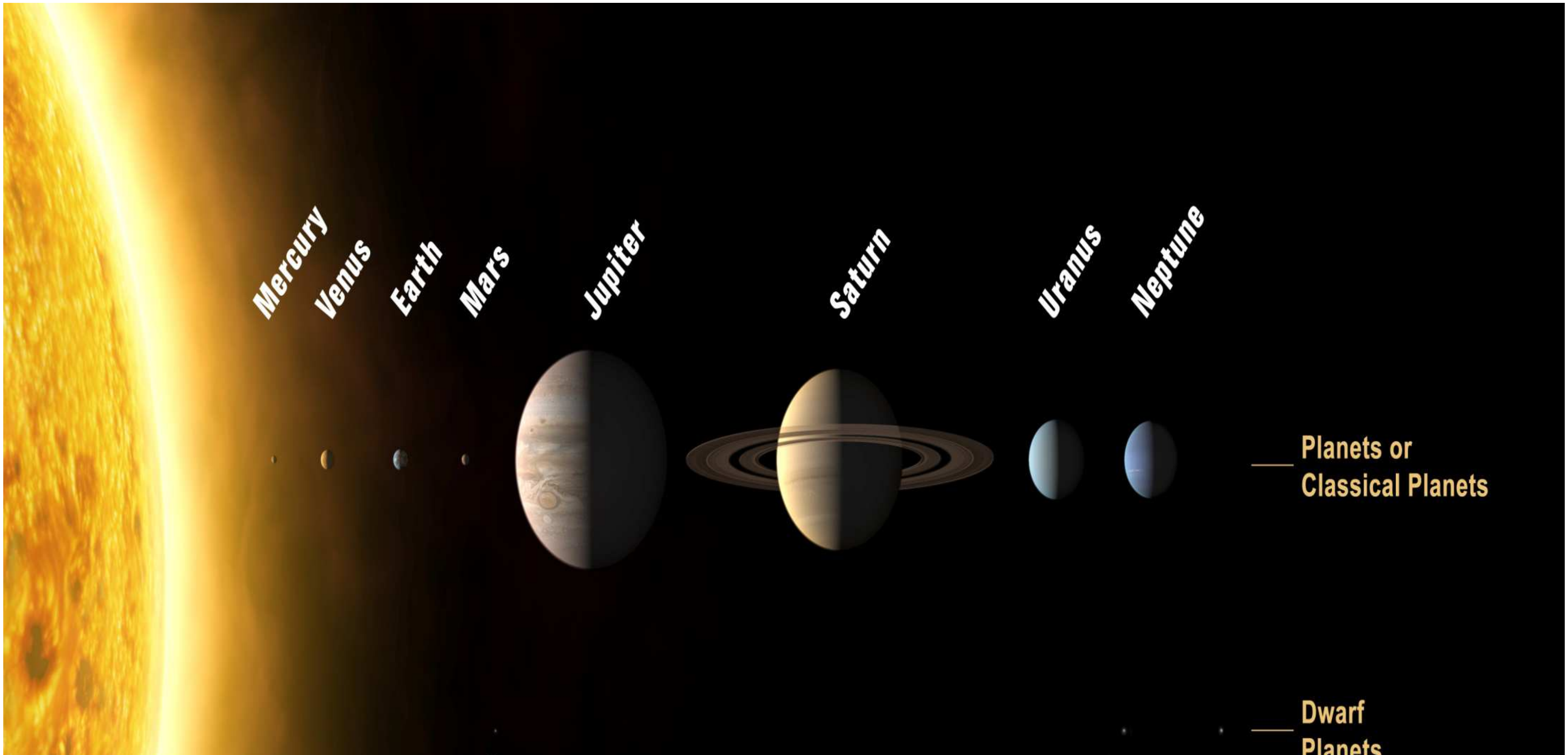
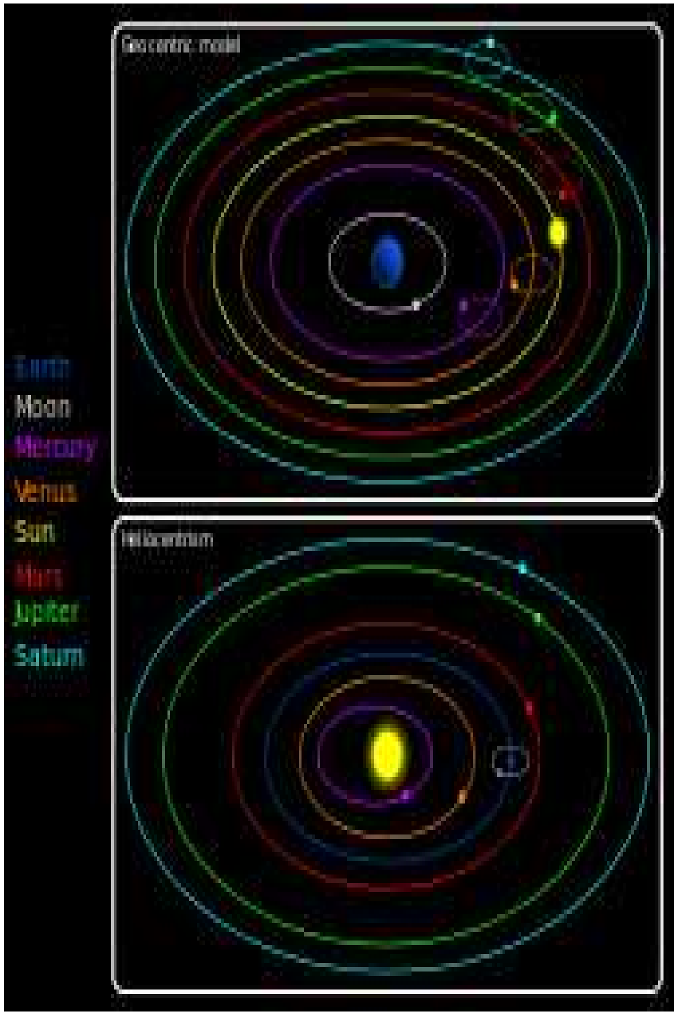


Chapter 2

The Copernican Revolution

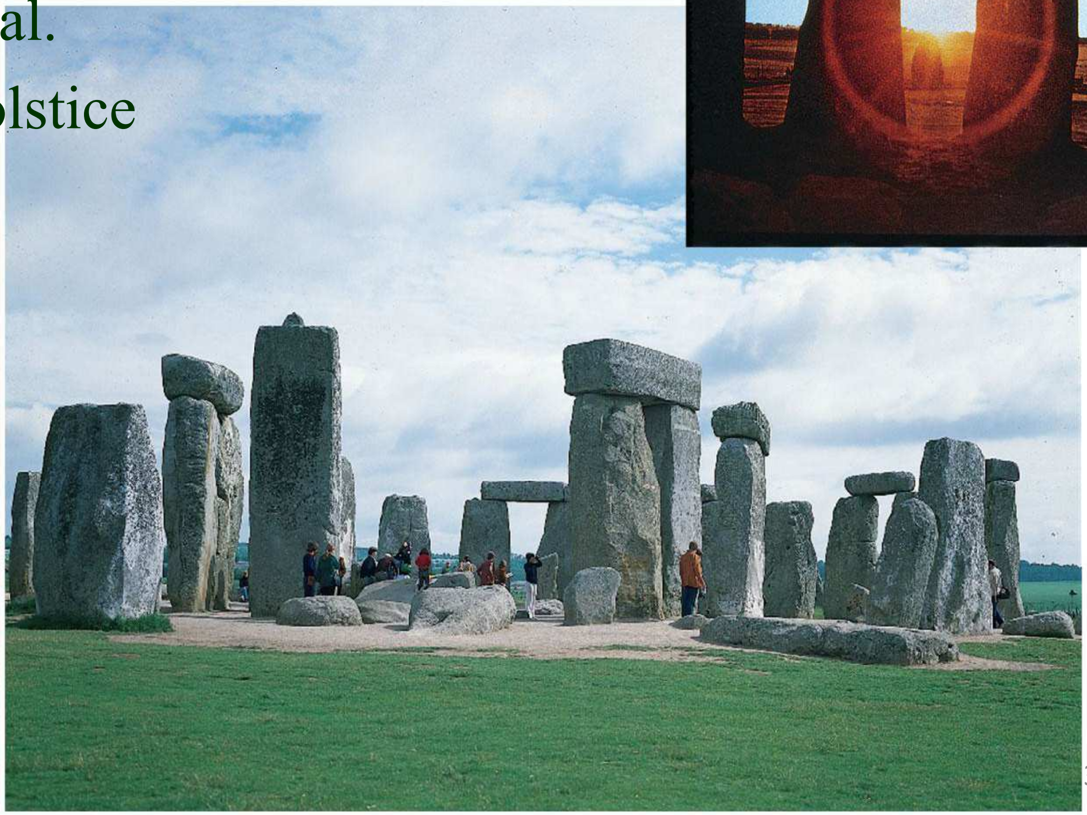


Learning Goals:

2.1 Ancient Astronomy
2.2 The Geocentric Universe
2.3 The Heliocentric Model
2.4 Birth of Modern Astronomy
2.5 Planetary Motion's Laws
2.6 Solar System's Dimensions
2.7 Newton's Laws (*Farah,Thurs.*)
2.8 Newtonian Mechanics Weighing the Sun

2.1 Ancient Astronomy

- Human minds & invention of constellations
- Practical means of tracking the seasons, …
- *Stonehenge*: England, early astronomical observatory
- Building span 17 centuries, 2800 – 1100 B.C.
- Stones aligned to point toward astronomical events.
- Uncertain & controversial.
- Sun rising @ summer solstice
- Moon's motion.



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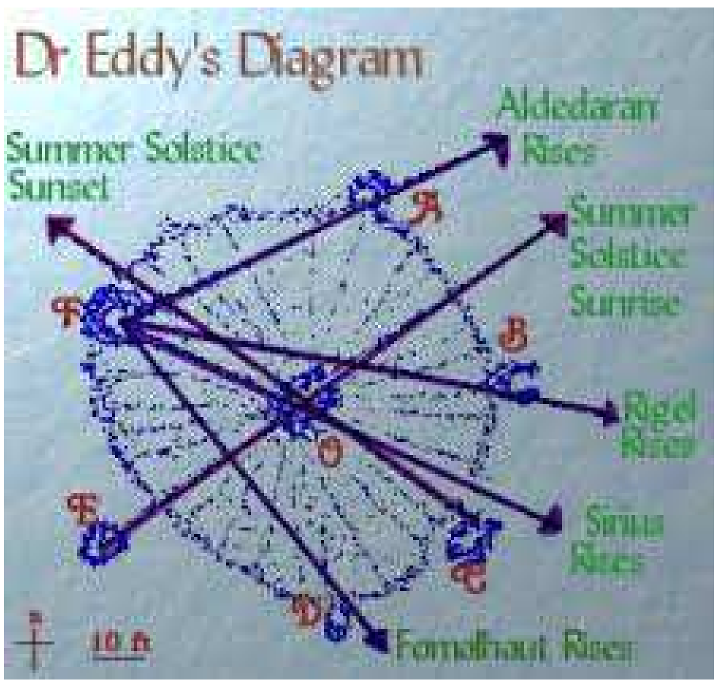
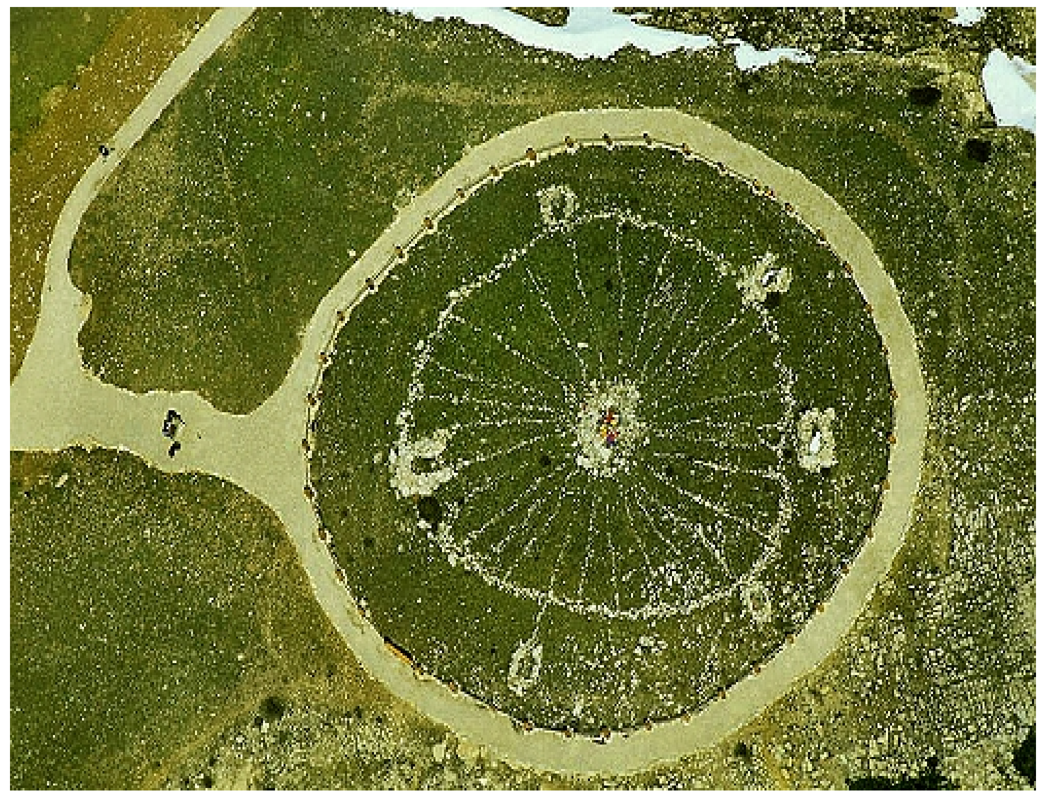
2.1 Ancient Astronomy

Big Horn Medicine Wheel, north America by Indians
→ rising and setting Sun at solstices and equinoxes, bright stars
→ Experts: inaccurate and consistent → Symplic





2.1 Ancient Astronomy

Caracol Temple,

Mexico 1000 A.D.

many windows that are aligned with astronomical events

(b)

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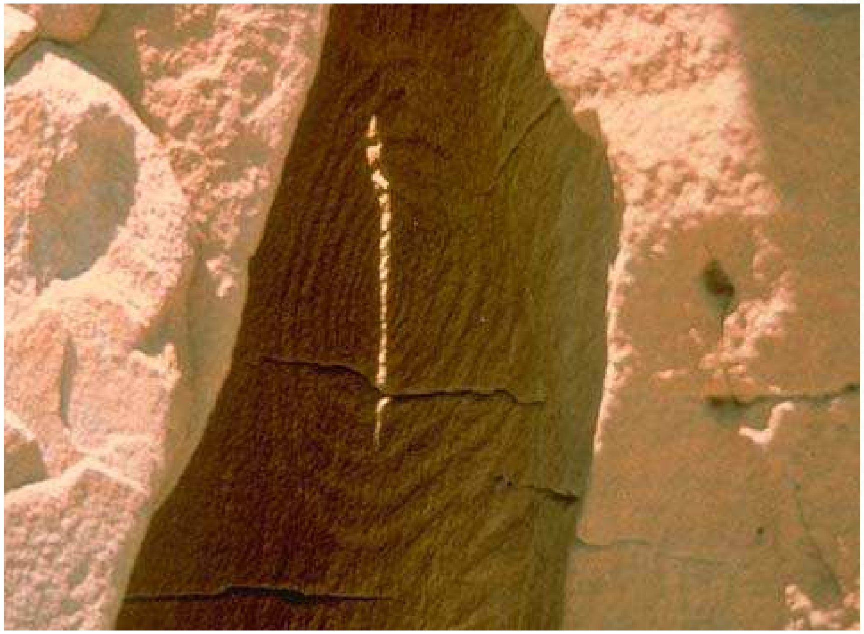
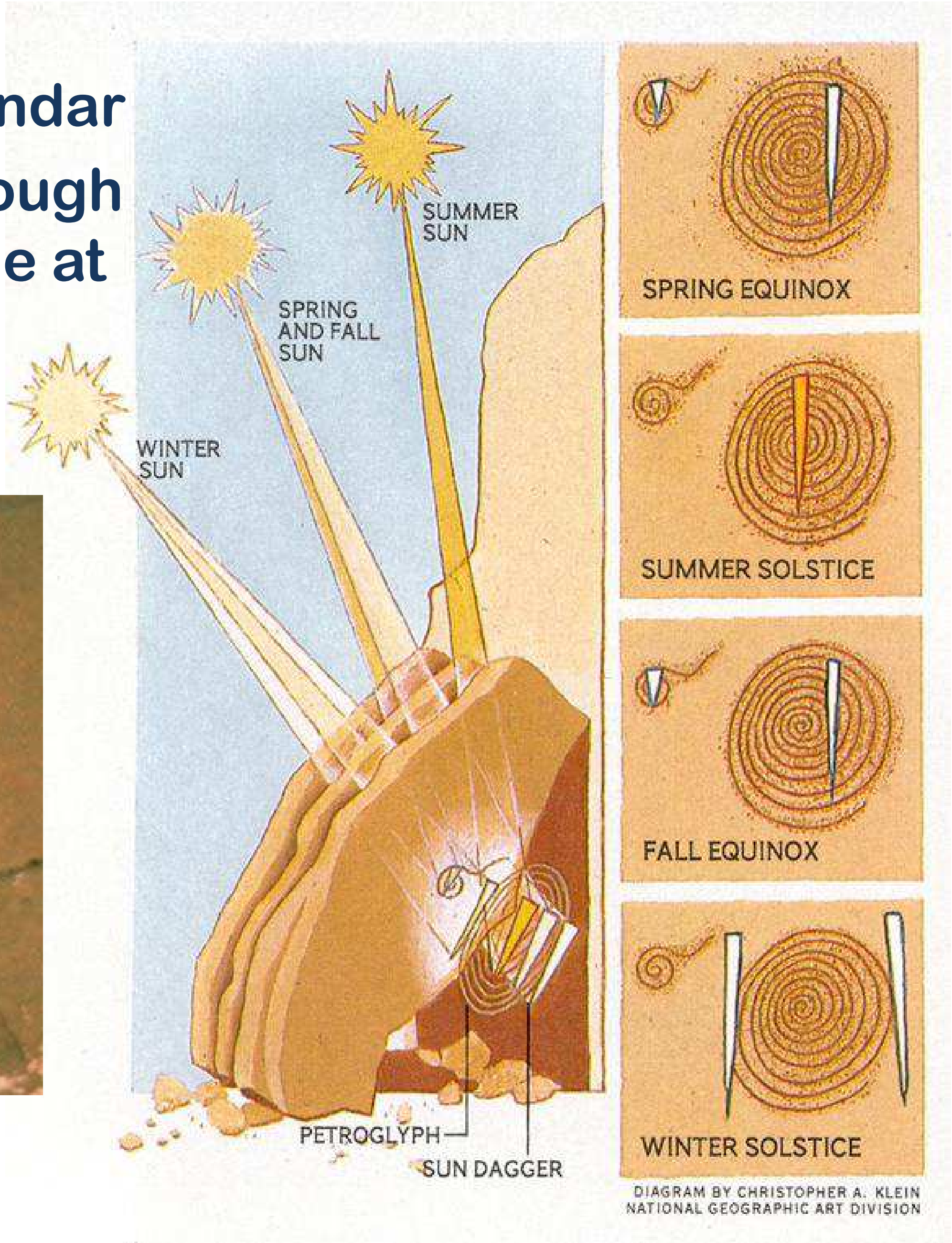
2.1 Ancient Astronomy

- **Sun Dagger: New Mexico**
- **Genuine astronomical calendar**
- **Light passes precisely through the center of a carved stone at noon.**





2.1 Ancient Astronomy

- **Chinese observations recorded.**
- **Islamic Astronomy flourished and grew, preserving Greeks' knowledge.**
- **Mathematical techniques to determine dates of holy days and location of Mecca.**
- **Zenith, Azimuth, names of stars..**

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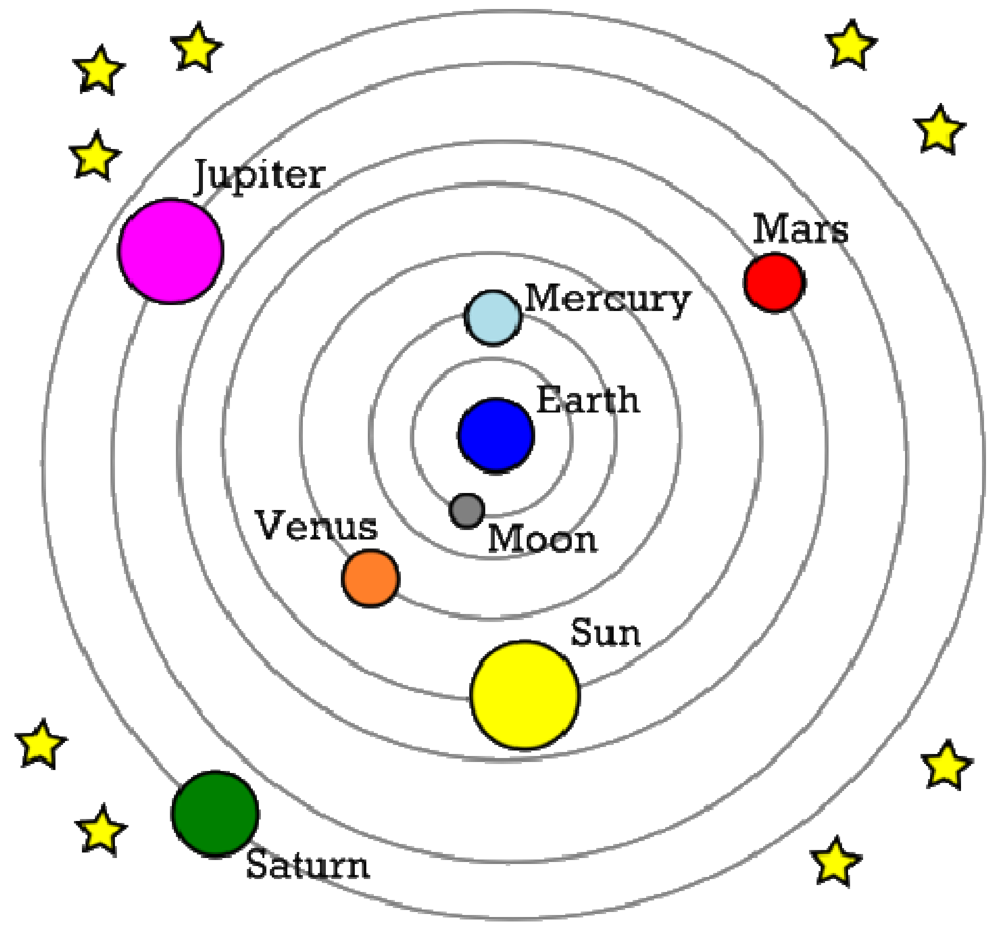
2.2 The Geocentric Universe

- **Ancient astronomers observed:**
  Sun
  Moon
  Stars

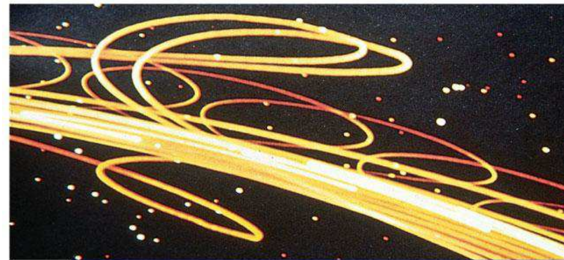
  Five planets:
  Mercury, Venus,
  Mars, Jupiter,
  Saturn

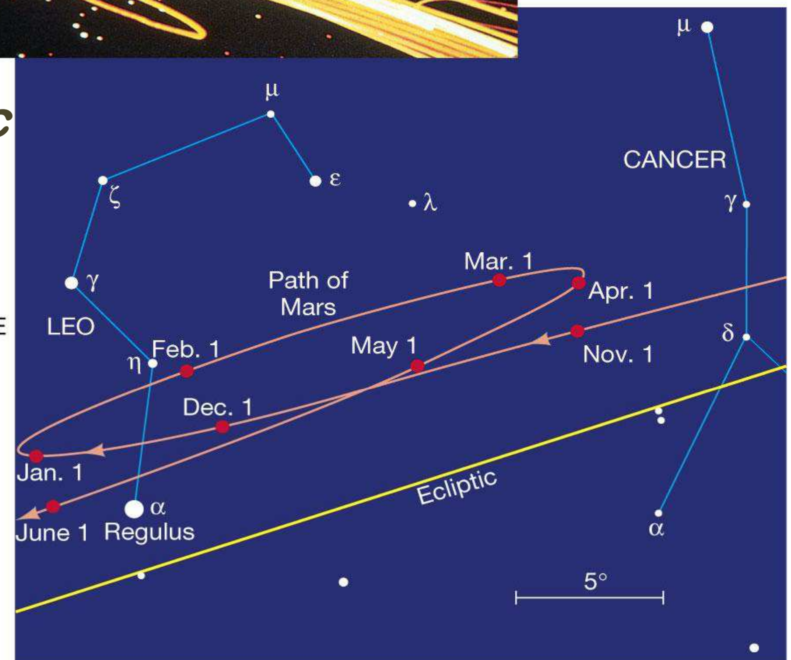


2.2 The Geocentric Universe

For Greeks, the universe is the solar system, observation:

- **Night:** ***stars slid smoothly.***
- **Month:** ***Moon moved Steadily.***
- **Year:** ***Sun progressed along the ecliptic at constant rate.***
- **Behavior of Sun and moon is OK!**
- **Vary Little in Brightness.**





- Planets (wanderer) motion difficult to grasp.

  Change in brightness

  Change speed

  Undergo retrograde motion

2.2 The Geocentric Universe

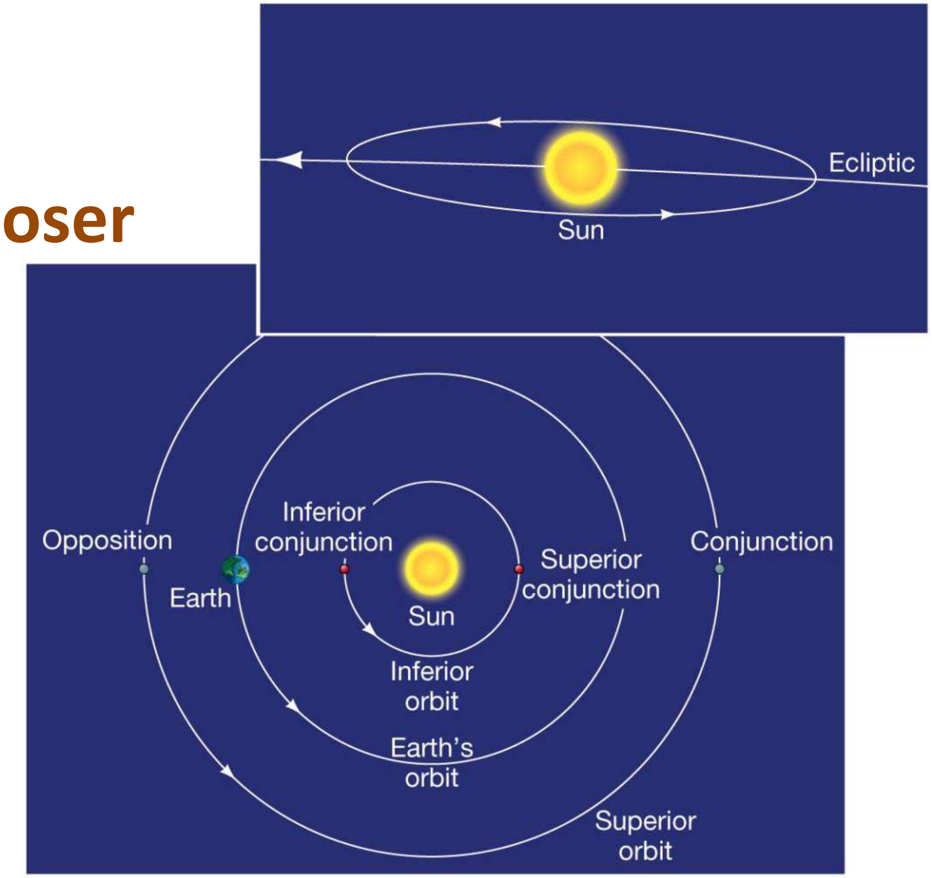
Inferior planets: Mercury, Venus

Superior planets: Mars, Jupiter, Saturn

Now know:

Inferior planets have orbits closer to Sun than Earth's

Superior planets' orbits are farther away



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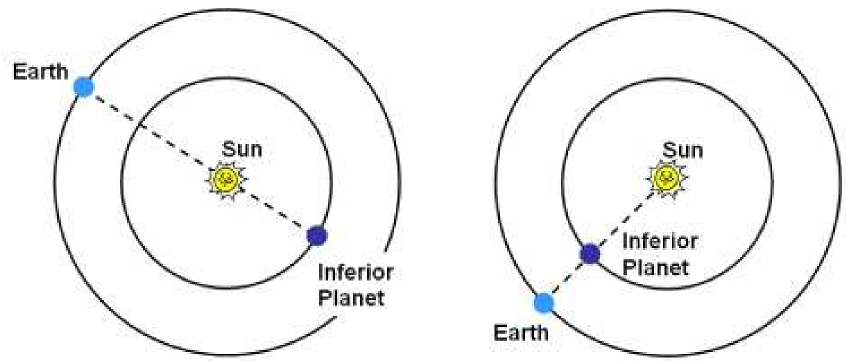
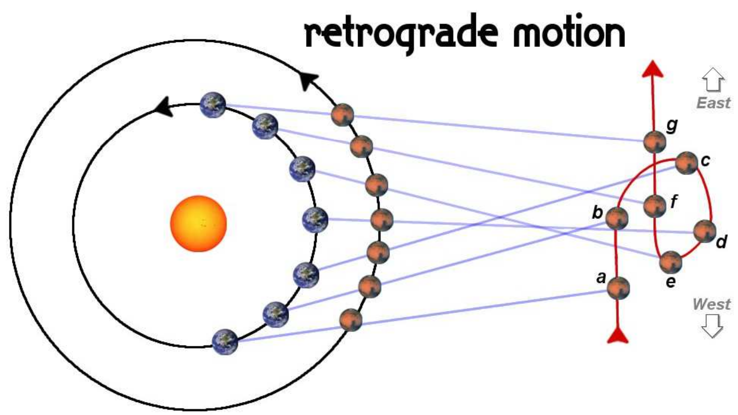
2.2 The Geocentric Universe

Early observations:

- **Inferior planets never too far from Sun,**
  Two conjunctions; inferior & superior



- **Superior planets not tied to Sun;**
  exhibit prograde & retrograde motion



- **Superior planets brightest at opposition**

- **Inferior planets brightest near inferior conjunction**

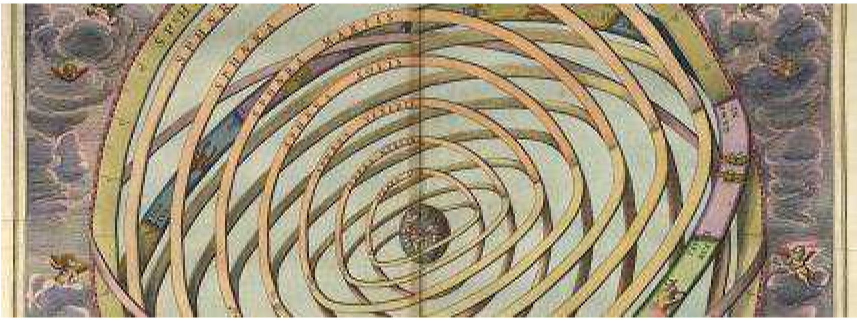
Astronomer: Finding a solar system model!

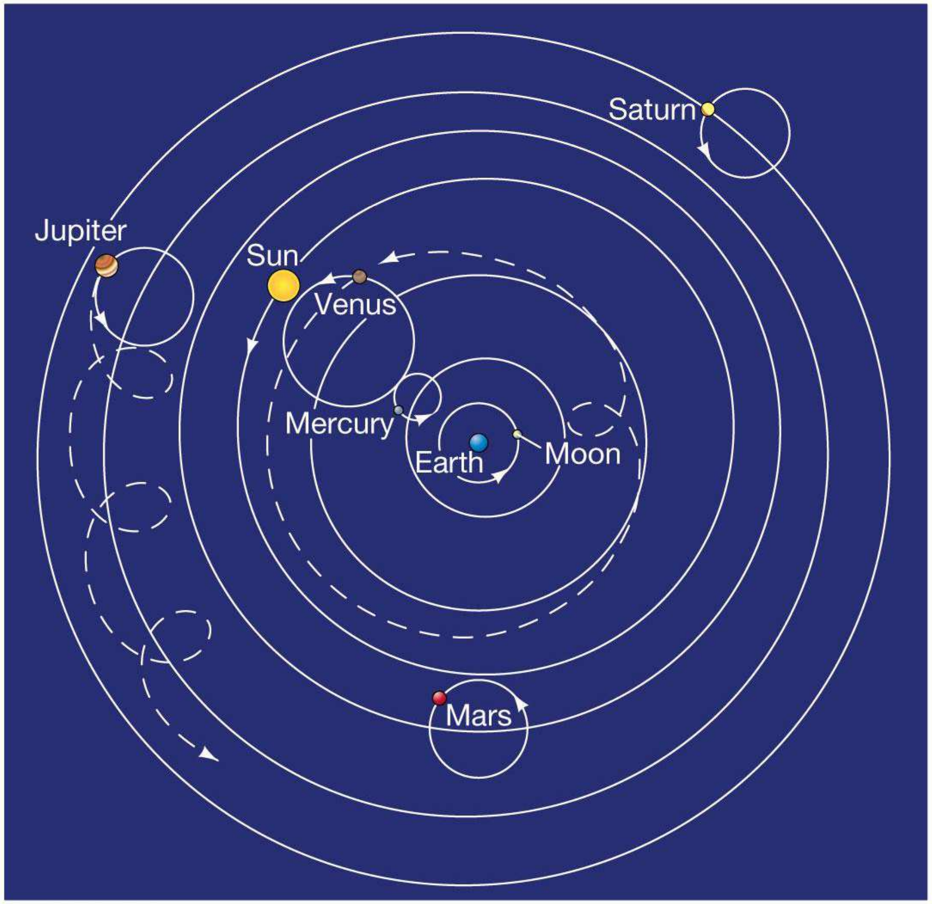
2.2 The Geocentric Universe

Geocentric: Earth lay at the center of the universe.

- **epicycle**: planet rotated around a small circle.
- **deferent**: planet rotated around the Earth in a large circle.
- Needed lots of complications to accurately track planetary motions

Ptolemaic model: 140 A.D.
most complete geocentric model
80 circles to account for paths.





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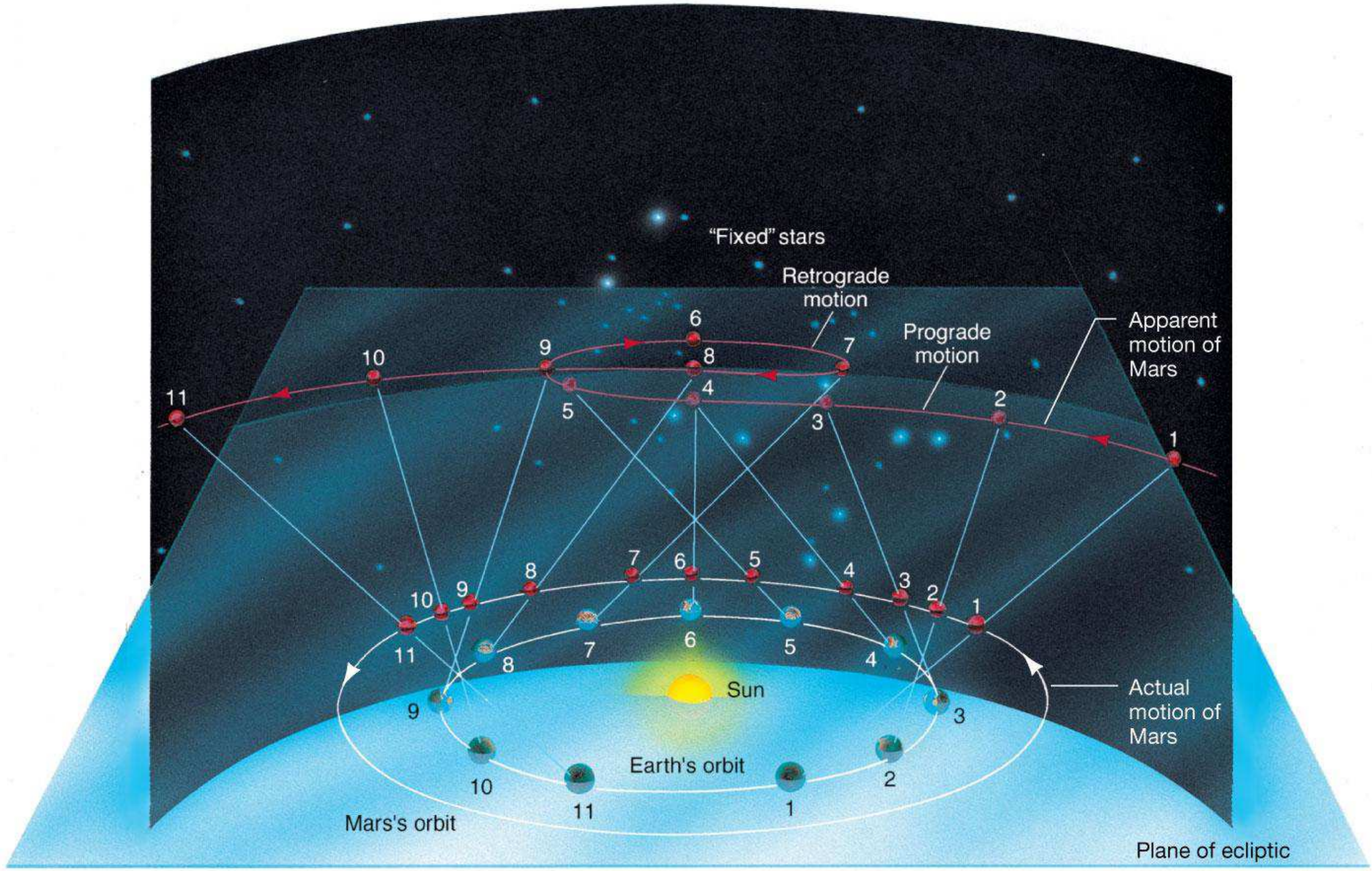
2.3 The Heliocentric Model



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https://www.youtube.com/watch?v=72FrZz_zJFU

2.3 The Heliocentric Model of the solar system

Aristarchus of Samos: 310 – 230 B.C.

"All planets revolve around the Sun, and the Earth rotates on its axis once each day"

Nicolaus Copernicus : 16th century.

"Sun is at center of solar system. Only Moon orbits around Earth; planets orbit around Sun."

Copernican Revolution (1473 – 1543)

1) The celestial spheres do not have just one common center, Earth is not at the center of everything.

2) Center of Earth is only the center of Moon’s orbit.

3) All planets revolve around the Sun.

4) The stars are very much farther away than the Sun.

5) The apparent movement of the stars around the Earth is due to the Earth’s rotation.

6) The apparent movement of the Sun around the Earth is due to the Earth’s rotation.

7) Retrograde motion of planets is due to Earth’s motion around the Sun.

2.4 The Birth of a new Astronomy

- ❖ The century following the death of Copernicus

- ❖ Telescope invented around 1600 Galileo built his own, (1564 – 1642)

made observations:

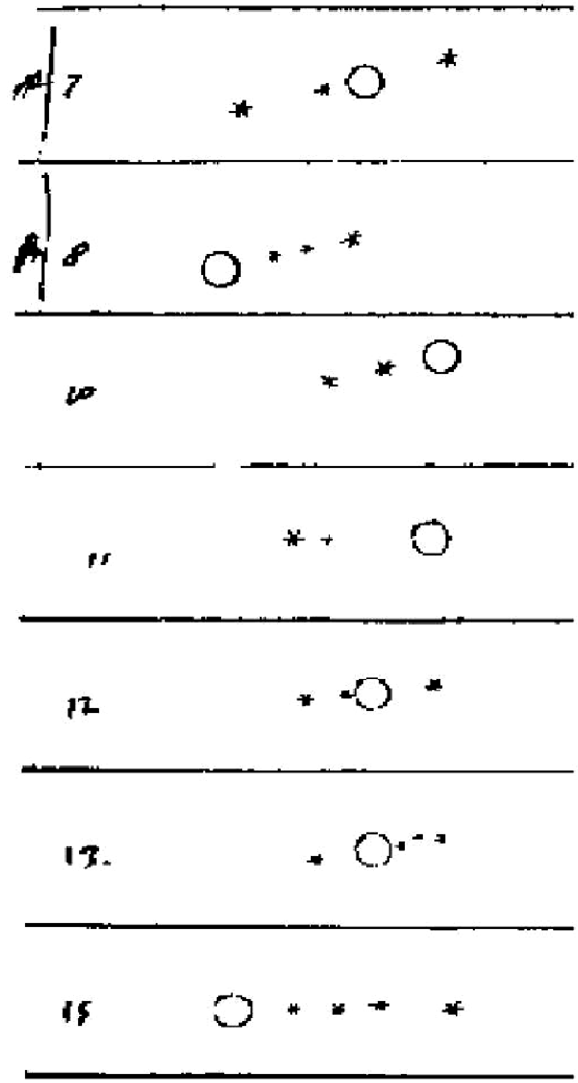
- ➢ Moon has mountains and valleys

- ➢ Sun has sunspots, and rotates 1/month

- ➢ Jupiter has moons → proof of the Copernicus model.

- ➢ Venus has phases like the moon

THE EARTH IS NOT CENTRAL



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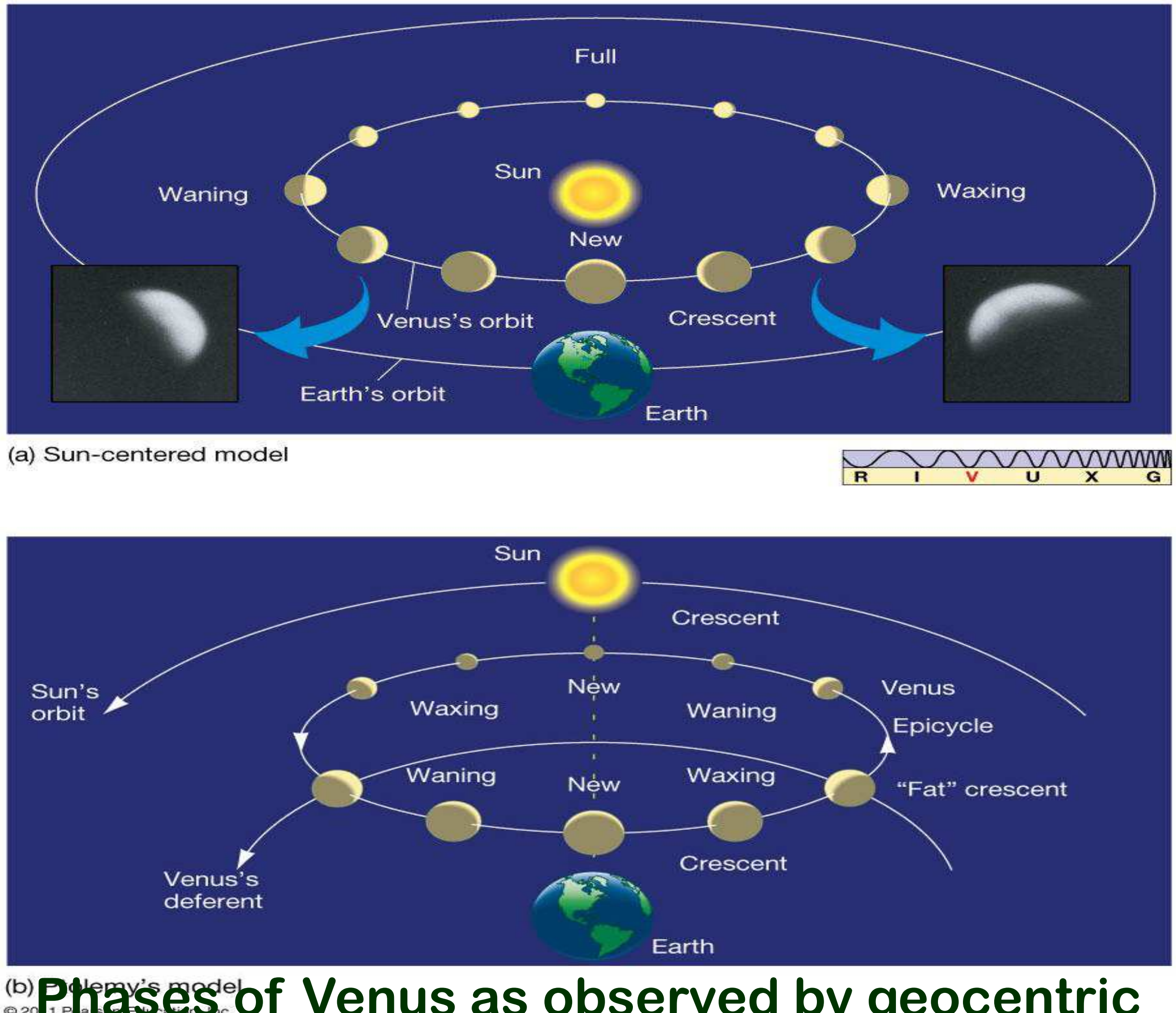
2.4 The Birth of a new Astronomy

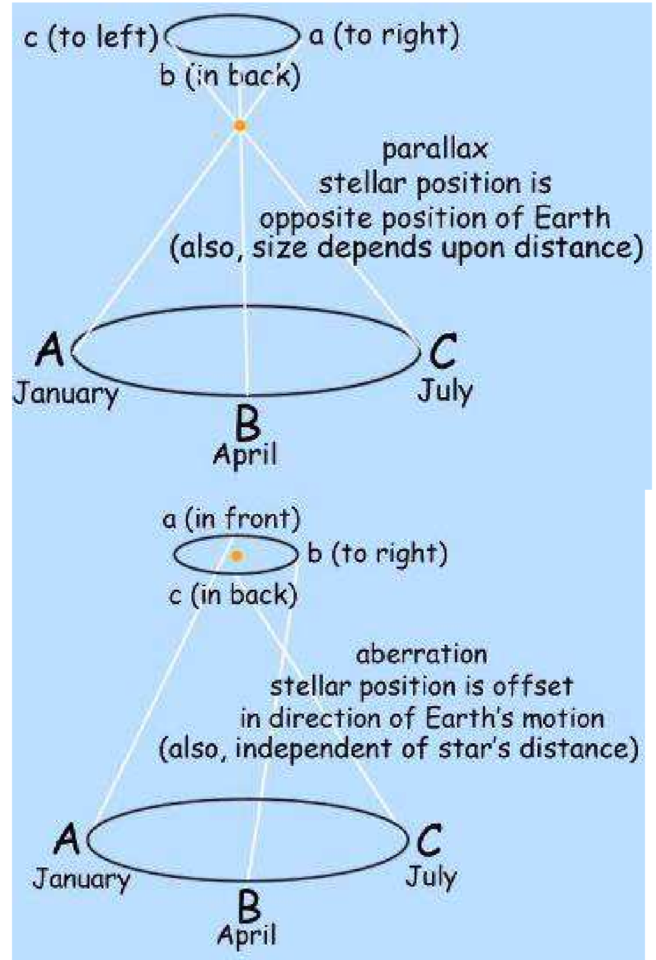


Phases of Venus as observed by geocentric & heliocentric models

2.4 The Birth of a new Astronomy

Aberration of a starlight:

- Discovered by James Bradley in 1728.
- An apparent motion of celestial objects about their true positions, dependent on the velocity of the observer.
- 20´´ in the observed direction of the star.
- Another Proof in 1838 by Friedrich Basel



2.5 The Laws of Planetary Motion

Johannes Kepler (1571 – 1630) & Tycho Brahe (1546 – 1601)

Brahe’s complex data by eye but accurate (1')

Brahe met Kepler in Prague ~ 1600

Kepler’s laws were derived using observations made by Tycho Brahe

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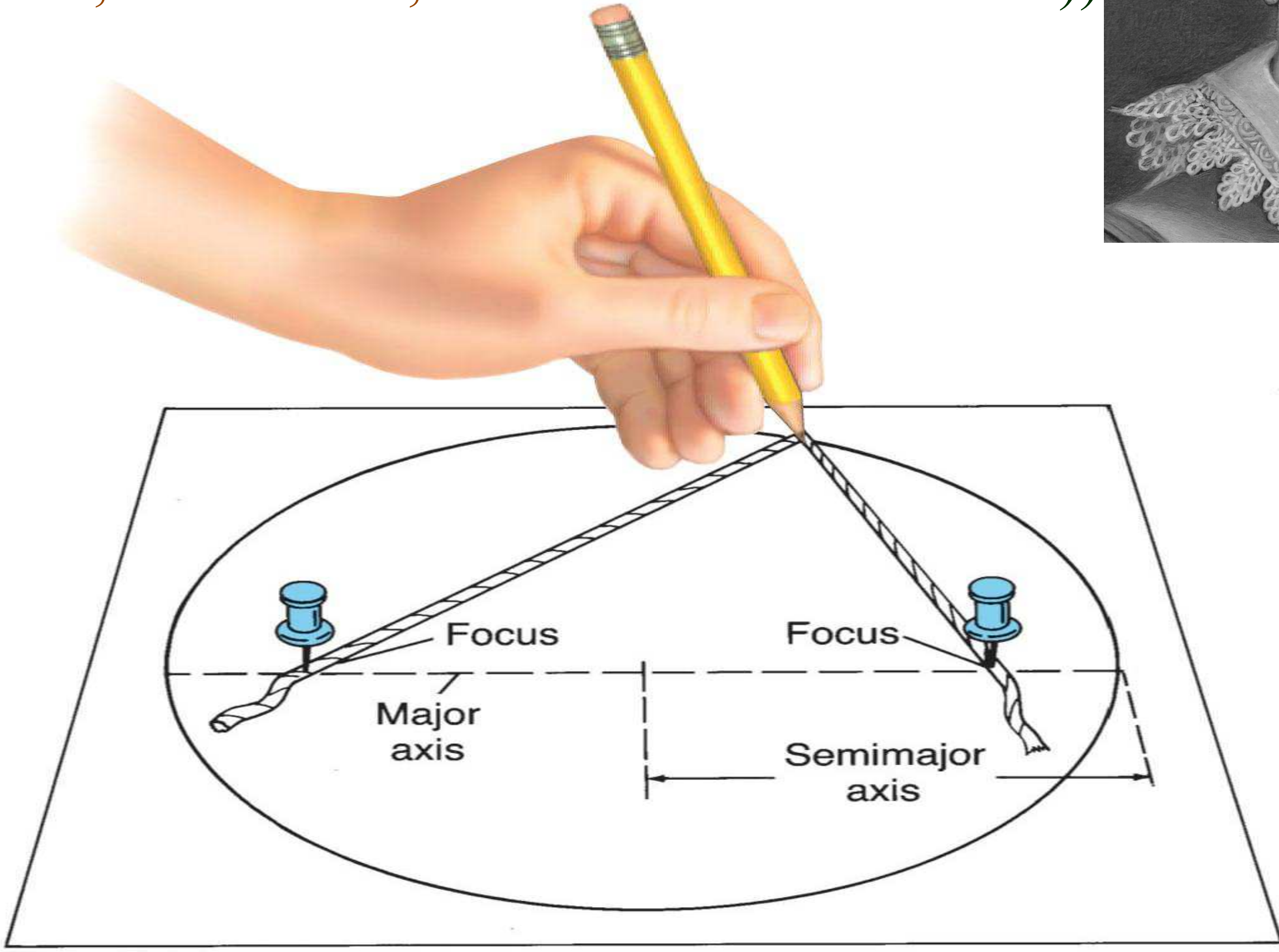
2.5 The Laws of Planetary Motion

First Law: ((The orbital paths of the planets are elliptical, not circular, with the sun at one focus))



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$$\text{eccentricity} = \frac{\text{distance between the foci}}{\text{length of the major axis}}$$

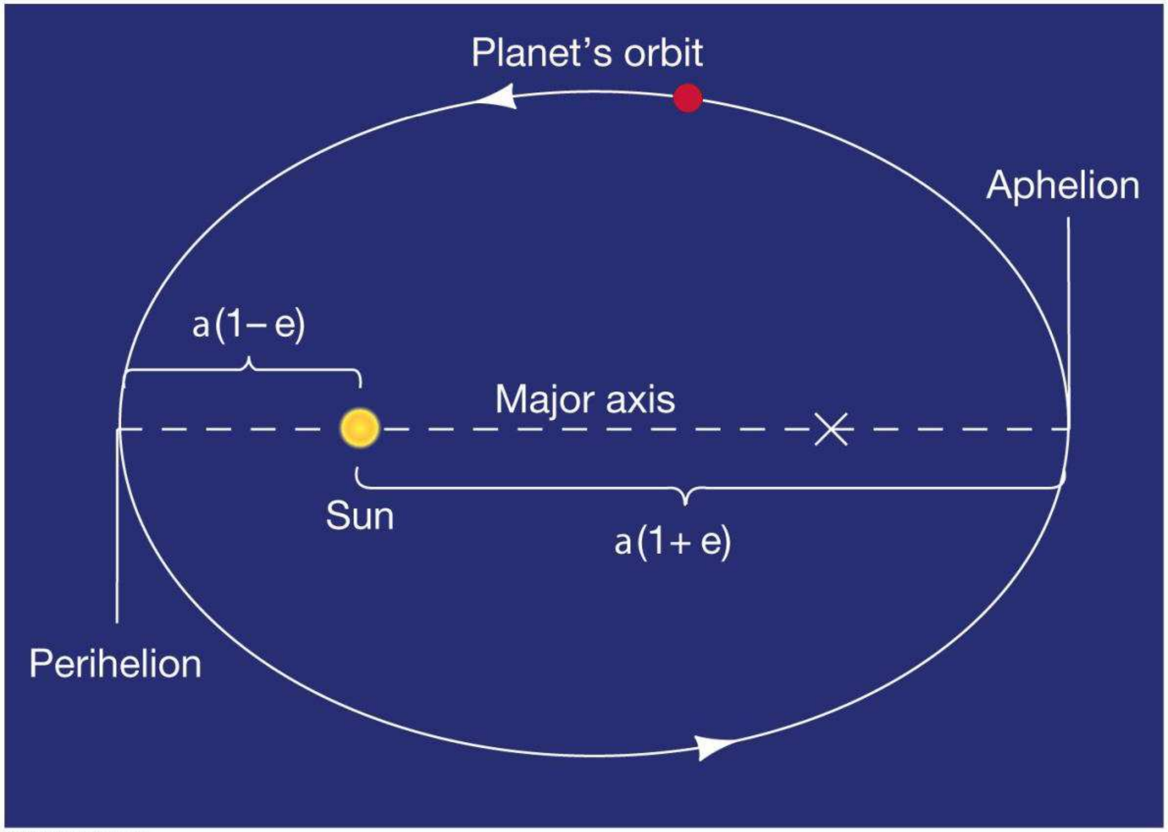
Some Properties of Planetary Orbits

Semimajor axis and eccentricity describe the size and shape of a planet's orbit.

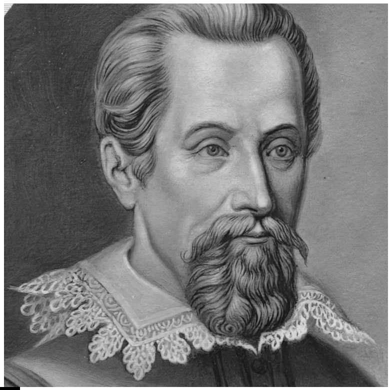
Perihelion: closest approach to Sun

Aphelion: farthest distance from Sun

The eccentricity of the Earth's orbit is currently about 0.0167; the Earth's orbit is nearly circular.



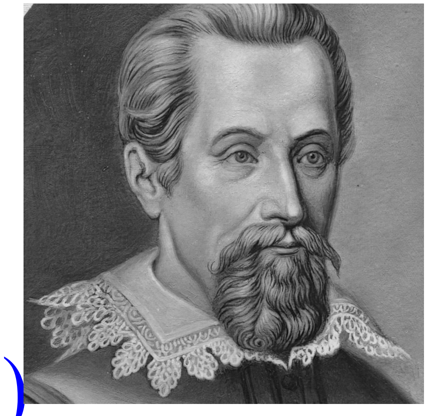
2.5 The Laws of Planetary Motion



Second Law: ((An Imaginary line connecting the Sun to any planet sweeps out equal areas of the ellipse in equal intervals of time))

2.5 The Laws of Planetary Motion

Third Law: ((The square of a planet's orbital period is proportional to the cube of its semimajor axis))



$$P^2\,(\text{in Earth years}) = a^3\,(\text{in astronomical units})$$

TABLE 2.1 Some Solar System Dimensions

Planet	Orbital Semimajor Axis, *a* (AU)	Orbital Period, *P* (years)	Orbital Eccentricity, *e*	P^2/a^3
Mercury	0.387	0.241	0.206	1.002
Venus	0.723	0.615	0.007	1.001
Earth	1.000	1.000	0.017	1.000
Mars	1.524	1.881	0.093	1.000
Jupiter	5.203	11.86	0.048	0.999
Saturn	9.537	29.42	0.054	0.998
Uranus	19.19	83.75	0.047	0.993
Neptune	30.07	163.7	0.009	0.986

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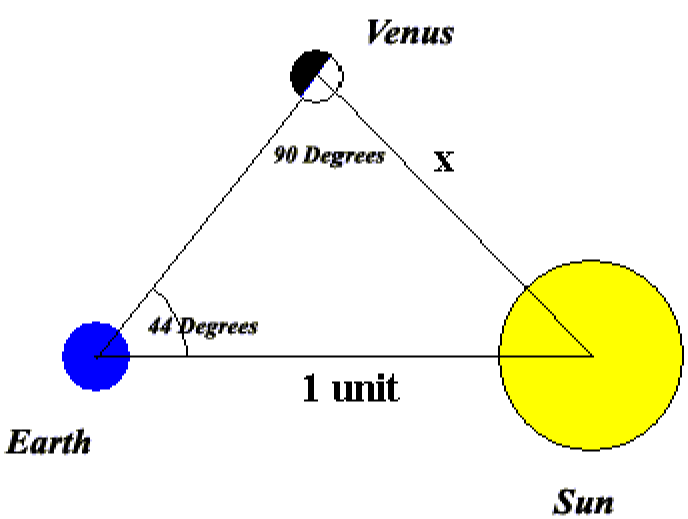
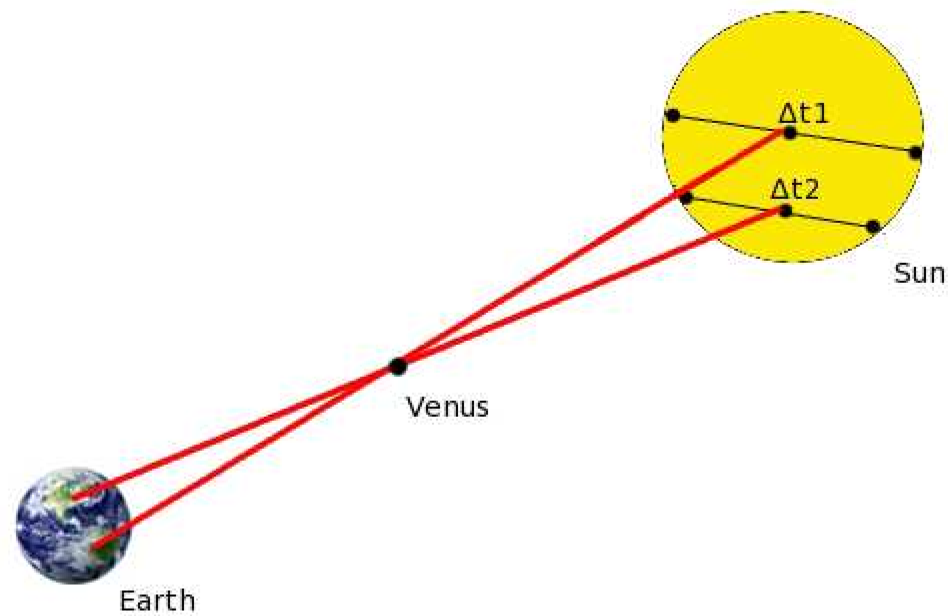
2.6 The Dimensions of the Solar System

- Kepler' s Laws: Correct shapes and relatively sizes of all the planetary orbits.
- But not the actual size of any orbit; Triangulations using portion of Earth's orbit as a baseline.
- Distance to any planet à distance from Sun to Earth
- Sun's Parallax is not possible, Sun is too bright, big, fuzzy,..
- Before 20th century, Triangulations of Mercury and Venus: ***transit***
- ***Knowing the distance to Venus ➔ 1 A.U. = 150,000,000 km***

$$1' \Rightarrow 13000km \times 57.3^o \Big/ \left(1/60^o\right) = 45,000,000km$$



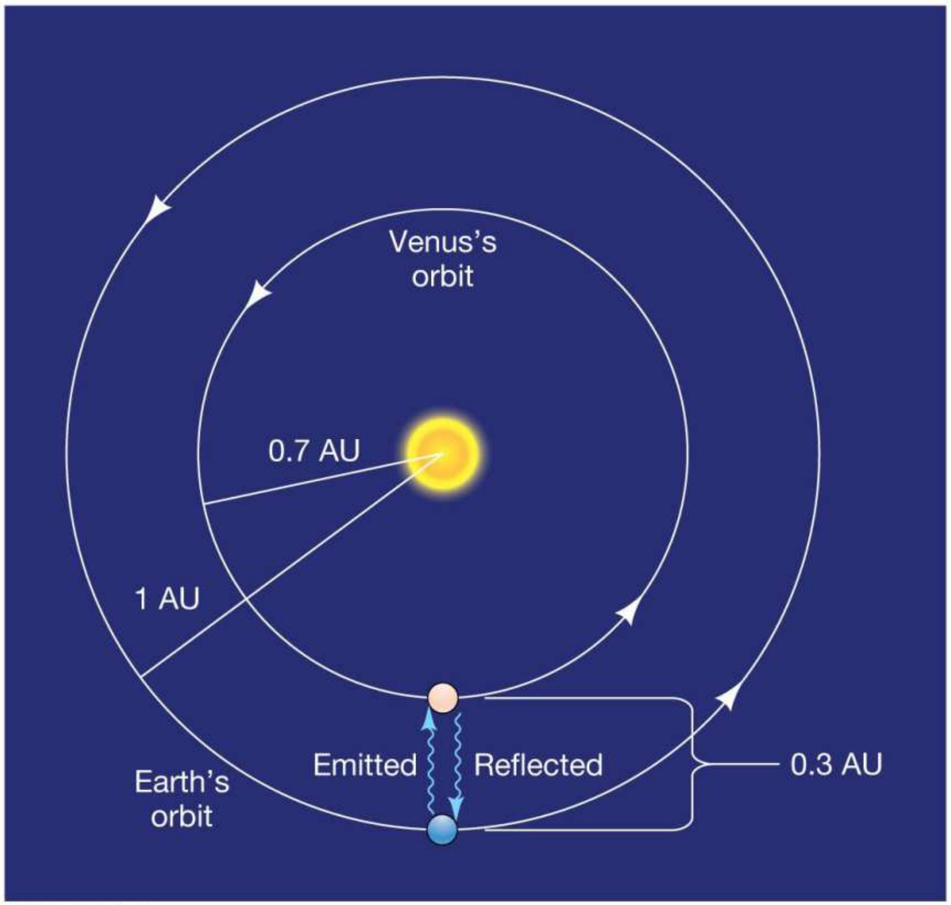


2.6 The Dimensions of the Solar System

- Modern Method ➔ RADAR ➔ radio detecting and ranging

- Signals sent to planets not the Sun, and detect the echo.

- ***1 A.U. = 149,597,870 km***



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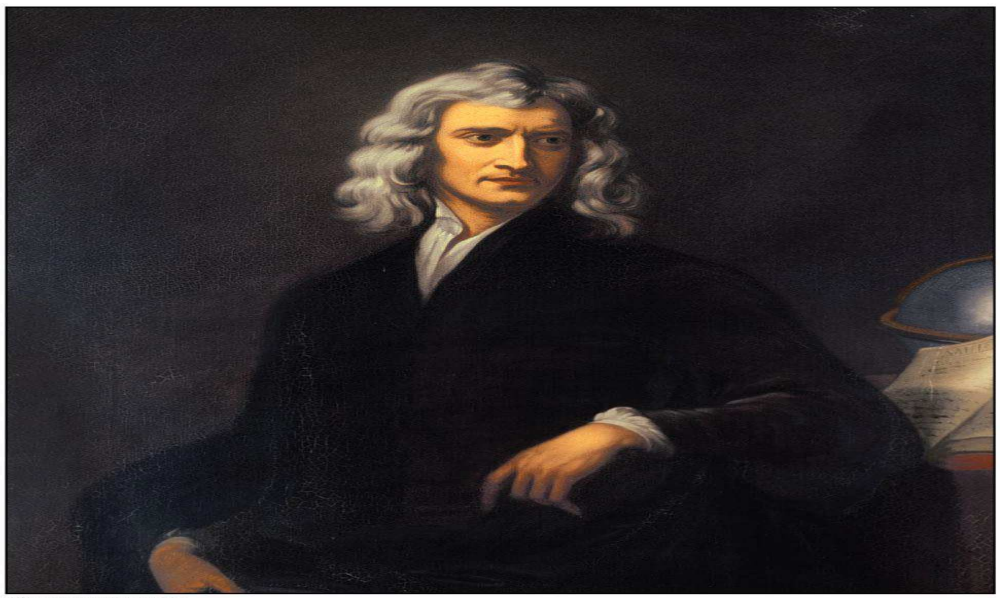
2.7 Newton's Laws

- Kepler's three laws were discovered empirically, from data not theory.
- Copernicus did not understand why his heliocentric model worked!
- ***Even Galileo (father of modern physics) failed to understand why the planets orbit the Sun.***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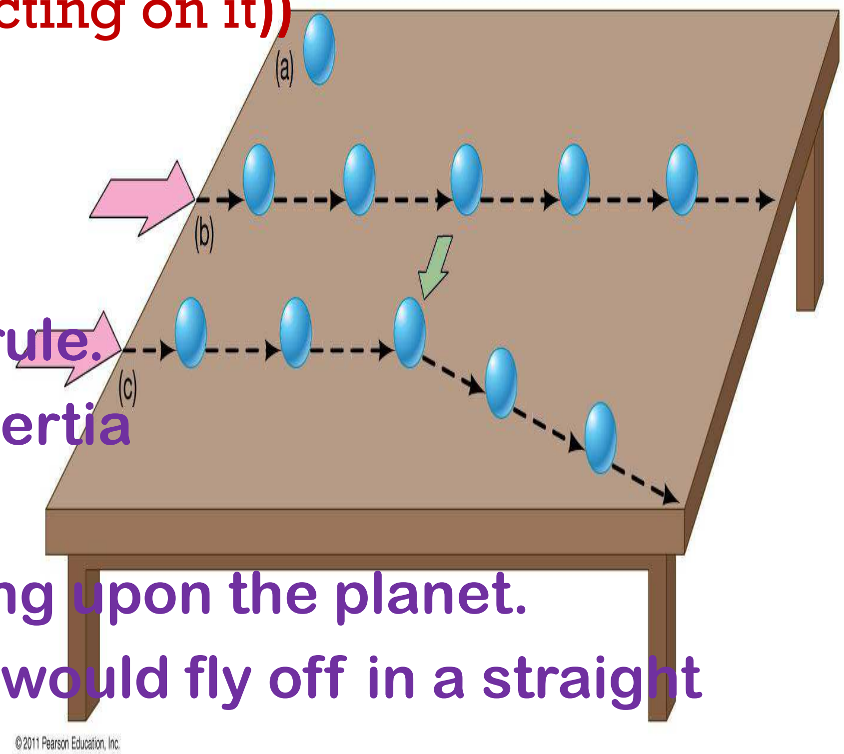
Issac Newton (1642 – 1727)

Newton's laws of motion explain how objects interact with the world and with each other.

2.7 Newton's Laws

1^{st} Law of Motion: Law of Inertia

((Every body continues is a state of rest or in a state of uniform motion in a straight line, unless it is compelled to change that state by a **FORCE** acting on it))



** The law of inertia.

** Example of a force: **Weight**

** Contradict Aristotle's stationary rule.

** **Mass** is a measure of an object inertia

** Planet is moving in an ellipse.

** There must be some "force" acting upon the planet.

** If there were no force, the planet would fly off in a straight line.

2.7 Newton's Laws

2[nd] Law of Motion

((When a force F acts on a body of mass m, it produces in it an acceleration a equal to the force divided by the mass, thus $F = ma$))

- The first law says that if no force is acting on an object, it will remain in motion.
- The second law tells how the motion will change when a force acts upon the object.
- Velocity is how fast an object is moving (speed or magnitude) *and* the direction it is moving.
- Acceleration is a change in velocity.
- An accelerating object can either change its speed, or the direction of its motion, or both.

2.7 Newton’s Laws

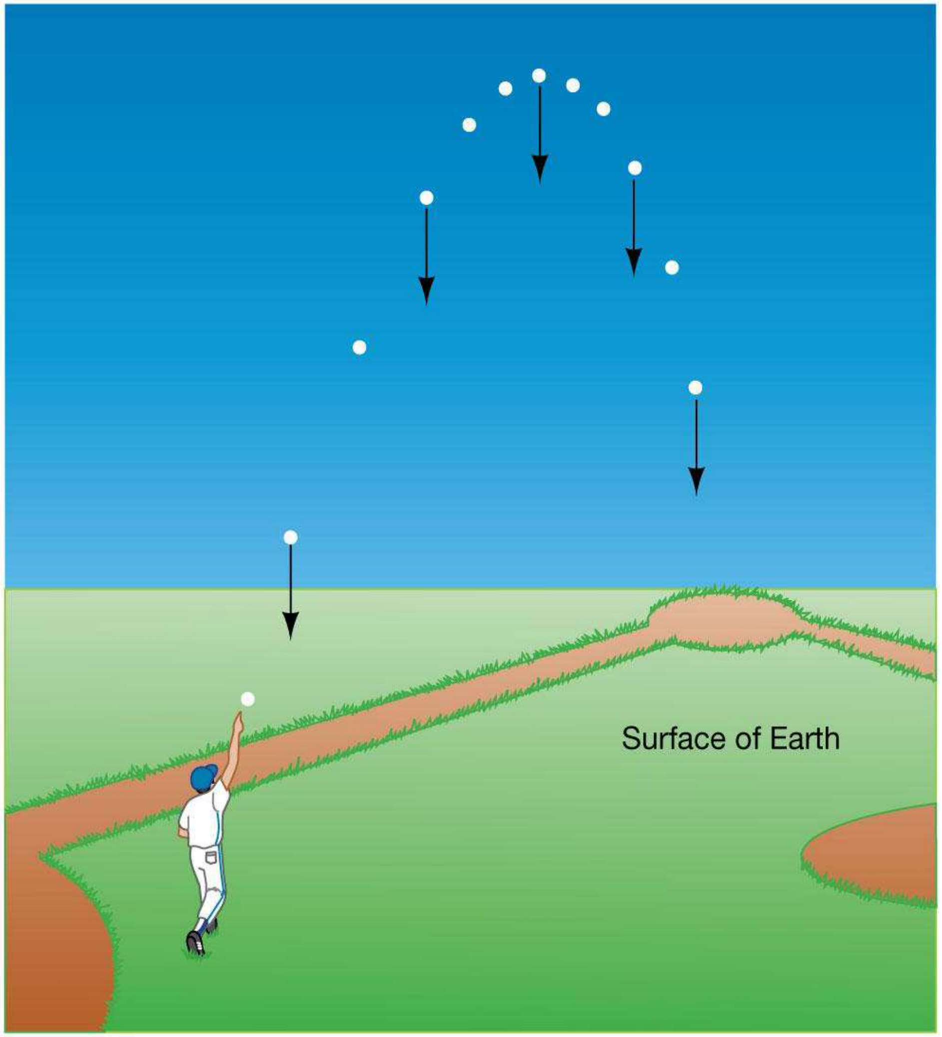
3rd Law: Law of Reciprocal Actions

((To every action, there is an equal and opposite reaction))

- “Whenever one body exerts force upon a second body, the second body exerts an equal and opposite force upon the first body.”
- When the sun pulls on a planet with the force of gravity, the planet pulls on the sun with a force of equal magnitude.
- The sun is so much more massive than the planet, ➔the Sun will experience much less acceleration.

Newton's Laws Gravity:

On the Earth's surface, acceleration of gravity is approximately constant, and directed toward the center of Earth



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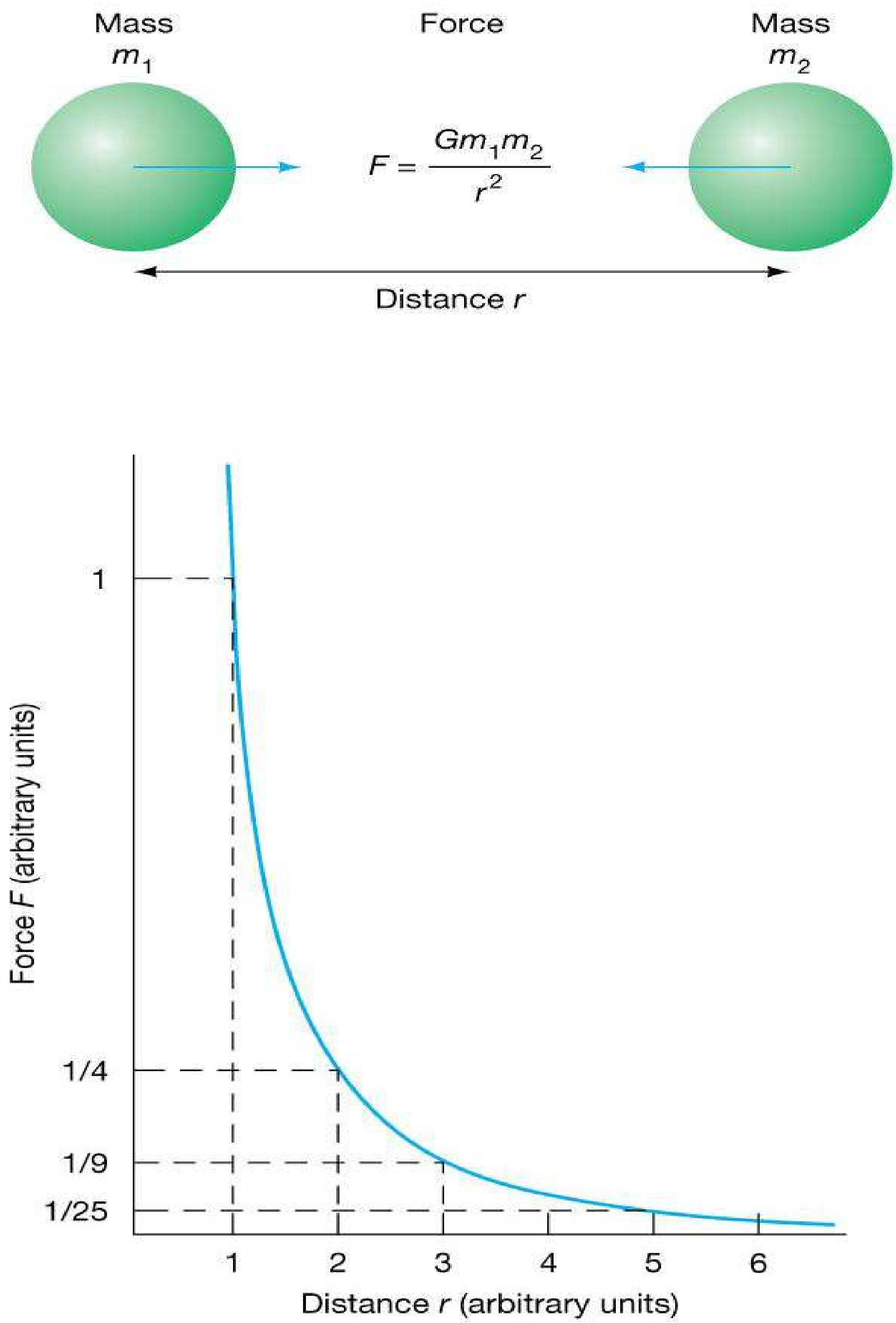
2.7 Newton's Laws



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For two massive objects, gravitational force is proportional to the product of their masses divided by the square of the distance between them

2.7 Newton's Laws

Law of Gravity $$F = \frac{Gm_1 m_2}{r^2}$$

The constant *G is called the gravitational constant; it is measured experimentally and found to be*

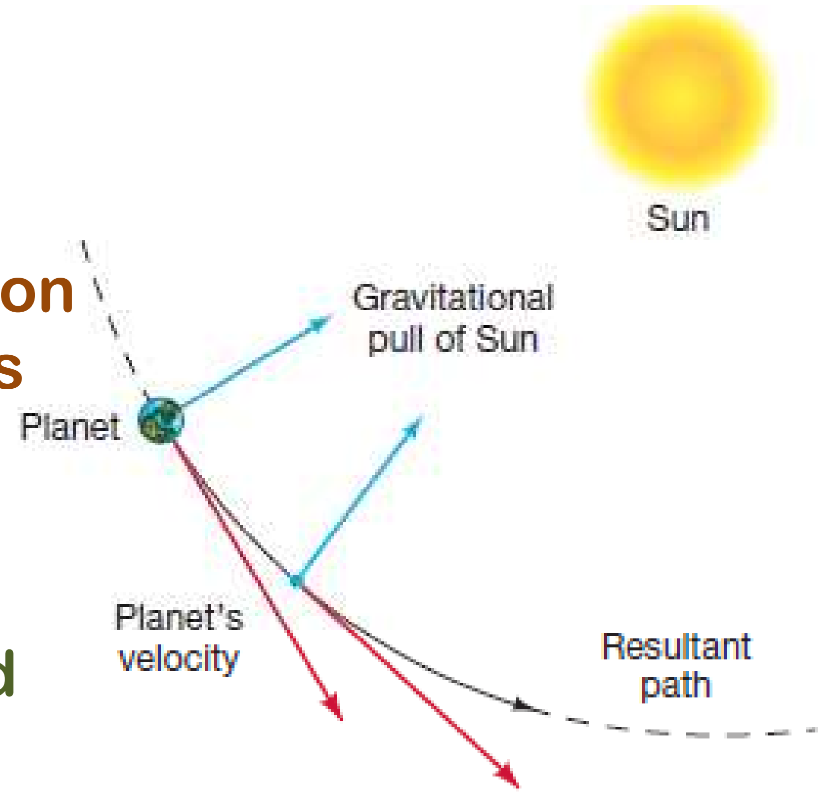
$$G = 6.67 \times 10^{-11}\ N\ m^2/kg^2$$

2.7 Newton's Mechanics

Planetary Motion

The mutual gravitational attraction between the Sun and the planets is responsible for the observed planetary orbits.

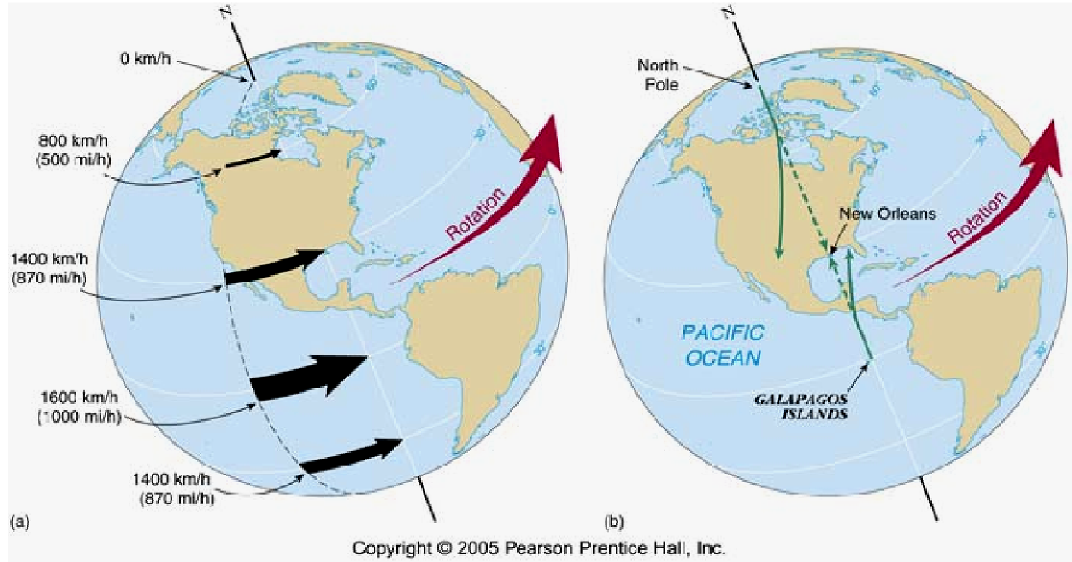
The earth is under the combined influence of gravity and inerti:
➔Stable orbit



2.8 Earth's Rotation

❖ R = 6,371 km, T = 24 hr

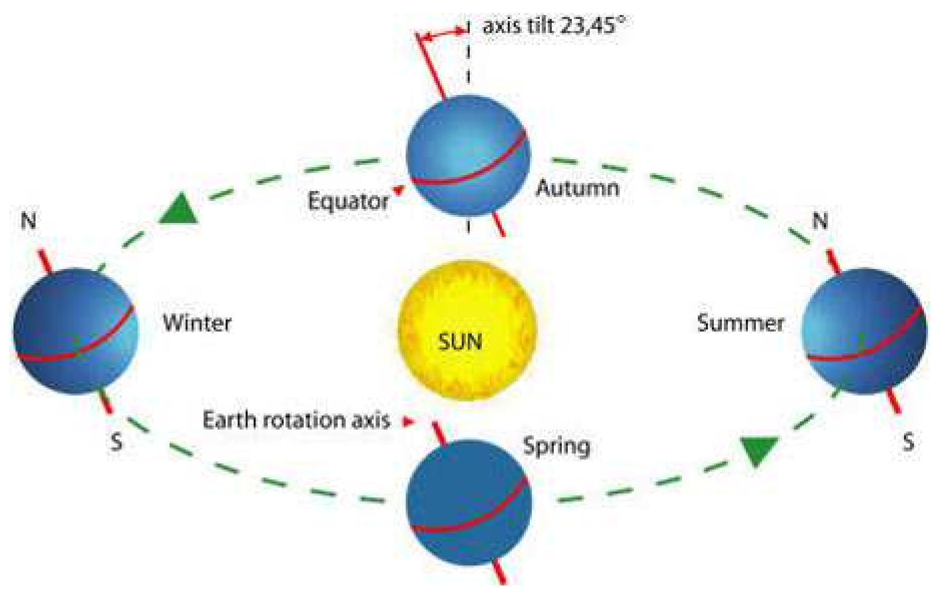
❖ 1,668 km/hr → 465 m/s



➢ R = 150,000,000 km

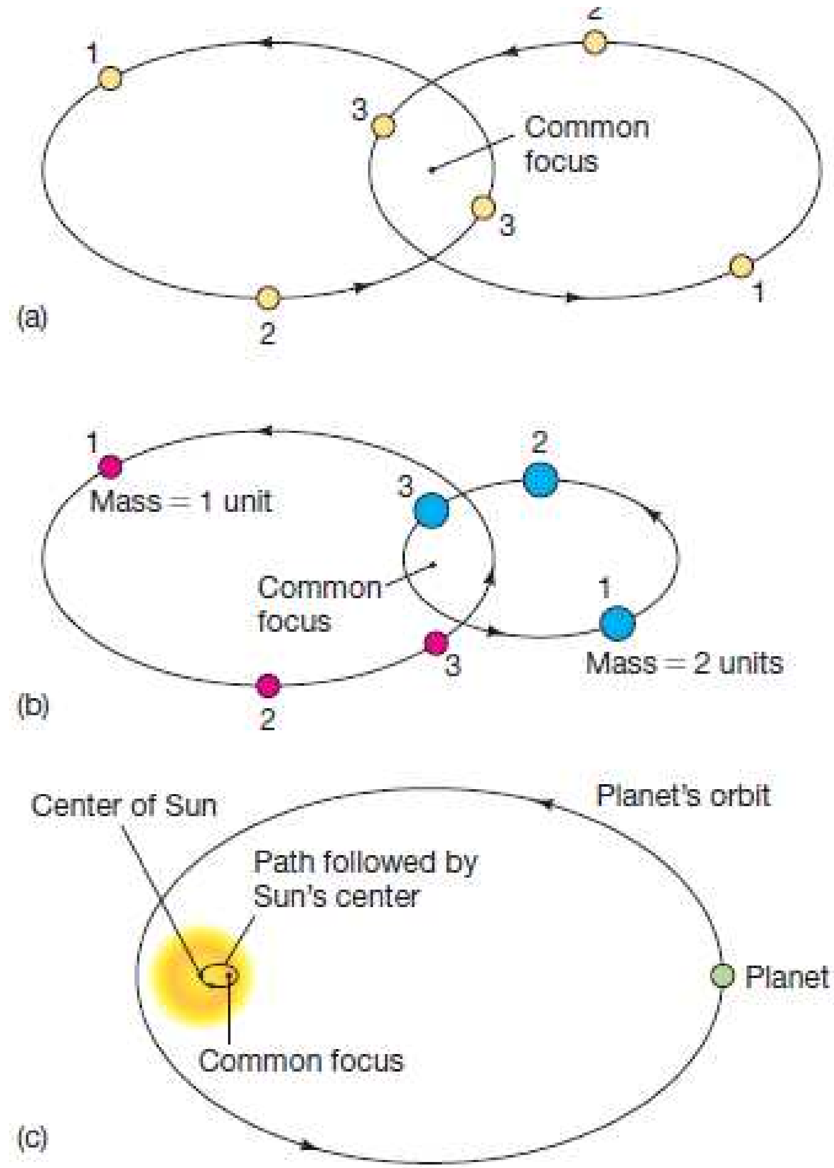
➢ T = 1 yr = 32 Ms

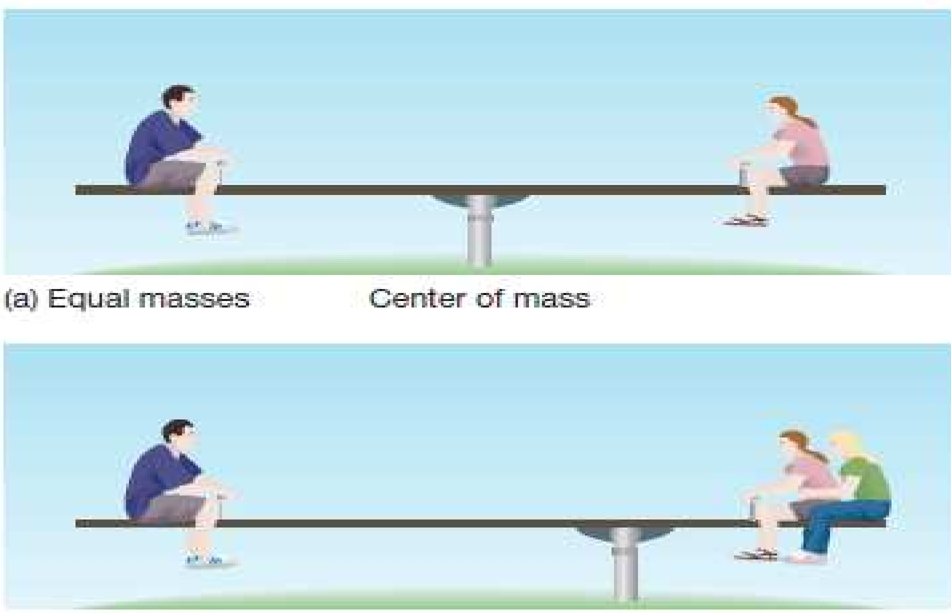
➢ 29.4 km/s



2.8 Newtonian Mechanics

- Change to the Kepler's 1st Law
- The center of a planet around the sun is an ellipse with the center of mass of the planet-Sun system at one focus.
- More massive object move more slowly on a tighter orbit.
- Center of the motion is almost the center of the Sun.





2.8 Newtonian Mechanics

- Change to the Kepler's 3rd Law is small $M_{tot} \approx M_{\odot}$

- More important for two massive stars.

$$P^2\,(\text{in Earth years}) = \frac{4\pi^2}{G}\frac{a^3\,(\text{in A.U.})}{M_{tot}\,(\text{in solar units})}$$

$$\frac{4\pi^2}{G} = 1$$

2.8 Newtonian Mechanics

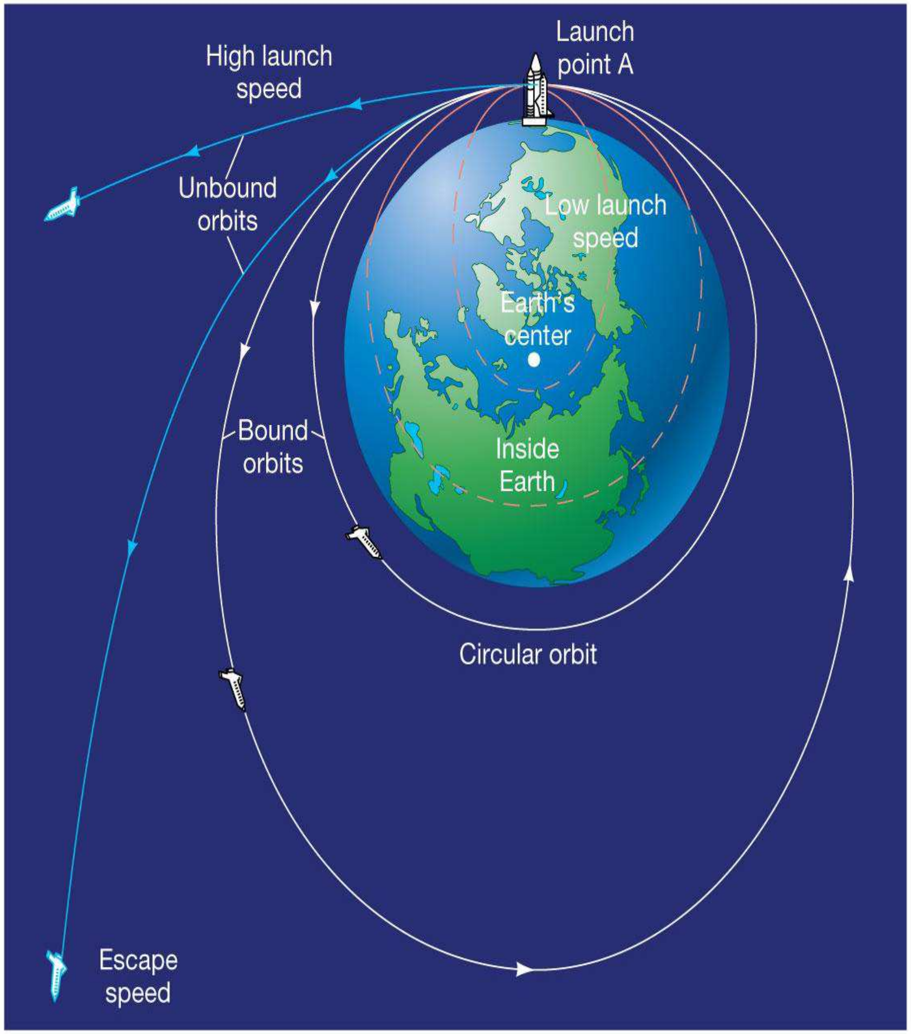
Newtonian Mechanics

Escape speed: the speed necessary for a projectile to completely escape a planet's gravitational field. With a lesser speed, the projectile either returns to the planet or stays in orbit.

$$\frac{GmM}{r^2} = \frac{mv^2}{r} \quad \text{or} \quad \frac{1}{2}mv^2 = \frac{GmM}{r}$$

$$v_{escape} = \sqrt{\frac{2GM}{r}} = 11.2 \text{ km/s}$$

$$v_{orbit} = \sqrt{\frac{GM}{r}} = 7.9 \text{ km/s}$$



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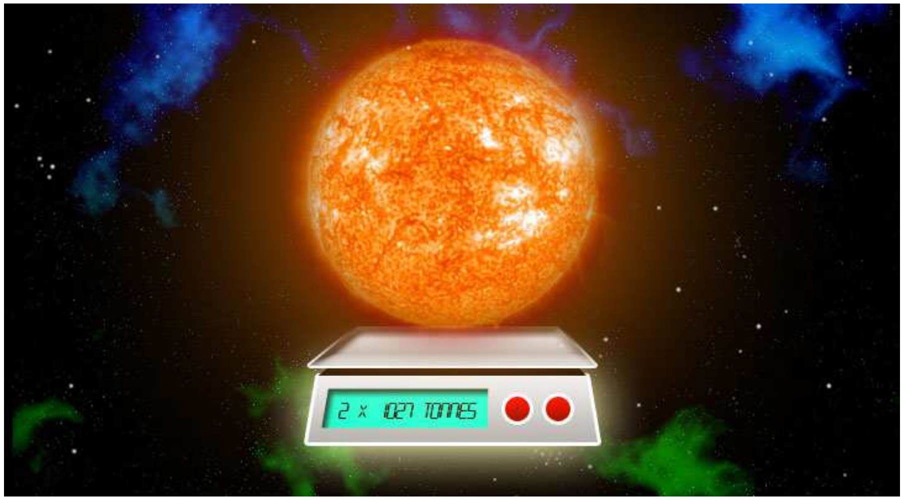
2.8 Weighing the Sun

Newtonian mechanics tells us that the force keeping the planets in orbit around the Sun is the gravitational force due to the masses of the planet and Sun.

This allows us to calculate the mass of the Sun, knowing the orbit of the Earth:

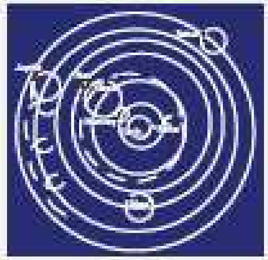
$$M = rv^2/G$$

The result is $M = 2.0 \times 10^{30}$ kg (!)



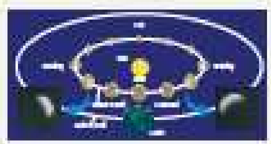
SUMMARY

1 **Geocentric (p. 38)** models of the universe had the Sun, the Moon, and the planets all orbiting Earth. The most successful of these was the **Ptolemaic model (p. 38)**. Planets sometimes appear to temporarily reverse their motion relative to the stars and later resume their normal "forward" course. This is called **retrograde motion (p. 37)**. Geocentric models explained retrograde motion as a real backward motion of a planet as it moved along its epicyclic path around Earth.

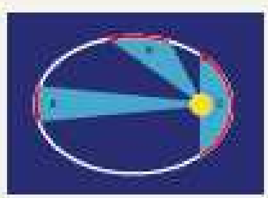


2 The **heliocentric (p. 39)** view of the solar system, due to Aristarchus and later Copernicus, holds that Earth, like all the planets, orbits the Sun. This model naturally explains both retrograde motion as Earth overtakes other planets in its orbit and the observed brightness variations of the planets. The widespread realization during the Renaissance that the solar system is Sun centered, and not Earth centered, is known as the **Copernican revolution (p. 39)**.

3 Galileo's telescopic observations of the Moon, the Sun, Venus, and Jupiter played a crucial role in supporting and strengthening the Copernican picture of the solar system. Johannes Kepler improved on Copernicus's model by condensing the observational data of Tycho Brahe into three **laws of planetary motion (p. 45)**.

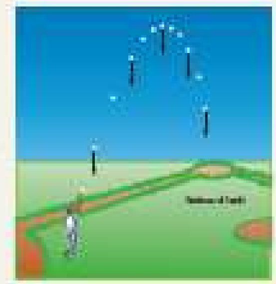


4 Kepler's Laws state: (1) Planetary orbits are **ellipses (p. 45)** with the Sun at one **focus (p. 45)**; (2) a planet moves faster as its orbit takes it closer to the Sun; (3) the **semimajor axis (p. 45)** of the orbit is related in a simple way to the planet's orbital **period (p. 47)**. Most planetary orbits differ only slightly from perfect circles.



5 The average distance from Earth to the Sun is one **astronomical unit (p. 47)**, today most accurately determined by bouncing **radar (p. 48)** signals off the planet Venus. Once this distance is known, the distances to all other planets can be inferred from Kepler's laws.

6 To change the body's velocity, a force (p. 48) must be applied. The rate of change of velocity, called **acceleration (p. 50)**, is equal to the applied force divided by the body's **mass (p. 50)**. When bodies interact, the forces between them are always equal and opposite to one another. To explain Kepler's laws, Newton postulated that **gravity (p. 51)** attracts the planets to the Sun. Every object having any mass exerts a **gravitational force (p. 51)** on all other objects. The strength of this force decreases with distance according to an **inverse-square law (p. 51)**.



7 For one object to escape from the gravitational pull of another, its speed must exceed the **escape speed (p. 54)** of that other object. By determining the gravitational force needed to keep one body orbiting another, Newton's laws allow astronomers to measure the masses of distant objects.


END CHAPTER2